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A Brief Overview of Utilizing Crumb Rubber as Asphalt Binder Modifier

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Abstract**:** ***The discarding of scrap tires is a serious environmental hazard worldwide. Simultaneously, the asphalt mixture containing neat binders do not always perform as required. Therefore, various efforts have been taken in the past to enhance the performance properties of the neat asphalt cements by modifying them with crumb rubber powder. Consequently, this will decrease the environmental hazards of waste tires. According to prior and ongoing research, the modification of asphalt mixtures using crumb rubber have enhanced the asphalt mixtures properties such as low and high temperature performance as well as rutting deformation resistance, fatigue cracking resistance. This paper affords via an overview of the physical and rheological properties of the rubberized asphalt binders under different conditions. This review transacts through the impact of crumb rubber particles on the asphalt binder's workability, rotational viscosity, the needle penetration, softening point, low- temperature and high-temperature performance. Furthermore, fatigue cracking resistance, rutting behavior and storage stability are in the focus.***

Keywords: Crumb Rubber, Asphalt Modification, Physical Behavior, Rheological Behavior

I. INTRODUCTION

Millions of tires wastes (Figure 1) are disposed every year because of the growth use of motor vehicles on the road worldwide [1]. Each year, about 17 million tons of discarded tires are produced worldwide [2]. It is predicted that the global yearly generation of waste tires may have exceed 5 billion tons by 2030 [3]. Scrap tires are hard to degrade due to their sold chemical composition which create a huge content of pollution [4]. The environmental issue formed by scrap tires has gotten further interest and awareness recently [5]. Also, the desire to build sustainable infrastructure [6] and the huge quantity of tire waste, push the usage of rubber waste in the pavement sector in order to decrees the tire scrap in landfills [7]. In addition to the rapid population growth and the rising in transportation needs around the world, better road surfaces with high performance and require low maintenance [8]. Therefore, many researchers have examined and investigated several possibilities to enhance the performance of the asphalt pavements and sustain the various types of distress resulted of the increased traffic volume, heavy loads and extraneous environmental conditions [9],[10]. The modification of the asphalt pavements using different materials [11], such as polymers and crumb rubber (Figure 2) have been widely used and found to be the most best solution for dealing with this issue [12]. The modification of the asphalt binder using crumb rubber could improve its performance and rheological properties significantly. Crumb rubber swelling and deterioration were shown to have a notable impact on the rheological properties of rubberized asphalt cements [13]. Crumb rubber (CR) modifier has achieved positive significance because of its advantages, such as (a) resistance to rutting deformation as well as fatigue cracking resistance, (b) reduction of pavement thickness, (c) low maintenance cost, (d) increased pavement life, and (e) less environmental problems [14-17]. The aim of this study is to review the earlier research, which carried on the asphalt binder modification using scrap tire rubber (crumb rubber). The preceding investigations summarized the processes and provided guidelines for using crumb rubber in asphalt concrete properly. Consequently, this review article has been written to collect and discuss prior findings on this topic in order to serve as a reference point for future research.

Figure 1: Waste Tires [18]

Figure 2: Tire rubber powder [19]

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II. UTILIZATION OF WASTE RUBBER IN ASPHALT

Waste tire was firstly used in asphalt concrete in the 1960s [20]. Waste tires can be used in asphalt as aggregate replacement (dry process) or to modify the neat binder (wet process) [21], [22]. The first method (dry process), the waste rubber is utilized to replace a small portion of the aggregates as shown in Figure 3. Before the binder material is introduced, the crumb rubber particles are mixed together with the aggregates [23]. Also, in dry method as mentioned by Feiteira Dias et al. [24], the reaction between bitumen and crumb rubber particles is considered insignificant due to the asphalt mixes are made in the absence of any major interaction period between binder and crumb rubber. In many dry method scenarios, rubberized is frequently manufactured in the site and utilized directly after production because it is not supposed to be stored or transported [25] . The second method (wet process), the asphalt binder is blended with crumb rubber powder in order to form the rubberized bitumen as shown in Figure 4, which is being used in several parts of the world. Different crumb-rubber modified asphalts, commonly characterized as "asphalt rubber", can be obtained depending on the conditions of the processing (the blending time and temperature, crumb rubber's amount and size) [26]. Therefore, the wet process required additional equipment in the plants or laboratories, which is not needed in the dry method. Using of dry method allows incorporating more amount of waste rubber in the asphalt mixes than the wet method does [27]. For dry method, the percentage of crumb-rubber used to modify the asphalt mixes is remarked as the percentage of the mixture's total weight, and in the total weight of the bitumen for wet processes [28].

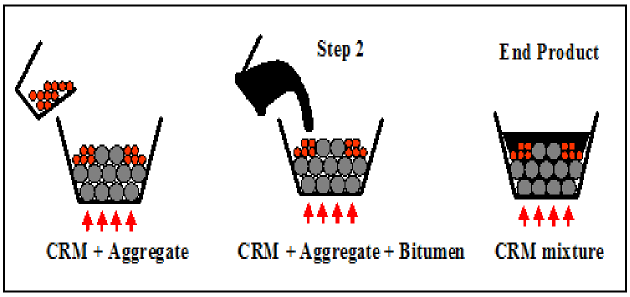

Figure 3: Dry process method [29]

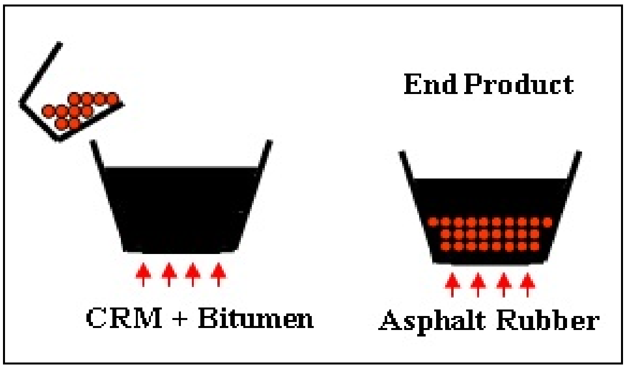

Figure 4: Wet process method [29]

According to some researches [30], [31], [32], [33], [34], [35], the advantages and drawbacks of the dry method and wet method can be summarized as shown in Table 1.

Table 1: Wet Method versus Dry Method

Method	Advantages	Drawbacks
Wet Process	High performances More popular	High productions costs High-energy consumption Required specific equipment More complex and expensive Carries environmental concerns
Dry Process	More crumb rubber usage Cheaper and easier Greater conserving resources Less popularity No need for additional equipment	Poor performance Less popularity Long digestion times

III. PHYSICAL PROPERTIES OF THE RUBBERIZED BINDERS

To understand the modified asphalt binder's stiffness/hardness and basic viscosity properties, the fundamental neat binder consistency tests, such as needle penetration, softening point (R&B), rotational viscosity and elastic recovery tests were discussed in this review.

A. Needle Penetration

The needle penetration is the most popular test for measuring the bitumen's consistency. Consistency is an objective indicator of the binder's resistance to the continue deformation when exposed to shearing stress. Low penetration asphalt binders provide a hard texture that is suited for hot regions, whereas asphalt binders with a high penetration value have a soft surface that suits cold areas [36]. The study prepared by Kebria and Moafimadani [37], a laboratory performance evaluation was carried out to look over the impact of introducing crumb rubber powder to the neat asphalt cement. According to their findings, as the crumb rubber amount increased, the degree of penetration decreased. The 16 % crumb rubber content showed the lowest penetration value of (42mm), which met the minimal standards for the standard penetration value of 4mm. Thus, the modified bitumen containing higher amount of crumb rubber is suitable to be used at higher temperatures. The obtained result is consistent with the conclusion drawn by Venudharan et al. [38] who studied the performance properties of the rubberized binder and found that the penetration values decreased with the addition of crumb rubber to the conventional asphalt binder. The authors noticed a decrease in the penetration value with the increasing amount of the crumb rubber percentage from 0 to 20%. However, it was found that the additional of crumb rubber amount with an increase of 10% 20 to 30%, the results showed a higher penetration values, and this may be attributed to the stiff virgin binder VG40 containing a low amount of oils and resins. Also, Poovaneshvaran et al. [39] confirmed that the penetration values reduced as the percentage of powder crumb rubber increased. The modified asphalt binder containing 15% of the crumb rubber powder showed the lowest penetration value of (42mm).

The decrease in the penetration values of the crumb rubber modified bitumen could result because of the increased blending time and temperature, which improved the particle size of the crumb rubber and increased the mass of the rubber during through the interaction and swelling of the rubber into the asphalt binder throughout the time of the mixing process. Thus, from all these findings, the modified asphalt binder's penetration values are significantly impact by increasing the crumb rubber content. This demonstrates that the crumb rubber modifier can improve the asphalt binder's stiffness.

B. Softening Point

The R&B softening point test is used to determine the temperature where such binder softens under a specific degree. At high temperatures, bitumen, which is a viscoelastic material, could then soften as well as becoming less viscous. Therefore, the softening points are determined as a result. [40].

Venudharan et al. [38] made a research on a rubberized asphalt binder, It was observed that as the dosage of powder crumb rubber increasing from 0% to 20%, an increase in the softening point value occurred. The inclusion of powder crumb rubber yielded extra stiffness to the binders resulting in higher values of the softening point, which were used to get the asphalt binders to a consistent degree of consistency (viscosity of about 13,000 P). Such findings were also similar to those of prior studies [37]. Poovaneshvaran et al. [39] found a similar trend when they evaluated the performance of the asphalt binder including crumb rubber particles and noticed that the change in softening points values because of the different content of crumb rubber which exhibited obviously positive outcomes for all rubberized binders. During the blending process, using the mixing temperature of 160 ℃ increasing the rubber mass due to the rubber's swelling and contact with the neat asphalt cement. According to their conclusion, the modified binder with 15% crumb rubber had the highest softening point value of 61℃, whereas the virgin binder showed the lowest softening point value of 49 ℃. The ability of crumb rubber to absorb the light oily components of bitumen in the crumb rubber–binder matrix, which decreased the quantity of free radicals, could explain the increase in the softening point values of the rubberized asphalt binders. The anti-oxidant capability of the rubber modified binder increased due to an antioxidant and anti-ozone agent in crumb rubber. These two factors directly led to the rubber-modified binder's increased anti-oxidative capacity, resulting in softening point with a higher value. Furthermore, the increased content of crumb rubber particles in the asphalt cement might be associated with increases in the asphaltene ratio that mostly improved the asphalt binder's stiffness characteristics, making the modified bitumen high sustain to temperature changes.

C. Rotational Viscosity

The viscosity of various asphalt binders must be determined to choose the appropriate working temperature and make sure that the bitumen is adequately pumpable throughout mixing, transporting, and rolling procedures. This step because it is well recognized that adding polymers to the asphalt binder modification process will result in a higher reading value of the viscosity. This increase in the viscosity's values should also conform to the specifications [41]. According to the Superpave requirements [37], [39], this characteristic is limited to under 3 Pa. Higher viscosity is usually undesirable since it can lead to higher blending and compaction temperatures, which can greatly increase energy consumption [42].

Poovaneshvaran et al. [39] evaluated the conventional and modified asphalt binders with crumb rubber at eight different temperature 125 ℃ to 195 ℃ with an increment of 10℃. The authors found that changing types of rubber, dosages, and testing temperatures had a major impact on the values of viscosity. It was observed that when the testing temperature increased the values of the viscosity decreased regardless of rubber concentration and types with a similar trend for the neat one. This indicated that temperature plays a major impact of the change happened for the modified binders' viscosity. The results of this study demonstrated that as the concentration of crumb rubber powder increased, the value of the viscosity of the bitumen also increased. The authors found that all rubberized asphalt binders met the Superpave specification at 135 ℃. In other research by Venudharan et al. [38], who studied the temperature susceptibility of the modified binders with crumb rubber using a rotational viscometry test on numerous of asphalt binders. The obtained findings showed that the modification of the virgin binders with powder crumb rubber decreased the viscosity-temperature susceptibility's rubberized bitumen comparing to the neat asphalt binder. The authors concluded that the higher percentages and finer gradations of crumb rubber might result a modified binder with lower viscosity-temperature susceptibility that could effectively work across a wide temperature range. The noticed increase in the viscosity value of the rubber modified binder has been verified by another effort of Kebria and Moafimadani [37]. The obtained results at 135℃ temperature of the asphalt binder showed an excessive viscosity with an increase in the crumb rubber percentage from 16% to 20%. The results exceeded the asphalt binders' permitted performance characteristics in the Superpave system. Authors observed that the percentage of 20% crumb rubber content in the hot-modified asphalt paving would cause application difficulties. Despite, the previous study, the modification of asphalt binder using 20% of crumb rubber is recommended for the production of rubberized asphalt [38]. This different depending on the type (originated from small or heavy vehicle tires), crumb rubber's size and the base binder used in the studies. This increase in viscosity might be due to the interaction between the asphalt binders and crumb rubber powder. The particles of crumb rubber in the rubberized asphalt absorb a percentage of the oils in the asphalt cement during their interaction with the bitumen, causing the particles to swell. As a result, the viscosity of the bitumen increased significantly due to higher swelling, a higher soluble fraction of crumb rubber components, and the smaller gradation of crumb rubber particles in the asphalt. Besides, a greater mixing temperature increased the flexibility of the rubber and broke down the crosslink; resulted in a thicker and more elastic modified binder.

D. Elastic Recovery

The elastic behavior of the bituminous material specifies how much the binders recover, whether all or some of its original elongation or shape, once the pressure that caused the damage is removed. The elastic recovery behavior of an asphalt cement is widely utilized to assess asphalt binder fatigue resistance, or the binder's capability to sustain high stresses without cracking or undergoing permanently deforming [43]. According to Poovaneshvaran et al. [39], the percentage of crumb rubber which used to modified the asphalt binder affects its elastic characteristics in general. Authors compared the elastic recovery behavior of the asphalt binders to that of the virgin one. They found that the using higher amount of crumb rubber, the higher the elastic recovery. The results demonstrated that the inclusion of 15% crumb rubber to the mix resulted in a 32 percent elastic recovery, compared to only 91.67 percent for the neat binder. The structure of this test, the lower recovering result means improved performance. This finding is accordance with the results of other study by Venudharan et al. [38] who found that adding crumb rubber particles to the binder result in an increase in its elasticity which caused by the crumb rubber inclusions' inherent resilience. The results also showed that the elastic recovery decreased as the crumb rubber contents in the neat binder increased from 20% to 30%, indicating saturation because of the low proportion of lower molecular weight binder elements wanted to swell crumb rubber additions. The authors noticed that the results of the elastic recovery test were varies with the different crumb rubber gradations. The finer asphalt rubber cements resulted in a higher percentage of elastic recovery. A similar trend was drawn by Kebria and Moafimadani [37] who observed that adding more percentage of crumb rubber powder, the elastic characteristics of the rubberized asphalt cement increased in comparison to its viscous behavior. In comparison to the continuous pavement deformation mechanism, this enhancement will lead to asphalt binders exhibiting improved resilience in high service temperatures of pavements. In short, improving binder resistance to rutting. Table 2 and Table 3 summarized the preparation and results of the rubberized binder of the above studies.

Table 2: Preparation of modified asphalt binders

Reference	[37]	[38]	[39]
Binder	60/70	VG40	60/70
Rubber Sieve Size (mm)	2.36-0	2.36-0	1.18-0
Rubber Content %	4,_8,_12,_16,_20	10,_20,_30	5,_10,_15
Blending Temperature (℃)	160- 180	170-180	160
Blending Time (min)	10 - 30	90	30
Blending Speed (rpm)	200 - 4500	2000	1000

Table 3: Physical properties of the rubberized binder

Reference	[37]	[38]	[39]
Rubber Optimum Content Wt. %	16	20	15
The Needle Penetration	↓	↓	↓
Softening Point R&B	↑	↑	↑
Viscosity	↑	↑	↑
Elastic Recovery	↑	↑	↑
Note: (↑) (↓) increase and decrease in the asphalt property			

IV. RHEOLOGICAL PROPERTIES OF THE RUBBERIZED ASPHALT BINDERS

The Dynamic Shear Rheometer (DSR) test is commonly carried out to identify the dynamic rheological characteristics of control and modified asphalt binders across a wide temperature range. The DSR test usually used to determines the sample's complex shear modulus $|G^*|$ and phase angle (δ), which could be used to forecast permanent deformation potential and fatigue life in hot mix asphalt pavements [44].

A. Complex Shear Modulus $|G^*|$

The asphalt binder resistance is indicated by the sample's complex shear modulus $|G^*|$. The higher $|G^*|$ value indicates a stiffer asphalt cement that resists deformation in high temperatures [45]. The research prepared by Poovaneshvaran et al. [39], to investigate the effect of crumb rubber on $|G^*|$, the DSR test was conducted on all asphalt binders with and without the inclusion of crumb rubber. By considering the study aim to assess the performance at high-temperatures, the temperatures for testing were set in the range of 46 - 82 ℃ with an increment of 6℃.

The obtained results showed that with the inclusion and increment content of the crumb rubber modifier, the value of $|G^*|$ increased. The authors observed that the 5% and 10% crumb rubber additive exhibited a lower value of $|G^*|$ in comparison to the 15% crumb rubber additive. It was also found that, at the temperature of 82 ℃, the $|G^*|$ value of all types of asphalt binders is comparable, regardless the content and types of the modifier. This result showed that at high temperature, the bitumen materials start to lose its resistance to deformation, regardless of the modifier's types and content.

In another study conducted by Venudharan et al. [38], twelve different binders were subjected to an oscillation test to determine $|G^*|$ at different frequency-temperature combinations. In compared to the conventional VG40 binder, $|G^*|$ magnitudes for asphalt rubber binders were found to be higher. With the addition of 10, 20, and 30% of CR, the increase in $|G^*|$ was 1.56, 1.67, and 1.72 times that of the neat binder, respectively. Similar findings were obtained in related research by Kebria and Moafimadani [37], who observed the increased value of $|G^*|$ at various temperatures for both aged and unaged in RTFO, with the increased amount of crumb rubber content.

This result approved that the modification of the neat binder using rubber content showed the potential to resist the deformation that occurs in road construction caused by increased traffic loads.

It has been demonstrated in the above researches that the rubberized bitumen with higher crumb rubber content resulted in a higher complex shear modulus $|G^*|$. The modification of asphalt cement with crumb rubber motivated the process of crumb rubber particles to absorb the low molecular weight fraction of the binders. Oil absorbed by crumb rubber particles (due to swelling) acted as higher molecular weight binder fractions, resulting in greater strength.

B. Phase Angle (δ)

The phase angle is defined as the difference among the applied stress and the associated strain on asphalt binder [46],[47]. The phase angle of bitumen can be easily differentiated, the 0 and 90 represent elasticity and viscosity respectively [48].

In a research conducted by Poovaneshvaran et al. [39], who observed the (δ) value of modified and unmodified binders draws a slow increase pattern when tested at higher temperatures. The obtained results showed that the rubberized asphalt binders had smaller phase angle values in comparison to the neat bitumen due to the present of the polymer. This shows that the modification of the bitumen materials exhibited more elasticity performance. The authors found that the addition of more amount of polymer in asphalt binder results in decreased the phase angel value (δ). In comparison to 5% and 10% crumb rubber modified asphalt binder, the asphalt binder containing 15% crumb rubber has the lowest (δ) value. The same results obtained in other related research by Venudharan et al. [38] who evaluated the phase angle (δ) at different frequency-temperature combinations for twelve different binders. With an increase in crumb rubber content, gradual reduction in phase angle (δ) observed. The same finding was also observed in another research by Kebria and Moafimadani [37]. The authors also observed a decrease of the value of phase angle (δ) at various temperatures for both aged and unaged in RTFO with an increase in the concentration amount of crumb rubber.

This decrease of the phase angle (δ) value because of the elastomeric properties of crumb rubber, which cause the asphalt cement to change from a viscous stage to a more elastic state. As the phase angle (δ) of the modified asphalt binder tends to reduce, the percentage of asphalt binder that can be recovered increases. Also, the addition of crumb rubber added more elasticity due to crumb rubber's inherent elasticity. At higher temperatures, this behavior is helpful to the anti-deformation performance of the asphalt pavement.

C. Fatigue Factor ($G^* \times \sin\delta$)

The resistance of asphalt pavements to fatigue cracking can be evaluated using complex modulus and phase angle measurements. At low and moderate service temperatures, the $G^* \times \sin\delta$ parameter indicates asphalt binder efficiency in the fatigue damage mechanism of the pavement. To avoid any damage attributed to asphalt binder paving fatigue in excellent pavement systems, the $G^* \times \sin\delta$ value for the residual asphalt binder of the PAV ageing process need to be at maximum value of 5000 kPa [49]. Therefore, when resistant to paving fatigue damage is needed, lower values of G^* and δ are desirable [50]. Kebria and Moafimadani [37], measured the factor ($G^* \times \sin\delta$) for fatigue cracking of the rubberized asphalt binder depending on the DSR results. The RTFO method was used to age the remaining asphalt binder from the PAV process at various temperatures. It was found that the $G^* \times \sin\delta$ value was not greatly changed for the modified bitumen containing 4% crumb rubber in comparison with the base binder. As the proportion of crumb rubber in the modified asphalt binder increased from 8% to 20% of the mass of the conventional binder, the indicator of fatigue cracking mechanism decreased in moderate temperatures of the pavement service. At temperatures of 20°C, the authors also observed the effect of the incorporation of crumb rubber powder in reducing the paving fatigue mechanism. As a result, it is reasonable that modifying base asphalt binders with more than 8% additive crumb rubber would minimize the possibility of cracking because of asphalt binder paving fatigue. The same finding was proved by Poovaneshvaran et al. [39] who used the elastic recovery to test the asphalt binder's fatigue resistance. The results ensured the ability of the asphalt rubber binder to withstand significant loads without any cracking or going through permanent deformation resulted in an increase in fatigue resistance. The Fatigue cracking encountered on pavement is as shown in Figure 5.

Figure 5: Fatigue cracking [51]

D. Rutting Factor ($G^* / \sin\delta$)

The rutting parameter $G^*/\sin\delta$ is used in the Superpave specification and Strategic Highway Research Program (SHRP), to classify the asphalt pavement's resistant to permanent deformation [32],[52]. Based in the Superpave specification, rutting is managed in the rolling thin film oven test (RTFOT) by limiting the value of $G^*/\sin\delta$ to be a minimum value of 1.0 KPa before aging the binders and to be at least of 2.2 KPa for aged binders. Mostly, high values of $G^*/\sin\delta$ indicate that the asphalt binder is more resistant to rutting deformation [53]. For higher temperature performance, a lower δ and higher G^* is desirable [54]. Poovaneshvaran et al. [39] observed an increase of the $G^*/\sin\delta$ value of the modified asphalt rubber even at high temperatures. The obtained results at a temperature of 64 °C, the virgin asphalt binder reached the minimal required value of 1.0 KPa. While the modification of asphalt binder with the amount of 5%, 10%, 15% crumb rubber, the rubberized bitumen met the minimum requirement at temperatures of 70 °C, 76 °C, 82 °C respectively. The authors found that the $G^*/\sin\delta$ factor increased as the modifier material increased. This means that, even when it is subjected to higher temperatures, the modified asphalt rubber will be less susceptible to rutting deformation.In related research, Venudharan et al. used the SHRP rutting parameter $G^*/\sin\delta$ to calculate the binder's penetration grade (PG) upper temperature. It was observed that the inclusion of crumb rubber resulted a higher value of the PG upper temperature. The results showed that the addition of 10% crumb rubber to the VG40 asphalt binder raised the PG upper temperature by one level (with a 6°C increment per level).

Also, when 20% and 30% crumb rubber doses were added into the conventional asphalt, the PG upper temperature improved by two degrees in comparison to the virgin binder. Adding more amount crumb rubber raised the PG upper temperatures, which indicates how resistant the asphalt rubber binders are to rutting across a wide range of temperature [38].

The study by Kebria and Moafimadani [37] also proved that the modification of the binder with such modifier, increased the binder's resistance to rutting distress. The authors discovered that with an increase in the amount of crumb rubber (16% and 20%), the $G^*/ \sin \delta$ values increased in all temperatures for the base asphalt binders and the aged one under the RTFO process. As a result, they recommended using a higher dose of crumb rubber as an effective treatment for the asphalt pavement's permanent deformations (rutting).

The modification of the asphalt binder using crumb rubber powder improved the stiffness, resulting in higher $G^*/ \sin \delta$ values and, as a result, a higher failure temperature. The chemical reaction between waste rubber and asphalt cement changed the binder's properties during the blending process. The crumb rubber particles swell as a result of the absorption of aromatic oils, leading to the formation of a viscous gel. The rutting deformation encountered on pavement is as shown in Figure 6.

Figure 6: Rutting Deformation [55]

V. STORAGE STABILITY

The most significant problem with using polymer-modified bitumen is its stability during storage, mixing and manufacturing. Phase separation can occur because of the variance in the particle size of the rubber, material solubility and the density of both the additive and neat asphalt cement [56]. Poovaneshvaran et al. [39] carried out a study to determine if storage instability happened within high-temperature storage stability using the adapted softening point techniques. According to EN 13399, the permissible limits variance in softening point between the top and bottom parts of the specimen is 5 °C to consider the modified asphalt binder is not subject to phase separation. According to the conclusion drawn by the authors, the difference in temperature for all bitumens are within the acceptable range of 0°C to 5°C. In other research by Venudharan et al. [38], who also observed that the variance in softening points between the top and bottom binder parts of the separation test was smaller. The fine rubber gradations mixed into the asphalt binder with greater homogeneity due to their bigger surface areas, which improving the binders' stability when it is stored. Besides that, it was noticed the increasing content of crumb rubber, increased the gap between top and bottom samples in softening point of the asphalt binders. Because of intramolecular repulsion, the effectiveness of crumb rubber particle suspension decreased as the content of crumb rubber increased. Other investigations have also found that decreasing the particle size of crumb rubber materials improves the storage stability [57], [58].

VI. CONCLUSION

The current state of using recycled crumb rubber in the asphalt pavement was discussed within this paper. Each review concluded different values but all approved the improvement in the pavement performance when utilizing crumb rubber powder in the asphalt mixes. Based on the findings of previous studies, it was believed that introducing more crumb rubber content and smaller size crumb rubber in bitumens would help produce a superior asphalt rubber that would perform better under different environmental conditions and high traffic loadings. Also, the increase of the amount of waste rubber particles caused a decrease in the $G^* \times \sin \delta$ values as well as an increase of $G^*/\sin \delta$ values which an indicate for a higher resistance to the rutting and fatigue distress. The increment in the dosage of crumb rubber caused a higher tensile strength and enhanced the binder's storage stability. From the economic and environmental standpoint, using crumb rubber in flexible pavement will serve to decrease the cost budget of road construction, reduces the sustainable use of asphalt binder and aggregates and will contribute towards efficient waste management of this hazardous material.

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