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Rutting resistance of toner-modified asphalt binder and mixture

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Abstract

Asphalt binder resistance to permanent deformation considerably influences total pavement resistance to rutting at the high service temperatures. To improve asphalt shear strength against rutting resistance, researchers have been used various modifiers and recently the use of waste materials as binder rheological enhancement agents is paid lots of attention. In this study, waste toner was adopted as an anti-rutting enhancement agent, and then neat asphalt binder was modified by waste toner at four dosages: 4, 8, 12 and 16% based on asphalt binder's weight. The effectiveness of binder modification by waste toner to improve asphalt binder and mixture's resistance to permanent deformation has been assessed by means of different methods: the Superpave specification parameter, *G*/sinδ*, and the multiple stress creep and recovery (MSCR) test for asphalt binder and wheel track test for asphalt mixture to determine the rut depth for a certain number of loadings. Results showed that adding toner to neat asphalt binder can meaningfully enhance the anti-rutting performance of asphalt binder and subsequently asphalt mixture. Moreover, increasing the dosage of toner up to 12% in the modified asphalt binder amplifies the trend of rutting resistance improvement.

Keywords: Stage crushing; Rutting, waste toner; Wheel track test; MSCR test; G*/sinδ

1. Introduction

Rutting distress has been recognized as one of the essential distress types of flexible pavement [1]. Also, rutting distress has hitherto prescribed for reducing road serviceability, which turned it in the functional distress types [1]. In this respect, rutting has considered as an important criterion for flexible pavement design [2,3]. This form of flexible pavement distress can appear as a longitudinal surface depression on the vehicle wheel path that reduces driver safety and affects the pavement functional capacity of roads [4]. Researchers have recognized accumulated strain as the main reason for appearing rutting on asphalt pavement surface due to lack of shear resistance of asphalt mixture against traffic loading [5].

However, overserved rutting distress on asphalt pavement can be considered to be the total accumulated permanent strain in the asphalt layer or other layers of a flexible pavement structure [6-8]. Rutting in the asphalt layer set to become a crucial factor, which is profoundly influenced by the aggregate properties, asphalt mixture air void percentage, binder-aggregate interactions, and binder shear resistance [9]. A substantial number of researchers have reported that the intrinsic characteristic of asphalt binder is the dominant factor influencing the binder shear resistance and aggregate-binder interactions, especially for modified asphalt binder which is mainly fabricated to enhance the high-temperature performance of asphalt pavements [6,10-17]. One of the waste materials that can be used as a modifier to improve asphalt binder intrinsic properties is waste toner [18,19].

A high amount of toner is produced by cartridge companies [19]. However, a significant amount of this production is rendered unusable during cartridge-filling process or left burns in printing process. Since, this waste is considered as an electronic waste material, as therefore, recycling of such waste is a great concern [20]. It has been claimed that about 5% by weight of fresh toner ends up as waste material from the toner production process [21]. Up to now, this waste material, neither the waste from production process nor left over burnt toner in the printing process, is landfilled [19,22]. Landfilling the waste toner triggers several negative environmental repercussions in which the toner landfilling is a threat for environment due to the presence of copolymers in toner such as polycyclic aromatic hydrocarbon [21]. These polymeric entities of toner can be placed useful for enhancing the rheological properties of asphalt binder. Notani and Mokhtarnejad have indicated that the waste toner can greatly enhance the rheological and self-healing capability of asphalt binder in which toner particles interact with the light portion of

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asphalt binder that results in a high viscosity asphalt binder due to the presence of high carbonyl functional group (C=O) [19]. Along with it, it was also showed that the modifying asphalt binder with waste toner up to 8%, increases CH_2/CH_3 ratio, which implies the idea that toner modified asphalt binder may enhance the molecular diffusion process of self-healing capability of asphalt binder [19]. In addition, in another study [22], it was showed that waste toner has almost a uniform particles size from 37-79 nm and then it is proved that using waste toner as modifier agent improves the low-temperature performance and fatigue resistance of asphalt binder [22-24]. Solaimanian et al. [25] demonstrated that using up to 10% of toner by weight of total binder increases the binder viscosity which it is expected to enhance rutting resistance of binder.

The properties associated with rutting performance should be examined in the high-temperature because rutting is more dominant at the high service temperatures that binder presents a high viscous behavior [26-28]. Several studies have been devoted to characterizing the rutting mechanism through asphalt pavement in order to formulate a specification parameter that can describe and measure the anti-rutting properties of an asphalt binder [29-31].

In this study, firstly, the rutting resistance of toner-modified asphalt binder is compared with that of neat binder at various toner dosages by two different methods: implementing the Superpave specification parameter, $G^*/sin\delta$, and utilizing multiple stress creep and recovery (MSCR) test based on the average non-recoverable creep compliance (J_{nr}) and the average percentage of recoverable strain (*R%*). Secondly, to find a correlation between asphalt binder and mixture, the wheel-track test was executed on toner-modified asphalt mixtures. Following sections of the paper are devoted to a brief overview of previous studies and theoretical basis of Superpave specification parameter: $G^*/sin\delta$, the MSCR test in terms of (J_{nr}) and (*R%*), and wheel track test results in terms of rut depths created on asphalt mixture slabs. Next, the rutting resistance of neat binder and toner-modified binder were investigated by using the approaches as mentioned above. Finally, the effect of modified binder on rutting resistance of asphalt mixture performance is discussed.

2. Theoretical background

2.1. Rutting resistance evaluation of asphalt binder

2.1.1. Superpave rutting specification parameter (G*/sinδ)

Asphalt binder is a viscoelastic material which easily can deform under high-temperature condition [32]. This deformation partially recovered by elastic components of the caused strain and rest of it dissipated by the viscous portion and heat generation happened within asphalt binder components. Anderson et al. [33] claimed that the dissipated energy causes the permanent deformation per each cycle of loading. Respect to this hypothesis for an oscillation mode of loading, the following equation can be acquired as:

$$\Delta U = \frac{\pi \tau_{\max}^{2}}{G^*/\sin\delta} \tag{1}$$

where, ΔU = dissipated energy for each loading cycle; τ_{max} = maximum shear stress; G^* = shear complex modulus; δ = phase angle.

Eq. (1) indicates that the Superpave rutting specification *(G*/sinδ)* has an adverse effect on the total dissipated energy. It means that increasing this parameter, reduce the total dissipated energy. From this standpoint, it can be concluded that $G^*/sin\delta$ has been identified as rutting resistance parameter in the Superpave specification protocol which commonly used to rank asphalt binders.

2.1.2. Multiple stress creep and recovery (MSCR) test

Emerging polymer modified asphalt binder in 2007, made some discrepancies on Superpave rutting specification parameter in which many believes that it cannot describe the modified asphalt binder performance especially in terms of anti-rutting behavior at the high-temperature serviceability. In this respect, the repeated creep and recovery test was introduced (NCHRP 9-10) to evaluate the permanent strain caused by a certain stress level [33]. One of the greatest challenges in this test is that it cannot describe the stress dependency of modified asphalt binder. As a result, the repeated creep and recovery (RCR) test has been revised to multiple stress creep and recovery test to characterize the anti-rutting resistance of modified asphalt binder under high temperature condition.

The permanent deformation of asphalt binder is characterized by two main parameters obtained by the MSCR test: average non-recoverable creep compliance (J_{nr}) and average percentage of recoverable strain *(R%)*. The average non-recoverable creep compliance at each stress level is defined by dividing the average non-recoverable strain for the 10 creep and recovery cycles to the applied stress for those cycles. The calculation method for J_{nr} at the stress level of σ ($J_{nr}(\sigma)$) is shown in the Eq. (2) and Eq. (3) based on ASTM D 7405 [34].

$$Jnr(\sigma, N) = \frac{\xi_{10}}{\sigma} \tag{2}$$

$$Jnr(\sigma) = \frac{\sum_{N=1}^{10} Jnr(\sigma, N)}{10} \tag{3}$$

where, $\xi_{10} = \xi_r - \xi_0$; ξ_r: strain value at the end of the recovery portion (i.e., after 10.0 s) of each cycle strain; ξ_0: initial strain value at the beginning of the creep portion of each cycle.

The J_{nr} parameter was proposed as a measure of asphalt binder contribution to mixture rutting performance. Lower J_{nr} denotes better resistance to rutting. Also Eq. (4) and Eq. (5) show the calculation method for *%R* at the stress level of *σ*.

$$\xi_r(\sigma, N) = \frac{(\xi_1 - \xi_{10}) \times 100}{\xi_1} \tag{4}$$

$$R(\sigma) = \frac{\sum_{N=1}^{10} \xi_r(\sigma, N)}{10} \tag{5}$$

where, $\xi_1 = \xi_c - \xi_0$; ξ_c: strain value at the end of the creep portion of each cycle; ξ_0: initial strain value at the beginning of the creep portion of each cycle.

The average percent of recoverable strain determines the elastic behavior of asphalt binders under loading. Elasticity is an important property that measures the ability of materials to recover after deformation. Asphalt binder with higher percent of recoverable strain shows lower propensity to permanent deformation.

2.2. Rutting resistance evaluation of asphalt mixture

It has been proved that the permanent deformation of asphalt mixture can be characterized in creep stage mode in which the permanent deformation happens in three creep stages: primary stage, secondary stage, tertiary stage. Before the first step, instantaneously after loading, a recoverable elastic strain is caused within asphalt mixture which after unloading will be recovered. In the first stage, the strain will increase if the loading continuously applies to asphalt mixture. Note that in this stage the increasing rate of strain will be reduced that commonly called strain hardening stage. In the second stage- referred to steady-state creep-many micro-cracks are formed in the asphalt mixture and propagate. As a result, the stability of asphalt mixture will fail at the end of this stage. In the last stage; the permanent strain increases following an exponential trend, which mainly happens because of joining micro-cracks to create more significant cracks. Moreover, in this stage, shear deformation will be observed and as a result, the mixture falls in the plastic failure mode.

2.2.1. Loaded wheel track test

Several laboratory tests have been introduced to characterize the rutting resistance of asphalt mixture such as: static creep test, repeated load permanent deformation test, and dynamic modulus test [35]. In addition, loaded wheel-track test have been recognized as appropriate test for evaluating the rutting resistance of asphalt mixture [36-40]. It has been proved that the evaluation and causing permanent strain within the asphalt mixture by loaded wheel-track tester is very similar to field condition, although asphalt mixture is loaded with different stress levels in the field [40,41].

In this research, the rut depth was recorded under applying reciprocal wheel loading on the asphalt specimens. The stress level was 0.7 MPa for causing rut on the specimen's surface. In addition to the rut depth, the dynamic stability (DS) of mixture can be calculated as:

$$DS = \frac{(t_2-t_1)\times N}{d_2-d_1} \times C_1 \times C_2 \tag{6}$$

where, d_i = rut depth at t_i; C_1 =device coefficient; commonly considered 1 for 42 cycle of loading per minute and for lower loading rate it is considered 0.8; C_2 = specimen geometry coefficient, which commonly considered 1 for 30*30 cm asphalt specimens; N= loading frequency (Reciprocating loading cycles per minute).

3. Experimental program

3.1. Materials and sample preparation

In this research, a neat asphalt binder with PG58-22 performance grade was used to prepare toner modified asphalt binders. Notani et al. [23] showed that modifying binder with waste toner at 163°C using an agitation rate of 500 rpm for 90 minutes gives a humongous binder [23]. In this research, toner-modified asphalt binders containing 4, 8, 12 and 16% by weight of asphalt binder were prepared in according to the procedure described by Notani et al. [23], and then obtained asphalt binders were labelled as TMA 4%, TMA 8%, TMA 12% and TMA 16%.

To prepare toner-modified asphalt mixture (TMAM), silica base aggregate with the gradation shown in Fig. 1 was used to fabricate toner modified asphalt mixtures. It is worth noting that the marshal mix design (ASTM D6927 [42]) method was employed to determine the optimum binder content, which in this study, it was found to be 5.6% by total mixture weight. Then, this percentage was selected to fabricate all TMAM mixtures.

Modifying asphalt binder by waste toner increases the viscosity of asphalt binder (See Fig. 2). This is because toner particles absorb the light portion of asphalt binder, which in turn decreases the asphalt binder fluidity [19]. As can be seen from Fig. 2, the highest viscosity value related to TMA 12% and for further content, it is relatively decreased due to the interruption of the colloidal structure of asphalt binder.

According to the Superpave mix design protocol, it is required to mix and compact asphalt mixture at temperatures that ensure the asphalt binder is fluid enough for mixing and compacting process. Following the Superpave procedure, the temperature corresponding to 0.170 ± 20 Pa·s and 0.280 ± 30 Pa·s for mixing and compaction, respectively, were identified and then presented in Table 1. To prepare asphalt mixture, TMA binders and aggregate were placed in an oven set at 150°C for 3 hours. Then, the aggregate and binder were mixed with Hobart mixer for 4 minutes at an agitation rate of 150 rpm. The obtained mixture was then placed in an oven set at the specified compaction temperature (See Table 1) for 2 hours to simulate short-term aging on the asphalt mixture. Afterward, the mixture was compacted by a Press Box device under a given pressure of 4 MPa. The primary target for terminating the compaction effort was the air void of specimens, which it was selected to be 6% for neat and TMA mixtures. Next, the slabs were cut to 300*300*50 mm. It should be noted that three replicate slabs were prepared for each type of asphalt binders.

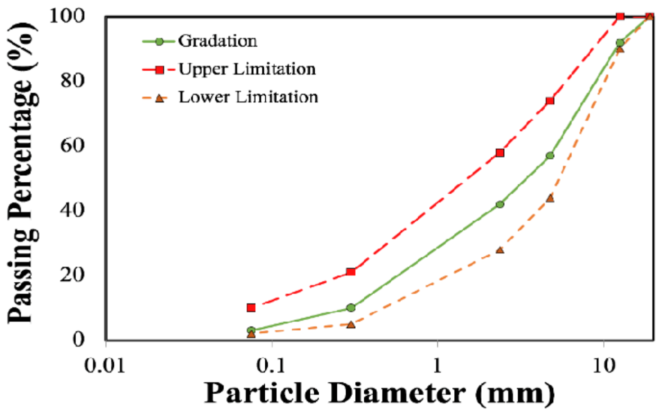

Fig. 1. Aggregate gradation curve.

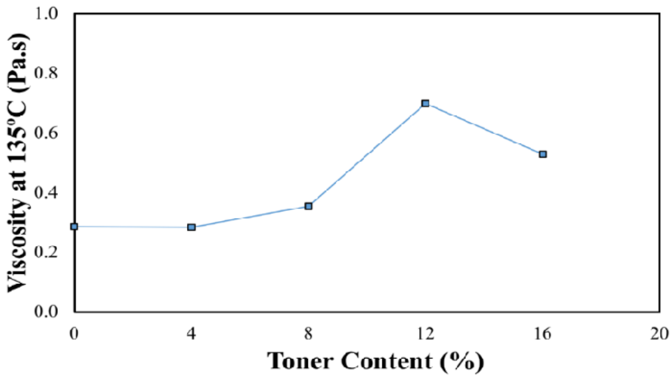

Fig. 2. Viscosity test result for original and toner modified asphalt binders at 135°C.

Table 1
Mixing and compaction temperatures of neat and toner-modified asphalt binders.

Binder	Neat binder	TMA 4%	TMA 8%	TMA 12%	TMA 16%
Mixing Temp. (°C)	145	145	150	155	155
Compaction Temp. (°C)	135	135	140	150	145

4. Test methods

4.1. Frequency sweep test

To obtain the viscoelastic properties of neat and toner modified asphalt binders along with Superpave rutting specification parameter, the frequency sweep test was performed by employing an Anton Paar A102 device using 25 mm diameter specimens and 1 mm gap opening at different test temperatures: 52, 58, 64 and 70°C in a range of loading frequency from 0.1 to 100 rad/s. complex shear modulus (G^*) and phase angle (δ) are the main outputs of this test.

4.2. MSCR test

The MSCR test was performed by using the Anton Paar A102 device using 25 mm diameter specimens and 1 mm gap opening following ASTM D 7405 at four test temperatures: 52, 58, 64, 70°C. This test executed at the two stress levels: 0.1 and 3.2 kPa. It should be noted that for each stress level, ten cycles of loading and resting were implemented as 1-second loading, and 9 seconds resting.

4.3. Loaded wheel track test

To investigate the rutting resistance of toner-modified asphalt mixtures, loaded wheel-track test was performed by using a wheel load tester STCZ1 in according to T0719-2011. This test was run at 60°C for one hour under a 0.7 MPa pressure (see Fig. 3).

Fig. 3. Wheel-track test setup.

5. Results and discussion

5.1. Superpave rutting specification parameter ($G^*/\sin\delta$)

The first set of analyses examined the effect of waste toner on the high-temperature performance of asphalt binder. $G^*/\sin\delta$ is the Surperpave rutting specification parameter, which the higher value of this parameter indicates better rutting resistance performance. This parameter is obtained for both unaged and short-term aged binders shown in Figs. 4 and 5. Based on Fig. 4, it is obvious that modifying binder by waste toner increases $G^*/\sin\delta$ value for all test temperatures in comparison with the neat binder. Moreover, the highest value obtained for TMA 16% at unaged condition, while TMA 12% reaches the highest value at short-term aged condition (Fig. 5). This analysis implies the idea that introducing waste toner as an anti-rutting enhancement agent significantly improves the high service temperature of binder based on the Superpave protocol. As a result, it can be concluded that the toner modification of asphalt binders presents an appropriate anti-rutting resistance. Yildrim et al. [43] showed that adding waste toner obtained from the toner production process increases the high service performance grade of asphalt binder, which placed in a good agreement of this study result. Moreover, it has been concluded extending the toner content in the modified asphalt binder, increases the complex shear modulus [19]. It should be noted that in this study for further content of waste toner (i.e., 16%), the modified asphalt binder did not present any considerable improvement, especially for short-term aged condition. This can be attributed to the idea that if the percentage of waste toner in the blend exceeds a certain amount (around 12%), the colloidal structure of the modified asphalt binder may be interrupted and lead to the deposition of heavy molecules and the additional non-reacted particles of waste toner.

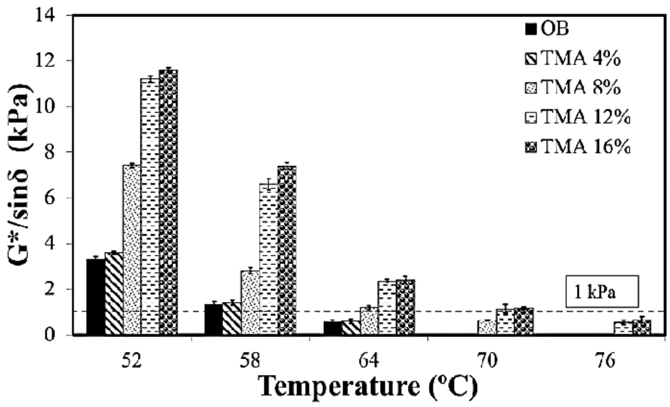

Fig. 4. $G^*/\sin\delta$ versus temperature for unaged neat and toner-modified asphalt binder at loading frequency of 10 rad/s.

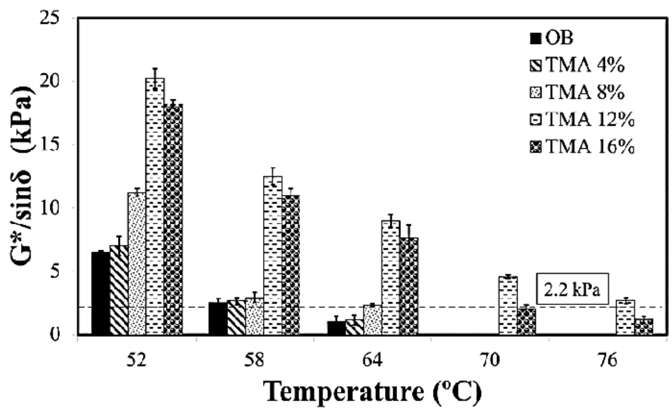

Fig. 5. $G^*/\sin\delta$ versus temperature for short-term aged neat and toner-modified asphalt binder at loading frequency of 10 rad/s.

5.2. Multiple stress creep and recovery test

The main purpose of running MSCR test in this study was to determine the effect of waste toner modification on elasticity of asphalt binder. Two main MSCR test parameters were presented in Figs. 6 and 7 for four test temperatures. In this test, an elastic strain of asphalt binder is developed under loading time and viscoelastic strain of asphalt was determined to represent the total creep strain accumulated at the time of unloading. The instantaneous elastic strain of asphalt disappeared after unloading while the delayed elastic strain recovered gradually. This is when the unrecoverable strain is left after unloading; this portion of strain referred to as permanent strain. Fig. 6 compares recovery percentage (*R%*) for neat and toner modified binders and indicates that using waste toner increases the elastic portion of asphalt binder significantly in which the highest value corresponded to TMA 12%. What is interesting in this data is that modified binder containing 12% of waste toner, improves binder elasticity for both stress levels more than TMA 16%. In addition, Fig. 6 also indicated that increasing the test temperature; reduces the recovery percentage for all binders due to prevalence role of viscous portion of binder at high-temperature condition.

Fig. 7 shows J_{nr} for neat and toner modified binders for two stress levels: 0.1 and 3.2 kPa at different test temperatures. It is apparent from this figure that increasing the test temperature increases J_{nr} value. The lowest value is related to TMA 12%. This result is significant at 64 and 70°C. Further analysis of this data implies that the total permanent strain will be reduced if binder is modified by waste toner up to 12%. As a result, it is expected that toner-modifier asphalt mixtures should present better rutting resistance in comparison with neat asphalt mixture.

Comparing the two main parameters of MSCR test, it can be seen that extending toner content from 12% to 16% change the trend of modified asphalt binder in which elasticity is degraded and consistency, the creep compliance is increased. This finding was expected and suggested that TMA 16% is a multi-phase asphalt binder due to interruption of the colloidal structure of modified asphalt binder. The previous study can support it by showing that toner has high-density ingredients as therefore when it interacts with asphalt binder constituents, the total molecular weight of asphalt binder is raised that increases the probability of phase segregation [19]. As a result, the elasticity of asphalt binder may decrease due to deposition of heavy molecular and non-reacted toner particles. In summary of MSCR result analysis, it was decided to grade the high service temperature of original and toner modified binders in accordance with AASHTO-TP70 [44] based on J_{nr} and *R%* values as therefore; the analysis is shown in Table 2. The data from this table indicates that TMA 4% does not change the allowance traffic volume category while for further content of toner, it will be changed in which TMA 12% can be recommended for using in an area with the average seven-day maximum pavement temperature of 70°C for carrying out of extremely heavy traffic volume.

It was decided to evaluate the permanent non-recovered strain for all binders at 52 and 70°C after last cycle of loading. Comparing data from Fig. 8 and Fig. 9, it can be seen that the left non-recovered strain will increase by increasing the test temperature. Moreover, these figures show that TMA 12% reduces the final strain significantly specially. In a study conducted by Soleimanian et al. [25], it was showed that increasing toner content in the asphalt binder increases the Hveem stability and also, it increases stiffness in terms of Superpave rutting specification parameter. However, the effect of toner on the elasticity of asphalt binder was not discussed. The result of this study showed that increasing toner up to 12% enhances the elastic portion of asphalt binder, and for further content, it will not be enhanced more. Such

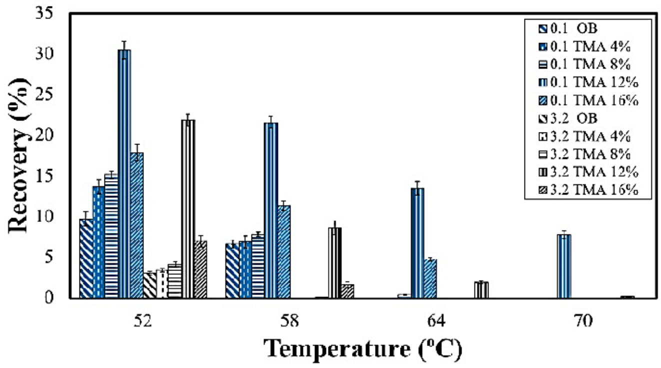

Fig. 6. Recovery percentage for unmodified and toner-modified binders at different test temperatures.

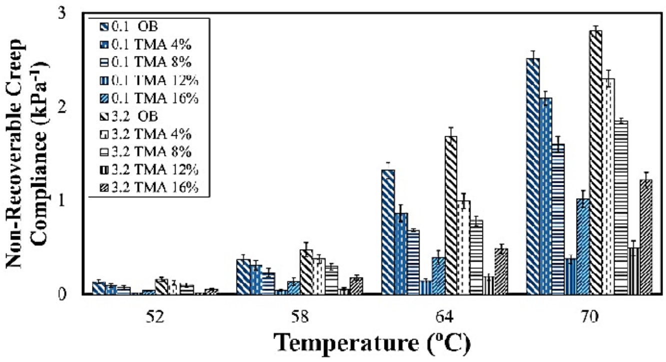

Fig. 7. J_{nr} for neat and toner-modified asphalt binders.

Table 2
High service temperature analysis of MSCR test result according to AASHTO-TP70.

Sample Code	HT based on PG grade (°C)	J_{nr} (3.2 kPa) (kPa-1)	$J_{nr-diff}$ (%)	Type of Traffic*
OB	58	0.48	29.73	E for 58°C
TMA 4%	58	0.38	22.58	E for 58°C
TMA 8%	64	0.79	14.49	V for 64°C
TMA 12%	70	0.49	28.95	E for 70°C
TMA 16%	70	1.22	19.61	H for 70°C

S: Standard traffic
H: Heavy traffic
V: Very heavy traffic
E: Extremely heavy traffic

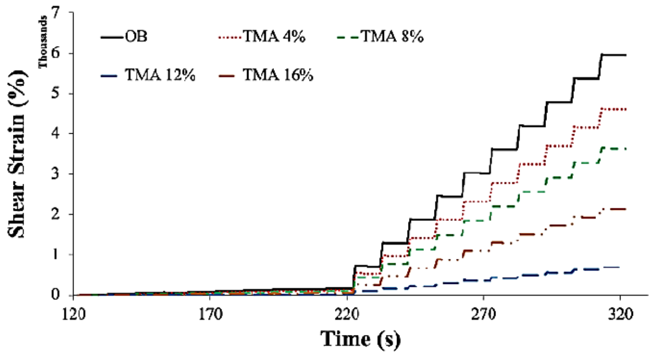

Fig. 8. Recoverable strain for neat and toner-modified asphalt binders at 52°C.

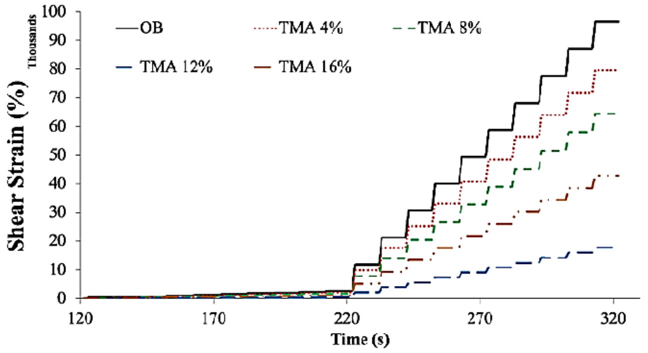

Fig. 9. Recoverable strain for neat and toner-modified asphalt binders at 70°C.

discrepancy may be related to the multi phases system of TMA 16% at which it has a high molecular weight due to the presence of ferric oxide [19], as therefore, it increases the probability of binder's phase segregation.

5.3. Wheel-track test result and analysis

The correlation between toner modified asphalt binders and mixtures was tested using wheel-track machine tester. Two main captured data from this test are dynamic stability (DS) and rut depth after a certain number of loading. The high-temperature dynamic stability of asphalt mixture is considered as a representative index for evaluating rutting distress on asphalt mixture and highly influenced by asphalt binder viscoelastic properties [38]. DS is accounted for asphalt mixture structural ability against deformation within asphalt components. From this point of view, it has been considered as a good anti-rutting representative for rutting resistance of asphalt mixture. In Fig. 10, there is a clear trend of increasing DS by extending the toner dosage in the incorporated binder. It can be perceived that the highest DS value related to TMA 16%. Regarding the SE range for TMA 16% and TMA 12%, it is difficult to say that incorporating 16% of waste toner results in highest DS value compared to TMA 12%. In all cases, the result shows that modifying binder with a toner percentage more than 8%, significantly enhance the dynamic stability of mixture.

Fig. 11(a) presents the rut depth in a wide range of time for neat and toner modified asphalt mixtures at a loading frequency of 42 times per minute. As it can be seen Fig. 11(a), increasing waste toner dosage in asphalt binder reduces the strain increasing rate (Loading

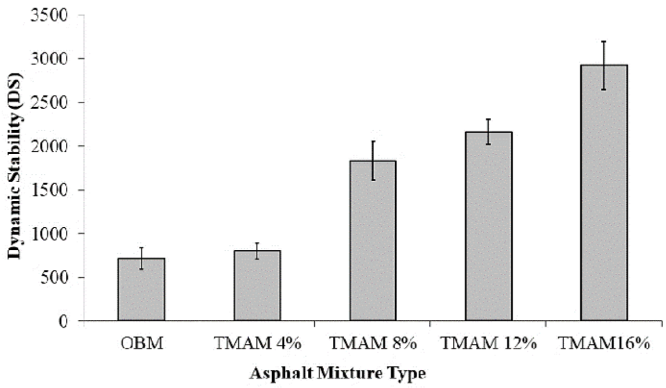

Fig. 10. Dynamic Stability of neat and toner-modified asphalt mixture

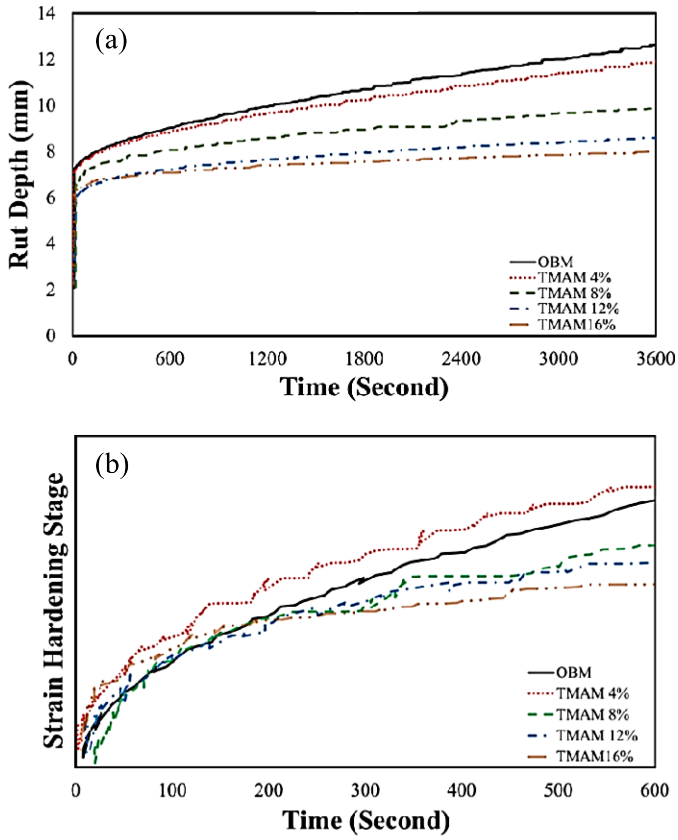

Fig. 11. Wheel track test result (a) rut depth for neat and toner modified asphalt mixture and (b) strain-hardening stage of neat and toner modified asphalt mixtures.

time from 0 to 600 s). As it was mentioned in the introduction part, before starting the strain-hardening stage (first stage), there is a recoverable elastic strain which after unloading it will be recovered. Moreover, as indicated in Fig. 11(a), this strain value is varied for each asphalt binders. Therefore, to understand better the effect of waste toner on the strain-hardening phenomenon, the first stage of the wheel track test was shown in Fig. 11(b). It should be noted that this figure was drawn without considering immediate recoverable elastic strain in order to be more representative of the strain-hardening stage.

It is apparent from Fig. 11(b), reducing the strain increasing rate could be attributed to the strain hardening phenomenon of asphalt mixture exposing a dynamic reciprocal loading in which waste toner accelerates the hardening stage of the mixture results in high mixture resistance against to the lateral movement of asphalt mixture components. In other words, in this stage, the asphalt mixture can be strengthened due to dislocation movement as therefore, the resistance of asphalt mixture against movement will be increased as resistance to plastic deformation. It should be noted that this phenomenon happens immediately after an elastic strain of the mixture. As can be seen from this chart, toner-modified asphalt binders present higher strain hardening behavior than neat asphalt binder that implies the idea that the waste toner improved the resistance of asphalt binder against plastic deformation. Among the asphalt binders, TMA 16% indicates the highest rutting resistance in comparison with other dosages. Further analysis from Fig. 11(a) demonstrates the second stage of wheel-track test result, as it can be observed the rate of strain increasing is constant for all mixtures (approximately it is linear). And by increasing toner concentration in the mixture, the slope was reduced that it is revealing the uncharted conclusion that modifying asphalt binder by waste toner decreases the steady-creep strain which results in a stiffer mixture against permanent deformation compared to neat asphalt mixture. From this point of view, TMAM 16% presents the lowest rut depth compared to others, while the anti-rutting enhancement is close to each other for TMAM 12 and 16% in comparison with OMAM and TMAM 4%

6. Conclusion

This study examines the effect of waste toner on the high service temperature of asphalt binder and mixtures. The effectiveness of toner modification on the rutting resistance of asphalt binder were evaluated using Superpave rutting specification parameter ($G^*/sin\delta$) and Multiple stress creep and recovery (MSCR) test. In addition, to demonstrate the capability of anti-rutting behaviour of toner modified asphalt binders, toner modified asphalt mixtures were produced and then the slab specimens were fabricated to run the loaded wheel-track test in order to simulate the actual field loading on rutting resistance. The results of this study provide the following conclusions:

1. Modifying asphalt binder by waste toner improves the high service temperature of asphalt binders in which the greatest improvement attributed to toner-modified asphalt binder containing 12% of the waste toner.
2. Increasing waste toner dosage in the modified asphalt binder up to 12% amplifies the enhancement trend of asphalt binder elasticity at the high temperatures.
3. Toner modified asphalt binder indicates a low non-recoverable creep compliance in comparison with neat binder in which TMA 12% presents the lowest value.
4. Comparing results of $G^*/sin\delta$ and results of MSCR test shows similar trend but using MSCR test conducted more precise result by determining both J_{nr} and $\%R$.
5. Using toner modified asphalt binder for fabricating asphalt mixture, enhance the anti-rutting behavior of asphalt mixture.
6. Extending toner content in the modified asphalt binder results in a stiffer asphalt mixture compared to the unmodified asphalt mixture in terms of strain hardening under wheel loading.
7. Extending the toner content in the modified asphalt binder improved the rutting resistance of asphalt mixture in which increasing the dosage up to 16% reduces the rut depth significantly after applying 2520 cycles of reciprocal wheel loading with a pressure of 0.7 MPa.
8. Comparing results of $G^*/sin\delta$ and results of MSCR test shows similar trend but using MSCR test conducted more precise result by determining both J_{nr} and $\%R$ because it accurately address mix failure by evaluating non-linear binder properties
9. Comparing the results for both asphalt binders and mixtures indicate there is a good correlation between the MSCR analysis on asphalt binder and wheel track result on asphalt mixture.

The theory of using waste toner as asphalt binder modifier provides a useful account for mitigating asphalt pavement distress and also, eliminating the threat from environmental by landfilling of waste toner. Since a few studies have examined the rheological and mechanical performance of toner-modified asphalt binder and mixture, as therefore, there remains a lack of evidence on the laboratory evaluation of toner-modified asphalt binders and mixtures. Therefore, it is recommended to investigate the rutting performance of toner modified asphalt mixture using static and dynamic creep test. Moreover, it is suggested to study the elastic behavior of toner modified asphalt mixture using dynamic modulus test.

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