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Granül kauçuk modifiyeli (CRM) asfalt karışımların kırılma özelliklerinin deneysel olarak incelenmesi

Experimental investigation of the fracture properties for crumb rubber modified (CRM) asphalt mixtures

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Experimental Investigation of the Fracture Properties for Crumb Rubber Modified (CRM) Asphalt Mixtures

Highlights

- *The reuse of waste tires in asphalt pavements provides benefits in terms of environmental sustainability.*
- *Asphalt mixtures containing waste tires are more resistant to brittleness at low temperatures.*
- *Waste tires had negative effects on the stability, but they provided sufficient Marshall deformation index.*
- *Fracture performance could be improved when waste tires processed up to 20% by dry method in HMA.*
- *Waste tires in HMA provide better fatigue resistance to pavements against traffic loads.*

Graphical Abstract

In this study, the fracture behavior of asphalt pavements on a semi-circular bending test at low temperatures was investigated. It has been shown that low temperature performance could be improved when waste tire powder-added bitumen processed by dry method is mixed to hot mix asphalt up to 20%.

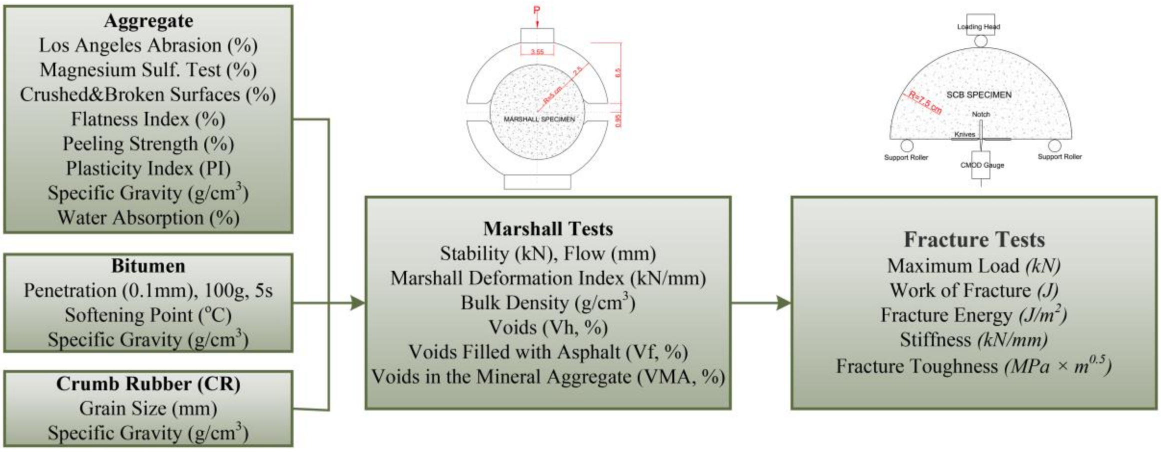

Figure. Scope of the methodology

Aim

In this study, it is aimed to examine the performance of flexible pavements with 20% waste tire additives at low temperatures.

Design & Methodology

The fracture behavior of normal and rubber-modified asphalt mixtures was investigated in accordance with AASHTO TP105 by adding waste tire granules at the ratio of 20% by weight of bitumen to hot mix asphalt.

Originality

Since the bitumen of the mixtures used in the fracture test is modified by the dry process, it is an original work in terms of sample production and test results.

Findings

It has been determined that when the waste tire granules are added to the hot mix asphalt by replacing 20% of the bitumen weight with the dry process, coatings with 37% more elastic ability could be made on sustainable pavements. It has been shown that low temperature performance could be improved when waste tire-added bitumen processed by dry method is mixed to hot mix asphalt up to 20%.

Conclusion

Considering that approximately 300,000 tons of tire wastes are produced in Turkey every year, it has been determined that the use of tire wastes can have economic and design advantages, both for making more economical and environmentally friendly roads in terms of sustainability, and because CRs have higher energy absorption capacity at low temperatures as seen in the fracture test, they provide better fatigue resistance to the pavements against the traffic loads.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Granül Kauçuk Modifiyeli (CRM) Asfalt Karışımların Kırılma Özelliklerinin Deneysel Olarak İncelenmesi

Araştırma Makalesi / Research Article

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ÖZ

Tekerlek yükleriyle birlikte çevresel ve mekanik etkilerden dolayı gün ve mevsim bazında ortaya çıkan çatlaklar, zamanla yayılarak esnek üstyapılarda önemli bir bozulma türü haline gelirler. Bu tür bir bozulma, üstyapıların bakım ve rehabilitasyon maliyetlerini önemli ölçüde artırabilmektedir. Bitüm içeriğine belirli oranlarda kauçuk tozu veya ince granüllerin katılması ile kaplamaların ömürleri uzatılabilmekte ve araç lastiği atıklarından kaynaklanan çevre sorunlarını azaltabilmektedir. Bu çalışmada, normal ve kauçuk modifiyeli asfalt karışımların kırılma davranışı AASHTO TP105'e göre, atık lastik granülleri bitümün ağırlıkça %20 oranında karışıma eklenerek incelenmiştir. Karışıma bitüm ağırlığının %20'si oranında atık lastik tozu eklendiğinde, sürdürülebilir kaplamalarda %37 daha fazla elastikiyete sahip üstyapıların yapılabileceği tespit edilmiştir. Atık lastik katkılı karışımlar, kontrol karışımlarına kıyasla maksimum yükte %118 ve kırılma tokluğunda %97 daha yüksek performans göstermiştir. Kuru yöntemle proses edilen atık lastik katkılı bitüm, %20'ye kadar bitümlü sıcak karışımlara eklendiğinde, karışımın düşük sıcaklık performansının iyileştirilebileceği tespit edilmiştir.

Anahtar Kelimeler: Kırılma tokluğu, asfalt kaplamalar, atık lastik, yarı dairesel eğilme testi.

Experimental Investigation of the Fracture Properties for Crumb Rubber Modified (CRM) Asphalt Mixtures

ABSTRACT

Cracks that develop daily and seasonally due to the environmental or mechanical effects caused by axle loads, propagate over time and become an important type of distress in asphalt layers. This type of distress can significantly increase the maintenance and rehabilitation costs of pavements. The use of rubber powder or fine granules in certain proportions to the bitumen content can extend the life of the pavements and reduce the environmental problems caused by waste tire disposal. In this study, the fracture behavior of normal and rubber-modified asphalt mixtures was investigated in accordance with AASHTO TP105 by adding waste tire granules at the ratio of 20% by weight of bitumen to hot mix asphalt. It has been determined that when the waste tire powders are added to the hot mix asphalt by replacing 20% of the bitumen weight, coatings with 37% more elastic ability could be made on sustainable pavements. Waste tire powder-mixes performed 118% higher in maximum load and 97% higher in fracture toughness compared to control-mixes. It has been shown that low temperature performance could be improved when waste tire powder-added bitumen processed by dry method is mixed to hot mix asphalt up to 20%.

Keywords: Fracture toughness, asphalt pavements, waste tire, semi-circular bending test.

1. INTRODUCTION

The original or coated tires that are removed from the vehicle and cannot be used for the vehicle again are called "End of Life Tires (ELTs)" because they have completed their useful life under the vehicle. It has been reported that approximately 300,000 tons of ELTs emerges annually in Turkey [1]. The recycling processes of these tires are becoming a very important issue in terms of sustainable economy and environment. Powder or fine granular rubber particles obtained by grinding used vehicle tires have particle sizes ranging from 4.75 to 0.075 mm and are defined as recycled material with a specific gravity of 1.15±0.05 [2]. In the US, around 300 million scrap tires are recycled each year, and 5.1% of this amount is civil engineering applications [3].

Asphalt paved roads are prone to cracking, especially at low temperatures, due to the aging of the bitumen over time. Modification of bitumen is one of the most used methods to increase the life of pavements exposed to high traffic and reduce maintenance costs. The use of rubber powder or fine granules in certain proportions to the bitumen content can extend the life of the pavements and reduce the environmental problems caused by tire waste disposal. Rubber crumbs were first used in the 1840s, and according to many researchers, the mechanical properties of asphalt mixtures can be increased significantly by adding rubber to bitumen [4-6]. It has been reported that although there is a slight decrease in Marshall stability values in rubber-modified bituminous hot mixtures, the

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required minimum standard conditions are achieved, thus providing a significant environmental benefit [7]. In a study in which rubber granules were added at the level of 25% of the bitumen weight, it was reported that the mechanical properties and durability of asphalt could be increased [8]. In another study, it was stated that the addition of rubber granules increased the fracture resistance of asphalt mixtures and improved pre-cracking performance at medium and low temperatures [9]. The use of waste tires as a recycling material added to bitumen in asphalt mixes; contributes to sustainability principles such as recovery, recycling, reuse and reduction also known as R^4. For ELTs management, disposal options vary according to the purpose of use and cost, and are generally grouped into four groups: recycling, reuse, storage, and energy/material recovery. It has been reported that the most suitable alternative in Turkey is recycling, and only the cost of installation criterion has a negative effect on the preferability of this alternative [10]. Rubber modified bitumen is defined as a material that can be used in bituminous layers that are aimed suitable for purposes such as reducing noise and increasing the coating performance in the Turkey Highway Technical Specification, Section-418. [11].

Many highway administrations allocate significant annual budgets for the maintenance, repair and rehabilitation tasks for the asphalt pavements. Cracks that develop daily and seasonally due to the environmental or mechanical effects caused by axle loads, propagate over time and become an important type of distress in asphalt layers. This type of distress can significantly increase the maintenance and rehabilitation costs of pavements. Therefore, investigation of crack initiation and propagation behavior for asphalt pavements is becoming an important issue for many designers to consider. Asphalt pavements behave like brittle materials at very low temperatures, and therefore the risk of immediate cracking increases due to pre-existing cracks. Some experimental studies have been carried out in the past using different test specimens to investigate crack initiation and propagation behavior in Hot-mix Asphalt (HMA). In order to obtain experimentally valid results, a suitable test specimen must have a simple geometry and a smooth loading pattern. For this purpose, specimens in different geometries were used by the researchers in order to obtain the fracture properties of HMA [12]. It is possible to divide the test specimens into three groups: three- or four-point bending test on the beam [13-15], direct testing of disc-shaped specimens [16,17], semi-circular bending (SCB) test [18-21], and a notch is cut in the lower-middle side of the specimen to allow controlled crack development. Since SCB specimen can be prepared in the laboratory by using a Marshall and gyratory compactor or by cutting cores from the road, it can offer more economical and faster test results compared to other specimens.

The SCB test was first used by materials scientists to determine the fracture properties of rocks [22]. Later, some studies were carried out by the pavement engineers to determine the fracture properties of different HMA and these studies allowed the development of standards under the monotonic loading conditions. For SCB test in HMA under the static loading conditions; EN12697-44 [23] and AASHTO TP105 [24] standards have been published, which contain instructions on parameters such as loading ratio, specimen geometry, support conditions, fracture toughness and fracture energy. Acceptable durability and mechanical strength for asphalt pavements depends on factors such as the composition of materials, manufacturing process, mix design, aggregate and binder types, service level and ambient conditions. For this reason, in terms of fracture energy, the effects of parameters such as maximum size of aggregate, air voids, aggregate and binder types in the mixture should be known.

The grain size, specific gravity and amount of the waste tire granules (rubbers) likely to be used in HMA have an effect on the fracture behavior of the specimens. In this study, the fracture behavior of normal and rubber-modified asphalt mixtures was investigated in accordance with AASHTO TP105 by adding waste tire granules at the ratio of 20% by weight of bitumen to HMA. For this purpose, Marshall briquette properties of the mixtures prepared with waste tire rubber modified bitumen were determined, then the fracture behavior of the samples on the SCB samples was examined, and finally a comparative analysis was made with reference (control) mixtures.

2. MATERIALS AND METHODS

2.1. Marshall Design

Marshall procedure is applied to compacted cylindrical specimens with different bitumen contents. After the specimens are kept in water at 60°C for 30-40 minutes, they are subjected to compression with a constant speed of 51mm/min. The Marshall stability (kN) is the maximum load recorded during the test, and the flow (mm) is the deformation recorded at the maximum load. Maximum unit weight, maximum stability, and 4%-air voids in the briquettes should be considered together to determine the optimum binder content [25]. The Marshall deformation index (kN/mm) can be calculated as the ratio of stability to flow and thus represents the ratio of load to deformation under certain test conditions and can be used as a measure of pavement resistance to permanent deformation. It has been reported that the Marshall deformation index should be in the range of 2 to 6 kN/mm for HMA tests carried out at 60°C. It has also been emphasized that mixtures with an index above 6 kN/mm have low resistance to fatigue and thermal cracking, while specimens with an index below 2 kN/mm may have high visco-plastic permanent deformation [26].

Aggregates obtained from Körfez, Hereke limestone quarries in Kocaeli were used for the preparation of HMA. As binder, PG64-22 bitumen was procured from Turkish Petroleum Refineries Corporation (TÜPRAŞ) Körfez Refinery, and the physical properties of aggregates and bitumen are given in Table 1. Crumb Rubber (CR) was obtained from old vehicle tires, it is 0.0-20.0 mm in size and has a specific gravity of 1.0 - 1.04 g/cm^3. In accordance with KTS [11], the gradation limit for Surface Course - Type 1 with a maximum aggregate size (D_{max}) of 19 mm is given in Figure 1.

Table 1. Physical properties of aggregate and bitumen

TEST	Aggregate		
	Coarse	Fine	Filler
Los Angeles Abrasion (%)	22	-	-
Magnesium Sulf. Test (%)	1	-	-
Crushed/Broken Surfaces (%)	100	-	-
Flatness Index (%)	19.5	-	-
Peeling Strength (%)	55	-	-
Plasticity Index (PI)	-	NP	NP
Specific Gravity (g/cm^3)	2.723	2.721	2.696
Water Absorption (%)	0.617	0.410	-
	Bitumen		
Penetration (0.1mm), 100g, 5s	54		
Softening Point (ºC)	52		
Specific Gravity (g/cm^3)	1.034		

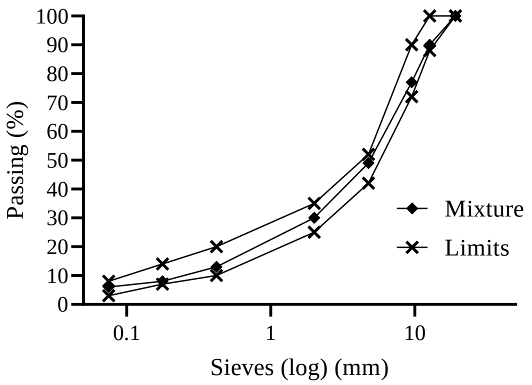

Figure 1. Gradation limits for HMA

In the design study based on the Asphalt Institute Method [27], the samples were compacted with a 2x75 blows using the Marshall hammer with a bitumen content of 4-7% relative to the dry aggregate and were removed from the molds with the jack after 24 hours. Mixing and compaction processes were carried out at 150 ºC and 135 ºC, respectively. After determining the unit weight of the samples, stability and flow values were read on the graphs. The optimum bitumen content was determined as 4.80%. Details of the tests are given in Section 3.1.

In the process of CR granules, two different methods called "dry" and "wet" processing are used. Dry processing has the potential to consume larger quantities of recycled vehicle tires compared to wet processing, which provides greater environmental benefits. In addition, the dry process is logistically easier compared to the wet process and therefore the dry process potentially appeals to a larger market [28, 29]. In the dry process, CR is used by substituting a certain part of the fine aggregate in the mixture content; the rubber particles are mixed with the aggregates, then bitumen is added and the mixing process is continued for a certain period of time. Literature studies on the dry process are limited [30]. In several studies, it has been recommended to use 15-25% of the total bitumen weight of CR granule for dry processing [31]. CR granules were replaced by 20% of the bitumen weight by dry process to obtain CR-containing briquettes (1150 g Aggregate + 10.93 g CR + 43.70 g Bitumen). Marshall tests were performed with the VJ Tech-TRISCAN 50 device in Kocaeli Metropolitan Municipality Building Materials Laboratory (Figure 2).

Figure 2. VJ Tech - TRISCAN 50 loading device

2.2. Preparation of SCB Specimens

After the Marshall procedure, cylindrical specimens (Φ150x50 mm) were produced in accordance with EN 12697-32 [32] for fracture tests. Four semi-circles were obtained from two identical disc specimens for each mixture (Control Mixes and CRM Mixes) and were prepared for the SCB tests. All specimens were compacted as a single layer in Φ150x116.4 mm Proctor-molds by vibration effect at 135 °C. A vibrating hammer (BOSCH-GBH 11 DE, 11kg) a capacity of 900 W and 2000 impacts per minute was used during the compaction process. Compaction time was determined by trial/error method; after the compaction level was checked according to the unit weight obtained with Marshall procedure, all samples where the minimum compaction level was below 98% and the air voids did not prove 4% were canceled and those which did not meet the conditions were excluded from the scope. The compacted specimens were removed from the molds with a jack one day later, cut into a semi-circle form by a disc-saw, then notch opened from the center points and made ready for the SCB test (Figure 3 (a-i)). In the AASHTO TP105-13 [24] standard, it is stated that the fracture test can be carried out at 10°C above the PG lower limit of the bitumen in the asphalt mixture, and for this purpose, the specimens should be conditioned in an air-conditioning cabinet for 2 ± 0.5 hours. In this study, SCB tests were carried out on specimens conditioned with -12 ºC.

Figure 3. Preparation steps of the SCB specimen

2.3. Fracture Tests

Monotonic (static) bending tests were carried out in the mechanical laboratory of KORDSA Teknik Tekstil A.Ş. in İzmit, Kocaeli by applying some changes on the INSTRON 5982 (100 kN capacity~0.16% kN sensitivity) test device. During the bending test, load and displacement data were simultaneously transferred to the computer with INSTRON CMOD-Gauge (0-4 mm capacity~0.003 mm sensitivity) placed at the crack mouth. Loading rate was kept constant as 0.5 mm/min at all stages (Figure 4).

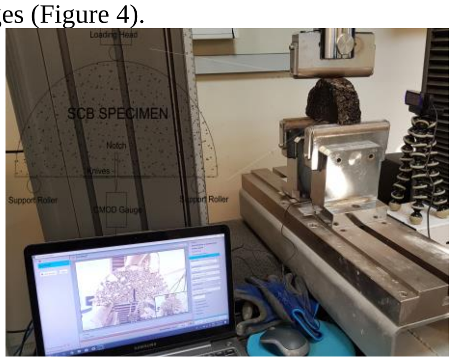

Figure 4. Positioning of the SCB specimen on the test device

The data obtained as a result of the tests were evaluated as stated in the AASHTO TP105-13 standard [24]:

- Determining Work of Fracture (W_f); The breaking of a solid body into two or more parts under the applied stresses is called "fracture". Damages in the materials occur in three ways, in the most general sense, as a result of elastic or plastic deformation and fracture. The area under the Load-CMOD (The Crack Mouth Opening Displacement) curve represents the work of fracture (W_f) and can be calculated by Eq.1.

$$W_f = AREA = \sum_{i=1}^{n}(u_{i+1} - u_i)x\,P_i + \frac{1}{2}x(u_{i+1} - u_i)x(P_{i+1} - P_i) \quad (1)$$

where:
W_f = Work of Fracture (J)
P_i = Load (N) applied at the i step
P_{i+1} = Load (N) applied at the i+1 step
u_i = CMOD (m) at the i step
u_{i+1} = CMOD (m) at the i+1 step

- Determining Fracture Energy (G_f); The energy absorbed until the material collapses with the crack propagation is defined as "fracture energy" for that material. Eq. 2 was used to calculate the Fracture Energy (G_f);

$$G_f = \frac{W_f}{A_{lig}} \quad (2)$$

where:
G_f = Fracture Energy (J/m^2)
W_f = work of fracture (J)
A_{lig} = ligament area (m^2)
$A_{lig} = (r - a) \times t$
r = specimen radius (m)
a = notch length (m)
t = specimen thickness (m)

- Determining Fracture Toughness (K_{IC}); When the stress intensity factor exceeds the value of Kc, the crack propagates abruptly and brittle fracture occurs. This critical value is called "fracture toughness" ant it is a material property. Because the K_{IC} is independent of the size of the material and is constant with little variation. The fracture toughness (K_{IC}) is obtained as the stress intensity factor at the maximum load by Eq. 3:

$$K_{IC} = Y_{I(0.8)}x\,\sigma_{max}x\sqrt{\pi a} \quad (3)$$

where:
K_{IC} = Fracture Toughness ($MPa \times m^{0.5}$)
σ_{max} = Pmax / (2 x r x t) (MPa)
P_{max} = maximum load (MN)
r = specimen radius (m)
t = specimen thickness (m)
a = notch length (m)

$Y_{I(0.8)}$ = the normalized stress intensity factor (dimensionless) (Eq. 4)

$$Y_{I(0.8)} = 4.782 + 1.219\left(\frac{a}{r}\right) + 0.063exp\left(7.045\left(\frac{a}{r}\right)\right) \quad (4)$$

- Determining Stiffness (S); The stiffness is the resistance of a material to resist deformation in response to an applied force. The stiffness (S) represents the initial linear part of the Load-CMOD curve and its unit is recorded as kN/mm.

3. RESULTS OF EXPERIMENTS

3.1. Marshall Tests

According to the results of the Marshall test in which six specimens were produced from each of Control and CRM Mixes, the following results were obtained; with the use of 20% CR in the mix, an increase of approximately 32%, 53% and 13% was observed in the flow, voids (Vh), and voids in the mineral aggregate (VMA) values, respectively (Figure 5, Table 2). One reason why CR particles create relatively more voids in the mixture may be that the bitumen and CR particles are treated to the dry process. In addition to this situation, as a result of the bitumen exhibiting a more elastic behavior, the flow levels tended to increase. It was observed that there was a 21%, 2% and 14% decrease in stability, bulk density and voids filled with asphalt (Vf) values, respectively (Figure 5, Table 2). The resulting void structure naturally decreased the stability and bulk density values of the mixtures. In a more comprehensive study, this porous structure should be observed with the microstructure examination to be carried out, and the effect of the interface properties of aggregate and bitumen on the formation of voids should be explained.

3.2. Marshall Deformation Index

The Marshall deformation index expresses the ratio of maximum stability to flow and this elasticity trend for the test specimens is illustrated in Figure 6(a), where CRM specimens have a more elastic capacity. The Marshall deformation index for each sample was calculated and shown in Figure 6(b). It was determined that the Marshall deformation indexes of the specimens decreased by approximately 37% with the use of 20% CR in the mix (Figure 6(b)). This result means that if CR is used in the mix, it will behave more flexibly under the traffic effect on the same conditions compared to the control sample. In addition, considering the recommendation that the Marshall deformation index should be in the range of 2 to 6 kN/mm on the HMA tests carried out at 60°C [26], it was observed that using CR in HMA could comply with these limits.

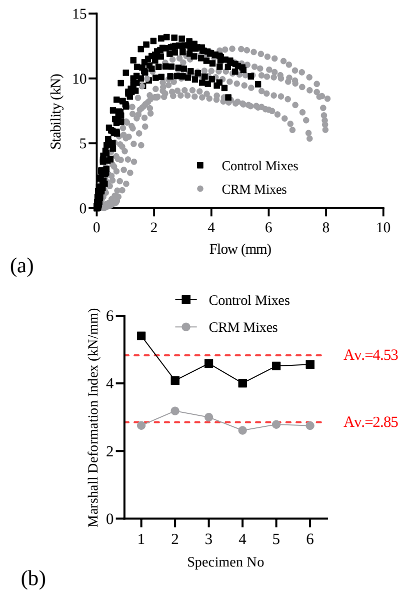

Figure 6. Marshall deformation index in specimens

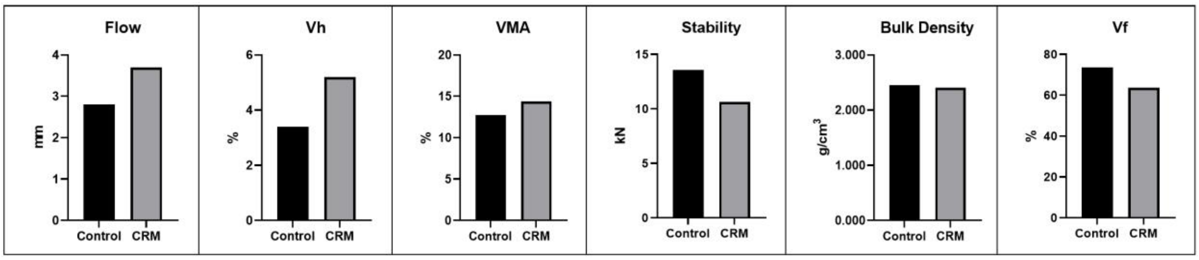

Figure 5. Marshall test results

Table 2. Marshall test results

Mix Type	Flow (mm)	Vh (%)	VMA (%)	Stability (kN)	Bulk Density (g/cm³)	Vf (%)
Control Mixes	2.8	3.4	12.7	13.55	2.456	73.6
CRM Mixes	3.7	5.2	14.4	10.64	2.408	63.6
Percentage of change (%)	*+32*	*+53*	*+13*	*-21*	*-2*	*-14*

3.3. Fracture Energy and Toughness

Results of monotonic (static) bending tests applied on SCB specimens are given in Figure 7 and Table 3. CRM mixes performed 118% higher in maximum load and 97% higher in fracture toughness compared to Control mixes. In a sense, it has been determined that CRM mixes are more flexible at -12°C. This behavior leads to the conclusion that the risk of cracking, which may occur in bituminous pavement due to traffic loads, especially at low temperatures, could be less for CRM mixes. In a study in which a comprehensive review of fracture mechanics for SCB specimen in HMA was made, it was reported that the fracture toughness ranged from 0.7 to 1.3 MPa × $m^{0.5}$ [33]. In this study, these limits could not be met for Control mixes due to differences in method of specimen production, test temperature, reference standard, rheological properties of bitumen and aggregate, but CRM mixes performed within these thresholds under the same conditions. These indicators showed that low temperature performance could be improved when CR-added bitumen processed by dry method is mixed to HMA up to 20%.

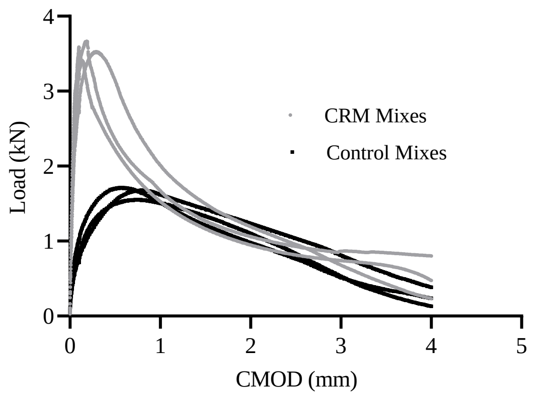

Figure 7. The work of fracture plots

Table 3. Results of SCB tests

EXPERIMENTAL NOTATION	Control Mixes	CRM Mixes	Percentage of change (%)
P = Maximum Load *(kN)*	1.6 *(5.2)**	3.6 *(1.9)*	+118.0
σ_{max} = P_{max} / (2 x r x t) *(kPA)*	259.5 *(6.5)*	516.7 *(3.1)*	+99.1
W_f = Work of Fracture *(J)*	4.1 *(8.7)*	5.4 *(7.4)*	+34.3
G_f = Fracture Energy *(J/m²)*	1773.5 *(10.2)*	2157.4 *(3.9)*	+21.6
S = Stiffness *(kN/mm)*	13.5 *(2.6)*	51.9 *(6.7)*	+284.3
K_{IC} = Fracture Toughness *(MPa × $m^{0.5}$)*	0.38 *(8.3)*	0.75 *(7.2)*	+96.9

* *The numbers in parentheses represent the Coefficient of Variation (COV)*

4. CONCLUSION

In this study, the fracture behavior of normal and rubber-modified asphalt mixtures was investigated in accordance with AASHTO TP105 by adding waste tire granules at the ratio of 20% by weight of bitumen to HMA. For this purpose, Marshall briquette properties of the mixtures prepared with waste tire rubber modified bitumen were determined, then the fracture behavior of the samples on the SCB samples was examined.

- It has been determined that when the CR are added to the HMA by replacing 20% of the bitumen weight with the dry process, coatings with 37% more elastic ability could be made on sustainable pavements. Considering that approximately 300,000 tons of ELTs are produced in Turkey every year, it has been determined that the use of tire wastes can have economic and design advantages, both for making more economical and environmentally friendly roads in terms of sustainability, and because CRs have higher energy absorption capacity at low temperatures as seen in the fracture test, they provide better fatigue resistance to the pavements against the traffic loads.
- Using gyratory or Marshall compactor in the laboratory to produce SCB specimens in accordance with AASHTO TP105 for HMA is not always possible due to economic reasons. It has been determined that fracture tests can be applied with the cores by cutting 150 mm diameter from the field or the use of a vibratory hammer in case of economic constraints for producing SCB specimens.
- Although the waste tires had negative effects on the stability of the specimens, they provided sufficient Marshall deformation index, and it has been shown that low temperature performance could be improved when CR-added bitumen processed by dry method is mixed to HMA up to 20%.
- The study should be extended on asphalt pavements produced with different maximum size of aggregate, air voids, aggregate and binder types, temperature levels, CR ratios and different compaction techniques. It can be aimed to make a comparative analysis of the specimens produced in the laboratory and the field, while determining the crack propagation rate under not only monotonic conditions but also cyclic loading conditions.

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DECLARATION OF ETHICAL STANDARDS

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Yavuz ABUT: Performed the experiments and analyse the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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