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DEVELOPMENT OF RUTTING PREDICTION MODEL FOR PAVING MIXES USING CREEP TEST

استنباط نموذج للتنبؤ بتخدد خلطات الرصف باستخدام اختبار الزحف

Mohamed Elsaid Abdel-Motaleh
Lecturer, Faculty of Engineering, Zagazig University, Egypt

المنخص العربي

يعتبر تخدد الرصف من المشاكل المعقدة بسبب تداخل العديد من العوامل في حدوثه. لذا تم اقتراح عدة وسائل لتقييم مقاومة خلطات الرصف للتخدد. من بين هذه الوسائل المقترحة، يعتبر اختبار الزحف أقرب وسيلة في مصر لهذا الغرض. يجري هذا الاختبار في درجة حرارة لاتقل عن ٤٠° م لمدة لاتقل عن ساعة طبقا للشروط القياسية ويعد تطبيق هذه الشروط في معامل الطرق المصرية أمرا صعبا نسبيا. لذلك تهدف هذه الدراسة إلى تبسيط وسيلة يمكن استخدامها أثناء مرحلة تصميم الخلطة في التنبؤ بالتخدد المتوقع في الطبقة الأسفلتية في ظل الظروف الحقيقية للرصف من حرارة وأحمال مرور. لتحقيق هذا الهدف تم تكوين عدة خلطات أسفلتية شائعة الاستخدام في حقل تشييد الطرق، حيث تم استخدام ثلاثة أنواع من الحجر وثلاثة تدرجات مع تغيير المحتوي الأسفلتي وتغيير طاقة الدمك. كما تم قياس عمق التخدد المتوقع لهذه الخلطات عند ثلاث درجات حرارة لأربع قيم لتكرار الحمل باستخدام اختبار الزحف، هذا بجانب قياس الخصائص التقليدية لهذه الخلطات. وباستخدام نتائج اختبار الزحف وخصائص الخلطة التقليدية تم استنباط عدة علاقات يمكن استخدامها في التنبؤ بعمق التخدد المتوقع في ظروف محددة من الحرارة وتكرار الأحمال. ومن ثم تم استنباط علاقة عامة للتخدد كدالة في خصائص الخلطة ودرجة الحرارة وتكرار الأحمال يمكن استخدامها في التنبؤ بقيمة التخدد المتوقع في الطبقة الأسفلتية لأي درجة حرارة ولأي تكرار للأحمال، وكانت القيم المحسوبة للتخدد باستخدام النموذج المستنبط قريبة جدا من القيم المقاسة. وأخيرا أوصت الدراسة باستخدام خلطات خشنة متدرجة ورمال ناتج تكسير كسارات مع تقليل المحتوي الأسفلتي بجانب الدمك الكافي لزيادة مقاومة خلطات الرصف للتخدد.

ABSTRACT

Rutting phenomena in asphalt pavement is a complicated problem because of the overlapping of many factors causing it. So, many methods have been proposed to assess rutting resistance of paving mixes. Among those proposed methods, the static creep test represents the most promising one for this purpose in Egypt. The test is typically conducted at 40° C for at least one hour. Hanging up the test for long period at elevated temperature may be difficult for routine laboratory mix design in Egypt. So, the current study is primarily concerned with simplifying a technique that can be used, in mix design phase for predicting the expected rut depth in asphalt layer at the actual temperature after actual wheel passes. To achieve this objective, many paving mixes typically used in pavement construction, were formed using different aggregate types and gradations, asphalt contents, compaction efforts. Then, the expected rut depths of these mixes were measured using creep test at three test temperatures along with four repetitions of wheel loads. Also routine mix characteristics of these mixes were measured. Rutting prediction models for each definite combination of traffic and temperature were developed using the results of creep tests and routine mix characteristics. Then, a general model was developed. This model can be used to predict the rut depth of an asphalt mix at the actual temperature along with the actual number of wheel passes with the aid of routine mix characteristics. The predicted values of rut depth using the developed model compared very closely with the measured values. Finally the study recommended to use coarse graded mix, crushed sand, low asphalt content and sufficient compaction to increase rutting resistance of paving mixes.

KEYWORDS:

Paving Mix, Rut Depth, Creep Test, Wheel Passes and Temperature.

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INTRODUCTION AND BACKGROUND

Pavement rutting is defined as the formation of twin longitudinal depressions in the wheel paths, resulting from progressive movement of materials under repeated loads in one or more layer of the pavement system. The drastic changes in traffic characteristics in Egypt have indicated that rutting is one of the principal distress modes surveyed due to its high severity and extent levels, and consequently its impact on the pavement conditions [1]. Important findings of a recent study in Egypt [2] have indicated that, the asphalt layer has contributed a significant amount, about 70% on the average, from the total pavement rutting. Many methods have been proposed to assess rutting tendency of paving mixes. These include the traditional Marshall and Hveem tests, uniaxial and triaxial static and dynamic creep tests, and SUPERPAVE direct shear test. Among those proposed testing methods, the static creep test represents the most promising one for assessing rutting tendency of paving mixes in Egypt because of its availability and simplicity [1, 3]. In 1970, Shell laboratories have developed mix evaluation procedures in which resistance to deformation was regarded as one of the decisive criteria. This technique is based mainly on the results of creep test. The most popular creep test is the static unconfined. It is a special type of triaxial test, in which the transverse stress is zero (i.e. uniaxial constant load compression test). This test involves application of a static load to the specimen for a specified time and temperature, and measurement of deformation with time [4]. Many investigators [3, 5] found that the correlation between the irreversible creep strain and the permanent rutting strain is equal to the correlation between the total creep strain and the permanent rutting strain. Therefore, in a creep test, the reversible part of the strain can be omitted. Since the asphalt creep curves are to be related to rutting performance, creep tests must be carried in the linear stress range, which means in practical terms at sufficiently low stress levels. Bolk and Van de Loo [5] indicated that most of the mixes are assumed to be in the linear stress range if they are tested at $\sigma = 0.1$ MN/m^2 (14.5 psi). They also conducted an experimental program in which the pre-load in combination with the pre-loading time was varied in the various creep testing apparatus. From the results and in combination with practical consideration, they recommended that pre-stress of 10^4 N/m^2 (1.45 psi.) and pre-loading duration of 2 minutes are realistic conditions for Marshall shape specimen. The main objective of this study is concerned with the development of a general rutting model to simplify measuring rut depth of paving mixes at different temperatures and different repetitions of wheel loads. To achieve this objective, a comprehensive experimental program was designed and explained as shown in the following sections.

EXPERIMENTAL DESIGN

The design of experiment of this study is concerned with selecting mix variables and testing conditions most related to rutting tendency of asphalt mixes to be investigated. Three types of coarse aggregate, two types of fine aggregate, three mix gradations and three compaction efforts were investigated in this study. Table (1) represents the used mix gradations and the corresponding specification limits. The compaction efforts were simulated in the laboratory by varying the number of blows for compacting the specimens. The considered number of blows was 35, 50 and 75. The different investigated mixes and their conditions are shown in Table (2). Also, three test temperatures (25, 40 and 60 °C) along with four repetitions of wheel loads (10^5, 10^6, 10^7 and 10^8) were investigated as 12 cases of testing conditions for Temperatures (T) and Wheel Passes (W) as shown in Table (3).

MATERIALS

Three types of coarse aggregates were used in this study. They are crushed limestone, crushed dolomite and crushed basalt. Limestone was obtained from "Al-Haram" quarry, Giza Governorate; dolomite was obtained from "ATAKA" quarry, Suez Governorate;and basalt was obtained from "Abu Zabal" quarry, Qalubia Governorate. The results of their qualification tests are presented in Table (4). Two types of fine aggregates were used. The first was natural siliceous sand with bulk specific gravity of 2.65, obtained from "Fayed" quarry, Ismailia Governorate. The second type was the fine material of crushed dolomite with bulk specific gravity of 2.68. These materials have been collected during coarse aggregate crushing operations. Only one type of mineral filler was used in preparing all the investigated asphaltic paving mixtures in this study. It was limestone filler of bulk specific gravity of 2.85. Gradations of the two types of sand and mineral filler are shown in Table (5). Suez asphalt cement (60/70-penetration grade) of 1.022 specific gravity was used as bituminous material. The engineering properties of the used asphalt cement are shown in Table (6).

TESTING PROGRAM

Two major tests were conducted through the laboratory-testing program of this study. These tests are: Standard Marshall and static creep tests.

Marshall Test

In order to find the Optimum Asphalt Contents (OAC'*) for the investigated mixes, Marshall mix design procedure was performed. The test criterion selected was for a 75 blows Marshall compaction according to ASTM D1559 and AASHTO T-245.

Creep Test

The creep test was conducted using the consolidation-testing machine with some modifications to accommodate the size of test specimen (Marshall specimen). The used technique to maintain the test temperature constant during the performance of the test was similar to that developed by Howeedy et al [6]. In which, the temperature of the test was controlled through the use of an ordinary electric heater. The electric heater was controlled by a thermostat to reach the desired temperature. Each specimen was pr-loaded by a weight of 8.1 Kg (to produce preconditioning stress of 0.01 Mpa) for a period of 2 minutes in order to press the protruding parts to define the best starting conditions of the test. The test was progressed by applying constant vertical stress level, σ = 0.1 Mpa in the axial direction of the tested sample in a very short time and then held constant until the test was completed at the specified temperature. The deformation was measured as a function of time. A dial gauge with an accuracy of 0.01 mm was used to measure the deformation. The vertical deformations and the corresponding loading times were recorded during the period of the test at five-minute intervals. The creep strain ($\varepsilon_c = \Delta H/H$; in which ΔH is the measured vertical deformation and H is the original height of the tested specimen) and the corresponding stiffness modulus of the mix ($S_{mix} = \sigma/\varepsilon_c$) were then determined at different time intervals during the load application.

ANALYSIS OF RESULTS

The routine mix characteristics according to Marshall test of the investigated mixes are shown in Table (7). The creep test results of the investigated mixes at the three test temperatures along with the four investigated numbers of wheel passes were determined as follows:

Determination of S_{bit}

A penetration index (PI) of 0.0 was calculated from Pfeiffer and Van Doormall [7] relations for the used asphalt cement. This asphalt cement has softening point ($T_{R\&B}$) of 52 °C and a penetration value of 63. Using Van der Poel's Nomograph [8] with these properties of asphalt cement along with the test temperature, the values of bitumen stiffness modulus (S_{bit}) were determined at the same time intervals as shown in Table (8).

Determination of $S_{bit,visc}$

$S_{bit,visc}$ was determined for each number of wheel passes according to the Shell technique using the following relation:

$$S_{bit,visc} = 3\times\eta / (W\ t_o) \qquad (1)$$

Where:

η = Absolute viscosity of asphalt cement (N.sec / m^2); was obtained from Van de Loo's nomogrph [9], using $T_{R\&B}$ and PI along with the three test temperatures. Results are shown in Table (8).

t_O = Time of one wheel pass, recommended as 0.02 sec. [9].

W = Number of wheel passes; taken in this study as 10^5, 10^6, 10^7 and 10^8.

The calculated values of $S_{bit,visc}$ of the investigated wheel passes are shown in Table (9).

Determination of $S_{mix,visc}$

Constructing the relationship between log S_{bit} and log S_{mix}, derived from the creep test, and using the value of (S_{bit}) equal to the calculated value of ($S_{bit,visc}$), the corresponding value of (S_{mix}) is in fact $S_{mix,visc}$. The values of $S_{mix,visc}$ of the investigated paving mixes are shown in Table (10).

Determination of Rut Depth

Using the calculated value of ($S_{mix,visc}$) at the time when the value of (S_{bit}) = ($S_{bit,visc}$), the rut depth values for the investigated mixes were calculated using the following relation [9]:

$$\text{Rut Depth} = C_m \times H \times \frac{Z\sigma_o}{S_{mix}} \qquad (2)$$

Where:

C_m = Correlation factor for the dynamic effect depending on the mix type, taken as 1.5;

H = The original thickness of the asphalt layer, taken as 60 mm;

Z = A correlation factor for the difference in the state of stress between the creep test and practice, taken as 0.60; and

σ_O = The contact stress between the standard wheel and road surface (6×10^5 N/m^2).

The rut depth values of the investigated mixes at the three test temperatures along with the four investigated numbers of wheel passes (12 cases) are shown in Table (11).

DEVELOPMENT OF TEMPERATURE AND WHEEL PASSES MODEL

The rut depth (RD) values of the investigated 12 cases of testing conditions presented in Table (11) were used for developing temperature and wheel passes effect model for rutting. A multiple regression analysis using SPSS program [10] was performed to determine RD at the most difficult conditions from those measured at easy conditions. The values of RD_o measured at T_o = 25 °C and W_o = 10^5 were used as a reference case to predict RD of the other 11 cases. By combining these cases (each of 20 observations) together, including 220 observations in multiple regression analysis and after several trials to obtain the best fit for the data, the following exponential relationship (R^2 = 0.99 and S_e = 0.038) provides the best fit of the data:

$$RD = RD_o \, (T/T_o)^{2.13} \, (W/W_o)^{0.27} \qquad (3)$$

Where:

RD = The predicted value of rut depth (mm);
RD_o = The measured value of rut depth (mm) at T_o and W_o;
T = The actual temperature (°C);
T_o = The test temperature (room temperature) (°C);
W = The predicted number of wheel passes; and
W_o = The number of wheel passes considered in the test (10^5 passes).

The developed relation can be used to determine RD at any T and W by conducting creep test at room temperature (T_o) for a period not more than one hour ($W_o = 10^5$). The existence of this relation is checked statistically using the F- test. The $F_{Comp.}$ is 11266.7 and the corresponding $F_{Crit.}$ value at a significant level α = 0.01 and degree of freedom 2, (n-1-2 = 217) is 4.61 (n = number of observations = 220). Since $F_{Comp.}$ is greater than $F_{Crit.}$, the relation exists at the chosen significant level.

ESTIMATING RUT DEPTH FROM ROUTINE MIX CHARACTERISTICS

The RD values of the investigated 12 cases of testing conditions, presented in Table 11 along with the routine characteristics of the investigated mixes, presented in Table (7), were used for developing the mix conditions effect models. A multiple regression analysis (SPSS) was performed to determine RD from these data. After considering a large number of trial and error solutions, the combination of mix characteristics, which gave the highest correlation and lowest standard error, was selected. The developed 12 models are presented in Table (12). The model which gave the highest correlation and lowest standard error (R^2 = 0 .971 and S_e = 0.036) for case T25W5 (T_o = 25 and $W_o = 10^5$), was selected as an example of these models with the form:

$$\begin{aligned} RD = & - 0.004 + 0.0066 \, (VFA) + 0.1615 \, (A) \\ & + 0.252 \, (G) + 0.213 \, (C) - 0.0096 \, (S_M) \end{aligned} \qquad (4)$$

Where:

RD = rut depth (mm) at T_o = 25 °C and $W_o = 10^5$;
VFA = % voids filled with asphalt;
A = aggregate factor (1.0, 0.75 and 1.20 for dolomite, limestone and basalt, respectively);
G = gradation factor (1.0, 0.75 and 1.40 for 4C, 3A and 5A, respectively);
C = compaction factor (1.0, 1.2 and 1.4 for high, medium and low compaction, respectively); and
S_M = Marshall stiffness (MPa).

For more simplification, the two developed models (3 and 4) were combined together into one general model for rutting prediction of paving mixes based on routine mix characteristics, temperature and wheel passes. By substituting T_o = 25° C and $W_o = 10^5$ for T25W5 case, the following exponential relation was suggested:

$$\begin{aligned} RD = & \, 4.7 \times 10^{-5} \, (T)^{2.13} \, (W)^{0.27} \{- 0.004 + 0.0066 \\ & (VFA) + 0.1615 \, (A) + 0.252 \, (G) + 0.213 \, (C) \\ & - 0.0096 \, (S_M)\} \end{aligned} \qquad (5)$$

This model was developed based on the asphalt mixes all using the same asphalt 60/70 binder. Applicability of this model should be further validated with asphalt mixes using different grades of asphalt binders. The predicted rut depth values using the developed model are presented in Table (13). The predicted values compare very closely with the measured ones.

CONCLUSIONS

Based on the methodology and analysis of results of this study, the following conclusions were drawn:

1. The probable rut depth of asphalt layer at any field condition can be predicted with good accuracy using the developed relations.
2. Rut depth values increase by a factor of 2.7 and 7 as the temperature increases from 25 to 40 ° C and from 25 to 60 ° C, respectively.
3. Increasing asphalt content by 1% above OAC leads to increasing rut depth by a factor of 1.5, while decreasing it by 1% leads to decreasing rut depth by a factor of 0.75.
4. Rut depths of paving mixes containing limestone and basalt were found to be about 0.75 and 1.40 times that containing dolomite, respectively.
5. Mixes containing basalt (as coarse portion) and crushed sand (as fine portion) showed 5% higher resistance to rutting than that containing dolomite and natural sand.
6. Rut depth of paving mixes using 3A gradation was found to be about 0.75 and 0.50 times that using 4C and 5B gradations, respectively.
7. Rut depths of paving mixes at medium and low compactive efforts were found to be about 1.20 and 1.40 times that at high compactive efforts, respectively.
8. The rutting rate of paving mixes decreases as the number of wheel passes increases.
9. It is recommended to use coarse graded mix, crushed sand and sufficient compaction at low asphalt content to reduce rutting tendency of paving mixes.

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Table 1: Gradations of the Investigated Mixtures used in the Study.

Sieve Size	Designed Gradation			Specification Limits		
	3A	4C	5B	3A	4C	5B
1 in	100	100	100	100	100	100
3/4 in	100	90	100	100	80 – 100	100
1/2 in	100	80	92	100	-	85 – 100
3/8 in	88	70	85	75 – 100	60 – 80	-
No. 4	45	56	73	35 – 55	48 – 65	65 – 80
No. 8	28	43	58	20 – 35	35 – 50	50 – 65
No.16	20	30	45	-	-	37 – 52
No. 30	16	24	33	10 – 22	19 – 30	25 – 40
No. 50	11	18	24	6 – 16	13 – 23	18 – 30
No. 100	8	11	15	4 – 12	7 – 15	10 – 20
No. 200	5	5.5	6.5	2 – 8	3 – 8	3 – 10

Table 2: Mix Variables used in the Study

Mix No	Coarse Aggr. Type			Sand type		Gradation			Asphalt Content (%)			Compaction Effort (blows)		
	D	L	B	NS	CS	4C	3A	5B	OAC -1%	OAC	OAC +1%	35	50	75
1	*			*		*			*					*
2	*			*		*				*				*
3	*			*		*					*			*
4		*		*		*			*					*
5		*		*		*				*				*
6		*		*		*					*			*
7			*	*		*			*					*
8			*	*		*				*				*
9			*	*		*					*			*
10	*				*	*				*				*
11		*			*	*				*				*
12			*		*	*				*				*
13	*			*			*			*				*
14	*			*				*		*				*
15	*			*		*				*			*	
16	*			*		*				*		*		
17	*			*			*			*			*	
18	*			*			*			*		*		
19	*			*				*		*			*	
20	*			*				*		*		*		

Notes. D = Dolomite, L = Limestone, B = Basalt, NS = Natural Sand, CS = Crushed Sand

Table 3: Cases of Testing Conditions for Temperatures (T) and Wheel Passes (W).

T&W	T = 25° C				T = 40° C				T = 60° C			
	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8
Case	T25W5	T25W6	T25W7	T25W8	T40W5	T40W6	T40W7	T40W8	T60W5	T60W6	T60W7	T60W8

Table 4: Properties of Coarse Aggregate Materials

Test No.	Test	AASHTO Designation No.	Results			Specification Limits
			Dolomite	Limestone	Basalt	
1	Specific gravity (S.G):	T-85				
	-Bulk S.G		2.512	2.285	2.782	-
	-Saturated surface-dry		2.539	2.413	2.836	-
	S.G		2.659	2.601	2.958	-
2	-Apparent S.G	T-85	2.6	4.75	2.12	≤ 5
3	Water absorption (%)	T-112	0.63	0.90	0.54	≤ 1
4	Disintegration (%)	T-96				
	Los Angeles Abrasion:		5.6	9.3	4.8	≤ 10
	-After 100 rev. (%)		24	39	20	≤ 40
5	-After 500 rev. (%)	T-182	> 95	> 95	> 95	≥ 95
	Stripping (%)					

Table 5: Gradations of Fine Materials

Sieve Size	Percent Passing			Specification Limits For Mineral Filler
	Natural Sand	Crushed Sand	Mineral Filler	
No. 4	100	100		
No. 8	95	96		
No. 16	84	85		
No. 30	64	63	100	100
No. 50	21	22	95	-
No. 100	3.5	2.6	88	≥ 85
No. 200	1.5	1.2	70	≥ 65

Table 6: Properties of Bituminous Material used in the Study

Test No.	Test	AASHTO Designation No.	Results of AC 60/70	Specification Limits of AC 60/70
1	Penetration (at 25 ^{o}C), 0.1 mm	T-49	63	60 - 70
2	Softening point. ^{o}C	T-53	52	45 - 55
3	Flash point, ^{o}C	T-48	+270	≥ 250
4	Kinematic Viscosity.(at 135 ^{o}C), Cst	T-72	353	≥ 320

Table 7: Routine Characteristics of the Investigated Mixes.

Mix No.	AC (%)	AV (%)	VMA (%)	VFA (%)	Unit weight (gm/cm^3)	Stability (N)	Flow (mm)	S_M (Mpa)
1	4.5	5.70	15.60	63.5	2.312	9118	2.35	61.14
2	5.5*	3.50	15.50	77.4	2.331	10008	2.67	59.11
3	6.5	1.80	17.00	89.4	2.362	7784	3.18	38.62
4	5.6	6.40	18.30	65.1	2.212	9786	2.29	67.43
5	6.6*	4.00	17.70	77.4	2.252	11787	2.60	71.32
6	7.6	2.00	19.10	89.5	2.273	12010	3.30	57.30
7	4.0	6.30	15.50	59.4	2.423	7339	2.41	47.91
8	5.0*	3.70	15.10	75.5	2.462	8674	2.92	46.78
9	6.0	1.90	16.60	88.6	2.472	7562	3.56	33.50
10	5.5	3.60	15.60	76.9	2.325	10675	2.54	66.21
11	6.6	4.10	17.85	77.1	2.244	12232	2.67	72.25
12	5.0	3.70	15.25	75.7	2.455	10230	2.73	59.02
13	5.2*	4.20	16.65	74.8	2.312	9519	2.41	62.14
14	6.2*	3.10	14.50	78.6	2.363	10920	3.11	55.28
15	5.5	3.70	15.60	76.3	2.325	9608	2.79	54.17
16	5.5	4.10	16.00	74.4	2.323	8407	2.98	44.37
17	5.2	4.50	18.00	75.0	2.300	11476	2.73	66.21
18	5.2	5.00	18.50	73.0	2.272	11076	3.11	56.08
19	6.2	3.25	15.25	78.7	2.301	8318	2.92	44.86
20	6.2	3.40	15.50	78.1	2.252	7740	3.24	37.65

Note: * OAC, obtained from Standard Marshall Design Method.
S_M Marshall Stiffness = Stability / (Flow * Specimen Height)

Table 8: S_{bit} Versus Loading Time and Absolute viscosity (η) of asphalt cement at Different emperatures

TR&B = 52 °C, Pen. = 63 and PI = 0.0			
Time of loading (min)	S_{bit} (N/m^2)		
	T = 25 °C	T = 40 °C	T = 60 °C
5	4500	200	8.00
10	2450	110	4.50
15	1700	70	2.70
20	1400	60	2.30
25	1200	45	1.60
30	1000	40	1.50
35	850	35	1.25
40	750	30	1.15
45	670	25	1.05
60	500	20	0.90
120	240	10	0.45
180	170	7	0.35
η (N.sec/m^2)	3 X 10^6	3 X 10^4	0.8 X 10^3

Table 9: $S_{bit,visc}$ at Different Temperatures (T) and Wheel Passes (W).

T & W	T = 25° C				T = 40° C				T = 60° C			
	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8
$S_{bit,visc}$ (Pa)	1500	150	15	1.5	45	4.5	0.45	0.045	1.2	0.12	0.012	0.0012

Table 10: $S_{mix,visc}$ (Mpa) of the Investigated Mixes at Different Temperatures (T) and Wheel Passes (W).

Mix No	T = 25° C				T = 40° C				T = 60° C			
	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8
1	70.28	38.62	21.22	11.66	28.24	15.52	8.53	4.69	11.01	6.05	3.32	1.83
2	64.51	31.05	16.67	8.95	22.43	12.05	6.47	3.47	8.43	4.53	2.43	1.31
3	41.36	20.45	11.24	6.18	14.96	8.22	4.52	2.48	5.83	3.20	1.76	0.97
4	101.3	51.50	28.96	16.28	38.11	21.43	12.05	6.78	15.40	8.66	4.87	2.74
5	78.74	40.01	22.50	12.65	29.61	16.65	9.36	5.27	11.97	6.73	3.78	2.13
6	56.75	27.31	14.67	7.88	19.73	10.60	5.69	3.06	7.42	3.98	2.14	1.15
7	59.58	30.27	17.02	9.57	22.40	12.60	7.08	3.98	9.05	5.09	2.86	1.61
8	46.48	22.99	12.63	6.94	16.81	9.24	5.08	2.79	6.55	3.60	1.98	1.09
9	36.64	18.37	10.21	5.68	13.51	7.51	4.18	2.32	5.36	2.98	1.66	0.92
10	70.80	35.02	19.24	10.57	25.61	14.07	7.73	4.25	9.98	5.48	3.01	1.66
11	88.33	44.88	25.24	14.19	33.22	18.68	10.50	5.91	13.42	7.55	4.24	2.39
12	67.48	32.48	17.44	9.37	23.47	12.60	6.77	3.63	8.82	4.74	2.54	1.37
13	79.54	40.41	22.73	12.78	29.91	16.82	9.46	5.32	12.09	6.80	3.82	2.15
14	46.40	22.33	11.99	6.44	16.13	8.66	4.65	2.50	6.06	3.26	1.75	0.94
15	53.41	25.71	13.81	7.41	18.57	9.97	5.36	2.88	6.98	3.75	2.01	1.08
16	46.58	22.42	12.04	6.47	16.20	8.70	4.67	2.51	6.09	3.27	1.76	0.94
17	67.53	33.40	18.35	10.09	24.42	13.42	7.37	4.05	9.52	5.23	2.87	1.58
18	56.75	27.31	14.67	7.88	19.73	10.60	5.69	3.06	7.42	3.98	2.14	1.15
19	39.52	20.08	11.29	6.35	14.86	8.36	4.70	2.64	6.01	3.38	1.90	1.07
20	36.72	18.66	10.49	5.90	13.81	7.77	4.37	2.46	5.58	3.14	1.76	0.99

Table 11: Measured RD of the Investigated Mixes at Different Temperatures (T) and Wheel Passes (W).

Mix No	T = 25° C				T = 40° C				T = 60° C			
	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8
1	0.492	0.895	1.628	2.963	1.224	2.227	4.052	7.374	3.140	5.714	10.39	18.92
2	0.536	1.113	2.073	3.859	1.541	2.869	5.342	9.947	4.099	7.633	14.21	26.46
3	0.836	1.690	3.075	5.595	2.311	4.205	7.651	13.92	5.929	10.79	19.63	35.72
4	0.341	0.671	1.193	2.122	0.907	1.613	2.868	5.099	2.244	3.991	7.096	12.62
5	0.439	0.864	1.536	2.731	1.167	2.075	3.691	6.563	2.888	5.136	9.133	16.24
6	0.609	1.265	2.356	4.387	1.751	3.261	6.072	11.31	4.660	8.676	16.16	30.08
7	0.580	1.142	2.030	3.610	1.543	2.743	4.878	8.674	3.817	6.788	12.07	21.46
8	0.744	1.503	2.736	4.978	2.056	3.741	6.808	12.39	5.276	9.600	17.47	31.79
9	0.943	1.882	3.385	6.089	2.558	4.602	8.278	14.89	6.446	11.60	20.86	37.52
10	0.488	0.987	1.796	3.268	1.350	2.456	4.469	8.133	3.463	6.302	11.47	20.87
11	0.391	0.770	1.369	2.435	1.040	1.850	3.290	5.851	2.575	4.579	8.142	14.48
12	0.512	1.064	1.981	3.689	1.473	2.742	5.106	9.509	3.918	7.296	13.59	25.30
13	0.435	0.855	1.521	2.704	1.155	2.055	3.654	6.498	2.859	5.085	9.042	16.08
14	0.745	1.548	2.882	5.366	2.142	3.989	7.427	13.83	5.699	10.61	19.76	36.80
15	0.647	1.344	2.503	4.661	1.861	3.465	6.452	12.01	4.951	9.219	17.17	31.97
16	0.742	1.542	2.871	5.345	2.134	3.973	7.398	13.78	5.677	10.57	19.69	36.66
17	0.512	1.035	1.883	3.427	1.415	2.575	4.686	8.528	3.632	6.608	12.02	21.88
18	0.609	1.265	2.356	4.387	1.751	3.261	6.072	11.31	4.660	8.676	16.16	30.08
19	0.874	1.721	3.060	5.442	2.325	4.135	7.353	13.08	5.754	10.23	18.20	32.36
20	0.941	1.852	3.294	5.857	2.503	4.451	7.914	14.07	6.193	11.01	19.59	34.83

Table 12: Rutting Prediction Models using Routine Mix Characteristics for Different Cases of Temperature (T) and Wheel Passes (W).

Case	Rutting Model	R^2	S_e
T25W5	RD = - 0.004 + 0.0066 (VFA) + 0.1615 (A) + 0.2520 (G) + 0.213 (C) - 0.0096 (S_M)	0.971	0.036
T25W6	RD = - 0.486 + 0.0162 (VFA) + 0.4172 (A) + 0.4914 (G) + 0.515 (C) - 0.0177 (S_M)	0.970	0.070
T25W7	RD = - 1.331 + 0.0317 (VFA) + 0.8660 (A) + 0.8630 (G) + 1.020 (C) - 0.0302 (S_M)	0.965	0.147
T25W8	RD = - 3.235 + 0.0621 (VFA) + 1.7700 (A) + 1.5200 (G) + 2.006 (C) - 0.0513 (S_M)	0.95	0.314
T40W5	RD = - 0.839 + 0.0230 (VFA) + 0.6130 (A) + 0.6600 (G) + 0.736 (C) - 0.0234 (S_M)	0.970	0.102
T40W6	RD = - 2.135 + 0.0450 (VFA) + 1.2600 (A) + 1.1600 (G) + 1.452 (C) - 0.0400 (S_M)	0.958	0.221
T40W7	RD = - 5.003 + 0.0870 (VFA) + 2.5600 (A) + 2.0400 (G) + 2.853 (C) - 0.0674 (S_M)	0.938	0.490
T40W8	RD = - 11.16 + 0.1700 (VFA) + 5.1400 (A) + 3.6000 (G) + 5.587 (C) - 0.1134 (S_M)	0.912	1.080
T60W5	RD = - 3.510 + 0.0660 (VFA) + 1.8950 (A) + 1.6040 (G) + 2.142 (C) - 0.0540 (S_M)	0.947	0.350
T60W6	RD = - 7.963 + 0.1277 (VFA) + 3.8220 (A) + 2.8250 (G) + 4.197 (C) - 0.0910 (S_M)	0.924	0.772
T60W7	RD = - 17.40 + 0.2466 (VFA) + 7.6340 (A) + 4.9780 (G) + 8.200 (C) - 0.1525 (S_M)	0.895	1.675
T60W8	RD = - 36.95 + 0.4747 (VFA) + 15.120 (A) + 8.7810 (G) + 15.96 (C) - 0.2540 (S_M)	0.862	3.570

Table 13: Predicted RD of the Investigated Mixes using the Developed General Model

Mix No	T = 25° C				T = 40° C				T = 60° C			
	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8	W = 10^5	W = 10^6	W = 10^7	W = 10^8
1	0.455	0.847	1.628	2.936	1.237	2.304	4.290	7.988	2.934	5.323	10.17	18.95
2	0.566	1.054	2.026	3.654	1.540	2.867	5.340	9.943	3.652	6.625	12.66	23.58
3	0.842	1.567	3.014	5.435	2.291	4.266	7.943	14.79	5.433	9.855	18.84	35.08
4	0.364	0.679	1.305	2.353	0.992	1.847	3.439	6.404	2.352	4.267	8.16	15.19
5	0.408	0.760	1.462	2.636	1.111	2.069	3.853	7.174	2.635	4.780	9.14	17.01
6	0.623	1.160	2.230	4.021	1.695	3.156	5.876	10.94	4.019	7.290	13.94	25.95
7	0.587	1.093	2.102	3.789	1.597	2.974	5.538	10.31	3.788	6.871	13.13	24.46
8	0.704	1.311	2.521	4.545	1.916	3.567	6.643	12.37	4.544	8.242	15.76	29.34
9	0.918	1.709	3.287	5.927	2.498	4.652	8.662	16.13	5.925	10.75	20.54	38.25
10	0.494	0.921	1.771	3.192	1.345	2.505	4.665	8.687	3.191	5.788	11.06	20.60
11	0.397	0.740	1.423	2.566	1.081	2.014	3.750	6.982	2.565	4.652	8.89	16.56
12	0.588	1.095	2.105	3.795	1.600	2.979	5.547	10.33	3.794	6.882	13.16	24.50
13	0.457	0.850	1.635	2.948	1.243	2.314	4.309	8.023	2.947	5.346	10.22	19.03
14	0.711	1.325	2.547	4.593	1.936	3.605	6.712	12.50	4.591	8.328	15.92	29.64
15	0.649	1.208	2.323	4.188	1.765	3.287	6.120	11.40	4.187	7.594	14.52	27.03
16	0.773	1.439	2.767	4.990	2.103	3.916	7.292	13.58	4.988	9.047	17.29	32.20
17	0.461	0.859	1.653	2.980	1.256	2.338	4.354	8.108	2.979	5.403	10.33	19.23
18	0.588	1.095	2.106	3.797	1.600	2.980	5.549	10.33	3.796	6.885	13.16	24.51
19	0.855	1.591	3.061	5.518	2.326	4.331	8.064	15.02	5.516	10.01	19.13	35.62
20	0.963	1.792	3.447	6.215	2.619	4.877	9.082	16.91	6.212	11.27	21.54	40.11