Primljen / Received: 31.8.2015.
Ispravljen / Corrected: 21.1.2016.
Prihvaćen / Accepted: 27.3.2016.
Dostupno online / Available online: 10.8.2016.

Elastic modulus of asphalt with chemically stabilized rubber bitumen

Authors:

Assoc.Prof. **Lajos Kisgyörgy**, PhD. CE
Budapest University of Technology and Economics
Department of Highway and Railway Engineering
kisgyorgy@uvt.bme.hu

Assoc.Prof. **Csaba Tóth**, PhD. CE
Budapest University of Technology and Economics
Department of Highway and Railway Engineering
toth@uvt.bme.hu

András Geiger, PhD. CE
MOL, Hungarian Oil and Gas Plc.
ageiger@mol.hu

Preliminary report

Lajos Kisgyörgy, Csaba Tóth, András Geiger

Elastic modulus of asphalt with chemically stabilized rubber bitumen

The chemically stabilized rubber bitumen (CSRB) has been developed by researchers from the company MOL and the Pannonian University (Hungary). The CSRB is made of used automobile tyres, and it improves the quality of pavement, while also enabling an efficient use of used automobile tyres. Mechanical properties of the chemically stabilized crumb rubber bitumen are analysed in the paper. Although test results have shown that CSRB properties are similar to those of the polymer modified bitumen, the CSRB results have proven to be better at low temperatures.

Ključne riječi:
chemically stabilized crumb rubber bitumen (CSRB), crumb rubber asphalt, elastic modulus, master curve

Prethodno priopćenje

Lajos Kisgyörgy, Csaba Tóth, András Geiger

Modul elastičnosti asfalta s bitumenom modificiranim gumenim granulatom kao vezivom

Bitumen modificiran gumenim granulatom (CSRB) razvili su istraživači tvrtke MOL i Panonskog sveučilišta (Mađarska). CSRB se proizvodi od rabljenih automobilskih guma, a njegovom se primjenom povećava kvaliteta kolnika i učinkovito postupa s rabljenim automobilskim gumama. Ovaj rad analizira mehaničke karakteristike asfalta s bitumenom koji je modificiran gumenim granulatom. Iako su rezultati ispitivanja pokazali da su svojstva CSRB-a slična svojstvima polimerom modificiranog bitumena, primjenom CSRB-a postižu se bolji rezultati pri niskim temperaturama.

Ključne riječi:
bitumen modificiran gumenim granulatom (CSRB), asfalt s dodatkom gume, modul elastičnosti, masterkrivulja

Vorherige Mitteilung

Lajos Kisgyörgy, Csaba Tóth, András Geiger

Elastizitätsmodul von Asphalt mit durch Gummigranulat modifiziertem Bitumen als Bindemittel

Durch Gummigranulat modifizierter Bitumen (CSRB) wurde von den Forschern des Unternehmens MOL und der Panonischen Universität (Ungarn) entwickelt. CSRB wird aus gebrauchten Autoreifen hergestellt. Dabei wird durch seine Anwendung die Qualität des Fahrbahnbelags verbessert und ein wirkungsvoller Umgang mit gebrauchten Reifen ermöglicht. In dieser Arbeit werden mechanische Eigenschaften von Asphalt mit durch Gummigranulat modifiziertem Bitumen analysiert. Obwohl Testresultate gezeigt haben, dass CSRB und mit Polymeren modifizierter Bitumen ähnliche Eigenschaften haben, werden durch die Anwendung von CSRB bei tiefen Temperaturen bessere Resultate erzielt.

Ključne riječi:
durch Gummigranulat modifizierter Bitumen (CSRB), Asphalt mit Zusatz von Gummi, Elastizitätsmodul, Masterkurve

1. Introduction

1.1. Applicability of recycled tyre crumb rubbers in road construction

Any innovation or development capable of reducing, even by a small percentage, the costs of road construction and maintenance, results in savings amounting to billions of euros on the national level. Significant research has been made in the field of asphalt technology in order to find solutions for producing more durable asphalt pavements and using less energy. Adopting these results could be highly beneficial economically, technically, and environmentally.

An increasing volume of road traffic and traffic load, as well as climate changes, continuously call for higher and higher standards regarding performance of asphalt mixtures. This shifts the focus of researchers to asphalt pavements and bitumen. As a result, various synthetic polymers have appeared in the asphalt technology, and they have significantly improved the quality of the conventional road bitumen. However, the price of modified bitumen has also increased dramatically during the past years, which underscores the need to find alternative solutions. It should also be mentioned that the decline in oil prices, which started in the mid of 2014, has also had a price lowering effect on bitumen products.

First experiments aimed at improving quality of asphalt mixtures by adding crumb rubber to mineral aggregate were conducted as early as in the beginning of the 20th century. Later on, numerous experiments and practical experience have revealed that the addition of rubber to asphalt mixtures decreases their cracking susceptibility, while increasing the life span of the pavement, etc.

Another aspect of this question is the waste management and environmental benefits of recycling waste tyres, because these tyres, being produced in large quantities, are among the largest and most problematic sources of waste. Several international waste tyres recycling examples and practices are currently available. In asphalt technology, two major approaches to the use of waste tyre crumb rubbers have been adopted in international practice: the so-called "dry process" and the "wet process" [1, 2].

1.2. Dry process: crumb rubber modified asphalt mixture production

In this process, a small quantity of rubber from discarded tyres is added to the mixture as a substitute for a certain amount of mineral aggregate. The crumb rubber is added to the mixer together with the mineral aggregate, and only after this is the crumb rubber combined with the binder. The advantage of the process is that the asphalt producer is able to modify the mixture independently from the bitumen producer. However, this process does not make use of potentially beneficial characteristics of the crumb rubber (or uses such characteristics to a minimum extent only), because the crumb rubber becomes an inactive filler in the asphalt mixture [3-5]. Although the dry process is used in international practice as widely as the wet one, no notable Hungarian research and experience about this process has so far been available.

1.3. Wet process: crumb rubber modified bitumen for asphalt mixture production

In this process, the crumb rubber is thoroughly mixed with hot bitumen and the mix is allowed to react for approximately one hour. This enables partial dissolution of the crumb rubber, which thus becomes an active modifying ingredient in the bitumen. This crumb rubber modified bitumen, which has beneficial engineering characteristics of both ingredients, is then used for asphalt mixtures [3, 4, 6]. Currently, the characteristics of asphalt mixtures made using the wet process are better compared to the dry process [7, 8].

Although the application of rubberized bitumen materials produced by wet process has proven to be successful, as demonstrated by numerous roads built over the past three decades, significant difficulties still exist that hinder its general and wide-spread use [9]. Namely, special equipment is needed due to its significantly higher viscosity compared to ordinary road bitumen [7, 10]. In addition, the changing quality of crumb rubber affects the quality of rubber modified bitumen [11, 12]. Due to the subsidence of rubber crumbs, it is advisable to use the modified bitumen within four hours after production, which limits its transportability [7, 10]. To handle the latter problem, mobile bitumen-mixing plants are used in the US to produce rubber modified bitumen, and the mixing is usually performed close to the road construction site.

2. Chemically stabilized rubber bitumen (CSRB)

2.1. Description

In recent times, after several years of research and development, the researchers from MOL and University of Pannonia have created a new type of asphalt binder, namely the chemically stabilized rubber bitumen (CSRB). The CSRB was granted the National Technical Approval in 2008 for application in road construction (ÉME 13/2008 H1), and the product and the production process were patented in 2009 (HU 226481) [13-15].

During this production process, in which disadvantages of the traditional wet process have been eliminated, a special kind of rubber modified bitumen is produced by incorporating bitumen and crumb rubber [7, 8]. The CSRB is a binder made of bitumen (85 ± 2 m/m%), crumb rubber (15±2 m/m%), and a special multifunctional additive (0,3 ± 0,2 m/m%). This additive partially reacts with crumb rubber and bitumen components resulting in an improved product quality (improved storage stability, reduced viscosity), while the applicability is similar to that of polymer modified bitumens. Due to its high molecular weight, this additive is not released from binder in vapour phase, even at the asphalt mixing temperature.

The production process requires a colloid mill and involves two technological steps that are carried out at different temperatures. The product is transportable and can be stored – for a limited time – in the mixing plant. The applied crumb rubber is produced at normal temperature out of waste tyres of trucks and passenger cars, and its maximum grain size is 1,25 mm. It should be noted that currently there is no approved regulation in Europe for the classification and nomination of crumb rubbers based on grain size. The mass ratio of crumb rubber is accurately determined to achieve a constant chemical composition.
During the CSRB production, the reaction between the bitumen and crumb rubber can be controlled by the mixing temperature, and/or mixing time, and/or mixing intensity, in such a way that the crumb rubber will partially be dissolved in the bitumen. Thus, some organic polymer components of the crumb rubber merge into the bitumen, modifying its quality.
Crumb rubber mostly consists of a mixture of natural and synthetic rubber, and it also contains carbon black, oils (plasticizer components) and inorganic fillers. In less than 2 % by mass, the crumb rubber may contain other additives that are used in tyre production, such as sulphur and zinc oxide.
The special characteristics of CSRB require certain modifications in the traditional process of asphalt production. The CSRB transported to the asphalt mixing plant is ready to be used, and its temperature must amount to no less than 170 °C. The asphalt mixing temperature is 175 to 190 °C. The capacity of the bitumen metering pump and pipe dimensions should be fitted to the CSRB viscosity. After production, the metering pump and the entire pipe network should be thoroughly cleaned with at least 150 l of 50/70 or 70/100 road bitumen. In the case of batch mixers, this means mixing two or three portions of asphalt with road bitumen.
Due to the current separation of components when stored, it is advisable to use the CSRB within 24 hours after its arrival to the asphalt mixing plant. This requires precise scheduling of asphalt paving works and logistics. If the CSRB needs to be stored, then it should be done in a standing tank equipped with a mixing device, [13-15].
MOL has established a prototype factory that produces 5000 t of the CSRB per year in Zala Refinery, Hungary. The amount of the produced and built-in CSRB asphalt mixture has recently exceeded the quantity of 80000 t. The experience has also confirmed that the CSRB asphalt mixtures are compliant with all relevant requirements.

2.2. Regulation

After acknowledgment and acceptance of the product in Hungary, the professional body of the Hungarian Road Association issued design guidelines for the application of CSRB [16]. These guidelines summarize product requirements for the use of CSRB in the construction and maintenance of roads and other transport surfaces, taking into consideration the transport and climatic conditions prevailing in Hungary.
According to these guidelines, 10 to 20 percent by mass of crumb rubber should be used in the final modified bitumen product. MOL uses crumb rubber concentration of 15±2 mass percent where the exact values depend on the milling granularity of the crumbs and the exact penetration value of bitumen used.
The crumb rubber used in the production of binder should be produced by grinding waste tyres at an ambient temperature or through a cryogenic grinding process, with the maximum grain size of 1,25 mm. The required granulation of crumbs is shown in Table 1.

Table 1. Gradation requirements of crumb rubber

Sieve [mm]	**Grading (Passing mass percent)** [m/m%]
0,5	20 - 80
1,0	70 - 100
1,25	100

Table 2. Chemically stabilized crumb rubber bitumen (CSRB) requirements

Properties		**CSRB end product requirements**	**Method**
Penetration at 25°C 0.1 mm		45-80	MSZ EN 1426
Softening point [°C]		≥ 55	MSZ EN 1427
Resistance to hardening (RTFO Test)	Change of mass [m/m%]	≤ 0,5	MSZ EN 12 607-1
	Retained penetration [m/m%]	≥ 50	MSZ EN 1426
	Increase in softening point [°C]	≤ 8	MSZ EN 1427
Elastic recovery at 25 °C [%] (1)		≥ 50	MSZ EN 13 398
Fraass breaking point [°C] (2)		≤ -16	MSZ EN 12 593
Storage stability difference in softening point [°C]		≤ 8	MSZ EN 13 399 MSZ EN 1427
Flash point [°C]		≥ 235	MSZ EN ISO 2592
Dynamic viscosity at 180 °C [mPa·s]		≤ 500	MSZ EN 13 302
Note: [1] Elongation of the investigated RmB sample is 100 mm, [2] Storage period is 24 hours			

The crumb rubber used in the production of CSRB can only be made of waste tyres (from passenger cars and trucks), and must not contain crumbs of any other rubber products. The crumb rubber must not contain any pollution substances, such as minerals, clay, etc., nor metal fibres used for tyres. The textile content of crumb rubber must not exceed 0,1 mass percent. Requirements for the CSRB distributed in Hungary are shown in Table 2. The product quality parameters should also be compliant with requirements contained in the relevant standard (*MSZ 930 Bitumen and bituminous binder. Rubber modified bitumen*) issued by the Hungarian Standards Institution in December 2015.

2.3. Binder tests

The CSRB produced by MOL (RmB 45/80-55) was and compared to other types of bitumen used in practice by the laboratory of Hungarian Public Road Ltc in Veszprém, Hungary. The results are shown in Tables 3 and 4.

Table 3. Comparison of results for three binders

	RmB 45/80-55	50/70	PmB 25/55-65
Penetration at 25°C 0,1 mm	66	53	40
Softening point [°C]	58	52	79
Fraass breaking point [°C]	-24	-15	-17
Elastic recovery at 25 °C [%]	63	-	90
Storage stability difference in softening point [°C]	6	-	3
Dynamic viscosity at 180 °C [mPa·s]	440	95	380

2.4. Advantages

Advantages of the CSRB produced by MOL can be summarized as follows [13-15, 17-18]:

- Due to the production technology applied, the crumb rubber does not serve as an inactive filler but approximately half of its quantity is dissolved in the bitumen, and thus it becomes a real modifier that improves the physical and chemical characteristics of the bitumen.
- Technical characteristics of the CSRB are fundamentally influenced by crumb rubber. The most valuable crumb rubber components are the polyisoprene and the styrene-butadiene rubber.
- Around 0,3 mass percent of a special multifunctional additive is used in the production of CSRB and its role is to enable dispersion and dissolution of crumb rubber in bitumen. The additive improves storage stability by dispersing the carbon black and inorganic fillers released after crumb rubber dissolution. At the same time this additive decreases the CSRB viscosity and so the viscosity value becomes similar to that of the polymer modified bitumens.
- As the CSRB is produced in a closed production system, no dissolution gas is emitted into the atmosphere. Dissolution and degradation gases have to be treated by the binder producer in accordance with relevant regulations.

The CSRB has been tested in the scope of mechanical tests for asphalt, and has been used in pilot road construction projects. The most significant project financed by Hungarian Infrastructure Developing Ltd was conducted in August-September 2014. More than 900 tons of CSRB were used for 22000 tons of asphalt mixture production, and a new road was planned and constructed near Villány, in the south of Hungary. The length of this road is 4.4 km. The experience gained on this project is also excellent. Besides the highest volume of CSRB used until now, the importance of this project also lies in the fact that this road construction is the first project on which all three asphalt layers

Table 4. Comparison of performance based results for three binders

	RmB 45/80-55	50/70	PmB 25/55-65
Original sample			
G*/sinδ, at 58 °C [kPa] (min 1,0)	6,3	3,5	13,9
After RTFOT			
G*/sinδ, at 58 °C, [kPa] (min 2,2)	9,7	8,2	22,0
After RTFOT + PAV			
G*sinδ at 22 °C [kPa] (max 5000)	1780	4950	4440
Stiffness at 12 °C [MPa] (max 300)	73	177	158
m-value at 12 °C (min 0,300)	0,352	0,326	0,326
Performance grade (PG)	PG 76-28	PG 64-22	PG 84-22
*Evaluation was carried out according to Hungarian climatic conditions. Based on it the Performance Grade (PG) 58-22 is the required grade in Hungary. Original and RTFOT aged samples were analysed at 58 °C. After RTFOT+PAV aging, 22 °C and -12 °C are the test temperatures			

(AC 32 base course, AC 22 binder, and AC 16 wearing course) were mixed and constructed using this type of binder.
The results have revealed that its quality is much higher compared to ordinary bitumen, and that its applicability is excellent. The application of CSRB improves the lifecycle and quality of roads by using waste materials, which is very valuable technically, economically and environmentally.
Although current regulations enable widespread application of the CSRB, the thorough mechanical analysis of CSRB asphalt mixtures is in still process. This paper is a part of this process: it compares the dynamic modulus of asphalt mixtures made of CSRB, polymer modified bitumen and normal, 50/70 road bitumen.

3. Dynamic stiffness moduls of CSRB

3.1. Research plan

Differences in mechanical characteristics of asphalts made of CSRB and asphalts made of conventional types of bitumen were analysed at the Department of Highway and Railway Engineering, Budapest University of Technology and Economics. Three asphalt mixtures were compared in the scope of this research:

- AC22 binder 50/70, as reference mixture
- AC22 binder PmB 25/55-65, as reference mixture
- AC22 binder RmB 45/80-55, as main investigation mixture

In all mixtures, the mineral aggregate was the same and the bitumen content was 4.5 percent by mass. The designed granulation and compounds of mineral aggregates are shown in Tables 5 and 6.
The aim was to produce different asphalt mixtures with the same body density In order to set the quality of binder as the only variable parameter. In the case of the AC 22 binder 50/70 mixture made of normal road bitumen, the mixing viscosity was 0,17 Pa and the compacting viscosity was 0,28 Pa according to requirements set by the Asphalt Institute, which means that the mixing and compacting temperatures were 160°C and 148°C, respectively.
In order to provide the body density similar to the reference Marshall body density of the AC 22 binder 50/70 mixture, the modified-bitumen asphalt mixtures were compacted at different temperatures according to Japanese method [19]. The results revealed the temperature values at which the body densities of the asphalts made of modified bitumen were approximately the same as the density of the asphalt made of normal bitumen. In the research, the temperature of 185°C was applied for mixing and compacting the AC 22 binder PmB 25/55-65 mixture, while the temperatures of 175°C for mixing and 165°C for compacting were applied in the case of the AC 22 binder RmB 45/80-55 mixture.
Viscosity values for applied binders (displayed in Table 7) were provided by MOL. MOL provided the G* complex shearing modulus and the δ phase-offset angle of the three types of bitumen as well, measured by a dynamic shear rheometer (DSR). Their temperature dependences are shown in Figure 1. These data provide information on the behaviour of bitumen at medium temperature (fatigue lifecycle) and at high temperature (susceptibility to plastic deformation).

Table 5. Planned composition of AC 22 binder

Sieve [mm]	**Grading (Passing mass percent)** [m/m%]		**By specified values (e-UT 05.02.11:2010)**
0,0	0,0	Filler 6,7	4,0-8,0
0,063	6,7	Fine aggregate 14,3	4,0-8,0
0,125	8		
0,25	9		
1,0	14		
2,0	21		20-40
4,0	33	Coarse aggregate 79	
5,6	38		
8,0	45		
11,2	54		
16,0	79		
22,4	99		90-100
31,5	100		

Table 6. Aggregate material

Description	**ML. Limestone flour**	**NZ 0/4 Dolomite**	**NZ 4/11 Dolomite**	**NZ 11/22 Dolomite**
Place of origin	Tatabánya	Iszka	Iszka	Iszka
Proportion [%]	4	30	21	45

Table 7. Dynamic viscosities measured at different temperatures (mPa·s)

Test temperature [°C]	50/70	PmB 25/55-65	RmB 45/80-55
135	527	3767	2727
160	170	987	930
180	86	428	477

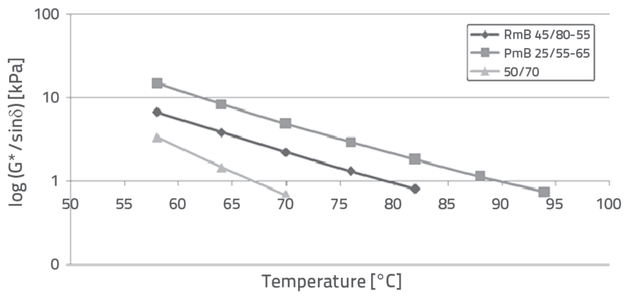

Figure 1. Temperature dependence of G * / sinδ

3.2. Master curve of mixtures

The additional information provided by the master curves of these mixtures was analysed in this research. The complex modulus and phase angle of the mixtures were established by the Simple Performance Tester (SPT). The stiffness values were measured for each mixture at three different temperatures and six different frequencies:

- temperatures: 10 °C, 20 °C, 30 °C
- frequencies: 0,1 Hz, 0,5 Hz, 1 Hz, 5 Hz, 10 Hz, 25 Hz

Based on the measured stiffness values, the dynamic modulus was determined according to the Huet-Sayegh model [20]. The general formula of the model is (1):

$$E^*(i\omega\tau) = E_0 + \frac{E_\infty - E_0}{1 + \delta \cdot (i \cdot \omega \cdot \tau)^{-k} + (i \cdot \omega \cdot \tau)^{-h}} \quad (1)$$

where:

E^* - complex modulus [MPa]
E_0 - limit of the complex modulus for $\omega\tau \rightarrow 0$
E_∞ - limit of the complex modulus for $\omega\tau \rightarrow \infty$ (Glassy modulus)
ω - 2π*frequency
τ - characteristic time varying with temperature accounting for the Time Temperature Superposition Principle
δ - dimensionless constant
k, h - exponents such that $0 < k < h < 1$.

The model uses the results of the tests carried out simultaneously at different temperatures and these values are taken into consideration by applying the so-called (τ) time decay constant. The application of the time decay constant is based on the superposition principle, and can be expressed by a quadratic relation as follows (2):

$$\tau = e^{a \cdot T^2 + b \cdot T + c} \quad (2)$$

where:

τ - time decay constant
T - temperature
a, b, c - constants.

The Huet-Sayegh model was optimized using the MS Excel Solver module. The results for asphalt mixes containing the CSRB are shown in the following figures. The measured and predicted Cole-Cole diagram of the mix is shown in Figure 2. The relation of the measured and predicted moduli is shown in Figure 3, and the measured and predicted phase angles are shown in Figure 4.

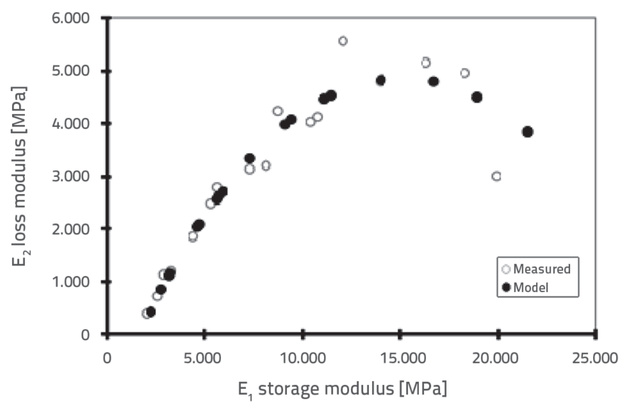

Figure 2. Comparison of measured and predicted Cole-Cole diagram

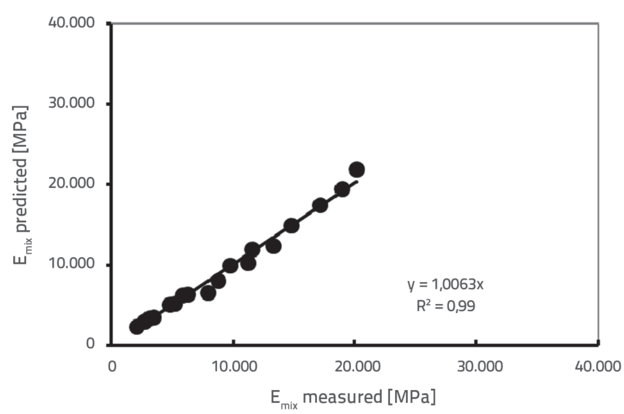

Figure 3. Relation of the measured and predicted moduls

Table 8. HS (Huet-Sayegh) model parameters

	E_0	E_{inf}	D	k	h	a	b	c
AC22 binder RmB 45/80-55	1 925	28 425	0,00302	1	0,4452498	-0,5161	-0,2475	0,00019
AC22 binder PmB 25/55-65	1 573	34 520	$1 \cdot 10^{-6}$	-2,9295	0,4383	1,0756	-0,2248	-0,0002
AC22 binder 50/70	1	34 124	$1 \cdot 10^{-6}$	0,6051	0,4179	0,021	-0,0954	-0,0026

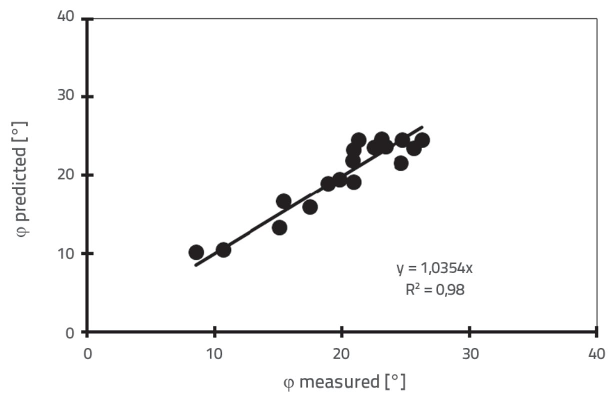

Figure 4. Comparison of measured and predicted phase angles

A good correspondence was obtained between the measured and predicted values. The coefficient of determination (R^2) is above 0,98 for both the observed and estimated stiffness values, and for the observed and estimated phase angles. The estimated parameters of the optimized models are shown in Table 8 for each of the three mixtures for the Huet-Sayegh (HS) model.

3.3. Characteristics of CSRB asphalt mixtures

Some observations can be made based on values presented in Table 8. The value of the E_0 parameter, which is directly related to inner friction of the mineral aggregate, and indirectly to the susceptibility to plastic deformation, is very high. In the case of asphalt mixtures made of CSRB, the value of the E_0 parameter is not only much higher compared to the mixture made of normal bitumen, but it also exceeds the value of the mixture made of polymer modified bitumen. This indicates a good wheel tracking resistance at high temperatures. The value of the E_{inf} parameter, which relates to cold behaviour, is lower than the corresponding values of other mixtures. This indicates less rigidity, which implies better crack resistance.

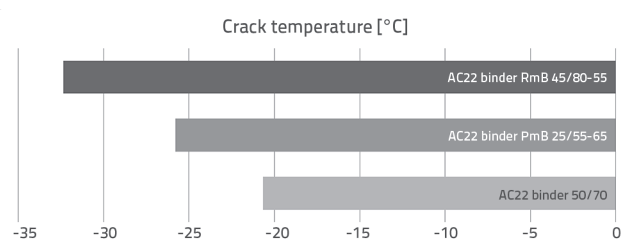

Figure 5. Diagram of the crack temperatures of the ARH test

Assumptions based on modelling results were checked through laboratory testing. The cold behaviour of the CSRB mixture was exceptionally good (Figure 5) [21]. The testing was conducted using the ARH test method developed at the Budapest University of Technology in the 1980s. The ARH test is fully compliant with the TSRST test method given by the European Standard EN 12697-46:2012 [22].

The so-called Cole-Cole diagram is one of possible representations of the complex modulus, and it displays the loss moduli (E2) determined at different temperatures as a function of the storage moduli (E1). The Cole-Cole diagram for the three examined asphalt mixtures is shown in Figure 6.

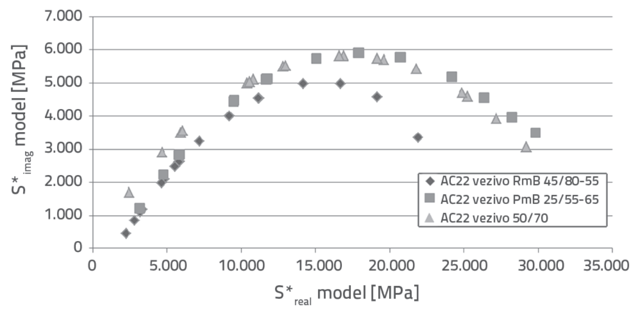

Figure 6 Presentation of HS model results on Cole-Cole diagram

The complex modulus can also be presented by the Black diagram which gives the change in phase angle with the change in complex modulus (Figure 7).

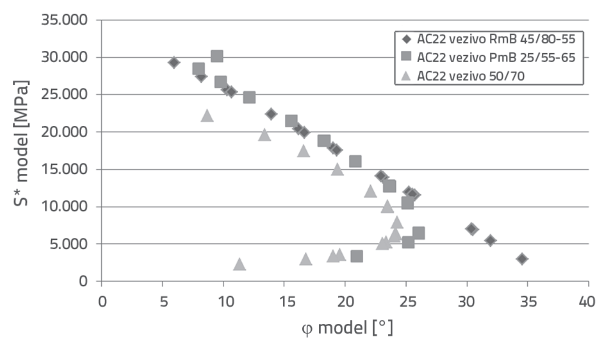

Figure 7. Presentation of HS model results using Black diagram

The following main results were obtained by the performance related characterisations carried out on three different binder types:
- The permanent deformation of asphalt mixtures is predicted by G*/sinδ values. In this respect, the performance of the

CSRB (RmB 45/80-55) can be situated between two other binders. The predicted rutting resistance is better compared to the 50/70 bitumen mixture and worse compared to the PmB mixture.
- The fatigue character of asphalt mixtures is predicted by G*sinδ values at an intermediate temperature (at 22 °C according to Hungarian climate) after the RTFOT and PAV aging. In this respect, the performance of CSRB exceeds not only the 50/70 bitumen but also the PmB 25/55-65.
- The cold behaviour of asphalt mixtures is predicted by the binder stiffness and m-value. The lower stiffness and the higher m-value were measured in case of the CSRB binder. It predicts that the asphalt mixture containing CSRB has the best cold side character compared to other asphalt mixtures. The Fraass breaking temperature of CSRB also indicates the best cold side character, which corresponds to rheological results.

4. Conclusion

The following conclusions have been reached based on results obtained during this research project:
- Rheological characteristics of the CSRB mixture properly reflect the experience gained in binder tests. The results definitely show that the characteristics of the CSRB mixture differ significantly from those of the mixtures made of normal bitumen.
- The cold behaviour of asphalt mixtures absolutely corresponds to cold behaviour of bituminous binders. Not only does the CSRB mixture have similar characteristics to those of the PmB mixture but, as indicated before, it even exhibits more favourable characteristics in the cold temperature range.
- The CSRB also improves the permanent deformation resistance of the asphalt mixture. Though better results can be achieved by applying PmB than CSRB, the application of CSRB is beneficial for the hot behaviour of the asphalt mixture.
- From the point of view of fatigue resistance the performance of CSRB is outstanding. The results clearly indicate that the mixtures made with the CSRB have a longer fatigue life compared to other mixtures.
- The production of CSRB and its application in road construction not only provide roads with a higher pavement quality compared to that of the roads made with normal bitumen, but the CSRB also offers a plausible solution for appropriate reuse of waste tyres. While being economically advantageous, it is also very favourable in terms of environmental management of waste materials.

The results of our research show the following major advantages of the CSRB:
- Based on better asphalt mixture properties, a longer lifecycle for asphalt pavements can be predicted in comparison with normal bitumen.
- Due to the excellent fatigue characteristics, asphalt pavements are more resistant to cracks.
- These pavements can bear higher loads and their wheel tracking susceptibility is lower.
- The longer lifecycle and better resistance result in lower maintenance costs.
- Waste tyres are utilized in an environmentally conscious and economical way.

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