Süleyman Demirel Üniversitesi
Fen Bilimleri Enstitüsü Dergisi
Cilt 21, Sayı 3, 683-688, 2017

Süleyman Demirel University
Journal of Natural and Applied Sciences
Volume 21, Issue 3, 683-688, 2017

DOI: 10.19113/sdufbed.18501

Investigation of Low-Temperature Behavior of Stone Mastic Asphalt Mixtures Modified with Paraffin and Crumb Rubber

Baha Vural KÖK*[1], Mehmet YILMAZ[1], Mustafa AKPOLAT[2]

[1]Fırat University, Engineering Faculty, Civil Engineering Department, 23169, Elazığ
[2]Munzur University, Engineering Faculty, Civil Engineering Department, 62100, Tunceli

(Alınış / Received: 31.03.2017, Kabul / Accepted: 11.06.2017, Online Yayınlanma / Published Online: 08.08.2017)

Keywords
Crumb rubber,
Paraffin,
Low-temperature crack,
Fracture toughness

Abstract: In hot mix asphalts at low temperatures, cracks occur due to thermal tension and these cracks cause water to leak inside the pavement and the pavement gets deformed sooner than expected. In order to improve the properties of bituminous mixtures, mostly polymer type additives are used in the modification of the bitumen. These types of improvements usually have positive effects on the high-temperature behavior of the mixture. In this study, semi-circular bending test, which is the most commonly used method in the literature to investigate the low-temperature behavior of bituminous mixtures, was performed. In the study, the resistance of stone mastic asphalt mixtures, which were prepared with modified bitumen with a constant 3% of paraffin and various amounts of crumb rubber, to crack formation and its movement was identified. As a result, it was concluded that the effects of additives on crack formation and its movement is varied and the relation between the fractured aggregate surface areas and the fracture toughness of the mixture can be determined by the image processing method.

Parafin ve Öğütülmüş Kauçuk ile Modifiye Edilmiş Taş Mastik Asfalt Karışımının Düşük Sıcaklık Davranışının İncelenmesi

Anahtar Kelimeler
Öğütülmüş kauçuk,
Parafin,
Düşük sıcaklık çatlağı,
Kırılma tokluğu

Özet: Düşük sıcaklıklarda bitümlü sıcak karışımlar içinde meydana gelen termal gerilmeler nedeni ile oluşan çatlaklar kaplama içine suyun girmesine neden olmakta ve kaplama beklenenden çok önce bozulmaktadır. Bitümlü karışımların özelliklerini iyileştirmek amacıyla çoğunlukla polimer türü katkı maddeleriyle bitüm modifiye edilmektedir. Bu tür iyileştirmelerin ise genellikle karışımın yüksek sıcaklık davranışı üzerinde olumlu etkileri olmaktadır. Bu çalışmada literatürde bitümlü karışımların düşük sıcaklık davranışını değerlendirmek için en çok kullanılan yöntem olan yarım daire eğilme deney yöntemi kullanılmıştır. Çalışmada sabit tutulan %3 Parafin içeriği ile birlikte değişik oranlarda öğütülmüş araç lastiği modifiyeli taş mastik asfalt karışımların çatlak oluşumuna ve ilerleyişine karşı dirençleri tespit edilmiştir. Sonuçta çatlak başlangıcı ve ilerleyişi açısından katkı kullanımının etkilerinin farklı olduğu, kırılan agrega yüzey alanları ile karışımın kırılma tokluğu arasındaki ilişkinin görüntü işleme yöntemi ile tespit edilebileceği belirlenmiştir.

1. Introduction

Asphalt pavements are exposed to some deformation types such as fatigue cracks, low-temperature cracks and reflection cracks due to traffic and environmental conditions. The cracks which are formed due to the thermal stress in the pavement at low temperatures cause leakage of water into the pavement and the infrastructure and lead to the deformation of pavements rather earlier than expected [1]. In the literature, the cracks which are formed only due to low temperatures are named as Mode-1, which are associated with tensile stress, the cracks which are formed due to traffic are named as Mode-2, which are associated with shear stress, and the cracks which are formed due to the effects of the both matters are called mixed-type and various mechanisms are built for laboratory experiments [2,3]. The formation of cracks in asphalt mixtures was first investigated by using fracture mechanics approach by Majidzadeh [4] and later several researchers employed semi-circular bending test setting according to Mode-1 method [5-

*Corresponding author: bvural@firat.edu.tr

7]. In the study, it was concluded that the mixtures prepared with polymer modified bitumen had high crack resistance, but the material behaved like a solid elastic object, making its fracture energy and rigidity stable at very low temperatures (-15 °C) [8]. The authors found that modification improved the crack resistance up to a point, after which the greater modification reduced resistance. However, all modifications tested performed better than neat mixtures [9]. The increased awareness on the protection of the environment has resulted in the widespread use of crumb rubber (CR) in bituminous mixtures. In the literature, there are a number of studies on the behavior of CR modified mixtures at medium and high temperatures. In these studies, it was stated that CR modification increased the asphalt mixture's fatigue life and resistance against permanent deformations at high temperatures. Also, CR can be used as an economical substitute of polymers [10-13]. In the few studies carried out on the low-temperature behavior of CR modification, it was reported that CR modification has positive effects on crack resistance. This effect was improved with decreased size of the CR. Moreover, CR modified mixtures have a slightly greater fracture energy than neat mixtures according to the J-integral method [14,15]. It has been proposed that this positive effect of CR modification is due to the improvements in viscosity and elastic components and the formation of thicker asphalt films around aggregate [15]. In addition to economic improvements of CR modification in asphalt mixtures, it affects the workability properties negatively by causing increases in viscosity [16]. In order to eliminate this negative effect, warm mixture additives, which reduces the viscosity considerably, are used [17-19]. In this type of study, which includes utilization of two different additives in a way that they can cancel out each other's negative effect, once again, the low-temperature behavior of the mixture is not investigated in detail. In this study, the low-temperature behaviors of stone-mastic mixtures which were prepared by using different amounts of CR and paraffin binders were investigated by the semi-circular bending test and availibility of additives in the same mixture was examined.

2. Material and Mehtod

In this study, B 50/70 class bitumen, which was supplied from Batman refinery, was used as the neat binder. In the modification of the neat binder, waste vehicle tires in 0.3 – 0.6 mm sizes, which were acquired from the Samsun Akın Rubber Company by mechanical shredding method and organic based paraffin (Sasobit®) which is used as a warm mix asphalt additive and supplied from Sasol Company were used. Modified binders, by adding determined amounts of additives to the neat binder, were obtained by mixing with a four-bladed mixer, which has a 1000 rpm speed, at a stable 180 °C temperature for 1 hour. The amount of paraffin was kept as constant at the ratio of 3% and CR was used at the rates of 6%, 8% and 10%. In the study, a neat binder without additives (0-0), a 3% paraffin-modified binder (0-3), binder containing 6% CR and 3% paraffin (6-3), binder containing 8% CR and 3% paraffin (8-3) and binder containing 10% CR and 3% paraffin (10-3), with a total of five different binders, stone-mastic-asphalt samples were prepared. The tests and results of modified binders were presented in Table 1. It is seen that while paraffin induces a reduction in viscosity, CR significantly induces an increase in viscosity.

Table 1. Binder tests results

	0-0	0-3	6-3	8-3	10-3
Penetraiton (1/100 cm)	51.2	40.7	31.3	21.8	19.6
Softening point (°C)	52.2	77.4	77.8	81.0	82.5
Viscosity @135 °C	0.600	0.462	1.238	1.925	2.950
Viscosity @165 °C	0.175	0.137	0.337	0.487	0.788

In the mixture samples, limestone, which has its properties and gradation presented in Table 2, was used as aggregate. Stone-mastic-asphalt mixture samples with a maximum diameter of 19 mm were prepared in a 150 mm diameter and 55-60 mm height gyratory compactor, under 600 kPa pressure and with 100 number of gyration. The optimum bitumen content was determined as 6.0% for the control mixtures and this rate was also adopted for other mixture types. 0.5% Viatop fiber was used for the weights of aggregate which had a Schellenberg percolation value lesser than 0.3%. The air void ratio (V_a), the void filled with asphalt (VFA), voids in the mineral aggregate (VMA), bulk specific gravity (G_{mb}), the mixing-compacting temperature of the mixtures were presented in Table 3. The mixing-compacting temperatures of the mixtures were determined by the temperatures correspond to 170 ± 20 and 280 ± 30 cP viscosity values, respectively.

3. Semi-Circular Bending Test and Results

This test determines the potentials of the samples against fracture toughness and crack movement. The tests were conducted according to Test EN 12697-44 standards and at 0 °C in order to evaluate the low-temperature behaviors of the mixtures. The samples were prepared in 150 mm diameter and 55-60 mm height in the gyratory compactor and they were divided into two equal semicircles from the center. 10 mm and 20 mm notchs were created on the centers of the samples. The load-deformation relations of the samples were recorded by applying 5mm/minute loads on the samples (Figure 1). The fracture toughness (K_{Ic}, N/mm$^{3/2}$) was calculated by Equation 2.

Table 2. Properties and gradation of aggregate

Sieve size (mm)	19.1	12.7	9.52	4.76	2.00	0.42	0.17	0.075
Passing (%)	100	95.0	65.0	37.5	25.0	17.0	13.0	10.0
Specific gravity (Coarse, fine, filler)				2.533	2.619	2.732		
Abrasion loss (%) (Los Angeles)					25			
Soundness (%) (with Na_2SO_4)					2.5			
Stripping resistance (%)(Nicholson)					70-75			

Table 3. Volumetric and physical properties of the samples

Mixture Type	W_a (%)	V_a (%)	VMA (%)	VFA (%)	G_{mb}	Mixing Temperature (°C)	Compaction Temperature(°C)
0-0	6.0	2.91	14.28	79.61	2.351	165.8	152.8
0-3	6.0	2.88	14.25	79.78	2.352	159.9	147.3
6-3	6.0	3.01	14.37	79.04	2.348	180.0	169.1
8-3	6.0	3.12	14.47	78.42	2.346	188.2*	176.8
10-3	6.0	3.18	14.52	78.11	2.344	219.4*	206.6*

*For the temperature above 185 ^{0}C, the mixing-compaction temperature was regarded as 185 ^{0}C.

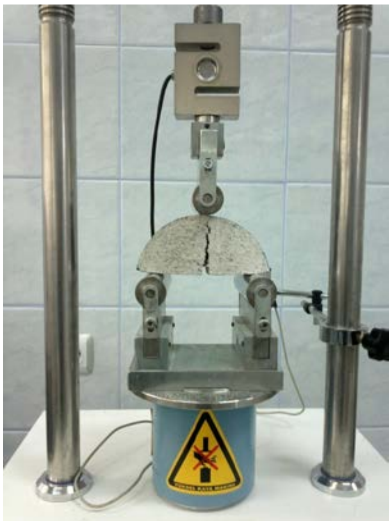

Figure 1. Semi-circular bending test setup

$$\sigma_{max} = 4.263.F_{max} / D.t \quad (1)$$

$$K_{Ic} = \sigma_{max}.5.956 \quad (2)$$

In these Equations, σ_{max} is the maximum stress at the moment of cracking (MPa), F_{max} is the maximum load (N) and, D and t are the sample diameter and thickness (mm). The fracture energies of the samples (Gf, J/m^2) were calculated with Equation 3, according to the method employed by Li and Maresteanu [6].

$$G_f = W_0 / A_{lig} \quad (3)$$

In this Equation, W_0 is the fracture work which is the area below the load-deformation curve until the maximum load and A_{lig} is the ligament area.

In Figure 2 and 3, at notch lengths in 10 mm and 20 mm, respectively, load-deformation relations were presented. As it is observed in the figures, load-deformation rates demonstrate differences in different notch sizes between the samples, especially for neat mixtures. In both of the notch sizes, 8-3 and 10-3 samples demonstrated very similar curves. The fracture loads and the area under the load-deformation curves are given in Table 4.

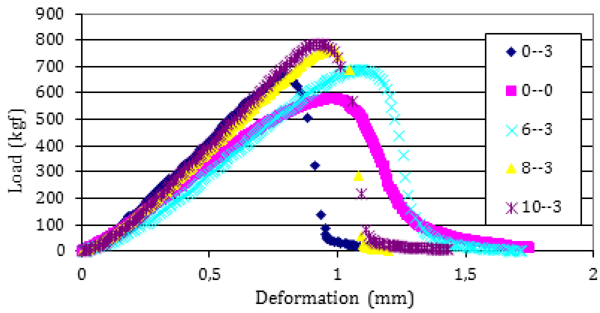

Figure 2. Load-deformation relation in 10 mm notch length

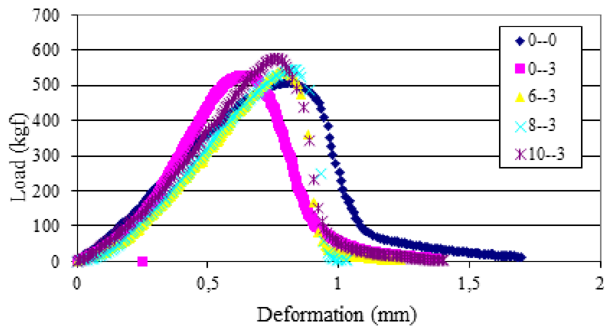

Figure 3. Load-deformation relation in 20 mm notch length

The lowest fracture load was observed in the neat mixture while the highest value was observed in the 10-3 mixture. In the 10mm notch size, with the increase of CR content from 6% to 10%; 18%, 32% and 35% increases, respectively, occurred in the fracture load compared to the neat mixture. The 0-3 mixture demonstrated a 14% higher fracture load compared to the neat mixture. In the 20 mm notch size, with the increase of CR content from 6% to 10%; 6%, 8% and 13% increases, respectively, occurred in the fracture load compared to the neat mixture. The 0-3 mixture demonstrated a 5.5% higher cracking load compared to the neat mixture. With the increased notch length, the cracking load increase of modified mixtures decreases compared to the neat mixture.

The changes occurred in the fracture toughness of the samples were presented in Figure 4. With the increase in the amount of the additives, the fracture toughness values increase, in parallel with cracking load, and this increase is not very distinctive in 20mm notch length. With the increase of CR content from 6% to 10% in the 10mm notch length, 16%, 29% and 32% increases, respectively, occurred in the fracture toughness values compared to the neat mixture while these values were observed as 6.5%, 7.5% and 12%, respectively, in the 20mm notch size.

The occurred increaments in the fracture toughness indicate a rigidity increase in the samples. The increase in the softening point and viscosity of the binders and a decrease in their penetration also indicate this conclusion.

The marked changes in the fracture were presented in Figure 5, 6 and 7 as until the maximum load, after the maximum load and during the whole load, respectively. It is possible to relate the fracture energy until the maximum load with the initiation of the crack and the fracture energy after the maximum load with the crack movement. The fracture energies of all the samples were observed to be higher than their fracture energies after the maximum load. This result explains the fact that all the samples acted rigidly and they are resistant to crack formation, but they couldn't resist to crack progression by demonstrating fragile properties. Within the scope of crack formation in 10 mm notch length, the samples of 6-3, 8-3, and 10-3 outputted 21%, 19% and 13% higher fracture energies, respectively, compared to the neat mixture while outputting 19%, 37% and 20% lower values after the crack formation.

In 20 mm notch length, none of the mixtures with the additives outputted a higher fracture energy compared to the neat mixture. The reason for this is believed to be the fact that in high notch lengths tensile stress is in effect rather than shear stress and modified binders have higher shear stress and lower tensile stress. While the most resistant sample, in terms of crack initiation, is the 6% CR + 3% paraffin-modified sample (6-3), the most resistant sample, in terms of crack movement, is the neat mixture. The 6-3 mixture, when the total load is taken into account, is the mixture with the highest fracture energy.

In all of the three situations, the lowest fracture energy was observed on the mixture with only 3% paraffin modification (0-3). While the fracture toughness of the samples increases with the additives, it was observed that this increase doesn't comply with the resistance to crack formation and progression.

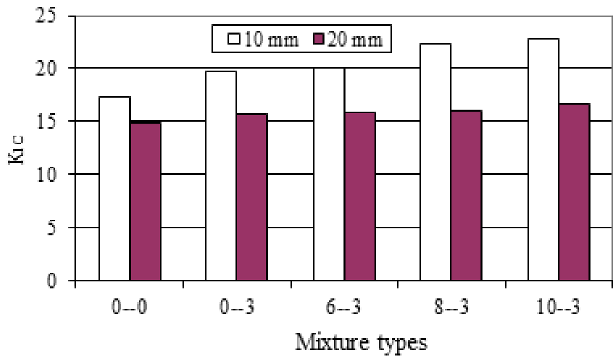

Figure 4. The changes in the fracture toughness of the samples

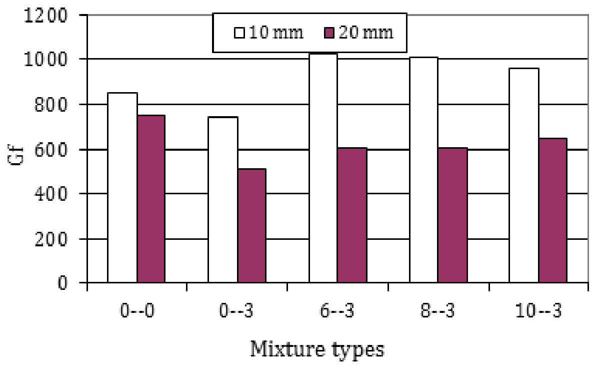

Figure 5. The changes in Gf until the maximum load

Table 4. Test results of 10 mm and 20 mm notch lengths 10 mm notch length

Sample type	Thickness (mm)	Ligament area(mm^2)	Maximum load (kg)	Total area (kg.mm)	The area until the maximum load (kg.mm)
0-0	57.04	3610	581	453	306
0-3	56.72	3592	662	343	266
6-3	57.85	3618	686	488	371
8-3	57.88	3638	765	444	368
10-3	58.08	3660	785	474	356
20 mm notch length					
Sample type	Thickness (mm)	Ligament area (mm^2)	Maximum load (kg)	Total area (kg.mm)	The area until the maximum load (kg.mm)
0-0	57.66	3138	505	347	236
0-3	57.37	3200	534	245	162
6-3	57.57	3078	537	249	186
8-3	57.78	3110	545	268	189
10-3	58.27	3069	574	293	199

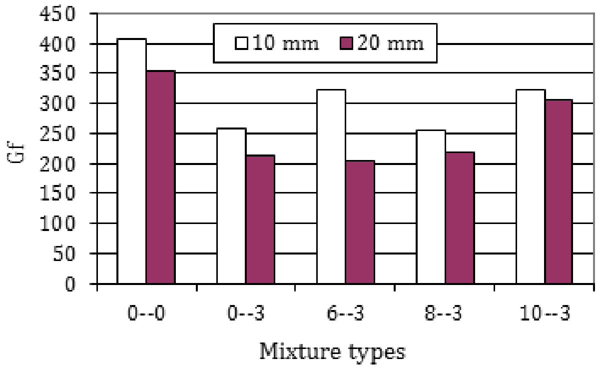

Figure 6. The changes in Gf after the maximum load

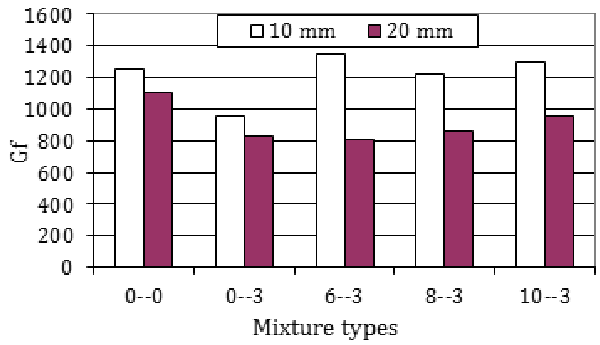

Figure 7. The changes in Gf until the load is discharged

Since the behaviors of the samples on 10 mm and 20 mm notch lengths are different in themselves, the sample's resistances to crack formation and progression were calculated by the J-integral method, presented in the Equation 4, and the results were presented in Figure 8. In this Equation, b is the sample thickness, a is the notch length and U is the energy at the moment of fracture.

$$J_c = -\left(\frac{1}{b}\right)\frac{dU}{da} \qquad (4)$$

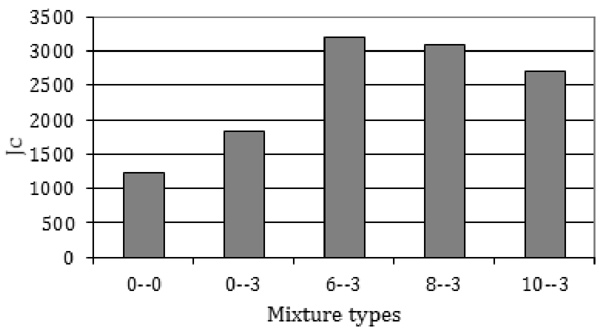

Figure 8. The changes in J_C values of samples

As it can be observed in the figure, in this method, which calculates the fracture according to the critical deformation energy discharge rate, all the samples, except neat and 0-3 mixture, demonstrated similar fracture toughness values until the maximum load. While the neat mixture which contains the lowest softening point and the bitumen with the highest penetration obtained the lowest Jc value, modified mixture demonstrated better results compared to the neat mixture. While the best performance was observed in the 6-3 mixture, which has 2.7 times more Jc value compared to the neat mixture, it was observed that with increased amount CR, the Jc value decreases. It is believed that the decrease in the resistance with the 8% and 10% CR content is due to the high CR content's gradual negative effect on the mixture's cohesion. According to the result of this test, in waste vehicle tire utilization, the optimal rate of CR content is 6%.

Following the breaking of the samples with 10 mm notch length, with the help of the pictures taken of their inner surfaces, the fractured aggregate surfaces were detected. In Figure 9, the sample pictures are presented in black-white forms. On these samples, the rate of white areas, which are the surfaces of fractured aggregates, to the total area was calculated by using MATLAB software on the pictures which were transformed to black-white and were presented in Figure 10. On these samples, it was observed that with the increase in the amount of additive, the amount of white area increased, which means that the aggregate was fractured. The fact that there are more white aggregate surfaces indicates a more rigid fracture and this result complies with the K_{IC} values.

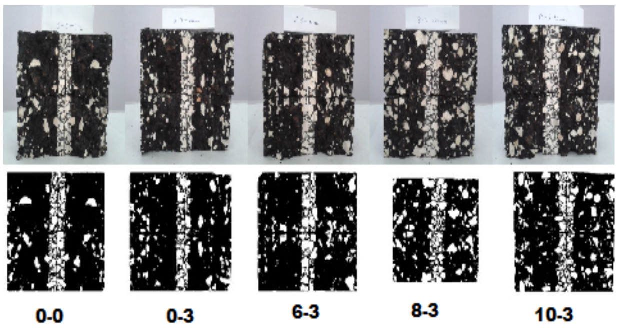

Figure 9. The pictures of fractured aggregate surfaces

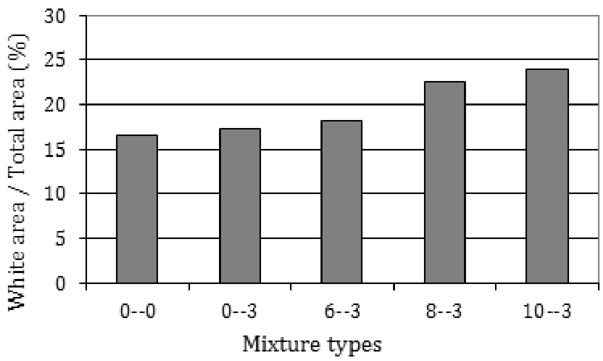

Figure 10. The changes in white area / total area, according to image processing method

4. Conclusion

In this study, with the constant rate of paraffin at 3%, stone-mastic asphalt mixtures modified with various amounts of crumb rubber were tested to determine their resistance to crack formation and movement.
According to binder test results, with increased CR content, the softening point and viscosity of the

modified bitumens increased compared to the neat mixture and their penetration rate was decreased while paraffin modification increased the softening point and decreased the viscosity.

According to semi-circular bending test, with the additive utilization, fracture load and fracture toughness values increased and this increase was observed to be more in 10 mm notch length. With increased notch length and additive utilization, the differentiations in the mixtures decrease. CR and paraffin-modified mixtures, in terms of fracture energy, performed better until the crack initiation yet performed worse against crack movement compared to the neat mixtures. In 20 mm notch length, none of the samples with additives demonstrated a better fracture energy compared to the neat mixture. According to critical fracture energy values, the neat mixture demonstrated the lowest cracking resistance while the highest cracking resistance was observed on 6% CR+3% paraffin-modified mixture. The aggregate surfaces, which were determined by image processing method, demonstrated compatible results with the fracture toughness values and it was determined that with the increased rigidity, the fractured aggregate surface increased.

References

[1] Öztürk, E.A. 2004. Karayolu esnek üstyapi tasariminda yeni bir yöntem: yüksek performansli asfalt kaplama. Journal of the Faculty of Engineering and Architecture of Gazi University 19(2): 175-184.

[2] Ameri, M, Mansourian, A.H., Khavas, M, et al. 2011. Cracked asphalt pavement under traffic loading – A 3D finite element analysis. Eng Fract Mech 78:1817–1826.

[3] Aliha, M.R.M., Behbahani, H, Fazaeli, H., Rezaifar, M.H. 2014. Study of characteristic specification on mixed mode fracture toughness of asphalt mixtures. Constr Build Mater 54:623–635.

[4] Majidzadeh, K. 1976. Application of fracture mechanics for improved design of bituminous concrete. Dept. of Transportation Federal Highway Administration ;;For sale by the National Technical Information Service, Washington ;Springfield Va.

[5] Molenaar, A.A., Scarpas, A.A., Liu, X., Erkens, G. 2002. Semi-Circular Bending Test; Simple But Useful. J Assoc Asph Paving Technol 71:794–815.

[6] Li, X-J, Marasteanu, M.O. 2010. Using Semi Circular Bending Test to Evaluate Low Temperature Fracture Resistance for Asphalt Concrete. Exp Mech 50:867–876.

[7] Baek, S-H, Hong, J-P, Kim, S., et al. 2011. Evaluation of Fracture Toughness of Semirigid Asphalt Concretes at Low Temperatures. Transp Res Rec J Transp Res Board 2210:30–36.

[8] Pérez-Jiménez, F., Botella, R., Moon, K-H., Marasteanu, M. 2013. Effect of load application rate and temperature on the fracture energy of asphalt mixtures. Fénix and semi-circular bending tests. Constr Build Mater 48:1067–1071.

[9] Huang, B., Shu, X., Zuo, G. 2013. Using notched semi circular bending fatigue test to characterize fracture resistance of asphalt mixtures. Eng Fract Mech 109:78–88.

[10] Kök, B.V., Çolak, H. 2011. Laboratory comparison of the crumb-rubber and SBS modified bitumen and hot mix asphalt. Constr Build Mater 25:3204–3212.

[11] Liu, Y., Han, S., Zhang, Z., Xu, O. 2012. Design and evaluation of gap-graded asphalt rubber mixtures. Mater Des 35:873–877.

[12] de Almeida Júnior, A.F., Battistelle, R.A., Bezerra, B.S., de Castro, R. 2012. Use of scrap tire rubber in place of SBS in modified asphalt as an environmentally correct alternative for Brazil. J Clean Prod 33:236–238.

[13] Bennert, T., Maher, A., Smith, J. 2004. Evaluation of Crumb Rubber in Hot Mix Asphalt. Piscataway, NJ

[14] Mull, M.A., Stuart, K., Yehia, A. 2002. Fracture resistance characterization of chemically modified crumb rubber asphalt pavement. J Mater Sci 37:557–566.

[15] Wang, H., Dang, Z., Li, L., You, Z. 2013. Analysis on fatigue crack growth laws for crumb rubber modified (CRM) asphalt mixture. Constr Build Mater 47:1342–1349.

[16] Çelik, O.N., Atiş, C.D. 2008. Compactibility of hot bituminous mixtures made with crumb rubber-modified binders. Constr Build Mater 22:1143–1147.

[17] Kim, H., Jeong, K-D, Lee, M.S, Lee, S-J. 2014. Performance properties of CRM binders with wax warm additives. Constr Build Mater 66:356–360.

[18] Oliveira, J.R.M, Silva, H.M.R.D., Abreu, L.P.F., Fernandes, S.R.M. 2013. Use of a warm mix asphalt additive to reduce the production temperatures and to improve the performance of asphalt rubber mixtures. J Clean Prod 41:15–22.

[19] Kök, B.V., Yılmaz, M., Akpolat, M. 2014. Evaluation of the conventional and rheological properties of SBS+Sasobit modified binder. Constr Build Mater 63:174–179.