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Analyzing the Performance Properties of Stress Absorbing Membrane Interlayer Modified with Recycled Crumb Rubber

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Abstract**—**Asphalt overlay is the most commonly used technique of pavement rehabilitation. However, the reflective cracks which occur on the overlay surface after a short period of time are the most important distresses threatening the durability of new overlays. Stress Absorbing Membrane Interlayers (SAMIs) are used to postpone the reflective cracking in the overlays. Sand asphalt mixtures, in unmodified or crumb rubber modified (CRM) conditions, can be used as an SAMI material. In this research, the performance properties of different SAMI applications were evaluated in the laboratory using an Indirect Tensile (IDT) fracture energy. The IDT fracture energy of sand asphalt samples was also evaluated and then compared to that of the regular dense graded asphalt used as an overlay. Texas boiling water and modified Lottman tests were also conducted to evaluate the moisture susceptibility of sand asphalt mixtures. The test results showed that sand asphalt mixtures can stand higher levels of energy before cracking, and this is even more pronounced for the CRM sand mix. Sand asphalt mixture using CRM binder was also shown to be more resistance to moisture induced distresses.

Keywords**—**SAMI, sand asphalt, crumb rubber, Lottman Modified Test.

I. Introduction

CRACKS transitioning to the surface of the overlay due to underlay ruptures is called reflective cracking [1]. These cracks are created by underlay displacement due to traffic and thermal tensions, and expansion of underlay cracks towards the overlay. In some studies, reflective cracks are referred to those created in position and direction of the previous cracks [2]. Additionally, expansion of cracks from older layers to the overlay is also called reflective cracking [3]. Researchers showed that reflection cracking propagates at a rate of 2.54 cm per year [4]. Transition ratio is dependent on climate variations and traffic factors. Once these cracks reach the surface, they create a path that causes water penetration to the layers underneath. Neglecting this issue results in failure growth and reduces utilization periods [5]. This would in turn undermine driving quality and produce extensive maintenance expenditures, and even road base reconstruction. Studies provide various methods to postpone reflecting cracking, including increasing overlay thickness, modifying the asphalt mixture, employing reinforced pavements, utilizing stress and SAMI, and the use of reinforcing layers.

SAMI is referred to a layer by high energy absorption characteristics. Through dissipating existing energy, this layer postpones development of reflective cracks in overlay for years. The first use of stress absorbing interlayer was in 1960 that an engineering firm in the state of Arizona, USA, used modified bitumen by addition of 33% crumb rubber and developed a modified surface overlay that showed significant resistance to reflective crack propagation [6]. For the first time at 1979, an analytical method was used to evaluate the performance of stress absorbing interlayers which contains crumb rubber [7]. In 1982, a modified interlayer with 25% of crumb rubber was used in the king-77 highway pavement in Ontario, Canada [8].

The SAMIs include various types, e.g. the sand asphalt stress absorbing interlayer, which is applied between the asphalt overlay and the underneath concrete layer, or between the asphalt overlay and the worn-out asphalt layer. Being fine grained, using considerable amounts of filler and bitumen, low air voids, high VFA, and good adhesion of filler and bitumen, enables proper connection between this layer and upward and downward layers. Results obtained by Yang [9] demonstrated that the thickness of 2-3 cm for this layer provides the best performance. Baek and Al-Qadi utilized asphalt grading with a maximum nominal size of 4.75 mm to study sand asphalt interlayer [10]. Sand asphalt which is produced by Moses contained 84% sand and 16% filler, and 10.3% of 160-220 penetration grade bitumen [11]. Furthermore, Baek and Al-Qadi applied polymer modified bitumen PG76-28 at a rate of 6.8 percent of weight to enhance bitumen characteristics in sand asphalt interlayer [10].

The amount and characteristics of bitumen used in sand asphalt generally affect sand asphalt properties such as resistance against cracking. The bitumen to be used should be chosen in such a way that satisfies sand asphalt properties such as flexibility and elastic properties [12], [9]. Discarded tires are one of the most serious environmental problems that most of municipalities in all countries faced with. Annually, about 300 000 tons of rubber are produced or imported only in Iran where most of that are car tires. Each discarding tire weights about 9 kg, which contains 58% rubber, 22% fiber, and 20% steel [12].

Over the years, many researchers concentrated on crumb rubber utilization in asphalt [13], [14] and showed that rubberized asphalt mixtures can exert different benefits to the pavements such as noise reduction, resistance to rutting, reduction in asphalt thickness, and resistance against cracking [12]. Studies indicated that addition of crumb rubber to

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bitumen improves many of its performance properties. Nejad et al. coworkers employed the elastic recovery test and showed that addition of crumb rubber increases bitumen elastic behavior [15]. Wang et al. indicated that utilizing CRM bitumen prevents the growth of cracks and increases the fatigue lifetime of the asphalt pavement. Other researches showed that crumb rubber can improve moisture susceptibility and increase resistance against stripping [16].

Fig. 1 Disposal tire

Crumb rubber physical and chemical properties such as the crumb rubber production method, its particle size, the specific surface area and its chemical composition (amount of natural rubber) have considerable effects on the modified bitumen characteristics [17]. The improved physical properties of CRM bitumen like elasticity and elongation are usually attributed to the three dimensional network made by connection of swollen strands [12]. Researches indicated that interaction between crumb rubber and bitumen is a kind of physical diffusion in which rubber particles absorb aromatic fraction of bitumen. This absorption makes crumb rubber particles larger and reduces bitumen aromatic oils resulting in a high viscosity binder. The high viscosity problem however can be controlled by adding some oily components like naphthenic oil.

Although it is proven that properties and chemical composition of aggregates have dominant effect on affinity between aggregates and bitumen, many studies showed that some additive, such as crumb rubber could increase adhesion between bitumen and aggregates [18]. Daučík et al. showed 6% increment in aggregates covered area in the water boiling test, after using crumb rubber modifier [18]. Nejad et al. showed that crumb rubber addition could increase aggregate-bitumen adhesion and resistance against stripping in asphalt [15]. Virginia Department of Transportation (VDOT) managed a research in which the effects of crumb rubber addition to the moisture susceptibility of asphalt mixtures were evaluated using the modified Lottman and Texas Boiling Water test. They showed that crumb rubber modifier could improve asphalt mixtures stripping and moisture susceptibility [19].

Various experiments are conducted to assess asphalt mixture resistance against cracking. For instance, IDT determines the tensile strength of asphalt samples. Since mode I cracking occurs in tension and it is the dominant mode in overlay, asphalt tensile strength can be considered as an important factor in cracking [20]. Fractural energy and tensile strength are known as factors affecting pavement effective lifetime [21].

By emergence of reflective cracks, runoff waters can penetrate into underlays. Mehrara and Khodai demonstrated that destructive effects of moisture could decrease asphalt module by 21% and increase rutting by 64% [22]. The study conducted by Tarefder and Zaman indicated that the destructive effects of moisture could occur due to two factors; first, loss of adhesion among bitumen and aggregate, resulting from water perching through the two layers, and second, the failure occurrence in bitumen-filler mixture [23]. The former can be evaluated through Texas Boiling Water test, while the latter is assessed to some extent using Modified Lottman test. Moisture susceptibility tests are divided into two categories, namely quantitative and qualitative. The qualitative tests cover experiments measuring asphalt vulnerability against moisture through examination and determination by a precise number. This category includes modified Lottman test (AASHTO T-283), standard density-immersion test (AASHTO T-165) and Hamburg wheel-track testing (AASHTO T-324). The qualitative tests employed to assess asphalt moisture susceptibility include experiments utilizing visual evaluation as asphalt quality measurement. Although these tests do not possess extensive accuracy, they are customary for being simple and independent from advanced devices. Boiling water test (ASTM D3625), static immersion standard test (AASHTO T-182), and Nicholson tests (ASTM D-1664) are the examples of qualitative moisture susceptibility tests.

II. Materials and Methods

The 60/70 penetration grade bitumen used in this study was supplied by Tehran refinery. The bitumen characteristics were shown in Table I. In addition, aggregates were provided from sand mines located in the west of Tehran. Aggregates physical characteristics were shown in Table II, while their chemical analysis, determined by XRF test, was presented in Table III. It can be seen that the aggregates are mainly of silica type. The grading No.5 of Iran specification which is suitable for designing asphalt pavement surface was used for overlay asphalt mixture. Grading details along with grading No.5 upper and lower limits were shown in Table IV. The grading No.6 of Iran specification, known as sand asphalt grading, was also utilized for interlayer asphalt mixture. Upper and lower limits, as well as the sieves used were introduced in Table V.

For the CRM bitumen, crumb rubber particles smaller than No. 40 sieve, at 15% of the bitumen weight, was utilized. Crumb rubber used in this research was shown in Fig. 2. The CRM bitumen was mixed at 180 °C for 60 min at 5000 rpm, using the high shear mixer.

TABLE I
60/70 Penetration Grade Bitumen Characteristics

Test	Standard	Result	Specification	
			Min	Max
Penetration	ASTM D5	63.5	60	70
Softening Point	ASTM D36	49.3	-	-
Ductility	ASTM D113	107	100	-
Density	ASTM D3289	1.014	1.013	1.017

TABLE II
AGGREGATES PHYSICAL CHARACTERISTIC

Test	Standard	Result	Specification	
			Min	Max
Percentage of Fractured Particles	ASTM D 5821	91	60	-
Soundness of Aggregate	ASTM C 88	1.4	-	8
Resistance to Degradation	ASTM C 131	13	-	25
Flat and Elongated Particles	ASTM D 4791	15	-	15

Fig. 2 Crumb rubber used in this research

TABLE III
ANALYTICAL COMPOSITION OF AGGREGATES (XRF TEST)

Oxide and Elements	Na_2O	MgO	Al_2O_3	SiO_2	$P2O_5$	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	Sr	Zr
Percent	2.4	1.9	11.8	53.9	0.1	2.4	12.2	0.37	2.9	0.03	0.02	0.02

TABLE IV
OVERLAY ASPHALT MIXTURE GRADING BASED ON IRAN SPECIFICATION

Sieve Size (mm)	0.075	0.3	2.36	4.75	9.5	12.5
Limits	2-10	7-23	32-67	55-85	90-100	100-100
Selected	6	15	49.5	70	95	100

III. MIX DESIGN

Marshall Mix design approach was employed to determine the optimum bitumen content for overlay and sand asphalt interlayer. For overlay, Marshall samples with 4.5%, 5%, 5.5%, 6%, and 6.5% bitumen contents were constructed. According to Marshall diagrams, the optimum bitumen content for overlay mix was determined as 5.25%. Moreover, to determine optimum bitumen for sand asphalt interlayer mixtures, Marshall samples with 7%, 8%, 9%, 10%, and 11% bitumen were constructed. The optimum bitumen content of sand asphalt interlayer mixture was chosen as 8.4%. It could be noted that the sand asphalt mixtures modified by crumb rubber were also constructed with 8.4% bitumen content.

TABLE V
SAND ASPHALT MIXTURE GRADING BASED ON IRAN SPECIFICATION

Sieve Size (mm)	0.075	0.15	0.3	0.6	1.18	2.36	4.75	9.5
Limits	2-10	3-20	7-40	25-65	40-80	65-100	80-100	100-100
Selected	5.5	11.5	23.5	45	60	82.5	90	100

IV. RESULTS AND ANALYSES

Stress-absorbing interlayer is a layer that postpones cracks propagation by absorbing the inserted energy, and resists against reflection of cracks in the overlay. Moreover, by providing resistance against penetration of runoffs to underneath layers, it prevents further destruction of the pavement structure. IDT test device was employed in this research to evaluate the asphalt mixture strength by measuring fractural energy. Using this method, the amount of energy absorbed by each of the two asphalt layers in the pavement structure, the interlayer and the overlay could be determined. Furthermore, using modified Lottman test and Texas Boiling Water test, the moisture susceptibility and the interlayer resistance against runoff penetration were evaluated in this research.

A. Fractural Energy

To evaluate sample performance against cracking, various parameters such as IDT strength, ultimate fractural energy, and fracture energy leading to the failure can be determined. Fractural energy is the amount of energy that should be applied to cause a unit area of cracking and it can be calculated by the area under the force-displacement diagram from the beginning if the loading to the maximum force (failure fractural energy). Moreover, the ultimate fractural energy is equal to total area under the force-displacement diagram. In this study, fractural energy for both sand asphalt mixture and sand asphalt mixture modified with crumb rubber are determined, and they are compared with the fractural energy of overlay asphalt samples. Fractural energy is calculated using the following equation:

$$F_E = \int_0^{\delta_M} P(\delta)d \Big/ (H \;) \qquad (1)$$

F_E: Failure fractural energy (J/m^2), P: Force (N), δ: Displacement (mm), H: Sample thickness (mm), D: Diameter (mm).

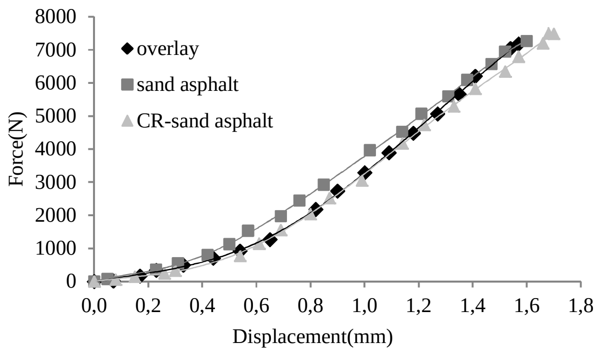


Fig. 3 Force-Displacement diagrams

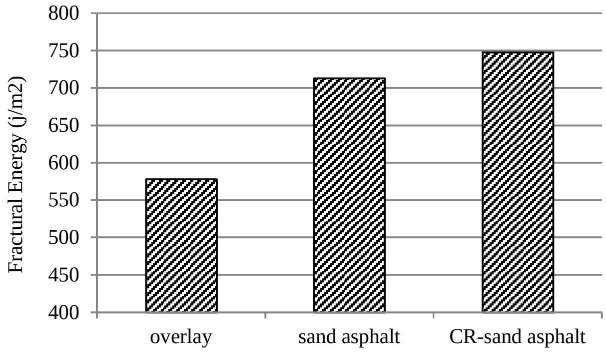


Fig. 4 Fractural energy for three asphalt mixtures

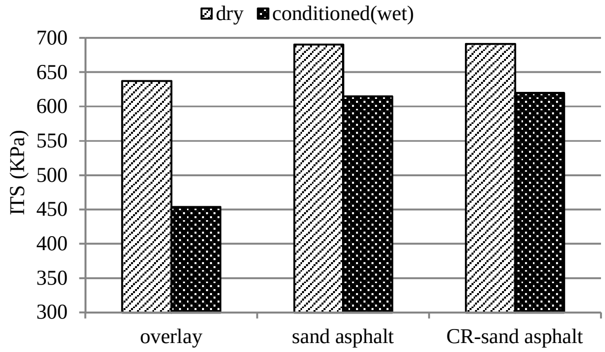


Fig. 5 IDT strength

Force-displacement diagrams for asphalt overlay and two types of sand asphalt mixtures were depicted in Fig. 3. It can be seen in this figure that the asphalt overlay and sand asphalt interlayer experienced the same levels of displacement, but the sand asphalt mixture absorbed higher levels of energy in the same displacement levels and its area under the curve became larger. Additionally, the modified sand asphalt mixture exhibited a higher displacement level than the overlay prior to rapture breakdown threshold, which resulted in a larger area under the curve compared to the overlay mixture sample. On the other hand, the comparison between the unmodified and CR modified sand asphalt mixtures showed that, although the unmodified sand asphalt absorbed higher level of energy in a fix displacement level, it reached the failure point in a lower final threshold. In fact, CR modified sand asphalt endures more displacements compared to unmodified sand asphalt mixture. Fractural energy for the mixtures was calculated and depicted in Fig. 4. As it can be seen, sand asphalt mixtures possess higher levels of fractural energy compared to the overlay asphalt mixture, which indicates the beneficial effect of this interlayer against the crack propagation in pavements. Furthermore, CR modified sand asphalt possesses higher fractural energy compared to unmodified sand asphalt mixture, which in turn highlights the comparative advantage of crumb rubber in interlayers.

B. Modified Lottman Test

This test is a quantitative experiment to evaluate the moisture susceptibility of asphalt mixtures. Six samples were constructed from each asphalt mixtures (asphalt overlay, unmodified sand asphalt mixture, and CR modified sand asphalt mixture), with optimum bitumen obtained from Marshall mix design. According to AASHTO T-283, three specimens are used for IDT strength in dry mode and the other three specimens are used for wet or conditioned mode. Dividing the results obtained for conditioned samples to the results of dry samples yields TSR ratio is an effective index for evaluating the moisture susceptibility of asphalt mixtures (2). IDT strength for dry and conditioned samples and their TSR ratio were illustrated respectively in Figs. 5 and 6.

$$T \quad = \frac{I' \quad c\ n}{I \quad d} \times 100 \qquad (2)$$

As can be seen in Fig. 5, sand asphalt and CR modified sand asphalt mixtures possess similar dry and conditioned (wet) tensile strengths, and relatively similar TSR ratios. This indicates that crumb rubber addition had neither positive nor negative effect on the IDT strength of the sand asphalt mixture. Moreover, IDT strength for overlay mixture in both dry and wet condition was less than those ones for sand asphalt mixtures, and the TSR ratio for overlay asphalt is also lower. Iran asphalt pavement specification requires a TSR ratio of more than 75% for the asphalt mixtures to be acceptable. Therefore, based on this result, the unmodified and CR modified sand asphalt mixtures both pass this requirement, while the overlay mixture cannot.

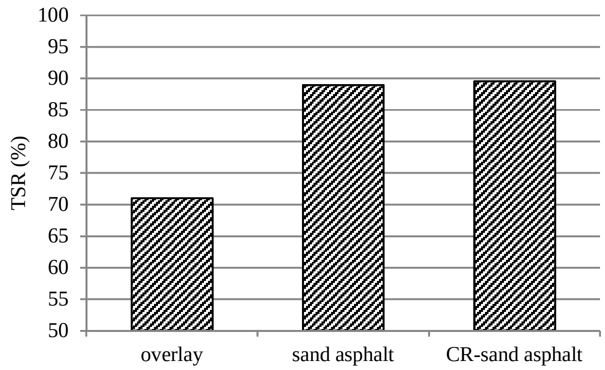


Fig. 6 Tensile Strength Ratio (TSR)

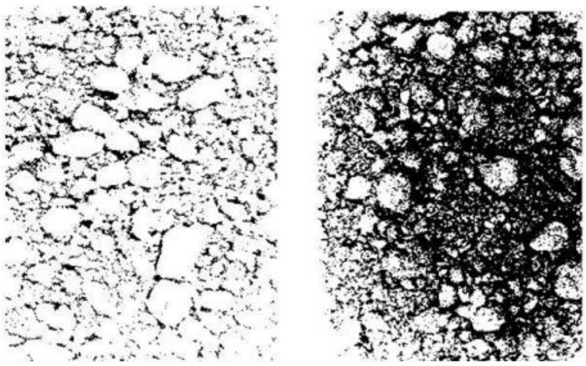
Lower moisture susceptibility and higher resistance of sand asphalt mixture against water flow penetration, which are due to extensive filler, high bitumen content, and lower air void of this mixture could be the reason towards adopting this interlayer as water sealant or a resistant layer against water penetration.

C. Texas Boiling Water Test

Texas boiling water test qualitatively and visually evaluates moisture susceptibility. In this experiment, first the aggregates are smeared with bitumen to the extent of entire impregnation. Then, the asphalt mixture is placed outdoors to cool down. After the aggregates are cooled down and detached particles are formed, the asphalt mixture is placed in the boiling water for 10 minutes and then removed. By visual observations of unmodified and CRM sand asphalt mixtures, the stripping level is approximately determined. The asphalt mixtures after Texas boiling water test were shown in Fig. 7. Visual evaluation is not sufficiently precise to present a reliable outcome. So, in this research, MATLAB software was used to make a fair judgment through image processing method. Based on the research of Otsu, brightness matrixes were extracted, and their average was regarded as a threshold of brightness or darkness [24]. Pixel values in matrix which have values more than the average were shown as white; otherwise, they were shown as black. Fig. 8 has been produced to evaluate effect of crumb rubber on stripping using the described technique. By dividing the number of white pixels to all pixels, stripping indexes were achieved and illustrated in Table VI.

(a) Sand asphalt (b) CR-sand asphalt

Fig. 7 Asphalt mixtures after Texas Boiling Test



(a) Sand asphalt (b) CR-sand asphalt

Fig. 8 Asphalt mixtures after Texas boiling test after image processing

TABLE VI
STRIPPING OF SAND ASPHALT MIXTURES

Mixture	All pixels	White pixels	Stripping (%)
Sand asphalt	118158	104000	88
CR-sand asphalt	118158	58766	50

Considering Figs. 7 and 8 and the results presented in Table VI, it can be seen that the CRM sand asphalt mixture showed considerably higher resistance against stripping compared to the unmodified sand asphalt sample. It should be noted that since sand asphalt mixture was constructed using silica aggregates, external additives were required to provide suitable resistance against stripping. Considering the high SiO_2 percentage, as well as considerable amounts of transition metals such as Al_2O_3 and Fe_2O_3, it can be concluded that small amounts of alkali elements (K_2O + Na_2O + MgO + CaO) do not have notable effect on improving stripping properties. Since silica aggregates are negatively charged on the surface, their tendency is towards attracting positive charge. On the other hand, since water molecules are polarized, they can neutralize the negative electrical charge on silica surface and replace bitumen, which results in stripping phenomena in siliceous materials. Furthermore, presenting crumb rubber as the additive increased sand asphalt resistance against stripping dramatically. Anderton et al. showed that CRM bitumen can coat aggregates by a thicker film due to its higher viscosity [25]. These findings represented a good compatibility with VDOT and the research results of Daučík [19], [18].

V. CONCLUSIONS

In this paper, performance of sand asphalt mixture as a SAMI was studied. The main purpose of employing stress-absorbing interlayers is reducing reflective cracks in asphalt overlay layer, alongside with preventing runoff penetration in pavement structure and postponing destruction of pavement structure. In this study, through conducting experiments such as fractural energy determination test, modified Lottman test and Texas boiling water test, the characteristics of sand asphalt membrane interlayer both with and without crumb rubber modifier were evaluated. Moreover, the effects of crumb rubber addition to the properties of sand asphalt interlayer were investigated, and the following results were obtained:

- According to energy absorbing characteristics of interlayers, it can be concluded that sand asphalt interlayers, and sand asphalt interlayers modified by crumb rubber, represent greater ability of absorbing and depreciating energy, with fractural energies of 713 and 748 joules per square meter, respectively, in comparison with asphalt overlay, with fractural energy of 578 joules per square meter.
- Modified Lottman test revealed that TSR ratio for sand asphalt mixture and sand asphalt mixture modified with 15% crumb rubber is 89 and 89.63%, respectively. This ratio was calculated as 71.16% for overlay layer. These values represent sand asphalt mixtures' higher resistance against moisture susceptibility.
- Texas boiling water test demonstrated that addition of crumb rubber to asphalt mixture increases the stripping resistance of this mixture by up to 38%.

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