INFLUENCE OF TEMPERATURE ON ASPHALT STIFFNESS MODULUS

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ABSTRACT

It is well known that temperature has a great influence on performance of asphalt layers. Low temperatures raise the asphalt stiffness modulus which finally results in low temperature cracking. On the other hand, the increase of the temperature softens the asphalt binder and the stiffness modulus significantly drops. This, in combination with traffic load, causes asphalt pavement distresses like rutting, corrugation and shoving.
In order to ensure reliability in asphalt pavement design, values of the design variables should, as much as possible, match the actual pavement performance conditions. As the asphalt stiffness modulus is one of the input parameters, it is important to know its values for temperatures that pavement will be subjected to during its life time. The temperature range in Croatia usually varies between -10°C and 40°C.

According to the test method prescribed by European standard EN 12697-26 (Stiffness), Annex C (Test applying indirect tension to cylindrical specimens, IT-CY), stiffness was tested at four different temperatures, on several types of hot mixed asphalt mixtures. Based on the test results, temperature-stiffness correlations were obtained for the asphalt mixtures typically used in Croatia, for bearing or wearing courses.

The application of the obtained stiffness modulus, as the parameter that describes the performance of asphalt layers under different temperature conditions, will enable the optimization of the existing pavement design method in Croatia.

Keywords: asphalt mixture, stiffness modulus, temperature susceptibility, pavement design

1. INTRODUCTION

In Croatia, pavement design is performed according to HRN U.C4.012, after which critical stresses and strains are verified by the mechanistic-empirical (analytically-based) analysis (by application of the BISAR computer program). The verification is performed based on outdated and inaccurate data about material properties obtained by the elasticity modulus tests, performed 40 years ago (Dormon and Edwards, 1967) [1]. In Croatia no major changes have been introduced in this field for a longer number of years, and with the traffic volume and the permissible axle load increased, "well designed" pavements started to degrade sooner than expected.

Since the asphalt mixtures stiffness is the necessary parameter to assess stresses and strains in the pavement structure, the goal of this research was to determine the stiffness modulus for several types of hot asphalt mixtures which are presently used for construction of roads in Croatia, at the temperatures to which pavement will be subjected to during its life time.

On the basis of the obtained results, the input parameters used in pavement design will be closer to the actual ones. . This will contribute to reduction of eventual deviations between the stress and strain obtained by calculations and those that occur in pavement layers as response to traffic load.

2. LABORATORY TESTING OF STIFFNESS MODULUS

In accordance with the standard HRN EN 12697-26 [2], the asphalt mixtures stiffness modulus can be measured in several ways. Because of the simplicity and quickness of measuring, as well as preparation of specimens (with respect to other methods of measuring from the standard), and because of the availability of the measuring equipment, indirect tensile test was selected (Annex C to the mentioned standard). 848 measurements of the stiffness modulus were carried out, at four different temperatures and on 106 specimens prepared from seven asphalt mixtures. In the continuation, the testing program, the measuring procedure and equipment are presented, and the tested materials and specimens are described.

2.1. Testing Program

Asphalt mixtures samples were delivered to the laboratory from several actual building sites in Croatia. Cylindrical specimens with the diameter ~100 mm and height 60-65 mm were prepared in laboratory, according to the standard Marshall procedure, with various number of compaction blows (Table 1).

Table 1. The asphalt mixtures testing program

Mixture		AB 11E (1)		HS 11$_D$ (SMA) (1)		BNHS 16		HS 11$_D$ (SMA) (2)		AB 11E (2)		VS 16		BNS 22s	
Binder		PmB 45/80-65		PmB 45/80-65		bit 50/70		PmB 45/80-65		bit 50/70		bit 50/70		bit 50/70	
Testing date		04/29/2010		05/10/2010		06/07/2010		06/29/2010		01/13/2011		01/25/2011		03/16/2011	
Number of compacting blows		2*50	2*75	2*50	2*50	2*50	2*50	2*50	2*75	2*50	2*75	2*50	2*75	2*50	2*75
Measurement temperature	Measurement direction	Number of specimens													
5°C	First	10	0	8	8	8	8	8	8	8	8	8	8	8	8
	Second	10	0	8	8	8	8	8	8	8	8	8	8	8	8
15°C	First	10	0	8	8	8	8	8	8	8	8	8	8	8	8
	Second	10	0	8	8	8	8	8	8	8	8	8	8	8	8
25°C	First	10	0	8	8	8	8	8	8	8	8	8	8	8	8
	Second	10	0	8	8	8	8	8	8	8	8	8	8	8	8
35°C	First	10	0	8	8	8	8	8	8	8	8	8	8	8	8
	Second	10	0	8	8	8	8	8	8	8	8	8	8	8	8

The intention was to cover the largest possible number of asphalt mixtures that are currently used in road construction in Croatia, as well as the largest possible number of specimens, in order to eliminate the possibility of excessive errors in final results.

A total of 7 mixtures was tested, 16 specimens of each, except for the first one, for which 10 specimens were produced, which comes to 106 specimens in all.

All the specimens were tested at four temperatures: +5^{O}C, +15^{O}C, +25^{O}C and +35^{O}C, with respect to the asphalt pavement temperature range in Croatia (-8°C to +38°C,) and with respect to the equipment manufacturer's recommendation (+0°C to +35°C) [3]. The four temperature measurements were selected as the optimum number for obtaining the curve of the stiffness modulus dependence on temperature.

There were 848 measurements by indirect tensile test of the asphalt mixtures stiffness modulus made in all.

2.2. Materials

Asphalt mixtures specimens were prepared in the laboratory from the materials delivered from actual building sites, depending on their availability.

Tests were conducted on:

- Four wearing course mixtures, two of which ware Stone mastic asphalt, with the maximum particle size 11 mm (HS $11_{D\ (SMA)}$), both with polymer modified bitumen PmB 45/80-65 (HRN EN 14023). The remaining two were Dense Graded Asphalt Mixtures, with the maximum particle size of 11 mm (HS-AB 11E), one of which was prepared with pure bitumen 50/70 (EN 12591), and the other with polymer modified bitumen PmB 45/80-65 (HRN EN 14023).
- Bituminized base-wearing course mixture BNHS 16, bitumen 50/70, is the wearing and the base course, and can be placed directly on the unbound granular base.
- The mixture VS16, bitumen 50/70, is placed in the pavement structure as the binding layer, between the wearing and the base course.
- The bituminized base course from the mixture BNS 22s, bitumen 50/70, is placed in the pavement structure under the wearing or binding layer.

Table 2 shows the composition and physical-mechanical properties of the mixtures tested in this paper.

2.3. Test Procedure

All the tests were conducted in 2010 and 2011 in *Laboratory for Asphalt and Road Geomechanics, Institut IGH d.d. Zagreb*. Measuring of the stiffness modulus was carried out in accordance with the Croatian standard HRN EN 12697-26 *Bituminous mixtures - Test methods for hot mix asphalt* - Part 26: Stiffness; Annex C: *Indirect tensile test on cylindrical specimen* (IT-CY) [2].

2.4. Test Equipment

Testing of the stiffness modulus was performed on the "NU-10" device, *Cooper Research Technology Limited* , 1998 [3] (Figure 1). The device was adjusted to the proposal of the standard EN 12697-26, Annex C, current at the time. It can be used for measurements of the stiffness modulus and the evaluation of fatigue cracking and plastic deformation resistance of asphalt materials.

Testing can be performed on the specimens with the diameter of 10 or 15 cm, height 3 to 8 cm, with the target loading time of 124 ms and the target horizontal deformation of 5 microns for the specimen with the 10 cm diameter. It is assumed that the Poisson ratio is 0.35.

In the equipment manufacturer's instruction [3], performing of measurements at temperatures under 0°C is not recommended due to accumulation of ice in the chamber and converters, which can have a considerable effect on the test results and cause major damages to the equipment. It is recommended to perform the testing at 5°C, 15°C and 25°C, to plot the *stiffness modulus-temperature* results on a logarithmic scale and to extrapolate them to lower values. Measuring at temperatures above 35°C is also not recommended because the asphalt material is too soft.

Table 2. Data on tested asphalt mixtures

Ordinal number		1	2	3	4	5	6	7
Mixture		HS 11_D (SMA) (1)	HS 11_D (SMA) (2)	AB 11E (1)	AB 11E (2)	VS 16	BNS 22s	BNHS 16
Binder		PmB 45/80-65	PmB 45/80-65	PmB 45/80-65	bit 50/70	bit 50/70	bit 50/70	bit 50/70
Particle size distribution (HRN EN 12697-2:2008)	Sieve opening, mm	Passing through sieve, % (m/m))						
	0.63	10	10	8.3	6.5	6.7	6.4	9.2
	0.09	10.6	10.7	9.9	7.2	7.2	7	10.1
	0.125	11.6	11.7	13.8	8.1	8	7.9	11.6
	0.25	13.2	13.3	18.5	10.8	10	9.9	14.9
	0.5	14.7	14.9	21.8	15.6	13.4	13.1	19.1
	0.71	15.8	16.0	25.3	19.6	16.6	15.7	22.5
	1	17.1	17.2	34.6	23.8	20.2	18.5	26.0
	2	22.3	21.8	54.6	38.9	34.5	28.5	38.6
	4	31.1	32.0	78	60.1	46.5	43.4	57.1
	8	50.4	49.5	97.7	83.9	60.6	55.2	72.3
	11.2	84.1	90.8	100	98.4	76.7	64.4	86
	16	100	100	100	100	100	81.1	99.3
	22.4	100	100	100	100	100	96.2	100
	31.5	100	100	100	100	100	100	100
	45	100	100	100	100	100	100	100
Soluble binder content (HRN EN 12697-1:2007; asphalt analyzer), % (m/m)		6.1	5.7	5.4	5.4	4.3	3.5	2.2
Bulk density of bituminous specimens, compacted with 2*50 blows (HRN EN 12697-6:2008; Item 9.3), kg/m^3		2453	2465	2456	2421	2390	2408	2567
Mass of dry specimen, g		1234.7	1228.5	1232.1	1228.8	1228.5	1204.4	1252.2
Asphalt mixture density (HRN EN 12697-5:2009; Item" 9.2- by solvent), Mg/m^3		2.56	2.58	2.59	2.57	2.52	2.567	2.624
Voids content (HRN EN 12697-8: 2003), % (v/v)		4.2	4.3	5.1	5.7	5.2	6.2	2.2
Stability (HRN EN 12697-34: 2008), kN		13.4	13.6	21.9	12.7	10.6	11.4	14.3
Tangential strain (HRN EN 12697-34: 2008), mm		1.7	1.6	1.7	1.2	0.9	1.0	1.9
Strain (HRN EN 12697-34: 2008), mm		6.7	4.4	5.0	2.7	2.0	2.4	3.1
Marshall quotient (HRN EN 12697-34: 2008), kN/mm		2	3.1	4.4	4.7	5.3	4.8	4.6

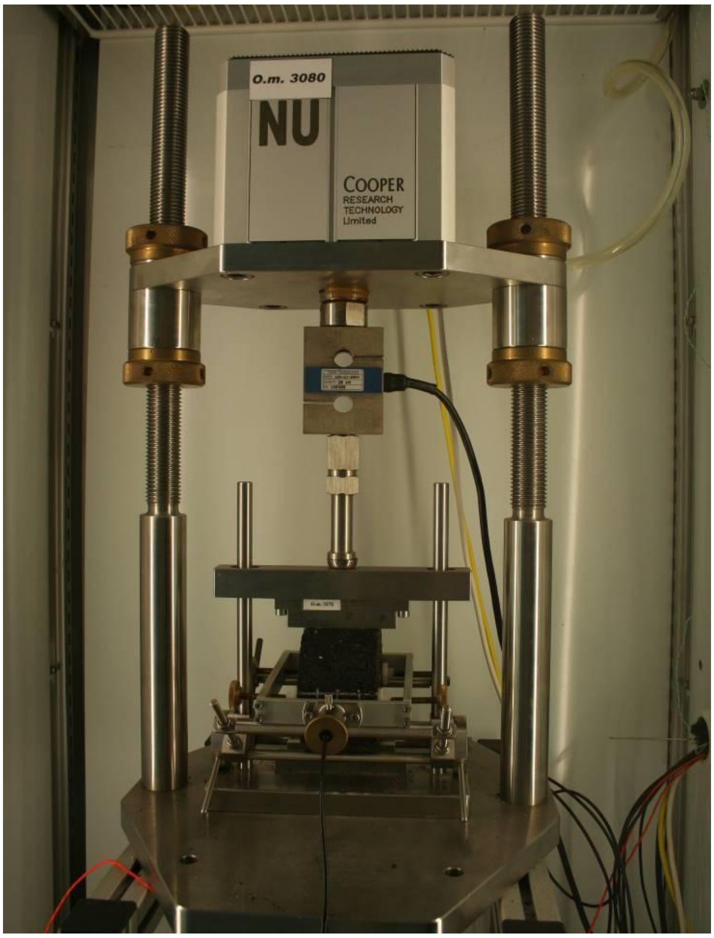

Figure 1. The "NU-10" device for measuring the stiffness modulus by indirect tensile testing

3. TEMPERATURES OF AIR AND PAVEMENT

Since the mechanistic-empirical design model for determination of stresses and strains in the pavement structure is based on material science, it is necessary to know the properties of the materials at the temperatures which they will be subjected to. The response of the pavement structure is determined for three representative climate periods in the year: summer, spring-autumn and winter.

The required temperature range was obtained by the analysis of monthly air temperatures in Croatia, and the data were taken over from the official website of the Croatian Meteorological and Hydrological Service [4] and the Croatian Bureau of Statistics [5]. They refer to the meteorological stations in different climate zones in Croatia: Zagreb, Varaždin, Osijek, Slavonski Brod, Rijeka, Zavižan, Ogulin, Gospić, Šibenik, Split and Dubrovnik. As the reference values for summer and winter, the 10-year averages of monthly minimum and maximum air temperatures were taken (data for the last 10 years). The highest average monthly maximum was recorded in Split (30°C), and the lowest in Zavižan (-9°C). For spring and autumn, the average multiannual monthly air temperatures (DZS, DHMZ) were taken as the reference values.

Croatia is situated in the northern temperate climate zone, and it is divided in several climate regions with respect to the geographic position, the relationship between the land and the sea, and relief features. According to the Köppen's division [7], the selected meteorological stations were classified by their geographic position into four climate zones (Figure 2):

1. Central and Eastern Croatia, and Lika with the moderately warm and humid climate with warm summers (Cfb, marked dark green on the map),
2. Istrian Coast, Kvarner and Dalmatian Hinterland with the moderately warm and humid climate with hot summers (Cfa, marked light green on the map),
3. Dalmatia – coast and islands with the Mediterranean climate (Cs, marked red on the map), and
4. The highest mountainous areas with the snow-boreal forest climate (D, marked blue on the map).

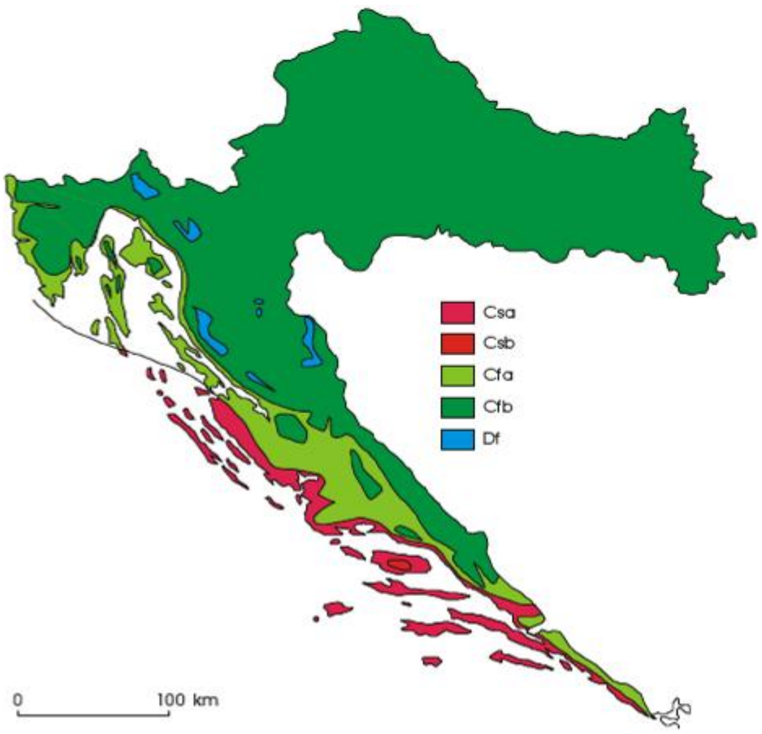

Figure 2. The geographic distribution of climate types in Croatia according to W. Köppen in the standard period 1961-1990: Cfa, moderately warm and humid climate with hot summers; Cfb, moderately warm and humid climate with warm summers; Csa, the Mediterranean climate with hot summers; Csb, the Mediterranean climate with warm summers; Df, boreal climate (Šegota, Filipčić, 2003) [7],

The data about the monthly and seasonal air temperatures from meteorological stations in Croatia correspond to such a division of Croatia by climate types.

Based on air temperatures, pavement temperatures were then determined, according to the *Asphalt Institute* equation (1982) [8]:

$$T_{asf} = T_{air} \cdot \left(1 + \frac{1}{z+4}\right) - \frac{34}{z+4} + 6 \quad (1)$$

Where:
T_{asf} - is the average monthly pavement temperature (°F) at the depth z,
T_{air} - is the average monthly air temperature (°F),
z - is the depth under the pavement surface on which temperature is to be determined (in)..

4. ANALYSIS OF LABORATORY TESTS RESULTS

Table 3 and Figure 3 show the mean values of the stiffness modulus of the tested asphalt mixtures, with differences in compacting of specimens, according to temperatures of measurements.

All the specimens were tested in two perpendicular directions and if the average value obtained by testing of the specimen in another direction deviated from the first one beyond the range from -20% to 10%, results were rejected [2],

The stiffness modulus obtained on the specimens compacted with 2*75 blows, i.e. on the specimens with less voids, are greater than those of the modulus obtained for the specimens compacted with 2*50 blows. Only the results of BNHS 16 mixtures, at 5°C, deviate from this rule. The differences in compacting of the specimens had the smallest effect on the stiffness modulus of the HS $11_{D\ (SMA)}$ mixture specimens (1), i.e. the modulus obtained by more compacted specimens are greater than those on the less compacted ones by 1% - 7%. The greatest differences of the stiffness modulus with respect to compacting of specimens were obtained for the BNS 22s, bit 50/70 mixture, the modulus of which were on more compacted specimens greater by 16% - 64% than those on less compacted specimens.

The rule of a decrease or an increase of the differences in modulus values (related to compaction rate) with temperatures, was not noticed.

Mixtures for wearing courses have lower stiffness modulus than those of the mixtures for the binding, base and base-wearing courses. The lowest stiffness modulus, at all temperatures, are those of the HS $11_{D\ (SMA)}$ mixture specimens , compacted with 2*50 blows, while the highest are those of the BNS 22s mixture specimens, compacted with 2*75 blows.

Table 3. Stiffness modulus values S_m (MPa) of asphalt mixtures, with differences in specimens compaction, in relation to temperatures

	Temperature of measurement							
Asphalt mixture, Number of compaction blows	5°C	$\frac{S_{m(2*75)}}{S_{m(2*50)}}-1$	15°C	$\frac{S_{m(2*75)}}{S_{m(2*50)}}-1$	25°C	$\frac{S_{m(2*75)}}{S_{m(2*50)}}-1$	35°C	$\frac{S_{m(2*75)}}{S_{m(2*50)}}-1$
HS 11 D (SMA) PmB 45/80-65 (1), 2*75	11656	3%	6047	7%	2640	5%	1052	1%
HS 11 D (SMA) PmB 45/80-65 (1), 2*50	11294		5645		2512		1044	
HS 11 D (SMA) PmB 45/80-65 (2), 2*75	11900	13%	5733	10%	2615	22%	1139	21%
HS 11 D (SMA) PmB 45/80-65 (2), 2*50	10536		5217		2150		941	
AB11E PmB 45/80-65, 2*50	12945		5535		2838		1133	
AB 11E, bit 50/70, 2*75	15851	13%	8153	13%	3843	15%	1374	24%
AB 11E, bit 50/70, 2*50	14027		7218		3336		1111	
VS16, BIT 50/70, 2*75	20029	10%	10307	7%	4499	8%	2082	15%
VS16, BIT 50/70, 2*50	18266		9595		4184		1817	
BNS 22, bit 50/70, 2*75	24519	16%	12595	21%	6517	49%	2446	64%
BNS 22, bit 50/70, 2*50	21159		10407		4387		1487	
BNHS 16, bit 50/70, 2*75	23327	-4%	11684	6%	4556	7%	1601	12%
BNHS 16, bit 50/70, 2*50	24268		11041		4270		1435	

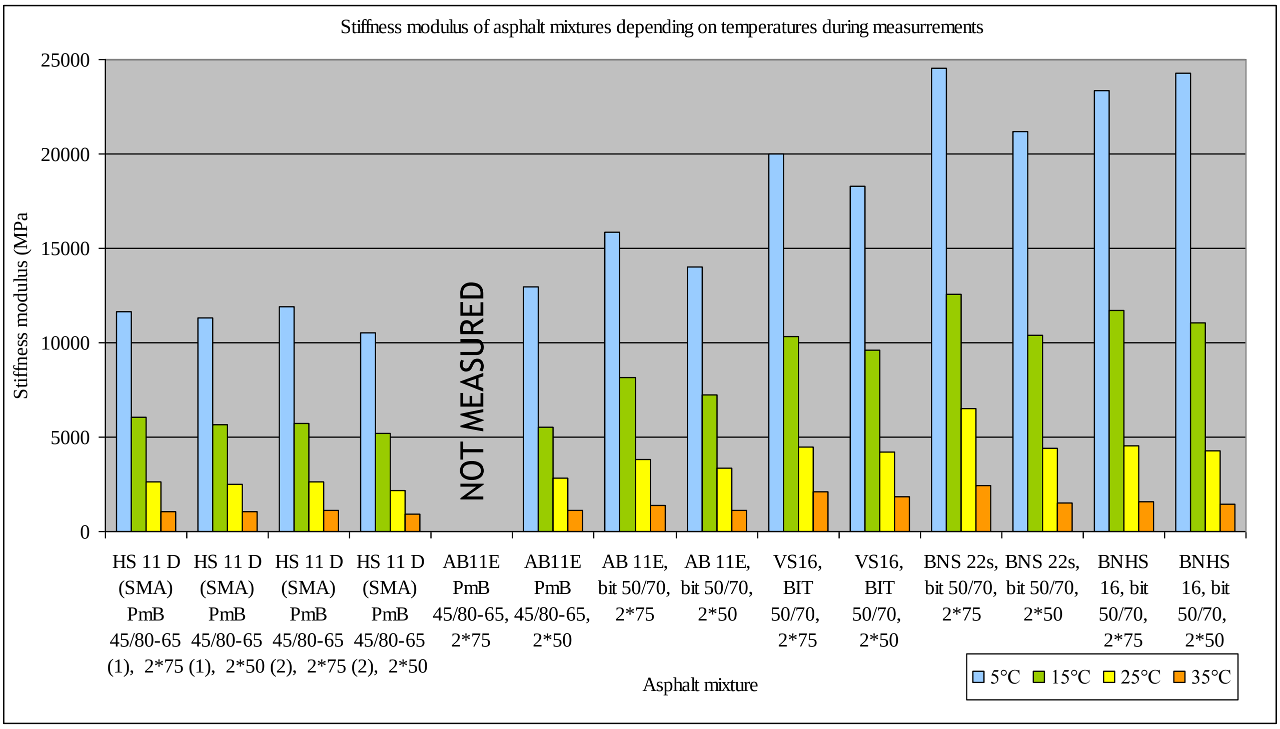

Figure 3. Asphalt mixtures stiffness modulus (MPa), with differences in compacting of specimens, at different temperatures

As expected, the values of the stiffness modulus, of all the mixtures, were reduced with the increase of the temperatures (Figure 4). The modulus values obtained at the maximum measured temperatures (35°C) were, on the average, by 91% lower than the modulus values determined at the minimum measured temperatures (5°C), for all the tested mixtures. The greatest modulus differences with respect to the temperature were manifested in the BNHS 16 specimens, compacted with 2*50 blows, i.e. the stiffness modulus was decreased by 94% with the temperature increase from 5°C to 35°C. The smallest modulus differences were those of the VS 16 specimens, compacted with 2*75 blows (the stiffness modulus was decreased by 89% with the temperature increase from 5°C to 35°C).

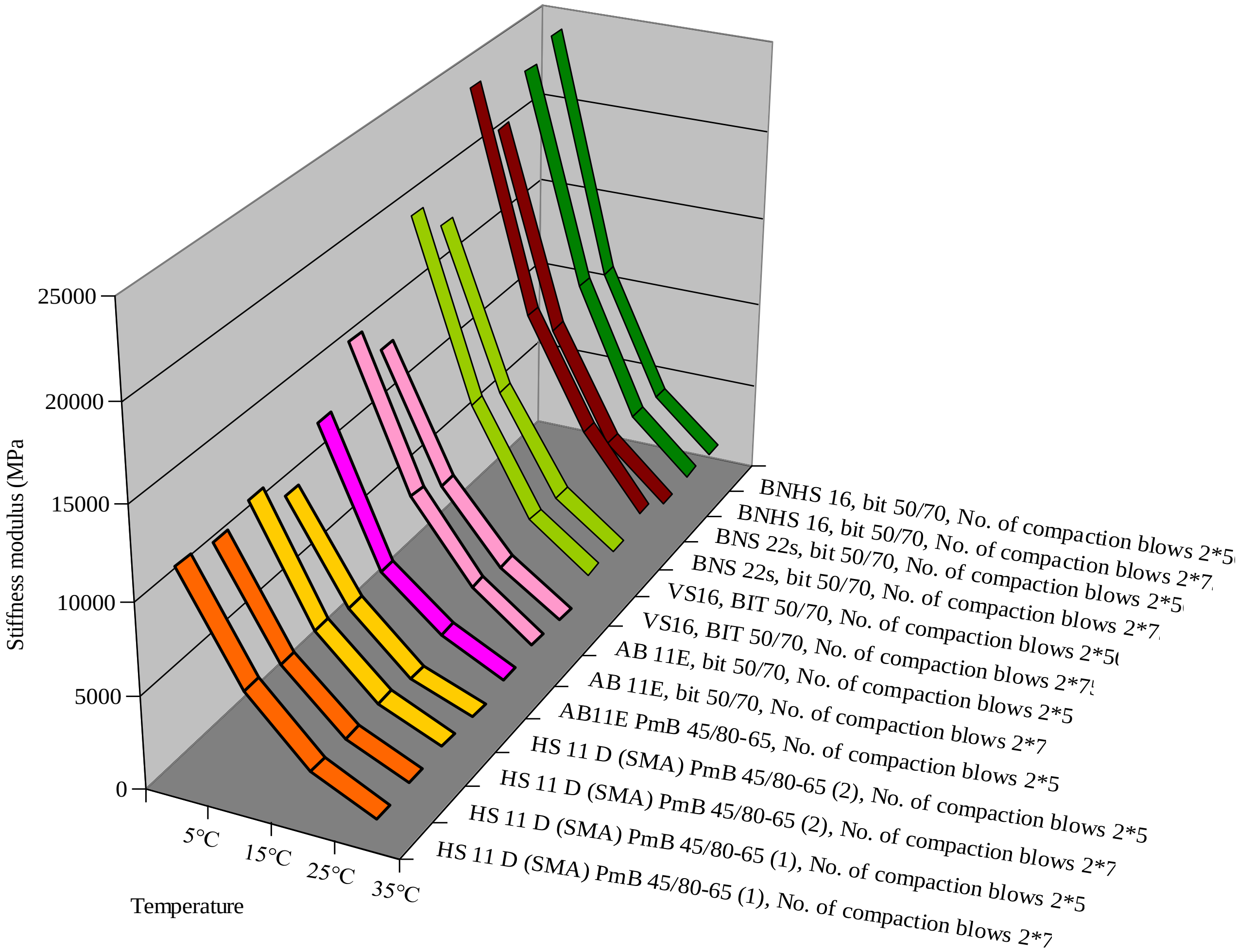

Figure 4. Change of the stiffness modulus of the tested mixtures with temperature

The trend of a decrease of the stiffness modulus of the VS 16 mixture, and particularly of the BNS 22s and BNHS 16 mixtures, with an increase of temperatures, is different from that of HS $11_{D\ (SMA)}$ and AB 11E mixtures. The mildest drop of the curve is shown by the HS $11_{D\ (SMA)}$ mixture (2), 2*50 compactor blows, and the sharpest by the BNHS 16 mixture with 2*50 compactor blows.

Since the temperatures to which asphalt mixtures will be exposed during pavements design life go beyond the temperature range within which the stiffness modulus were measured, those values of the stiffness modulus were extrapolated.

Table 4 shows, along with the values of the stiffness modulus determined by tests (from Table 3.), interpolated and extrapolated values of the stiffness modulus at temperatures from -5°C to +45°C, at 5 degree steps. The values for temperatures higher than 5°C were obtained using exponential function based on four known points. This fixed points of the curve are the modulus values obtained by measurements at the temperatures of 5°C, 15°C, 25°C and 35°C. For temperatures lower than 5°C, linear extrapolation was made, because the curve obtained for higher temperatures becomes very steep at lower temperatures and the obtained modulus values are unrealistically high (over 50000 MPa).

The results obtained for two HS $11_{D\ (SMA)}$ mixtures, with the same working composition, are very similar. The differences are somewhat greater on the specimens compacted with 2*50 blows. Further in the paper, the mean values of the two tested mixtures were taken for the stiffness modulus of the HS $11_{D\ (SMA)}$ mixtures at different temperatures.

Table 4. The stiffness modulus of asphalt mixtures (MPa) depending on temperatures, determined by interpolation and extrapolation based on the measured values

Asphalt mixture		Temperature °C										
		-5	0	5	10	15	20	25	30	35	40	45
Specimens compacted with 2*50 blows	HS 11$_{D\ (SMA)}$, PmB 45/80-55	17453	14184	10915	7646	5431	3422	2331	1531	992	685	458
	AB11E (1), PmB 45/80-65	21536	17241	12945	8650	5535	3896	2838	1755	1133	790	530
	AB 11E (2), bit 50/70	21733	17880	14027	10173	7218	4401	3336	1904	1111	824	542
	VS16 bit 50/70	28560	23413	18266	13119	9595	6042	4184	2782	1817	1281	870
	BNS 22s, bit 50/70	33705	27432	21159	14887	10407	6156	4387	2546	1487	1053	677
	BNHS 16, bit 50/70	40102	32185	24268	16351	11041	6365	4270	2478	1435	965	602
Specimens compacted with 2*75 blows	HS 11$_{D\ (SMA)}$, PmB 45/80-55	18715	15246	11778	8309	5890	3759	2627	1701	1096	770	518
	AB 11E (2), bit 50/70	24601	20226	15851	11476	8153	5111	3843	2276	1374	1014	677
	VS16 bit 50/70	31670	25850	20029	14208	10307	6631	4499	3095	2082	1444	987
	BNS 22s, bit 50/70	37828	31173	24519	17864	12595	8376	6517	3927	2446	1841	1261
	BNHS 16, bit 50/70	37202	30264	23327	16389	11684	6677	4556	2720	1601	1108	707

Since the number of blows for production of Marshall specimens depends on the expected intensity of traffic on the road section in which the asphalt mixture will be placed (Table 5), the results in Tables 6 and 7 are presented depending on the anticipated traffic load.

Table 5. Marshall criteria for mixture design of finishing and base course layers (number of compaction blows)

Traffic intensity		
Weak	Medium	Heavy
35	50	75

Tables 6 and 7 show the values of the stiffness modulus for tested mixtures, presented by seasons and climate regions of Croatia in which mixtures will be laid. With respect to the position of the layer in the pavement structure (the approximate depth at which the mixture will be placed), for each mixture, the depth at which its temperature was determined, was selected. For wearing courses, the temperature was determined at the depth of 2 cm, for the binding layer at 6 cm, and for the base course at 10 cm under the pavement surface.

For roads with light and middle-intensity traffic load, the stiffness modulus are presented in Table 6, which contains the results obtained on the specimens compacted with 2*50 blows. For roads with heavy and very heavy traffic load, the stiffness modulus are presented in Table 7., which shows the results obtained on the specimens compacted with 2*75 blows.

The stiffness modulus read from Tables 6 and 7 can be used in determining the stresses and strains in critical points of the pavement structure (for example, for use in the BISAR, computer program) with respect to the geographic location at which the mixtures will be laid, the position in the pavement structure, and the anticipated traffic load. It is recommended to round the values of stiffness modulus to the nearest hundred for the purpose of the calculation.

Table 6. The stiffness modulus of mixtures (MPa) depending on seasons and the geographic location, for roads with very light, light, and middle-intensity traffic load

Location in Croatia	Months in year	Season	Selected air temperatures for season (°C)	Asphalt Institute (1982) formulas: Temperature at depth z under pavement surface* $z = 2$ cm	$z = 6$ cm	$z = 10$ cm	Stiffness modulus (MPa): HS $11_{D(SMA)}$ PmB 45/80-55	AB 11E (1) PmB 45/80-55	AB 11E (2) bit 50/70	VS16 bit 50/70**	BNS 22s bit 50/70	BNHS 16 bit 50/70
Central and Eastern Croatia and Lika	3, 4, 5	spring	11	16	15	15	4720	5360	6154	9595	10407	11041
	6, 7, 8	summer	26	34	33	32	1110	1275	1362	2205	2134	1699
	9, 10, 11	autumn	11	16	15	15	4720	5360	6154	9595	10407	11041
	12, 1, 2	winter	-3	-1	-1	-1	14838	18100	18650	24442	28687	33768
Istrian coast, Kvarner and Dalmatian Hinterland	3, 4, 5	spring	12	18	18	17	4019	4570	5204	7055	8024	7687
	6, 7, 8	summer	27	35	34	33	992	1133	1111	2041	1953	1435
	9, 10, 11	autumn	14	20	20	19	3422	3896	4401	6042	6725	6365
	12, 1, 2	winter	3	7	7	7	9731	10988	13081	16544	19402	21700
Dalmatian coast and islands	3, 4, 5	spring	14	20	20	19	3422	3896	4401	6042	6725	6365
	6, 7, 8	summer	28	37	36	35	872	1004	1059	1747	1487	1280
	9, 10, 11	autumn	17	23	23	22	2688	3067	3423	4788	5160	4796
	12, 1, 2	winter	4	8	8	8	8980	10146	12029	15319	17762	19747
Highest mountain areas	3, 4, 5	spring	2	6	6	6	10546	11901	14224	17889	21193	23848
	6, 7, 8	summer	17	23	22	22	2688	3067	3423	5174	5160	4796
	9, 10, 11	autumn	5	9	9	9	8286	9368	11063	14176	16261	17969
	12, 1, 2	winter	-9	-7	-7	-7	18761	23254	23274	30619	36214	43269

* For the HS $11_{D(SMA)}$ and AB 11E wearing course mixtures, the temperature was determined at the depth of 2 cm, for that of the binding layer, VS 16, at the depth of 6 cm, and that of the base coarse, at 10 cm under the pavement surface

**The binding layer (VS 16) is embedded on motorways, roads with very heavy and heavy traffic load, so that the values of its stiffness modulus are not presented in this Table.

Table 7. The stiffness modulus of mixtures (MPa) depending on seasons and the geographic location, for roads with heavy and very heavy traffic load

Location in Croatia	Months in year	Season	Selected air temperatures for season (°C)	Asphalt Institute (1982) formulas: Temperature at depth z under pavement surface*			Stiffness modulus (MPa)					
				z = 2 cm	z = 6 cm	z = 10 cm	HS $11_{D(SMA)}$ PmB 45/80-55	AB11E (1) PmB 45/80-55	AB 11E (2) bit 50/70	VS16 bit 50/70	BNS 22s bit 50/70	BNHS 16 bit 50/70**
Central and Eastern Croatia and Lika	3, 4, 5	spring	11	16	15	15	5163	Not measured	7064	10307	12595	9562
	6, 7, 8	summer	26	34	33	32	1238		1647	2462	3375	1899
	9, 10, 11	autumn	11	16	15	15	5163		7064	10307	12595	9562
	12, 1, 2	winter	-3	-1	-1	-1	15940		21101	27014	32504	31652
Istrian coast, Kvamer and Dalmatian Hinterland	3, 4, 5	spring	12	18	18	17	4406		6009	7723	10513	7990
	6, 7, 8	summer	27	35	34	33	1096		1374	2282	3129	1601
	9, 10, 11	autumn	14	20	20	19	3759		5111	6631	9035	6677
	12, 1, 2	winter	3	7	7	7	10542		14627	17858	22421	21455
Dalmatian coast and islands	3, 4, 5	spring	14	20	20	19	3759		5111	6631	9035	6677
	6, 7, 8	summer	28	37	36	35	976		1292	1959	2446	1451
	9, 10, 11	autumn	17	23	23	22	2963		4010	5276	7199	5100
	12, 1, 2	winter	4	8	8	8	9738		13491	16547	20786	19613
Highest mountain areas	3, 4, 5	spring	2	6	6	6	11412		15859	19272	24185	23471
	6, 7, 8	summer	17	23	22	22	2963		4010	5694	7199	5100
	9, 10, 11	autumn	5	9	9	9	8995		12442	15333	19270	17929
	12, 1, 2	winter	-9	-7	-7	-7	20102		26351	33998	40489	39977

* For the HS $11_{D(SMA)}$ and AB 11E wearing course mixtures, the temperature was determined at the depth of 2 cm, for that of the binding layer, VS 16, at the depth of 6 cm, and that of the base coarse, at 10 cm under the pavement surface

**The BNHS mixture is placed exclusively on roads intended for light or very light traffic load, so that the values of its stiffness modulus are not presented in this Table.

5. SUMMARY

Based on the analysis of the results obtained by measurements of the stiffness modulus by indirect tensile test, on seven different asphalt mixtures and at four temperatures, on the total of 106 specimens, the following was observed:

- Values of the stiffness modulus, of all the tested mixtures, decrease with the temperature increase.
- The *stiffness modulus-temperature* curves of the tested mixtures are the steepest at low temperatures, and the mildest at high temperatures.
- The content of cavities is inversely proportional to the stiffness modulus, i.e. the specimens compacted with 2*75 blows have a greater stiffness modulus than those compacted with 2*50.
- The wearing course mixtures have lower values of the stiffness modulus than the mixtures for the binding, base course and base-wearing course layers.
- The increase of the stiffness modulus with the decrease of temperatures is slower for the mixtures of wearing courses.
- The values of modules obtained by measuring in the first direction were higher than those in the other direction in 65% of the cases.

6. CONCLUSION

Until today, no systematic research of the asphalt mixture stiffness modulus and its temperature dependence have been conducted in Croatia. Therefore, this values are supposed on the basis of tests carried out 40 years ago (Dormon and Edwards, 1967) [1], on the mixtures that were used at the time, and under the conditions in which they were used. In this paper, stiffness modulus of asphalt mixtures currently in use in Croatia were determined, with the purpose of obtaining representative values for use in pavement design.

The results indicate that at all (particularly low) temperatures, the tested mixtures were considerably stiffer than it has been supposed until now. That means that the values of the stiffness modulus used in determination of the critical stresses and strains, were considerably lower than the actual ones, so that there is a possibility that the calculated critical stresses were underestimated (particularly for the winter period). In the cases where critical stresses exceeded the allowed ones, there is a great chance of low temperature cracks appearance. Better knowledge of asphalt mixtures performance will enable preventing of early appearance of damages due to the traffic load and the environment conditions. Also, the realistic values of parameters entered in the calculations will, in the end, contribute to selection of the most suitable combination of quality and the price of materials.

Using results shown in Tables 6 and 7, where asphalt stiffness modulus are presented with respect to the location at which the mixture will be (or has been) placed, the season temperature and the expected traffic load, the procedure of determining the response of the pavement structure to loads will be simpler and more reliable than the existing one.

With respect to the fact that the deviations of tests results of particular specimens from the mean values were within 10% in most cases (in 96% of the cases), it can be concluded that indirect tensile testing is a reliable method for measuring the asphalt mixtures stiffness modulus

REFERENCES

[1] Developments in the application in practice of a fundamental procedure for the design of flexible pavements, Dormon G.M., Edwards J.M., Proceedings of the second international conference on the design of asphalt pavements, pp. 99–107, 1967

[2] HRN EN 12697-26, Bitumenske mješavine - Ispitne metode za asfalt proizveden vrućim postupkom *(Bituminous mixtures - Test methods for hot mix asphalt* - Part 26: Stiffness; Annex C: *Indirect tensile test on cylindrical specimen* (IT-CY) (EN 12697-26:2004), First Edition, December 2001

[3] NU-10 & NU-5, The Operation and Maintenance Manual, Cooper Research Technology Limited, 1998

[5] http://klima.hr/klima.php?id=mjes, 2011.

[6] http://www.dzs.hr/Hrv/publication/stat_year.htm, 2011.

[7] Köppenova podjela klima i hrvatsko nazivlje *(Köppen's Climate Division and Croatian Terminology)*, Šegota T., Filipčić A., Geoadria, vol. /1, pp. 17-37, 2003

[8] Design of Full Depth Asphalt Airfield Pavements, Witczak, M.W., Proceedings - Vol. I, Third International Conference on the Structural Design of Asphalt Pavements, pp 550-567, London, 1972