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Engineering properties of asphalt binder modified with cup lump rubber

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Abstract. Polymers are being extensively used for modification of asphalt which yields several key benefits over conventional asphalt. Interest in using natural rubber polymer i.e. cup lump in asphalt modification has increased recently due to fluctuation in natural rubber prices and demand for improved asphalt properties. Since this current innovative road building technique is still new and there is limited information available on this topic, more studies are needed for better understanding the cup lump rubber modified asphalt (CMA). Therefore, this study investigates the engineering properties of the rubberised asphalt binder with 5, 10 and 15% cup lump rubber compared to conventional asphalt binder of 60/70 pen. Laboratory tests, i.e. penetration, softening point, ductility, viscosity, loss on heating and storage stability were performed and compared to the specification. From the results, the addition of cup lump rubber was found to harden the asphalt binder, produced low ductility, high softening point and viscosity resulting in less temperature susceptibility. Remarkably, 5% cup lump rubber gives better performance compared to other rubber percentages.

1. Introduction

Over the past decades, research on polymer-modified asphalt (PMAs) and its benefits has dramatically increased and has been reported in many studies [1-3]. The use of PMAs can improve the performance of asphalt mixtures and substantially increase the service life of road pavement. In fact, the addition of polymer significantly improves asphalt properties in terms of elasticity, cohesion, stiffness, and adhesion. One of the most well-known used categories of polymer is thermoplastic elastomers (TE). TE polymers were stated to derive strength and elasticity from a physical cross-linking of molecules within a three-dimensional network. TE such as styrene isoprene styrene (SIS), styrene-butadiene-styrene (SBS), crumb rubber, polyisoprene and natural rubber (NR) were also being used as a modifier in asphalt modification. Although the chain molecules of NR are not undergoing cross-linking like the other polymer, it still can be efficiently added into asphalt. The elastomeric properties of NR were found to show better reactivity compared to crumb rubber [4]. In fact, NR can potentially impart high stability, excellent tear strength and fatigue resistance which could enhance the durability of asphalt pavement [5]. The reacted particles become tacky, improve adhesion properties and cohesion between aggregates, thus lower the rate of stripping [6]. Therefore, the improvements made on the quality of asphalt for road construction are practical to prolong the lifetime of roads and save the maintenance cost [7]. Nevertheless, it is noted that NR exhibit poor grip properties and poor weather resistance [8].

Many studies were found using NR as a modifier in asphalt modification through binder replacement [9-11]. Apart from skim and fresh latex, NR powder, concentrated latex, crepe rubber and technically specified rubber (TSR) are extensively being used as a modifier in NR modified binder. TSR, more specifically known as Standard Malaysian Rubber grade (SMR), was used in a study from Yousefi [12], which claimed that rubberised asphalt improved its properties at high temperature but make it brittle at low temperature. In addition, Tuntiworawit et al. Nopparat et al. and Fernando and Nadarajah [9, 10, 13] reported that NR in latex and ribbed smoked sheet (RSS) forms produced stiff asphalt binder with high softening point at 6-9% natural rubber percentages. Thus, this produced rubberised asphalt with low temperature susceptibility. Similar researchers also declared that the viscosity, ductility, storage stability, torsional recovery, toughness, and tenacity were higher than conventional asphalt properties. However, Swetha and Rani and Nair et al. [11,14] found that the ductility result of natural rubber modified asphalt contradicted other research, which was decreased as the NR content increase at low temperature.

Adding excessive amount of natural rubber in asphalt modification (i.e. >9%), however, interchanged the physical properties results by producing low quality of rubberised asphalt compared to the conventional binder. In fact, the storage stability of rubberised asphalt for more than 9% rubber content passed the allowable limit of storage stable [15]. This is due to the fact that natural rubber owns high molecular weight, which later gives effect on low compatibility in rubberised asphalt [16]. As the molecular weight of the polymeric chains is higher than or similar to those of the asphaltenes, they compete for the solvency of the maltene fraction and a phase separation may occur if there is an imbalance between the components [17]. Therefore, selecting the optimum content of natural rubber was a crucial step prior to blending with asphalt binder to produce qualified modified asphalt.

Recently, researchers have been working on coagulated latex, another latex product after concentrated latex [18]. The coagulated latex, namely cup lump, blended together with asphalt to value its workability and effectiveness in order to improve pavement performance and stabilise rubber market. Nevertheless, limited research was found to be used as guidance and references in contributing NR as additive for asphalt modification. Therefore, this study is undertaken to investigate the engineering properties of using cup lump in asphalt modification through binder replacement. Laboratory tests such as storage stability, penetration, softening point, viscosity, loss on heating and ductility were carried out and the results were compared with conventional asphalt 60/70 pen.

2. Experimental programs

2.1 Materials

Details on the laboratory work and materials properties i.e. cup lump and asphalt binder are provided in the following sections.

2.1.1 Asphalt binder

Base asphalt binder of grade 60/70 pen was used for the sample preparation and the binder tests were conducted according to the Jabatan Kerja Raya Malaysia (JKR) specification [19]. Table 1 shows the characteristics of base asphalt binder for physical properties testing.

Table 1. Properties of asphalt binder 60/70 pen.

Material	Properties	Test Standard	Requirement [18]	Result
60/70 pen	Penetration at 25ºC (dmm)	ASTM D5	60-70	60.4
	Softening point (˚C)	ASTM D36	49-52˚C	43˚C
	Viscosity at 135˚C (Pa·s)	ASTM D4402	3.0 (Max)	0.5
	Specific gravity	ASTM D70	-	1.030

Ductility at 25˚C (cm)	ASTM D113	100 (Min)	136
Loss on Heating (%)	ASTM D6	0.80 (Max)	0.32

2.1.2 Cup Lump rubber

The processed cup lump rubber was collected from rubber factory. Cup lump was first cut into small pieces into a size of approximately ≤2cm as shown in Figure 1. Note that the cup lump rubber was initially processed under TSR schemes, where the samples were obtained after passed through the auto-creper machine and labelled as 'rubber crumb'. Subsequently, after the collection, the rubber crumb was preliminarily treated in the laboratory with chemical solvent to steadily blend with asphalt binder.

(a) (b) (c)

Figure 1. Processed rubber crumb from (a) fresh cup lump, (b) processed cup lump, generally known as rubber crumb and (c) rubber crumb that has been cut into pieces.

2.2 Test method

2.2.1 Mixing and sample preparation

The cup lump rubber modified asphalt (CMA) was prepared using high shear mixer blending technique, as suggested by Nopparat et al. [10]. 5, 10 and 15% rubber crumb was prepared with toluene for 24 hours with 1:2 rubber-toluene ratio. The blending process was divided into two stages. First stage focuses on tearing the surface texture of treated rubber crumb, and the next process was subjected to blending with asphalt binder. In the first stage, the sample of treated rubber crumb was attached in the middle of supporting column which consists of a shaft that connected to motor at one end and another to the head as shown in Figure 2. By applying 2000 rpm of speed, treated rubber crumb was rotated for 2 minutes with the purpose of tearing the rubber surface. This technique could reduce aging of asphalt due to the shorter duration needed in blending both materials and also helps to release toluene through evaporation.

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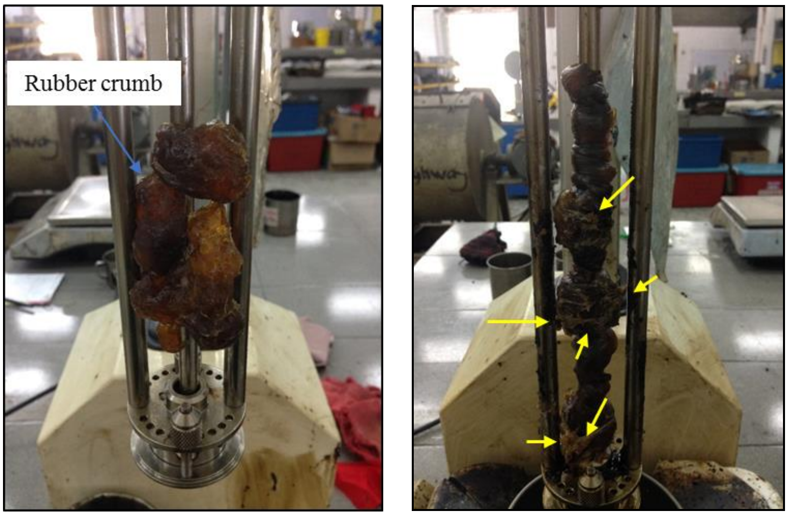

(a) (b)

Figure 2. The 1st stage blending process of treated rubber crumb. (a) Treated rubber crumb was glued to mixer rod. (b) Treated rubber crumb with the coarse surface texture after being rotated for 2 minutes.

Second stage of blending involved the mixture of torn treated rubber crumb and melted asphalt which was stable at 160˚C of temperature. The materials were mixed by a high shear mixer, with 5000rpm of speed for 2 hours [20]. For this task, the 60/70 pen asphalt binder was mixed with the cup lump rubber through binder replacement at various rubber-asphalt binder ratios (5, 10 and 15% rubber crumb by asphalt weight). The high speed rotation of the rotor blades within the precision machined mixing workhead exerts an intense hydraulic shear followed by a powerful suction at high velocity. This technique creates an excessive frictional force between the two contact surfaces of the semi-solid rubber and the viscous fluid of asphalt. This may lead to the degradation of the rubber crumb components (drawing of the treated rubber crumb) which were then dissolved within the asphalt through the surface friction. Based on the contact surface properties (friction between surfaces), this is contributed by two important elements during the mixing process, i.e. internal friction of the solution and the diffusion of the dissolved substance within the solvent. In addition, the torn surface of the rubber crumb helps the asphalt to penetrate into rubber excessively. Figure 3 demonstrates the required process of mixing rubber with asphalt binder.

(a) (b) (c)

Figure 3. 2nd stage of blending treated rubber crumb and asphalt 60/70. (a) Torn rubber crumb gets contacted with asphalt through mechanical stirring of the rotational column mixer. (b) Rubber crumb was pushed down from the supporting column. (c) After 15 minutes of gradually adding rubber crumb into asphalt.

2.2.2 Penetration test

Penetration test was conducted for conventional and modified asphalt binder. According to ASTM D5, melted sample was poured into flat bottomed cylindrical metallic dish of penetration cup (55 mm diameter and 35 mm in depth) and was allowed to penetrate using vertical penetrometer needle for about 5s with 100g load at 25˚C to measure the hardness of the asphalt binder. The results were documented with distance close to one tenth of millimetre.

2.2.3 Softening point test

This test was performed for conventional and modified asphalt binder based on ASTM D36 specification. This test was performed to determine the degree of softening the asphalt binder attains by placing the steel ball on the sample in steel ring brass. The sample was poured into the rings and was conditioned in 5˚C water bath temperature. The data were collected right after the steel ball touched the flat plate 2.36 mm under the ring.

2.2.4 Viscosity test

Viscosity test was performed for conventional and modified asphalt binder. The viscosity was performed to obtain the viscosity of the binder in the high temperature range of manufacturing and construction. This test helps ensure that the asphalt binder is sufficiently fluid for pumping and mixing. The standard procedure was based on ASTM D4402 where temperature of 135˚C and 165˚C was selected for compaction and mixing temperature, respectively.

2.2.5 Ductility test

The ductility test gives a measure of adhesive property of bitumen and its ability to stretch. In flexible pavement design, it is necessary that binder should form a thin, ductile film around aggregates so that physical interlocking of the aggregates is improved. Binder material having insufficient ductility gets cracked when subjected to repeated traffic loads. Ductility of a bituminous material is measured by the distance in centimetres to which it will elongate before breaking when two ends of standard briquette specimen of material are pulled apart at a specified speed and specified temperature. This test was performed according to ASTM D 113-07.

2.2.6 Storage stability

The storage stability of the modified asphalt binder was tested to determine the sample homogeneity. The sample was poured into an aluminium foil tube, 30 mm in diameter and 15.0 cm in length with a closure at one end. The samples of CMA were stored vertically at 163°C in an oven for 48 hours. At the end of the heating period, the samples were removed from the oven and immediately placed in freezer at – 6.7˚C for 4 hours to solidify the samples as specified in ASTM D5976. The tubes containing the CMA were cut horizontally into three equal sections and each section was labelled as 'top', 'middle' and 'bottom' parts. The cut part will be used for storage stability test by measuring the difference in softening point between the top and the bottom sections of the tube. In accordance to Fu et al. [21], when the difference was less than 2.5˚C, the sample could be regarded as having good storage stability.

2.2.7 Loss on heating

In this study, loss on heating test was performed to determine the percentage of the weight loss that occurs on the conventional and CMA as the effect of temperature at 163˚C for 5 hours duration. This test is necessary to provide information based on the weight loss of bitumen by its reaction towards heat when toluene is added. This test was performed according to ASTM D6M.

3. Results and Discussion

3.1 Penetration and softening point

Figure 4 shows the results of penetration values, softening point, and penetration index (PI) of the CMA and conventional asphalt of 60/70 pen at 60.9 dmm. The penetration decreased by 20% at 5% treated rubber crumb with the penetration value of 48.4 dmm. The result shows that adding treated rubber crumb hardened the asphalt, thus enhanced the stiffness and increased its softening point value by 8%, which sustain high temperature to 47˚C. From both results of penetration and softening, the PI was reduced from -2.69 (conventional asphalt) to -2.04. On the other hand, the penetration value was increased as much as 26% and 152% for 10 and 15% treated rubber crumb content, with the value of 76.7 and 153.5 dmm, respectively.

Further addition of treated rubber crumb softens the asphalt binder by high amount, thus affects the corresponding softening point value by 45.4 and 43°C for 10 and 15% CMA samples, respectively. This trend can be correlated with the previous studies by Tuntiworawit et al. and Nopparat et al. [9,10] which reported that adding rubber more than 9% develops low softening point with high penetration value. The result of obtaining soft asphalt was predicted for high natural rubber content based on the storage stability data, where a layer of treated rubber crumb accumulates on the top surface of the sample. In fact, the high polymer content makes the non-uniformity of the particle distribution, thus producing low quality of asphalt. However, as the treated rubber crumb content increases, the decrement on PI was obtained, thus can be correlated with low temperature susceptibility of asphalt.

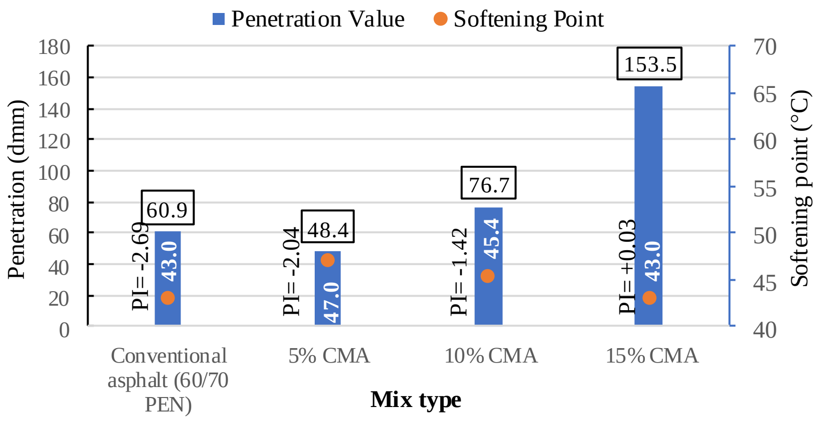

Figure 4. Treated rubber crumb (%) modified asphalt binder.

3.2 Viscosity

As presented in Figure 5, the viscosity results of the CMA are 0.9, 1.6 and 3.1 Pa·s for 5, 10 and 15% treated rubber crumb content at 135°C; these values are higher than 0.5 Pa·s of the 60/70 pen asphalt binder. The viscosity is reduced as the temperature increased to 165˚C, where the values are 0.3 Pa·s, 0.6 Pa.s and 1.1 Pa.s for 5, 10 and 15%, respectively. Expected asphalt-rubber reactivity is to form the cross-linking structure and leads to the increase of asphalt binder viscosity [22]. Since the movement of the asphalt molecular chain is limited by the layers of treated rubber crumb at high temperature, the viscosity results of the CMA are increased from low to the highest treated rubber crumb percentage. According to Stastna et al. [23], extremely high viscosity due to the high polymer content may negatively affect the process of mixing with aggregates in the asphalt mixture. However, dilution of light solvent into asphalt cause viscosity reduction without disturbing its original characteristics of hydrocarbon [22].

The existence of chemical solvent used to treat rubber crumb was successful in lowering the viscosity value, thus enhancing the CMA performance without weakening its properties. Adding solvent can inadvertently change the structure of the samples. According to its type, the solvent can contribute to the dissolution or aggregation of the heaviest or the most polar molecules of asphalt binder, thus a less viscous binder is produced [23]. Therefore, adding NR can influence the adhesion properties of asphalt when mixed together, which helps strengthen the bonding with aggregates and potentially reduce the rate of stripping [9]. On the other hand, 15% treated rubber crumb amount produces viscosity higher than 3.0 Pa·s, which passes the maximum allowable viscosity value. In practice, because the viscosity of rubber asphalt will increase with increasing rubber content, rubber asphalt with high rubber contents will be too thick for industrial operation. Viscosity that passed the limitation tends to face the problem of unable to spray the asphalt to mix with aggregates and clogged the system, thus double the construction costs.

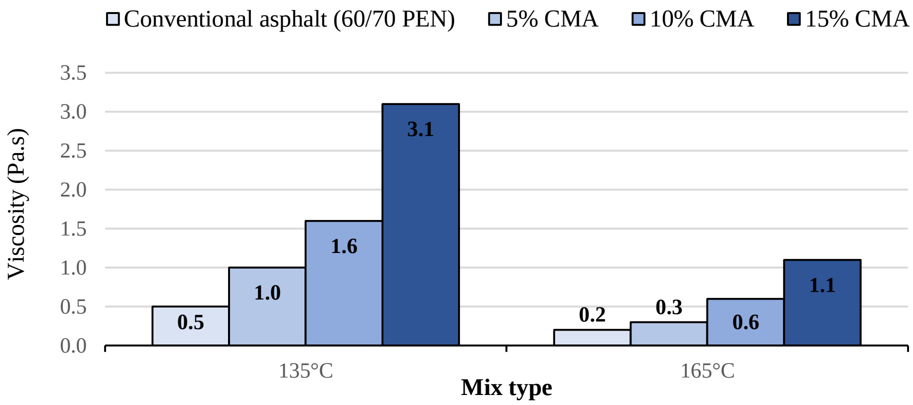

Figure 5. Viscosity of CMA.

3.3 Ductility

Figure 6 shows the ductility results of the conventional asphalt and the CMA. Decreasing trends can be observed with the increase in treated rubber crumb content. The ductility of the CMA is lower than that of the conventional asphalt by 29%, 53% and 80% for 5%, 10% and 15% of treated rubber crumb, respectively. The ultimate elongation for 5, 10 and 15% are up to 96, 64 and 27 cm compared to conventional asphalt, which is 136 cm. This finding is similar to Swetha and Rani and Nair et al. [11,14], in which ductility results decreased as the NR content increases. The low ductility observed could be due to the effect of non-homogeneity of high cup lump amount indicated stiff and hard to stretch because of the high cohesion of the rubberised asphalt. The strain-induced crystallisation of NR properties is assumed to influence the reduction in ductility of modified asphalt by restricting the action of rubber molecules being stretched at 25˚C [24]. Ductility is an important property of paving bitumen, which is very much related to cracking property of pavement [25]. These results showed that the CMA has capabilities to crack due to the asphalt binder elongation as the rubber content increased. Although stiffness and the ability to elongate are not fundamentally related, one may expect that binders with high ductility are tending to have lower stiffness (higher compliance) [26]. In addition, ductility of modified asphalt decreased slightly in the presence of chemical solvent of rubber. During the test, it was discovered that the CMA blend was pulled as thin as fine thread; however, the thickness of CMA thread was higher than CMA without chemical solvent by sight observation. Therefore, the chances of CMA with chemical solvent content to break apart was high compared to non-solvent inclusion.

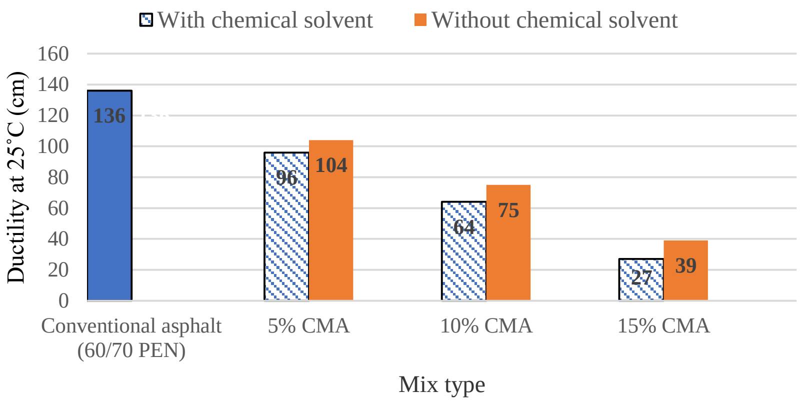

Figure 6. Ductility of CMA.

3.4 Storage stability
The effect of adding treated rubber crumb on storage stability of CMA is shown in Table 2. When 5% treated rubber crumb was added, the storage stability of the compound passed the specification. This demonstrates that the blend of the treated rubber crumb and the asphalt binder is stable and homogeneous after placed at high temperature conditions. Obviously, for asphalt modified with high content of treated rubber crumb, i.e. 10 and 15%, the difference in softening point is large. This implies that the phase separation of the CMA is serious, by leaving excessive treated rubber crumb to generate a layer on the surface of the CMA samples. In accordance with de Carcer et al. [27], NR exhibits high molecular weight properties, which later gives results on the homogeneity when mixed with asphalt binder. As the molecular weight of the polymeric chains is higher than or similar to those of the asphaltenes, they compete for the solvency of the maltene fraction and a phase separation may occur if there is an imbalance between the components [17]. Therefore, it is advisable to partially decomposed and mechanically homogenised the NR prior to mixing with asphalt binder. In the case of CMA, treating rubber crumb with chemical solvent does not solve the compatibility problems.

Table 2. Storage stability of CMA.

Cup lump (%)	Diff. top and bottom parts (°C)	Specification <2.5 °C
5	1.50	Pass
10	2.70	Fail
15	3.75	Fail

3.5 Loss on heating
The loss of oil and asphaltic compounds of CMA samples was evaluated by the mass loss corresponding to treated rubber crumb percentages at 163˚C. The effect of adding cup lump on asphalt loss due to heating is given in Table 4.3. The specification limits to determine the allowed mass loss percentage of asphalt binder was referred by a study of Asi [28]. 5% treated rubber crumb content decreased by half of the conventional asphalt percentage loss, which indicates that treated rubber crumb could retain the asphaltic compounds when exposed to high temperature during bulk storage. As the treated rubber crumb content increase to 10 and 15%, the volatility loss of rubberised asphalt increases. Such increment is explained in Figure 4.10, which shows that the 10 and 15% treated rubber crumb generates a layer on the top surface of the storage stability samples (based on high softening point value). This suggests that at high temperature, the contribution of high volatility loss in 10 and 15% CMA is mainly due to chemical solvent.

Table 3. Loss on heating of CMA.

Mix type	Percentage of Loss (%)	Specification <0.8 °C
Conventional asphalt (60/70 pen)	0.32	Pass
5% CMA	0.18	Pass
10% CMA	0.40	Pass
15% CMA	0.42	Pass

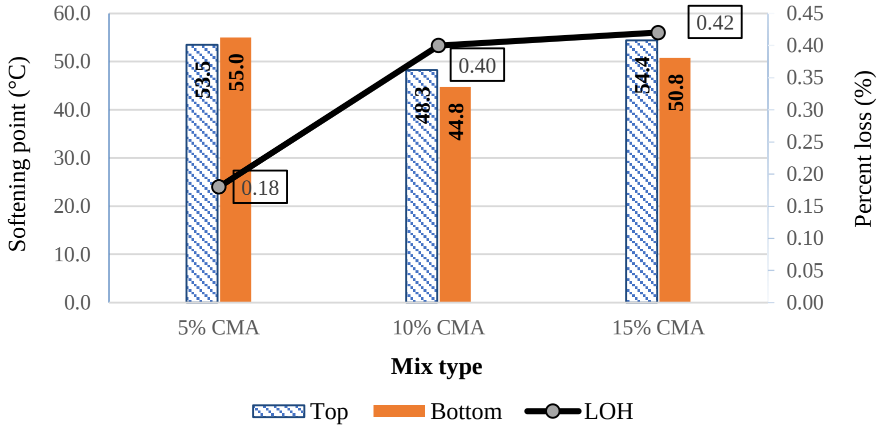

Figure 7. Percentage volatile loss of CMA related with the difference in the softening point of storage stability.

4. Conclusion

This study was conducted to investigate the effect of cup lump rubber on the engineering properties and storage stability of asphalt. In fact, the possibility to blend cup lump and asphalt was determined by the inclusion of chemical solvent as rubber softener. Based on the softening and penetration results, the mechanism of modification of cup lump seems to entail a stiffening of the base asphalt (60/70 pen). The ductility decreased after adding cup lump indicated a performance decrement at 25˚C. Furthermore, the increase in viscosity of CMA binder as the amount of rubber increases demonstrated that entanglements of polymer thickened the modified binder. Inclusion of chemical solvent, however, makes the CMA binder to lower its viscosity value. Moreover, the storage stability test results indicated that 5% of treated rubber crumb content for binder was stable for use at high temperature. The use of chemical solvent did not solve the compatibility issue between natural rubber and asphalt binder. As a result, the engineering properties indicated that 5% treated rubber crumb content optimally modified the asphalt.

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