EVALUATION AND PREDECTION OF STRUCTURAL PROPERTIES OF ASPHALT CONCRETE

تقييم الخواص الإنشائية للخرسانة الأسفلتية والتنبؤ بها

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الملخص العربي

لقد ازدادت أهمية قياس الخصائص الإنشائية لمواد الرصف، خاصة و أن معظم هيئات الطرق أصبحت تتبنى نظرية الطبقات المرنة في تصميم قطاع الرصف. ويعتبر معامل المرونة ونسبة بواسون من أهم هذه الخصائص المطلوبة للطبقة الأسفلتية في نظام الطبقات المرنة. لذلك تهدف هذه الدراسة إلى تبسيط وسيلة يمكن استخدامها أثناء مرحلة تصميم قطاع الرصف المرن في تقدير هذه الخصائص الإنشائية للطبقة الأسفلتية في ظل ظروف الرصف الحقيقية من حرارة ومعدل تحميل. ولتحقيق 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 استخدام اختبار الشد غير المباشر في قياس الخصائص الإنشائية لهذه الخلطات عند ثلاث درجات حرارة لأربع قيم لمعدلات التحميل، هذا بجانب قياس الخصائص التقليدية لهذه الخلطات باستخدام اختبار مارشال. وباستخدام نتائج اختبار الشد غير المباشر وخصائص الخلطة التقليدية تم استنباط عدة علاقات يمكن استخدامها في إيجاد الخصائص الإنشائية المتوقعة للطبقة الأسفلتية في ظروف محددة من الحرارة ومعدل التحميل. ومن ثم تم استنباط عدة علاقات عامة للخصائص الإنشائية كدالة في خصائص الخلطة التقليدية ودرجة الحرارة ومعدل التحميل يمكن استخدامها في التنبؤ بالخصائص الإنشائية المتوقعة للطبقة الأسفلتية لأي درجة حرارة ولأي معدل تحميل، وكانت معظم القيم المحسوبة للخصائص الإنشائية باستخدام النماذج المستنبطة في حدود ٩٥ % من القيم المقاسة.

ABSTRACT

The ability to characterize paving materials in terms of fundamental properties is becoming increasingly more important. This is partially due to the fact that many agencies are beginning to use pavement design system based on elastic theory. The most required inputs in the elastic theory are Elasticity modulus (E) and Poisson's ratio (μ) of asphalt layer. So, the current study is primarily concerned with simplifying a technique that can be used, in pavement design phase, for predicting the expected structural properties of asphalt layer at the actual temperature and loading rate of traffic. To achieve this objective, many paving mixes typically used in pavement construction, were formed using different aggregate types and gradations, asphalt contents and compaction efforts. Then, the structural properties of these mixes were measured using indirect tensile test at three test temperatures along with four rates of loading. Also routine mix characteristics of these mixes were measured using Marshall method. Prediction models for a definite combination of temperature and rate of loading were developed using the results of indirect tensile tests and routine mix characteristics. Then, a general models were developed. These models can be used to predict the expected structural properties of an asphalt mix at the actual temperature along with the expected loading rate of traffic with the aid of routine mix characteristics. The estimated values of the investigated structural properties using the developed models are within 95 % of the measured values.

KEYWORDS:

Asphalt concrete, Elasticity modulus, Poisson ratio, Tensile strength, Tensile strain, Indirect Tensile Test, Rate of loading and Temperature.

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INTRODUCTION AND BACKGROUND

During the past few years, the design of flexible pavement has rapid developed from empirical and semi-empirical to pavement design systems based on elastic or viscoelastic theories [1, 2, 3]. In many applications of asphaltic concrete, the elastic characteristics of the material must be known not only to assess the behavior of the mix itself but also to evaluate the performance of an engineering structure of which the mix is a part, such as a highway pavement [4].

So, the ability to characterize asphalt concrete mixtures in terms of fundamental properties is becoming increasingly more important. This is partially due to the fact that many agencies are beginning to use pavement design systems based on elastic theory in one form or onthor for new pavement and overlay designs [5, 6]. The basic material properties required as inputs for elastic layer analysis of an asphalt pavement are: (a) elasticity modulus of each material, including variations with temperature and rate of loading, (b) poisson's ratio for each material, and (c) tensil strength which are primarily required for thermal or shrinkage cracking analysis [7].

Indirect tensile test has been used for measuring modulus of elasticity, poisson's ratio, tensile strain and tensile strength of paving materials [7, 8, 9]. Anderson and Hahan [10] consider tensile failure strain the most significant parameter. That is because the occurance of cracking was found to increase as tensile failure strain decreased.

So, the main objective of this study is concerned with the development of general models to simplify estimating Elasticity modulus (E), Poisson ratio (μ) and tensile strain (ε) and strength (σ) of asphalt layer at different temperatures and loading rates from routine mix characteristics along with the measured values of E, μ, ε and σ obtained from indirect tensile test at easy testing conditions. To achieve this objective, a comprehensive experimental program was designed and explained 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 elastic properties 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 different investigated mixes and their conditions are shown in Table (2). Also, three test temperatures (20, 40 and 60 °C) along with four rates of loading (0.05, 0.5, 1 and 2 in / min) were investigated as 12 cases of testing conditions for Temperatures (T) and Rate of loading (R) 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 indirect tensile tests.

Marshall Test

To determine the optimum asphalt contents (OAC'S) and to prepare test specimens for the investigated mixes, Marshall mix design procedure was performed. The test criterion selected was for a 75 blows Marshall compaction according to ASTM D1559-71 and AASHTO T-245.

Indirect Tensile Test

Indirect tensile test is carried out by loading test specimens (Marshall specimen) with compressive vertical loads that act parallel to and along the vertical diameter plane until failure using the specified rate of loading. The test set up is the same used in privious work [11, 12, 13], in which steel loading strip 0.50 in wide with a curved loading surface is used to distribute the load uniformly and to maintain a constant loading area. Also, three arms attached with micrometers dial gauges (sensitivity 0.01-mm division) are clamped on the samples. One vertically for measuring vertical deformation (Y). Whereas a device consisting of two cantilevered armes are clamped horizontally on the opposite sides of the sample for measuring the horizontal deformation (X). The structural characteristics measured form this test were calculated using the simplified equations developed by Kennedy [7] for 4.0-inch diameter specimen as follows:

1- Indirect tensile strength; σ

$$\sigma = 0.156\ P/H \quad (1)$$

2- Poisson's ratio; μ

$$\mu = (0.0673\ DR - 0.8954) / (-0.2494\ DR - 0.0156) \quad (2)$$

3- Modulus of Elasticity; E

$$E = P/(X\ H)\ (0.2692 + 0.9974\ \mu) \quad (3)$$

4- Tensile stain; ε

$$\varepsilon = X\ (0.03896 + 0.1185\ \mu) / (0.0673 + 0.2494\ \mu) \quad (4)$$

Where:

P = Total load at failure (Ib)

H = Height of specimen (in)

X = Total horizontal deformation at failure (in).

Y = Total vertical deformation at Failure (in).

DR = Deformation ratio (Y/X)

ANALYSIS OF RESULTS

The routine mix characteristics according to standered Marshall test of the investigated mixes are shown in Table (7). The measured values of failure loads P and deformation X, Y according to indirect tensile test at the three test temperatures along with the four loading were used in calculating structural properties (μ, E, ε and σ) of the investigated mixes using the previous equations and their values are listed in Tables (8, 9, 10 and 11), respectively.

ESTIMATING STRUCTURAL PROPERTIES FROM ROUTINE MIX CHARACTERISTICS

The values of structural properties presented in Tables (8, 9, 10 and 11) along with the routine characteristics of the investigated mixes, presented in Table (7), were used for developing the mix condition effect models. A multiple regression analysis (SPSS) [14] was performed to determine structural properties (E, σ, ε and μ) from these data. After considering a large number of trial and error solutions, the combination of mix characteristics, which gave the highest correlation (R^2) and lowest standard error (S_e) for (E, σ, ε and μ), were selected for case T20R05 ($T_o = 20^o$ C and $R_o = 0.05$ in/min), with the form:

$$E\ (psi) = 1.58\ (S_M) - 375\ (VFA) + 13400\ (A) + 8017\ (G) + 17922\ (C) - 350 \quad (5)$$

$$(R^2 = 0\ .99 \text{ and } S_e = 350)$$

$$\sigma\ (psi) = 0.0084\ (S_M) - 2\ (VFA) + 70.84\ (A) + 42.3\ (G) + 96.4\ (C) - 1.8 \quad (6)$$

$$(R^2 = 0\ .99 \text{ and } S_e = 1.92)$$

$$\varepsilon\ (\%_o) = -0.0001\ (S_M) + 0.013\ (VFA) - 0.22\ (A) - 1.4\ (G) - 1.25\ (C) + 11.5 \quad (7)$$

$$(R^2 = 0\ .955 \text{ and } S_e = 0.112)$$

$$\mu = -6E\text{-}6\ (S_M) + 8.4E\text{-}4\ (VFA) - 0.01(A) - 0.075\ (G) - 0.08\ (C) + 0.37 \quad (8)$$

$$(R^2 = 0\ .96 \text{ and } S_e = 0.0065)$$

Where:

E, σ, ε and μ are the structural properties at T =20° C and R = 0.05 in/min;

VFA = % voids filled with asphalt;

A = aggregate factor (0.8, 1.0 and 1.30 for basalt, dolomite and limestone, respectively);

G = gradation factor (0.7, 1.0 and 1.30 for 5A, 4C and 3A, respectively);

C = compaction factor (0.7, 0.8 and 1.0 for low, medium and high compaction, respectively); and

S_M = Marshall stiffness (psi).

DEVELOPMENT OF TEMPERATURE AND LOADING RATE MODEL

The values of structural properties of the investigated 12 cases of testing conditions presented in Table (8, 9, 10 and 11) were used for developing temperature and loading rate effect models for structural properties. A multiple regression analysis using the SPSS program was performed to determine the investigated structural properties (E, σ, ε and μ) at the most difficult conditions from those measured at easy conditions. The values of E, σ, ε and μ measured at $T_o = 20^o$ C and $R_o = 0.05$ in/min were used as a reference case to predict structural properties (E, σ, ε and μ) 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 relationships provide the best fit of the data:

$$E = E_o\ (T/T_o)^{-2.12}\ (R/R_o)^{0.196} \quad (9)$$

$$(R^2 = 0.996 \text{ and } S_e = 0.026)$$

$$\sigma = \sigma_o\ (T/T_o)^{-2.56}\ (R/R_o)^{0.192} \quad (10)$$

$$(R^2 = 0.997 \text{ and } S_e = 0.027)$$

$$\varepsilon = \varepsilon_o\ (T/T_o)^{0.16}\ (R/R_o)^{-0.036} \quad (11)$$

$$(R^2 = 0.98 \text{ and } S_e = 5.63E\text{-}3)$$

$$\mu = \mu_o\ (T/T_o)^{1.21}\ (R/R_o)^{-0.06} \quad (12)$$

$$(R^2 = 0.991 \text{ and } S_e = 0.022)$$

Where:

E, σ, ε and μ are the predicted value of structural properties at T and R;

E_o, σ_o, ε_o and μ_o are the measured values of structural properties at T_o and R_o;

T = The actual temperature (°C);

T_o = The room temperature (°C);

R = The actual loading rate(in/min);

R_o = The loading rate considered in the test (in/min).

The developed relations can be used to determine the values of E, σ, ε and μ of asphalt concrete at any T and R by conducting indirect tensile test at room temperature (T_o) at (R_o = 0.05 in/min). The existence of these relations is checked statistically using the F- test. The $F_{Comp.}$ is 60 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.

For more simplification, each pairs of the four developed models were combined together into one general model for predicting structural properties (E, σ, ε and μ) of paving mixes based on routine mix characteristics, temperature and rate of loading. By substituting $T_o = 20°$ C and R_o = 0.05 in/min for T20R05 case, the following exponential relations were suggested:

$$E = 1031\,(T)^{-2.12}\,(R)^{0.196}\,\{1.58\,(S_M) - 375\,(VFA) + 13400\,(A) + 8017\,(G) + 17922\,(C) - 350\} \quad (13)$$

$$\sigma = 3806\,(T)^{-2.56}\,(R)^{0.192}\,\{0.0084\,(S_M) - 2\,(VFA) + 70.84\,(A) + 42.3\,(G) + 96.4\,(C) - 1.8\} \quad (14)$$

$$\varepsilon = 0.56\,(T)^{0.16}\,(R)^{-0.036}\,\{-10^{-4}\,(S_M) + 0.013\,(VFA) - 0.22\,(A) - 1.4\,(G) - 1.25\,(C) + 11.5\} \quad (15)$$

$$\mu = 0.022(T)^{1.21}\,(R)^{-0.06}\,\{-6E\text{-}6\,(S_M) + 8.4\,E\text{-}4\,(VFA) - 0.01(A) - 0.075\,(G) - 0.08\,(C) + 0.37\} \quad (16)$$

These models were developed based on the asphalt mixes all using the same asphalt 60/70 binder. Applicability of this models should be further validated with asphalt mixes using different grades of asphalt binders. The predicted values of structural properties (E, σ, ε and μ) using the developed models are presented in Tables (12, 13, 14 and 15) respectively. Comparing the predicted values of structural properties using the developed models with the measured ones, it can be seen that the predicted values slightly deviate from the measured values. Only 20, 22, 27 and 2 out of 240 predicted values deviated by more than 5 % for E, μ, σ and ε, respectively with the maximum deviation of 11 %.

CONCLUSIONS

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

1. The expected structural properties (E, σ, ε and μ) of asphalt layer at any field condition of temperature and loading rate can be predicted with good accuracy using the developed relations.
2. Elasticity modulus values decrease by a factor of 0.23 and 0.10, while tensile strength values decrease by a factor of 0.17 and 0.06 as the temperature increases from 20 to 40 ° C and from 20 to 60 ° C, respectively.
3. Poisson's ratio values increase by a factor of 2.3 and 3.78, while tensile strain values increase by a factor of 1.12 and 1.20 as the temperature increases from 20 to 40 ° C and from 20 to 60 ° C, respectively.
4. Both elasticity modulus and tensile strength values increase by a factor of approximately 2.0 as the loading rate increases from 0.05 to 2 in/min.
5. Poisson's ratio values decrease by a factor of 0.8, while tensile strain values decrease by a factor of 0.9 as the loading rate increases from 0.05 to 2 in/min.
6. Increasing asphalt content by 1% above OAC leads to decreasing elasticity modulus and tensile strength by a factor of 0.65, while decreasing it by 1% leads to increasing them by a factor of 1.30.
7. Both elasticity modulus and tensile strength of paving mixes containing limestone and basalt were found to be

about 1.30 and 0.80 times that containing dolomite, respectively.

8. Mixes containing crushed sand as fine portion exhibit elasticity modulii and tensile strength values 20% higher than that containing natural sand.
9. Mixes containing basalt (as coarse portion) and crushed sand (as fine portion) exhibit elasticity modulii and tensile strength 5% higher than that containing dolomite and natural sand.
10. Elasticity modulus and tensile strength of paving mixes using 3A gradation was found to be about 1.30 and 1.85 times that using 4C and 5B gradations, respectively.
11. Elasticity modulus and tensile strength of paving mixes at medium and low compactive efforts were found to be about 0.80 and 0.70 times that at high compactive efforts, respectively.
12. Aggregate types and gradation, asphalt conent and compactive effort slightly affect Poisson's ratio and tensile strain.

REFERENCES

1. "AASHTO Interim Guid for Design of Pavement Structures," American Association for State Highway and Transportation Officials, 1979, Chapter III (revised), 1981.
2. Baladi, G. Y., "Characterization of Flexible Pavement; A Case Study," Properties of Flexible Materials, ASTM STP 807, Philadelphia, 1983, pp 164-71.
3. Baladi, G. Y., and Harichandran, R. S.," Asphalt Mix Design and the Indirect Test: A New Horizon," Asphalt Concrete Mix Design: Development of More Rational Approaches, ASTM STP 1041, Philadelphia, 1989, pp. 86-105.
4. Finn, F. N., "Factors Involved in the Design of Asphaltic pavement Surfaces," National Cooperative Highway Research Program No. 39, 1967, pp. 1-112.
5. Yoder, E. J., and Witczak, M. W., "Pricipals of Pavement Design, 2nd ed., Wiley, New York, 1975.
6. "Asphalt Overlays for Highway and Street Rehabilitation," The Asphalt Institute, Manual Series No. 17 (MS-17), June 1983.
7. Kennedy, T. W., "Characterization of Asphalt Pavement Materials using the Indirect Tensile Test", Proceedings, AAPT, Vol. 46, Feb. 1977, pp. 132-149.
8. Kennedy, T. W., "Tensile and Elastic Characteistics of Black-Base Materials", HRB, Highway Transportation Record 510, 1974, pp. 31- 40.
9. Maupin, G. W., jr. " Results of Indirect Tests Related to Asphalt Fatigue", HRB, Highway Ressearch Record 404, 1972, pp.1-7.
10. Anderson, K. O., and Hahan, W, O., "Design and Evaluation of Asphalt Concrete with Respect to thermal Cracking", Proceedings, AAPT, Vol. 37, Feb. 1968, pp. 1-31.
11. Mekkawi, A. H., "Effect of Sulpher on Road Paving Mixtures using Low Cost Aggregates", Ph. D. Thesis, Faculty of Eng., Cairo University, 1992.
12. Abdel-Motaleb, M. E., "Effect of Mixing Technology on Hot Asphaltic Mixtures Properties", M. Sc. Thesis Faculty of Eng., Zagazig Univ., 1996.
13. Abdel-Motaleb, M. E., and Mohamady, A., "A Simplified Technique for Measuring Dynamic Modulus of Aphalt Concrete", Mansura Engineering Journal, Volume 29, No. 3, September 2004, Mansura, Egypt.
14. Statistical Package for Social Science under Windows "SPSS win" Program, Ver. 7.5.2, May 1997.

Table 1: Gradations of the Investigated Mixes

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 Rate of Loading (R)

T (°C)	T = 20°C				T = 40°C				T = 60°C			
R(in/min)	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
Case	T20R05	T20R0.5	T20R1	T20R2	T40R05	T40R0.5	T40R1	T40R2	T60R05	T60R0.5	T60R1	T60R2

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 S.G		2.539	2.413	2.836	-
	-Apparent S.G		2.659	2.601	2.958	-
2	Water absorption (%)	T-85	2.61	4.75	2.12	≤ 5
3	Disintegration (%)	T-112	0.63	0.90	0.54	≤ 1
4	Los Angeles Abrasion;	T-96				
	-After 100 rev. (%)		5.6	9.3	4.8	≤ 10
	-After 500 rev. (%)		24	38	20	≤ 40
5	Stripping (%)	T-182	> 95	> 95	> 95	≥ 95

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	3.3	2.9	88	≥ 85
No. 200	1.5	1.3	70	≥ 65

Table 6: Properties of Bituminous Material

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 (lb)	Flow (0.01 in)	S_M (psi)
1	4.5	5.70	15.60	63.9	2.312	1966	9.25	8502
2	5.5*	3.50	15.50	77.9	2.331	2171	10.50	8270
3	6.5	1.80	17.00	88.9	2.362	1782	12.50	5702
4	5.6	6.40	18.30	61.3	2.212	2453	9.00	10902
5	6.6*	4.00	17.70	77.5	2.252	2583	10.25	10080
6	7.6	2.00	19.10	89.5	2.273	2171	13.00	6680
7	4.0	6.30	15.50	62.8	2.423	1461	9.50	6150
8	5.0*	3.70	15.10	75.5	2.462	1611	11.50	5602
9	6.0	1.90	16.60	83.5	2.472	1831	14.00	5230
10	5.5	3.60	15.60	76.9	2.325	2402	10.00	9607
11	6.6	4.10	17.85	74.4	2.244	2927	10.50	11150
12	5.0	3.70	15.25	70.1	2.455	2311	10.75	8600
13	5.2*	4.20	16.65	73.8	2.312	2351	9.50	9898
14	6.2*	3.10	14.50	82.5	2.363	2174	12.25	7100
15	5.5	3.70	15.60	76.3	2.325	2162	11.00	7860
16	5.5	4.10	16.00	74.2	2.323	1909	11.75	6500
17	5.2	4.50	18.00	75.0	2.300	2582	10.75	9607
18	5.2	5.00	18.50	73.0	2.272	2251	12.25	7350
19	6.2	3.25	15.25	78.1	2.301	2007	11.50	6980
20	6.2	3.40	15.50	76.5	2.252	1823	12.75	5720

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

Table 8: Measured Values of μ for the Investigated Mixes at Different T and R

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	0.20	0.17	0.15	0.14	0.45	0.40	0.37	0.36	0.70	0.64	0.60	0.58
2	0.21	0.18	0.16	0.15	0.47	0.42	0.39	0.37	0.73	0.66	0.62	0.60
3	0.25	0.21	0.19	0.18	0.52	0.47	0.44	0.42	0.81	0.73	0.69	0.67
4	0.19	0.16	0.14	0.13	0.44	0.39	0.36	0.35	0.69	0.62	0.59	0.57
5	0.20	0.17	0.15	0.14	0.45	0.40	0.37	0.36	0.71	0.64	0.60	0.58
6	0.23	0.19	0.17	0.16	0.49	0.44	0.41	0.39	0.77	0.69	0.65	0.63
7	0.21	0.18	0.16	0.15	0.47	0.42	0.39	0.37	0.73	0.66	0.62	0.60
8	0.23	0.20	0.18	0.17	0.50	0.44	0.41	0.40	0.77	0.70	0.66	0.64
9	0.24	0.21	0.19	0.18	0.52	0.46	0.43	0.41	0.80	0.72	0.68	0.66
10	0.20	0.17	0.15	0.14	0.45	0.40	0.37	0.36	0.70	0.64	0.60	0.58
11	0.18	0.15	0.13	0.13	0.43	0.38	0.35	0.34	0.67	0.61	0.57	0.55
12	0.21	0.18	0.16	0.15	0.47	0.42	0.39	0.37	0.73	0.66	0.62	0.60
13	0.18	0.15	0.13	0.13	0.43	0.38	0.35	0.34	0.67	0.61	0.57	0.55
14	0.26	0.22	0.20	0.19	0.54	0.48	0.45	0.43	0.83	0.75	0.71	0.68
15	0.23	0.19	0.17	0.16	0.49	0.44	0.41	0.39	0.77	0.69	0.65	0.63
16	0.24	0.21	0.19	0.18	0.52	0.46	0.43	0.41	0.80	0.72	0.68	0.66
17	0.20	0.17	0.15	0.14	0.45	0.40	0.37	0.36	0.70	0.64	0.60	0.58
18	0.21	0.18	0.16	0.15	0.47	0.42	0.39	0.37	0.73	0.66	0.62	0.60
19	0.26	0.23	0.20	0.19	0.55	0.49	0.46	0.44	0.84	0.76	0.72	0.69
20	0.29	0.25	0.23	0.21	0.58	0.52	0.49	0.47	0.89	0.81	0.76	0.74

Table 9: Measured Values of E (psi) for the Investigated Mixes at Different T and R

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	28267	44287	50697	58034	6548	10259	11744	13443	2783	4361	4992	5714
2	22730	35020	41200	46800	5020	8050	9300	10600	2020	3600	4100	4750
3	14973	23459	26854	30740	3468	5434	6221	7121	1500	2310	2644	3027
4	37709	60001	66700	78411	8600	12686	14700	17100	3820	6000	6800	7800
5	29279	45873	52512	59010	6782	10626	12164	12900	2850	4517	5250	6010
6	20004	31300	36100	41070	4200	7100	8200	9514	1870	3200	3560	4100
7	22149	34702	39724	44570	5131	8039	9202	9500	2000	3417	3911	4477
8	16836	26450	31100	34565	3750	5850	6800	7850	1700	2700	3200	3500
9	13446	21200	24115	28010	3115	4880	5586	6395	1260	2074	2374	2718
10	25635	40163	45500	52629	5750	9100	10450	11500	2524	4200	4650	5210
11	32859	51550	58500	68200	7450	11926	13652	14600	3150	5069	5803	6642
12	23780	37257	42649	49100	4800	8350	9680	11309	2240	3680	4300	4900
13	29590	47001	52600	59500	6854	10739	12293	13500	3010	4565	5300	5982
14	16345	25700	29315	32100	3650	5701	6501	7773	1609	2700	2886	3304
15	19320	31000	35500	38900	4475	7012	8027	8200	2000	3050	3550	4010
16	16408	25708	30100	33687	3650	5760	6616	7605	1616	2531	2898	3450
17	24446	39001	43843	49500	5663	8672	10156	11626	2650	3850	4550	4942
18	20001	31337	36500	41063	4450	7259	8120	9300	2010	3086	3600	4015
19	14699	24100	26363	31200	3405	5200	5950	6991	1447	2380	2596	3010
20	11673	18288	21500	23964	2600	4210	4849	5200	1250	1801	2150	2405

Table 10: Measured Values of ε (‰) for the Investigated Mixes at Different T and R

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	8.6	8.0	7.7	7.6	9.7	9.1	8.7	8.5	10.2	9.5	9.2	9.0
2	8.8	8.3	7.9	7.8	10.0	9.3	9.0	8.8	10.5	9.8	9.4	9.2
3	9.4	8.8	8.4	8.3	10.7	10.0	9.6	9.4	11.2	10.5	10.1	9.9
4	8.5	7.9	7.6	7.5	9.6	9.0	8.6	8.4	10.1	9.4	9.0	8.9
5	8.6	8.1	7.8	7.6	9.8	9.1	8.8	8.6	10.3	9.6	9.2	9.0
6	9.0	8.5	8.2	8.0	10.3	9.6	9.2	9.0	10.8	10.1	9.7	9.5
7	8.8	8.3	7.9	7.8	10.0	9.3	9.0	8.8	10.5	9.8	9.4	9.2
8	9.1	8.5	8.2	8.0	10.3	9.7	9.3	9.1	10.9	10.2	9.7	9.5
9	9.3	8.7	8.4	8.2	10.6	9.9	9.5	9.3	11.1	10.4	10.0	9.7
10	8.6	8.0	7.7	7.6	9.7	9.1	8.7	8.5	10.2	9.5	9.2	9.0
11	8.3	7.8	7.5	7.4	9.4	8.8	8.5	8.3	9.9	9.3	8.9	8.7
12	8.8	8.3	7.9	7.8	10.0	9.3	9.0	8.8	10.5	9.8	9.4	9.2
13	8.3	7.8	7.5	7.4	9.4	8.8	8.5	8.3	9.9	9.3	8.9	8.7
14	9.5	8.9	8.6	8.4	10.8	10.1	9.7	9.5	11.4	10.7	10.2	10.0
15	9.0	8.5	8.2	8.0	10.3	9.6	9.2	9.0	10.8	10.1	9.7	9.5
16	9.3	8.7	8.4	8.2	10.6	9.9	9.5	9.3	11.1	10.4	10.0	9.7
17	8.6	8.0	7.7	7.6	9.7	9.1	8.7	8.5	10.2	9.5	9.2	9.0
18	8.8	8.3	7.9	7.8	10.0	9.3	9.0	8.8	10.5	9.8	9.4	9.2
19	9.6	9.0	8.7	8.5	10.9	10.2	9.8	9.6	11.5	10.8	10.3	10.1
20	10.0	9.4	9.0	8.8	11.4	10.6	10.2	10.0	12.0	11.2	10.8	10.5

Table 11: Measured Values of σ (psi) for the Investigated Mixes at Different T and R

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	150	236	270	309	26.8	42.1	48.1	55.1	9.0	14.1	16.2	18.5
2	121	186	219	249	20.6	33.0	38.1	43.5	6.6	11.7	13.3	15.4
3	80	125	143	164	14.2	22.3	25.5	29.2	4.9	7.5	8.6	9.8
4	201	319	355	417	35.3	52.0	60.3	70.1	12.4	19.5	22.1	25.3
5	156	244	280	314	27.8	43.6	49.9	52.9	9.2	14.7	17.0	19.5
6	106	167	192	219	17.2	29.1	33.6	39.0	6.1	10.4	11.6	13.3
7	118	185	211	237	21.0	33.0	37.7	38.9	6.5	11.1	12.7	14.5
8	90	141	166	184	15.4	24.0	27.9	32.2	5.5	8.8	10.4	11.4
9	72	113	128	149	12.8	20.0	22.9	26.2	4.1	6.7	7.7	8.8
10	136	214	242	280	23.6	37.3	42.8	47.1	8.2	13.6	15.1	16.9
11	175	274	311	363	30.5	48.9	56.0	59.9	10.2	16.4	18.8	21.6
12	127	198	227	261	19.7	34.2	39.7	46.4	7.3	11.9	14.0	15.9
13	157	250	280	317	28.1	44.0	50.4	55.3	9.8	14.8	17.2	19.4
14	87	137	156	171	15.0	23.4	26.7	31.9	5.2	8.8	9.4	10.7
15	103	165	189	207	18.3	28.7	32.9	33.6	6.5	9.9	11.5	13.0
16	87	137	160	179	15.0	23.6	27.1	31.2	5.2	8.2	9.4	11.2
17	130	208	233	263	23.2	35.6	41.6	47.7	8.6	12.5	14.8	16.0
18	106	167	194	219	18.2	29.8	33.3	38.1	6.5	10.0	11.7	13.0
19	78	128	140	166	14.0	21.3	24.4	28.7	4.7	7.7	8.4	9.8
20	62	97	114	128	10.7	17.3	19.9	21.3	4.1	5.8	7.0	7.8

Table 12: Predicted Values of E (psi) for the Investigated Mixes using the Developed Model (13)

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	28460	44692	51195	58645	6547	10281	11777	13491	2772	4352	4986	5711
2	22843	35872	41092	47072	5255	8252	9453	10829	2225	3493	4002	4584
3	14661	23023	26373	30210	3373	5296	6067	6950	1428	2242	2568	2942
4	37247	58491	67002	76752	8568	13456	15414	17657	3627	5696	6525	7475
5	29873	46911	53738	61558	6872	10792	12362	14161	2909	4569	5233	5995
6	20001	31409	35979	41215	4601	7225	8277	9481	1948	3059	3504	4014
7	22476	35295	40432	46315	5171	8120	9301	10655	2189	3437	3938	4511
8	16848	26457	30307	34717	3876	6086	6972	7987	1641	2577	2952	3381
9	13260	20823	23853	27324	3050	4790	5487	6286	1291	2028	2323	2661
10	25331	39778	45567	52197	5827	9151	10482	12008	2467	3874	4438	5083
11	32726	51392	58870	67437	7529	11823	13543	15514	3187	5005	5733	6567
12	23610	37075	42471	48651	5431	8529	9770	11192	2299	3611	4136	4738
13	29358	46103	52811	60496	6754	10606	12149	13917	2859	4490	5143	5892
14	16864	26483	30337	34752	3880	6092	6979	7994	1642	2579	2954	3384
15	19211	30168	34558	39587	4419	6940	7950	9107	1871	2938	3366	3855
16	16057	25216	28885	33089	3694	5801	6645	7612	1564	2456	2813	3222
17	24864	39045	44727	51235	5720	8982	10289	11787	2421	3803	4356	4990
18	20256	31808	36437	41739	4660	7317	8382	9602	1973	3098	3549	4065
19	14740	23148	26516	30375	3391	5325	6100	6988	1436	2254	2582	2958
20	11557	18149	20790	23816	2659	4175	4783	5479	1126	1768	2025	2319

Table 13: Predicted Values of σ (psi) for the Investigated Mixes using the Developed Model (14)

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	151	236	269	307	25.7	39.9	45.6	52.1	9.1	14.1	16.2	18.5
2	121	189	216	247	20.6	32.0	36.6	41.8	7.3	11.3	13.0	14.8
3	78	121	138	158	13.2	20.5	23.5	26.8	4.7	7.3	8.3	9.5
4	198	308	352	402	33.6	52.2	59.7	68.2	11.9	18.5	21.1	24.1
5	159	247	282	322	26.9	41.9	47.8	54.6	9.5	14.8	16.9	19.3
6	106	165	189	215	18.0	28.0	32.0	36.5	6.4	9.9	11.3	12.9
7	120	186	213	243	20.3	31.6	36.1	41.2	7.2	11.2	12.8	14.6
8	90	139	159	182	15.2	23.6	27.0	30.9	5.4	8.4	9.6	10.9
9	71	110	125	143	12.0	18.6	21.3	24.3	4.2	6.6	7.5	8.6
10	135	209	239	273	22.8	35.5	40.6	46.4	8.1	12.6	14.4	16.4
11	174	271	309	353	29.5	45.9	52.4	59.9	10.4	16.2	18.6	21.2
12	126	195	223	255	21.3	33.1	37.9	43.3	7.5	11.7	13.4	15.3
13	156	243	277	317	26.4	41.2	47.0	53.7	9.4	14.6	16.7	19.0
14	90	140	159	182	15.2	23.7	27.0	30.9	5.4	8.4	9.6	10.9
15	102	159	181	207	17.3	26.9	30.7	35.1	6.1	9.5	10.9	12.4
16	85	132	151	173	14.4	22.4	25.6	29.3	5.1	7.9	9.1	10.4
17	132	205	234	268	22.4	34.8	39.7	45.4	7.9	12.3	14.1	16.1
18	107	167	191	218	18.2	28.3	32.3	36.9	6.4	10.0	11.4	13.1
19	78	122	139	159	13.3	20.6	23.6	26.9	4.7	7.3	8.3	9.5
20	61	95	109	124	10.4	16.1	18.4	21.1	3.7	5.7	6.5	7.5

Table 14: Predicted Values of ε (‰) for the Investigated Mixes using the Developed Model (15)

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	8.6	7.9	7.7	7.5	9.6	8.9	8.6	8.4	10.3	9.5	9.2	9.0
2	8.8	8.1	7.9	7.7	9.9	9.1	8.9	8.6	10.5	9.7	9.4	9.2
3	9.2	8.5	8.3	8.1	10.3	9.5	9.3	9.0	11.0	10.1	9.9	9.6
4	8.3	7.6	7.4	7.3	9.3	8.5	8.3	8.1	9.9	9.1	8.9	8.6
5	8.6	7.9	7.7	7.5	9.6	8.8	8.6	8.4	10.2	9.4	9.2	9.0
6	9.1	8.3	8.1	7.9	10.1	9.3	9.1	8.9	10.8	10.0	9.7	9.5
7	8.9	8.2	8.0	7.8	9.9	9.1	8.9	8.7	10.6	9.8	9.5	9.3
8	9.1	8.4	8.2	8.0	10.2	9.4	9.1	8.9	10.9	10.0	9.7	9.5
9	9.2	8.5	8.3	8.1	10.3	9.5	9.3	9.0	11.0	10.1	9.9	9.7
10	8.7	8.0	7.8	7.6	9.7	8.9	8.7	8.5	10.3	9.5	9.3	9.1
11	8.4	7.8	7.6	7.4	9.4	8.7	8.5	8.2	10.0	9.2	9.0	8.8
12	8.7	8.0	7.8	7.6	9.8	9.0	8.8	8.5	10.4	9.6	9.3	9.1
13	8.2	7.5	7.4	7.2	9.2	8.4	8.2	8.0	9.8	9.0	8.8	8.6
14	9.4	8.7	8.5	8.2	10.5	9.7	9.4	9.2	11.2	10.3	10.1	9.8
15	9.1	8.4	8.2	8.0	10.2	9.4	9.1	8.9	10.8	10.0	9.7	9.5
16	9.3	8.6	8.4	8.2	10.4	9.6	9.4	9.1	11.1	10.2	10.0	9.7
17	8.5	7.8	7.6	7.4	9.5	8.7	8.5	8.3	10.1	9.3	9.1	8.9
18	8.8	8.1	7.9	7.7	9.8	9.1	8.8	8.6	10.5	9.7	9.4	9.2
19	9.6	8.9	8.6	8.4	10.8	9.9	9.7	9.4	11.5	10.6	10.3	10.0
20	9.9	9.1	8.8	8.6	11.0	10.1	9.9	9.6	11.7	10.8	10.5	10.3

Table 15: Predicted Values of μ for the Investigated Mixes using the Developed Model (16)

Mix No	T = 20° C				T = 40° C				T = 60° C			
	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00	R = 0.05	R = 0.50	R = 1.00	R = 2.00
1	0.20	0.17	0.16	0.15	0.43	0.39	0.36	0.34	0.70	0.61	0.59	0.56
2	0.21	0.18	0.17	0.16	0.46	0.42	0.38	0.37	0.75	0.66	0.63	0.60
3	0.23	0.20	0.19	0.18	0.52	0.47	0.43	0.42	0.85	0.74	0.71	0.68
4	0.18	0.15	0.14	0.13	0.38	0.35	0.32	0.31	0.63	0.55	0.52	0.50
5	0.19	0.17	0.15	0.15	0.43	0.39	0.36	0.34	0.70	0.61	0.58	0.56
6	0.23	0.20	0.18	0.17	0.50	0.45	0.42	0.40	0.82	0.71	0.68	0.65
7	0.21	0.18	0.17	0.16	0.47	0.43	0.39	0.37	0.76	0.66	0.64	0.61
8	0.23	0.20	0.18	0.17	0.50	0.45	0.42	0.40	0.81	0.71	0.68	0.65
9	0.23	0.20	0.19	0.18	0.52	0.47	0.43	0.42	0.85	0.74	0.71	0.68
10	0.20	0.17	0.16	0.15	0.44	0.40	0.37	0.35	0.72	0.63	0.60	0.58
11	0.19	0.16	0.15	0.14	0.41	0.37	0.34	0.33	0.66	0.58	0.55	0.53
12	0.20	0.18	0.16	0.15	0.45	0.41	0.37	0.36	0.73	0.63	0.61	0.58
13	0.17	0.15	0.14	0.13	0.38	0.35	0.32	0.30	0.62	0.54	0.51	0.49
14	0.24	0.21	0.19	0.19	0.54	0.49	0.45	0.43	0.88	0.77	0.73	0.70
15	0.23	0.20	0.18	0.17	0.50	0.46	0.42	0.40	0.82	0.71	0.68	0.66
16	0.24	0.21	0.19	0.19	0.53	0.49	0.45	0.43	0.87	0.76	0.73	0.70
17	0.19	0.17	0.15	0.15	0.42	0.39	0.35	0.34	0.69	0.65	0.62	0.58
18	0.21	0.18	0.17	0.16	0.47	0.43	0.39	0.37	0.76	0.67	0.64	0.61
19	0.26	0.22	0.21	0.20	0.57	0.52	0.48	0.46	0.83	0.78	0.73	0.70
20	0.27	0.24	0.22	0.21	0.60	0.54	0.50	0.48	0.89	0.86	0.77	0.75