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Evaluating the Moisture Resistance of Foam Warm Mix Asphalt Using Image Processing Method

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Keywords

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TSR,
Image processing method.

Abstract

Moisture damage is one of the major concerns of asphalt mixes. Warm mix asphalts (WMA) are more prone to this distress. Various methods were suggested during the recent years for evaluating the performance of asphalt mixes against this failure. Image processing method was employed to detect the stripping severity of mixes after Texas boiling test. Since this test is based on visual evaluation, a novel index was suggested to quantify the results and decrease the impact of operator mistake. Furthermore, modified Lottman test was used to determination of tensile strength ratio (TSR) index. Finally, a statistical model was regressed to evaluate the signification and correlation of stripping index and TSR. The results of statistical analysis showed that relation between suggested stripping index and TSR is significant with respect to 95% confidence level. In addition, high magnitude of R2 (94%), shows that the regressed model is able to predict the TSR satisfactory based on stripping index.

1. Introduction

Moisture susceptibility is one of the major concerns of asphalt pavement researchers and experts. Stripping is defined as weakening and collapse of bonding between bitumen and aggregates. This failure is occurred by loss of adhesion of asphalt and aggregate and cohesion of bitumen that leads to decline stiffness and resistant of asphalt mixes [1-3]. Generally, this failure is occurring in different shapes: weakening of adhesion between bitumen and aggregate, cohesion loss of bitumen at presence of moisture, conjunction of aggregates, emulsifying of bitumen and freezing of the imprisoned water [4]. Previous researches indicated that loss of adhesion between bitumen and aggregates in present of moisture and weakening of bitumen is because of bitumen cohesion loss are major reasons of this failure [5]. Generally, most of pavements are prone to moisture damage [4]. Therefore, different research works were performed to recognize the reason of this failure and propose test method to study the moisture susceptibility of asphalt mixes [6-8]. Therefore, they employed novel concepts to explain the performance of asphalt materials against moisture damage, such as fracture mechanic parameters, surface free energy and adhesion properties.

Warm mix asphalt is produced at 17 to 30° C lower than conventional hot mix asphalt (HMA). Different methods are suggested to produce WMA. The main aim of these are to reduce mixing temperature, fuel consumption and environmental pollution and also, producing suitable mixes. Multiple researches were performed to evaluate the moisture susceptibility of warm mix asphalt. Based on NCHRP Project 9-43, it can be seen that in most of cases, unmodified WMAs are more prone to moisture susceptibility than conventional HMA. Nevertheless, using anti-stripper agents improved the performance of these mixes against of moisture distress [9]. Kavussi et al. investigated the effect of hydrated lime as an anti-stripper on the moisture resistance of warm mix asphalts that produced using organic agents. They indicated that indirect tensile strength of modified WMA is lower than HMA [10]. Zelelew et al. performed a research study on the moisture susceptibility of WMA mixes that produced using different type of technologies. They indicated that Foam WMA and Sasobit modified WMA are more prone to moisture damage [11]. In addition, Xiang Shu et al. evaluated the performance of foam WMA mixes that produced using foaming additives. They found that presence of RAP materials in foam WMA mixes leads to more resistant WMA mixes against moisture damage [12]. Hill et al. performed a research work to investigate the interaction

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of different percentage of RAP materials and different WMA technologies (organic additives, chemical additives and foaming additives) on the rutting resistance and moisture susceptibility of WMA mixes. They found that presence of RAP materials leads to higher rutting resistance. Likewise, WMA mixes that produced using chemical additives are more resistant to moisture damage than organic WMA mixes [13]. Zhao et al. performed a research work to evaluate the moisture resistance of foam warm mix asphalt that contain different percentage of RAP material and prepared using water injection method. They indicated that presence of RAP materials in foam WMA mixes leads to improvement of moisture resistance of foam WMA mixes [14]. Mogawer et al. reported positive effect of RAP materials on moisture resistance of WMA mixes [15]. Other researches in this area show that presence of RAP materials reduced the severity of moisture damage [16, 17]. Moghadas Nejad et al. performed an investigation on the rutting and moisture resistance of high-RAP WMA mixes. They indicated that presence of RAP materials have negative effect on the moisture resistance of WMA mixes [18]. In addition, Lu et al. studied the effect of RAP materials on the moisture susceptibility of WMA mixes. They concluded that the performance of WMA mixes with and without RAP materials strongly depended on the WMA technology [19]. Previous research works that reviewed in this section are indicated that moisture susceptibility of WMA mixes strongly depend on the WMA technology that used to mix production. Furthermore, the negative effect of foam bitumen technology on the moisture performance of WMA is clear.

2. Objective

The main aim of this research work is to investigation the moisture resistance of foam WMA. To reach the aim of this study, foam bitumen content (FBC) and mixing temperature were selected as experimental factors. In addition, the lateral objective of this work is investigation of relationship between modified Lottman test and image processing results that gained from Texas boiling test. Furthermore, an experimental index is proposed to study the stripping severity of foam WMA mixes using image processing method.

3. Experimental Plan

3.1. Materials

Aggregates that used in this research work were obtained from an asphalt plant located in east of Tehran. Also, the No. 4 gradation with respect to Iranian Code No. 234 was used to mix blending [20]. Aggregate gradation and physical properties of them are presented in Tables 1, 3 and Figure 1. Furthermore, properties of Pen. 60-70 bitumen that employed in this research work are shown in Table 2.

Table 1. Physical properties of mineral aggregates

Properties			Aggregate Type			Limits
			Coarse Aggregate	Fine Aggregate	Filler	
Specific gravity (gram/cm3)	ASTM C 127 & 128		2.523	2.486	2.578	-
Sand Equivalent (SE)	-	-	-	73	-	Min. 50
Los Angeles Abrasion Value	AASHTO T96	Number of Rotation	500	-	-	-
		Abrasion value	14.4	-	-	Max. 30
Percentage of Fractured Particles in Coarse Aggregate	ASTM D5821	One Side	100	-	-	Min. 100
		Two Side	94	-	-	Min. 90
Flakiness and Elongation	BS 812	Elongation	19.4	-	-	Max. 20
		Flakiness	3.1	-	-	Max. 5

Table 2. Binder physical properties

Parameter	Results	Unit	Method
Penetration at 25 °C	65	0.1 mm	ASTM D5
Softening point (R&B)	51.2	°C	ASTM D36
Specified gravity at 25 °C	1.0291	g/cm3	ASTM D70

Table 3. Aggregate grading

Type of aggregate	Sieve size (mm)	Percent passing (%)
Coarse aggregate	12.5(#1/2)	100
	9.5(#3/8)	95
	4.75(#4)	59
Fine aggregate	2.36(#8)	43
	0.3(#50)	13
	0.075(#200)	6

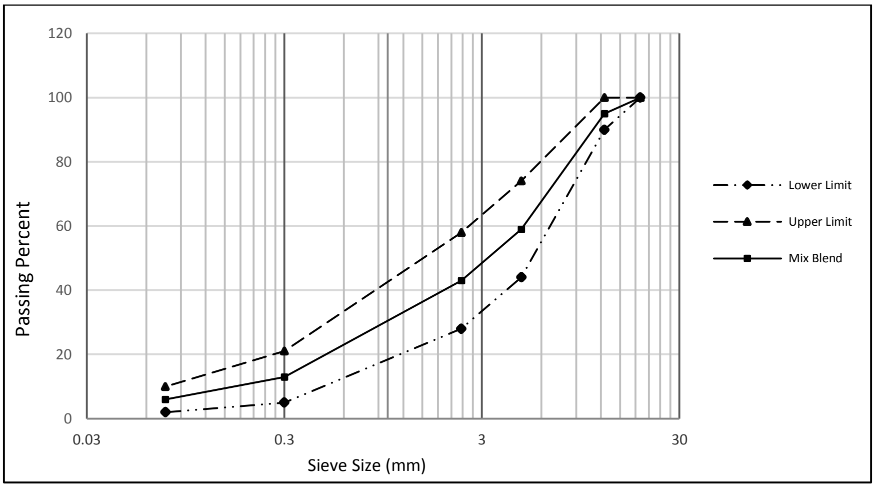

Figure 1. Aggregate gradation

3.2. Foam Bitumen Production in Laboratory

As previously mentioned, foam bitumen is one of the WMA technologies. Generally, there are two ways to produce foam bitumen, foaming additives and water injection method. In the first method, when hot bitumen are added to aggregates and foaming additive, the thin coverage of additive are melted and presence of water in hot bitumen leads to producing foam. Evotherm, Zeolite and Advera are some of foaming additives. However, second method (water injection method) is based on injection of cold water to the hot bitumen (160-180° C) in the presence of high pressure. Generally, presence of the heat leads to evaporation of water and increase its volume about 70 times. Therefore, injection of water to the hot bitumen in presence of high-pressure condition leads to expanding its volume up to 17 times. This progress is used to produce water injection foam bitumen. In this research work, the Wirtgen WLB-10 was used to preparing foam bitumen (Figure 2). This apparatus employed cold water and high-pressure air (6 bar) and hot bitumen (160-180° C) to producing foam bitumen. The Wirtgen Foamed bitumen machine use an electromotor to circulation of hot bitumen. In addition, cold water and high-pressure air that exist in their tanks are injected to the hot bitumen in certain time duration. It should be noted that the amount of water should be determined with respect to half-life and expansion ratio of foam bitumen.

Figure 2. Wirtgen foam bitumen machine

3.3. Modified Lottman Test (Tensile Strength Ratio)

TSR is used to investigate of moisture resistance of asphalt mixes. In addition, ASTM D4867 was used to preparing the specimens and condition set-up. So, the conditioned and unconditioned specimens were subjected to loading at 25° C. it should be noted that, the conditioned specimens before performing this test were exposed to freeze-thaw cycle. For this purpose, the specimens were saturated using vacuum pomp at the first step. Then, they were placed at -18° C for 16hours and next were immersed at 60° C water bath for 24 hours. Finally, they were subjected to the monotonic displacement using 50.8 mm/min vertical speed. The ITS index is calculated using maximum vertical load and Eq. (1) [18]. Furthermore, the TSR index were calculated using ITS results and Eq. (2) [14].

$$ITS = \frac{(2P)}{(\pi D t)} \qquad (1)$$

$$TSR = 100 \times \frac{ITS_{Cond.}}{ITS_{uncomd.}} \qquad (2)$$

where:
P: maximum load (KN)
t: Specimen Thickness
D: Specimen Diameter (m)

3.4. Boiling Texas Test

Kennedy et al. introduced Texas boiling test at 1984 [20]. Then, ASTM D3625 was released to investigate the loos asphalt mixes [20, 21]. In this test method, loose mixes are subjected to boiling water for 10 minutes. Then, the boiled mixes are placed on the white paper to drain its water completely. Finally, the severity of its stripping are determined using visual evaluation [22]. Reduction amount of aggregate coating was introduced as percentage reduction in the aggregate surface area coated (PRC) index that introduced in Eq. (3) as

$$PRC = \left(\frac{A\% - B\%}{A\%}\right) \times 100 \quad (3)$$

where

PRC: Percent Reduction in the aggregate surface area Coated
A: Coating percentage of specimens before boiling process
B: Coating percentage of boiled specimens

3.5. Application of Image Processing for Analyzing the Texas Boiling Test Results

As previously mentioned, there are various experimental tests for evaluating the moisture sensitivity of asphalt mixtures. Modified Lottman test (AASHTO T 283), Marshall Stability Ratio and Texas boiling test could be mentioned. These tests apply on loose or compacted mixture [1]. Since the results of Texas boiling test are qualitative and use visual inspection, several studies have been conducted to quantify results. Merusi et al. used an image processing algorithm to evaluate moisture sensitivity of modified asphalt mixtures with wax additives [23]. In similar studies, Kim et al. evaluated stripping of HMA mixture [24], and Amelian et al. evaluated stripping of HMA mixture with different aggregates and anti-stripping additives [1]. In all of these studies, digital images partitioned in two segments by using image threshold segmentation. The basic problem in all of these studies was using a specific threshold for all image to segment images. In image segmentation using thresholding method, each of the images has a specific threshold that determine base on properties of the image [25]. In this study to improve experiment result of Texas boiling test and reduce errors due to visual inspection, Otsu method used for image segmentation. Finally, based on the result of this study, a new index was developed. Using this index is not necessary to use a specific threshold. This index was validated using moisture sensitivity of foamed asphalt mixture results.

3.5.1. Image Processing Methodology

After conducting Texas boiling test, the mixture was spread on a paper and after drying mixture surface, image was took. At first, image background was removed to just consider mixture surface in analysis. Then, image was converted from RGB to gray scale. Gray scale images are the result of measuring the intensity of light at each pixel with a range from 0 (black) to 255 (white). Using Otsu method for image segmentation, image was partitioned into two segment with similar properties (Stripping and not stripping) [25]. Image segmentation thresholding methods partition an image into foreground and background classes. Objective of these methods is to find best threshold for dividing image into two classes. Otsu method search threshold that minimizes the intra-class variance. After applying Otsu method and determining two classes of image, the average of gray scale intensity of stripping and non-stripping segments was extracted. Stripping index has been defined as Eq. (4).

$$stripping\ index = \frac{A_s}{A_t} \times \frac{M_s}{Agg_{int}} \quad (4)$$

where

A_s: Area of stripping segment as pixel,
A_t: Area of mixture surface as pixel,
M_s: Average of gray scale intensity of stripping segment,
Agg_{int}: Average of gray scale intensity of aggregates.

This index theoretically could be greater than 1, but practically be between 0 and 1. If the average of gray scale intensity of stripping segment is more than the average of gray scale intensity of aggregates and a big portion of area have been stripped ($\frac{A_s}{A_t} = 1$), stripping index could be greater than 1 that such a situation rarely happens. Asphalt mixture has more stripping potential as the number is closer to 1. If stripping index is equal to 0, there is not any stripping.

4. Results and Discussion

Moisture resistance of foam WMA mixes were studied in this research work. So, these mixes were fabricated with respect to different bitumen content and mixing temperature. Then, modified Lottman test and Boiling Texas test were used to examine their moisture susceptibility. In the following, results of these tests are mentioned and discussed.

4.1. Modified Lottman Test (Tensile Strength Ratio)

The results of indirect tensile test at 25°C are shown in Table 4. It can be seen in this table that:

1- When injection time of foam bitumen fixed at 2.5 second, maximum TSR index (0.83) was belonged to mixture that mixed at 130°C ($M_{130\text{-}2.5}$). However, when the injection time was fixed at 3 second, maximum TSR index that is 0.9 was happened under 150°C mixing temperature ($M_{150\text{-}3}$).
2- Maximum indirect tensile strength of conditioned and unconditioned specimens were happened under 150°C mixing temperature and bitumen injection time of 2.5 second ($M_{150\text{-}2.5}$). $M_{150\text{-}2.5}$ is placed at second place.

This phenomenon shows that higher amount of foam bitumen have negative impact on the indirect tensile strength of asphalt mixes. In addition to indirect tensile strength, moisture resistance of asphalt mixes are sensitive to mixing temperature and bitumen content. As it can be seen in Figure 4, $M_{130\text{-}2.5}$, $M_{130\text{-}3}$ and $M_{150\text{-}3}$ were reached to minimum requirements of TSR. In addition, Table 4 and Figure 4 show that M130-2.5 had better performance than other mixes with respect to TSR index.

Table 4. Results of indirect tensile strength tests and TSR

Mixture	Temp.	Pumping time	ITS_{dry}	ITS_{wet}	TSR
$M_{110\text{-}2.5}$	110°C	2.5s	959	725	0.75
$M_{130\text{-}2.5}$	130°C	2.5s	1130	944	0.83
$M_{150\text{-}2.5}$	150°C	2.5s	1533	1123	0.73
$M_{110\text{-}3}$	110°C	3s	1271	941	0.74
$M_{130\text{-}3}$	130°C	3s	1116	921	0.82
$M_{150\text{-}3}$	150°C	3s	978	881	0.9

Indirect tensile strength of conditioned and unconditioned foam WMA mixes are very different. When mixes that produced using 2.5 second of bitumen injection were examined without conditioning cycle, increase of mixing temperature has positive significant effect on the indirect tensile strength. $M_{150\text{-}2.5}$ is more resistant than other mixes to moisture damage. However, performing ITS test on unconditioned mixes that produced using 3-second bitumen injection, showed negative impact against of higher mixing temperature. Furthermore, the mixes that conditioned using freeze-thaw cycles are followed this path. These observations indicated that performance of specimens that produced using 2.5 and 3 second bitumen injection against of moisture damage significantly depends on the mixing temperature. In other words, interaction of bitumen content and mixing temperature are very impressive on their moisture resistance.

Results of TSR tests on the conditioned foam WMA mixes show that specimens prepared using lower bitumen content at higher mixing temperature and mixes with higher bitumen content at lower mixing temperature are more resistance to moisture damage. As shown in Figure 3, mixes that produced at 110°C and using 2.5-second bitumen injection, are more resistant than mixes produced at 110°C and using 3-second injection time. It should be noted that, increasing the mixing temperature up to 150°C have significant effect on the moisture resistance of mixes. In this case, specimen that produced using lower bitumen content were more resistant. Furthermore, this figure shows mixes that produced with 2.5-second bitumen injection and at 130°C mixing temperature leads to higher TSR index.

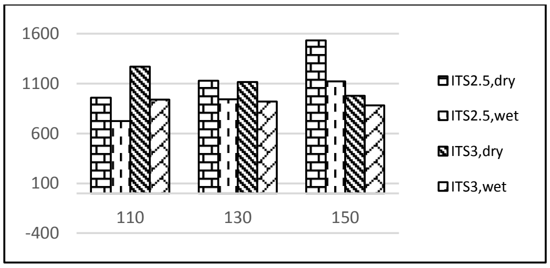

Figure 3. Indirect tensile strength of conditioned and unconditioned specimens

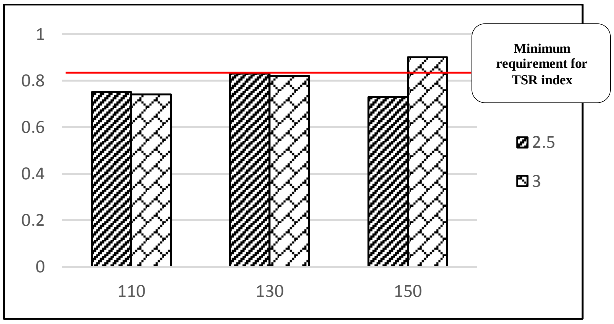

Figure 4. TSR index

4.2. Image Processing Results

As mentioned previously, the results of Texas boiling test is based on visual inspection of specimens. Hence, human error has a significant effect on results. In this study, potential of moisture sensitivity of asphalt mixture was evaluated using image processing. Images were took from mixtures dried in open air. Then, the images were analyzing based on presented algorithm by coding in MATLAB software. Figure 5 shows the process and output of suggested image processing algorithm. As seen, at the first step the background of images have been removed. After that, threshold has been identified for each image. Finally, stripping surfaces has been determined (marked with red). To calculate the stripping index as equation 4, it is needed to determine the average of gray scale intensity of aggregates. In doing so, image of aggregates used in mixture was process as Figure 5.

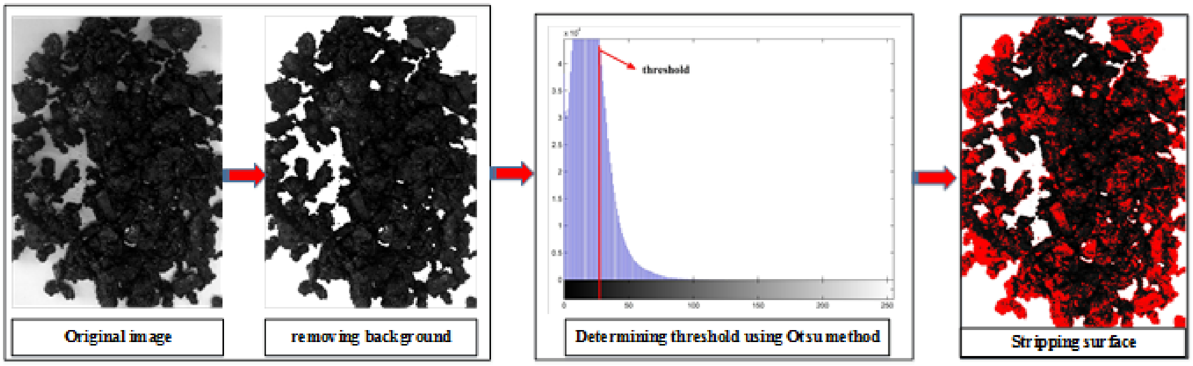

Figure 5. Image-processing steps

Figure 6. Determination of gray scale of aggregates

In order to validate the proposed index in detecting stripping area of asphalt mixture, relationship between the stripping index and the results of TSR test was investigated by linear regression model. As seen in Table 5, P-value for model is less than 0.05 which means that the model is meaningful at 95% confidence level. The R2 value is 0.938, this means that TSR explain 93.8 percent of variation in stripping index. High R2 indicate better predictive power. Table 6 shows values of regression coefficients of model.

As can be seen in this table, coefficient of TSR variable is statistically significant at 95% confidence level (P-value = 0.0000<0.05). According to the above mentioned, it can be concluded that stripping index could be a good surrogate or complementary criterion for TSR to evaluate potential of moisture sensitivity of asphalt mixtures. Figure 7 indicates linear regression model between stripping index and TSR.

Table 5. ANOVA table

	DF	SS	MS	F-value	P-value
Total	8	0.001474	0.000184	-	-
Model	1	0.001383	0.001383	107.24	0.0000
Residual error	7	0.000090	0.000013		
R^2	0.938	-	-	-	-
Adjusted R^2	0.930	-	-	-	-

Table 6. Values of regression coefficients for stripping index

Independent variable	Regression coefficient	P-value	t-value	Standard error
Constant	0.198	0.000	28.44	0.006946
TSR	-0.097	0.000	-10.36	0.009389

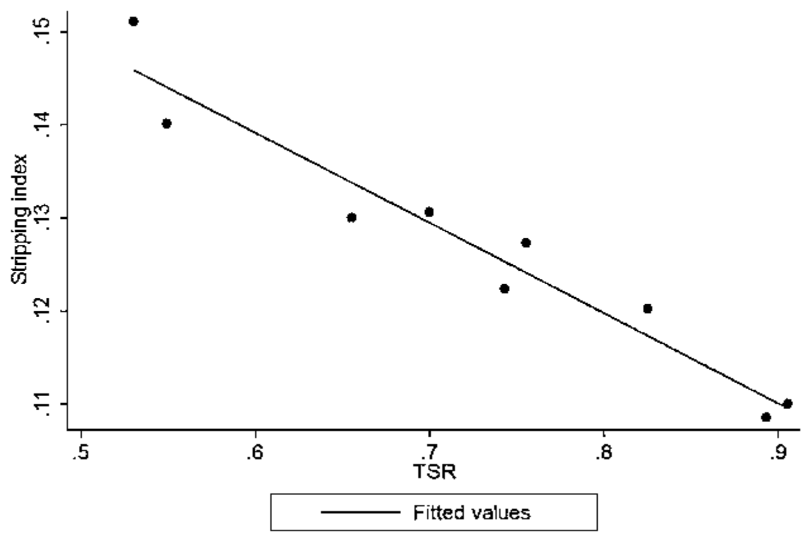

Figure 7. Observation and fitted value of linear regression model between stripping index and TSR

5. Conclusion

This research work was performed to investigate the moisture resistance of foam warm mix asphalt. Considering the sensitivity of foam WMA mixes to interaction of mixing temperature and bitumen content, this work was conducted based on different percentages of bitumen and mixing temperatures. In addition, Tensile Strength Ratio (TSR) test and Texas boiling test were used and concluded that:

Both conditioned and unconditioned Mixes that fabricated at 150°C and using 2.5-second bitumen injection had maximum indirect tensile strength. Nevertheless, because of inappropriate TSR index of this mix (M150-2.5) an anti-stripper should be used to meet minimum requirement of TSR. However, M130-2.5 showed suitable moisture resistance. Although, indirect tensile strength of this mix was 26% lower than $M_{150-2.5}$.

Mixes that fabricated at higher mixing temperature and using lower bitumen content are more resistant to indirect tensile strength. Nevertheless, impact of mixing temperature on the mixes that produced using higher percent of bitumen is very different. Actually, increase of mixing temperature have negative impact on the ITS index of mixes that produced using higher percent of foam bitumen.

Maximum amount of TSR index belong to M_{150-3} (mixed at 150°C and 3-second injection). In addition, $M_{130-2.5}$ and M_{130-3} are placed at the later rank.

Stripping index was investigated based on the results of Texas boiling test and using image-processing method. Results of this index show that $M_{130-2.5}$ is the most resistant mix against of moisture damage.

Statistical model that regressed based on the results of TSR and stripping index showed that results and correlation of them is meaningful. Therefore, stripping index is satisfactory index to use as substitution of TSR index.

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