World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:18, No:2, 2024

Investigating the Properties of Asphalt and Asphalt Mixture Based on the Effect of Waste Toner

P. I. Itoua, D. Sun, S. Shen

***Abstract*—**This study aimed at investigating the properties of asphalt and mix asphalt based on the effects of waste toner sources (WT1 and WT2) with 8% dosage waste toner powders (WT). The test results included penetration, softening points, ductility, G*sinδ, G*/sinδ, Ideal cracking test (IDEAL-CT), and Ideal shear rutting test (IDEAL-RT). The results showed that the base binder with WT2 had a significantly higher viscosity value compared to the WT1 modified binder, and thus, higher energy for mixing and compaction is needed. Furthermore, the results of penetration, softening points, G*sinδ, and G*/sinδ were all affected by waste toner type. In terms of asphalt mixture, the IDEAL-RT test revealed that the addition of waste toner improved the rutting resistance of the asphalt mixture regardless of toner type. Further, CTindex values for waste toner-modified asphalt mixtures show no significant difference. Above all, WT-modified asphalt mixtures produced by the wet process have better rutting performance.

***Keywords*—**Waste toner, waste toner-modified asphalt, asphalt mixture properties, IDEAL-RT test, IDEAL-CT test.

I. INTRODUCTION

DUE to the rapid growth of the printing industry, a large number of waste toners are generated globally each year, which has resulted in a noticeable increase in waste toner (WT). These toners are occasionally utilized in other applications [1]-[3]; however, they are frequently discarded in landfills, posing a significant environmental challenge [2]. Therefore, the utilization of such material may benefit the environment in different aspects [3].

In the past several years, WT has been adopted in pavement engineering as an asphalt modifier [4]. Khedaywi [5] researched the effect of WT on asphalt cement properties and, found that the asphalt binder modified with WT performed well in cold climates compared to base asphalt. This finding was supported by Notani and Mokhtarnejad's research [6], which indicated that incorporating WT into the asphalt binder improved the physical properties of penetration and viscosity. In addition, the feasibility and potential benefits of using such material were investigated by Solaimanian et al. [7] indicating that after adding WT, the stiffness is increased as a result of the effect of WT on asphalt binder. On the other hand, the addition of WT enhances the resistance to permanent deformation of the asphalt binder at high temperatures [7]. Notani et al. [8] also found that the asphalt binder modified with WT has a great high service temperature compared to the base binder. In addition to the above-mentioned findings, the effect of WT on the properties of asphalt binder such as self-healing capability, fatigue resistance, and workability was investigated. It was found that the self-healing property of asphalt binder enhanced as the WT content increased to 8% [6]. Moreover, increasing WT content to 8% also increased the DER value of asphalt binder, which benefits the low-temperature property of the asphalt binder [9]. On the contrary, extending the WT content up to 12% resulted in greater fatigue resistance of the modified binder [10]. Further, Huang et al. [11] pointed out that adding WT decreased both the workability and the moisture-induced damage performance of the asphalt binder. Besides, it has been demonstrated that WT also could significantly improve the anti-rutting performance of asphalt mixture [10], [13]. A mixing time of 60-90 min before mixture tests was considered suitable based on research conducted by Yildirim et al. [12] in Texas. Furthermore, compared to existing asphalt modifiers (e.g. crumb rubber and styrene-butadiene-styrene), using WT is less expensive due to the WT recycling demand around the world.

Few studies have been conducted on the effect of WT with different content on the asphalt binder properties, however, the present state of research on the effect of different types of WT on asphalt and asphalt mixture, as well as the investigation of the effects of various mixture production processes (e.g., wet and dry processes) on waste toner asphalt mixture properties, is still unclear. Especially, further investigation and analysis are needed to explore the influence of WT source on the physical properties of asphalt and asphalt mixture. Thus, because of the source variation of WT materials which is also visible in chemical composition, it is necessary to evaluate their effect on asphalt and asphalt mixture performance.

The objective of this research was to investigate properties of asphalt and mix asphalt containing two types of WT. This was achieved by assessing asphalt binder properties such as penetration, softening point, ductility, fatigue resistance and rutting resistance. While, the asphalt mixture cracking and rutting properties were evaluated by using IDEAL-CT and IDEAL-RT, respectively.

In order to achieve the objective of this study, this paper was divided into five parts. To begin, the previous research findings related to WT recycling and its utilization in pavement engineering were resumed in the introduction part. Second, the materials and methods used for obtaining the experiment results were presented in the materials and methods part. In third part, the results obtained from each test were analyzed and discussed. In the fourth and final part the conclusions were drawn based

P.I. Itoua & D. Sun* are with Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai, China (*e-mail: dqsun@tongji.edu.cn).

S. Shen is with Department of Engineering, Penn State Altoona, Altoona, USA.

on the research results.

II. Materials and Methods

A. Materials

In this research, one PG70-22 neat binder was used, which was from Jiangsu province (China). The physical properties of the base asphalt binder are indicated in Table I.

Two modifiers used in this study were toner printed and banknote toner (used to produce Chinese currency) and are referred to as WT1 and WT2, respectively. The appearance and chemical composition of these materials are shown in Fig. 1 and Table II, respectively.

One type of gradation AC-13C (Coarse-grained Asphalt Concrete Mixture) according to JTG F40-2004 (Chinese standard) was used in this study. Fig. 2 shows the selected gradation, and the designed asphalt content was 5.0% for unmodified and modified asphalt mixtures.

TABLE I
PHYSICAL PROPERTIES OF BASE ASPHALT BINDER

Test index	Unit	Measured value	Typical values value
Penetration (25 °C) 5s, 100 g)	0.1 mm	68	60~80
Ductility (15 °C)	cm	>100	100
Softening	°C	50	≥ 46
Penetration index	—	-0.98	-1.5~+1
Relative density	—	1.038	—
Flash point	°C	> 300	260

TABLE II
CHEMICAL COMPOSITION OF WTS

Element	WT type 1	WT type 2
Carbon (%)	59.45	55.88
Oxygen (%)	18.93	9.46
Calcium (%)	17.43	/
Iron (%)	/	33.54
Others (%)	4.19	1.1

Fig. 1 WTs

B. Test Methods

Fig. 3 indicates the experimental design utilized in this study. First of all, two different sources of WT (WT1 and WT2) with 8% dosage WT powders were incorporated into base asphalt to produce WT-modified asphalt. Then, toner asphalt mixtures were prepared through both wet and dry processes. A series of tests such as penetration test, softening point test, ductility test, viscosity test, and Dynamic Shear Rheometer (DSR) test were conducted to evaluate the asphalt binders' performance. Finally, the rutting resistance and fatigue cracking properties of toner-modified asphalt mixtures were investigated, and the influence of both wet and dry mixing processes on toner asphalt mixtures was compared and analyzed.

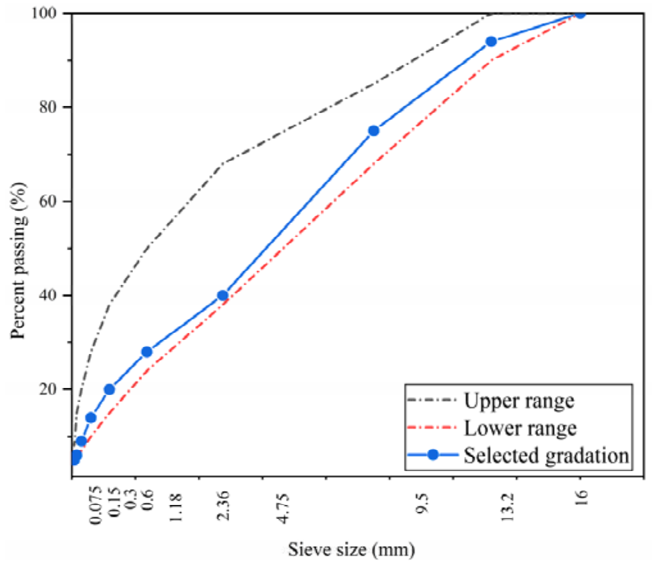


Fig. 2 Selected aggregate gradation

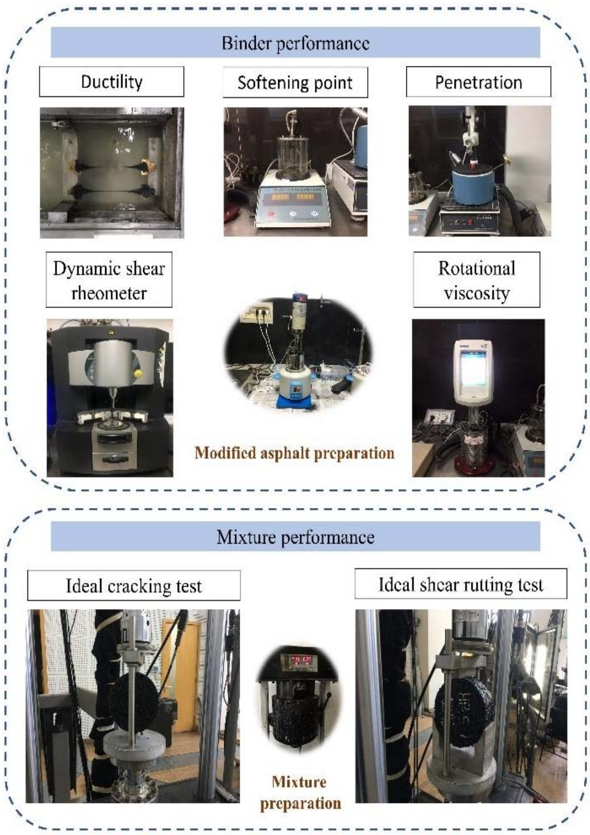


Fig. 3 Experimental design

1. Preparation of Modified Asphalt

In this study, two types of WT with 8% of toner powder based on the asphalt weight were used. To this end, the neat asphalt was heated at 150 ℃. Then, the WT was added to the hot asphalt and mixed for 30 min using a high-speed mixer with a speed of 3000 rpm at 160 ℃. Finally, the toner-modified asphalt was sheared at a speed of 5000 rpm and 160 ℃ for 30 min.

2. Preparation of Modified Asphalt Mixture

Wet Process

First, the aggregates and minerals were heated at the temperature of 175 ℃ for 3 h. Then, the heated aggregates were added to the mixing bowl and stirred at 165 ℃ for 90 s. Further, the WT-modified asphalt was added and stirred for 90 s. Last, the mineral powder was added and the entire blend was stirred for 90 s.

Dry Process

Similar to the wet process, the aggregates and minerals were heated at 175 ℃ for 3 h. Then, the heated aggregates were put in the mixing bowl and stirred at 165 ℃ for 90 s. After that, the WT and mineral powders were added into aggregates and mixed for 90 s. Finally, the neat asphalt was added to obtain the WT-modified asphalt.

3. Binder Tests

The physical properties of binders at low temperatures were characterized. The penetration (25 °C), softening point, and ductility (15 °C) tests were carried out in accordance with the ASTM D5, ASTM D36, and ASTM D113 standards, respectively.

The viscosity of different binders was tested at 135 ℃ using a Brookfield viscometer as per AASHTO T316. A DSR was utilized to measure two parameters: The fatigue factor (G*sinδ), and the rutting factor (G*/sinδ). For all samples, the diameter of the plate was 8 mm and the gap was 2 mm at medium temperature, while the diameter was 25 mm and the gap was 2 mm at high temperature, according to AASHTO 315.

4. Mixture Tests

In this study, both the IDEAL-CT and IDEAL-RT tests were used to investigate the cracking and rutting performance of asphalt mixtures, respectively. All the mixture specimens with a diameter of 150 mm and a thickness of 62 mm were compacted to 7 ± 0.5% air voids using a Superpave gyratory compactor. Before the compaction, the loose mixtures were conditioned in an oven for 2 h at 135 °C in order to simulate short-term aging that occurs during field fabrication.

Cracking Test

The Ideal cracking (IDEAL-CT) test was performed at 25 °C (according to ASTM D8225) by measuring the cracking tolerance index (CT_{index}) to determine the cracking performance of asphalt mixtures. Test specimens were kept at 25 °C for about 2 h, and then an MTS testing machine was used to load the test specimens at a room temperature of 25 °C with a linear loading rate of 50 mm/s. The data sampling frequency was at least 40 data points per second. In this study, the sampling frequency was set to 100 Hz. When the load value after splitting of the specimen was less than 0.1 KN, the loading was stopped, and the load-displacement data during the loading process were recorded. A typical IDEAL-CT test set-up and a typical load vs. displacement curve are illustrated in Fig. 4. The CT_{index} was used to evaluate the cracking performance of asphalt mixtures [13].

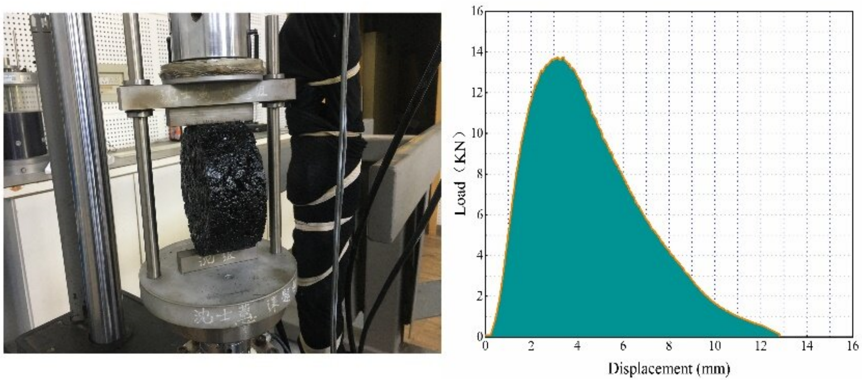


Fig. 4 A typical IDEAL-CT set-up for cracking investigation of asphalt mixtures and a typical load versus displacement curve experimental design

Rutting Test

The IDEAL-RT test is a new, simpler, and quicker method for evaluating the rutting performance of asphalt mixtures developed by Zhou et al. [14]. Based on the ideal shear rutting test method, the effect of different toner powders on the rutting potential of asphalt mixtures was evaluated by calculating shear strength (rutting tolerance index, RT_{index}). All test samples are placed on a u-shaped shear mold as illustrated in Fig. 5. Prior to testing, the specimens were kept at 50 °C for 2 h, and the MTS testing machine was used to apply a linear loading rate of 50 mm/s on specimens at 50 °C. Fig. 5 also depicts a typical IDEAL-RT load vs displacement curve. Finally, the shear strength (RT_{index}) was calculated according to Zhou et al.'s research [15].

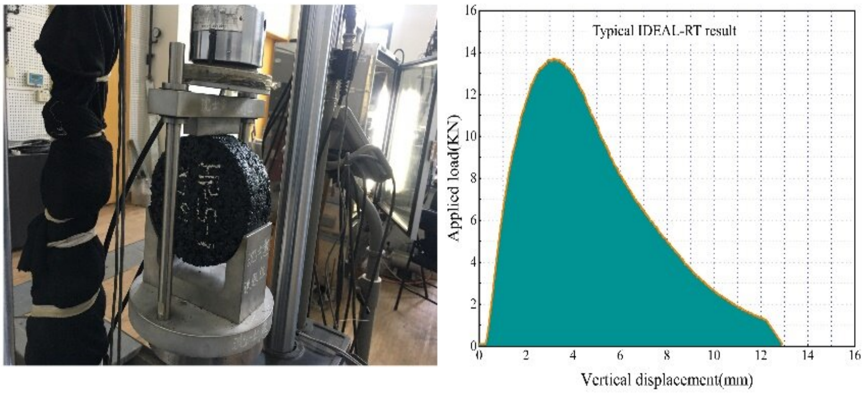


Fig. 5 A typical IDEAL-RT set-up for rutting investigation of asphalt mixtures and a typical load versus displacement curve

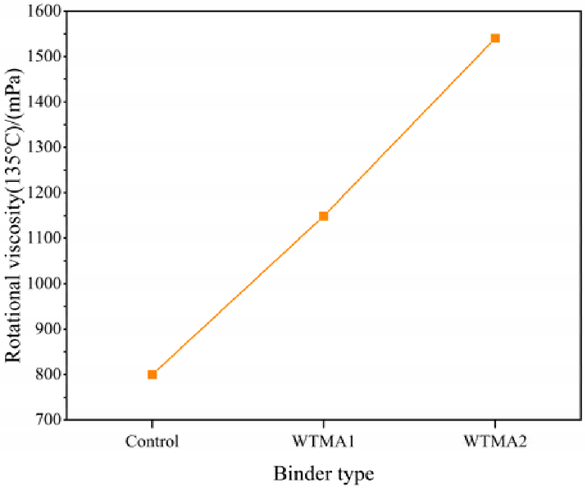


Fig. 6 Viscosity values of asphalt binders

III. Results and Discussion

A. Rotational Viscosity

Fig. 6 depicts the viscosity values of asphalt binders at 135 °C. According to SHRP binder specifications, the viscosity of the asphalt binder should not be greater than 3 Pa.s at 135 °C. As shown in Fig. 6, the viscosity values of unmodified and modified asphalt binders are lower than 3 Pa.s. According to Fig. 6, the base binder has the lowest viscosity value while WT asphalt binders show the highest ones regardless of WT type. The possible reason may be because of the strong absorption proportion of toner particles, WT-modified asphalt binders result in toner particles surrounded with an asphaltene layer, causing low mobility of the base binder, in turn leading to the increase of viscosity. Other researchers came to similar conclusions [16], [17]. In addition, the modified binder containing WT2 has a higher viscosity value compared to that containing WT1. Thus, WTMA2 requires high mixing and compaction temperatures during construction. Furthermore, the WTs (WT1 and WT2) have the ability to significantly increase the viscosity of the asphalt binder used in this study.

B. Physical Property Tests

Penetration, softening point, and ductility tests were conducted to characterize the physical properties of asphalt binders. Fig. 7 shows the results obtained from this study.

Figs. 7 (a) and (b) show the penetration and softening point values of asphalt binders. The results indicate that the penetration values decreased and the softening point values increased after adding WTs, meaning that the addition of WT increased the consistency and decreased the temperature sensitivity of the base asphalt binder, regardless of the WT type. Furthermore, the binder modified by WT1 not only has lower penetration values, but also exhibits higher softening point values compared to the binder modified by WT2. This possibly could be because of the difference in chemical composition of WTs. As can be seen from Fig. 7 (c). The ductility of the base binder decreased when WT1 and WT2 were added. In other words, it can be said that the addition of WT exhibits a negative impact on the base asphalt's low temperature extensibility.

C. Rutting Resistance Factor

Rutting factor (G*/sinδ) is frequently used to describe the rutting resistance of asphalt binder at high-temperature.

Fig. 8 shows the effect of various WTs on the rutting resistance factor (G*/sinδ) of control and modified binders from 58 °C to 82 °C.

As shown in Fig. 8, it is observed that the G*/sinδ values of control and modified binders decreased as the test temperature increased. Additionally, the results indicated that as the temperature increases, the G*/sinδ value of asphalt binder modified with WT2 is greater than that of asphalt binder modified with WT1. In other words, the asphalt binder modified with WT1 becomes less temperature susceptible in the context of deformation, which could be due to the inclusion of an extremely limited amount of light component in WTMA1.

In summary, the addition of WTs improves the rutting resistance of asphalt binders, regardless of WT type, and it is worth noting that the improvement attributable to WTMA2 was marginally greater.

D. Fatigue Resistance Factor

Fatigue factor (G*sinδ) obtained from DSR is used to characterize the fatigue resistance of asphalt binder at medium temperature.

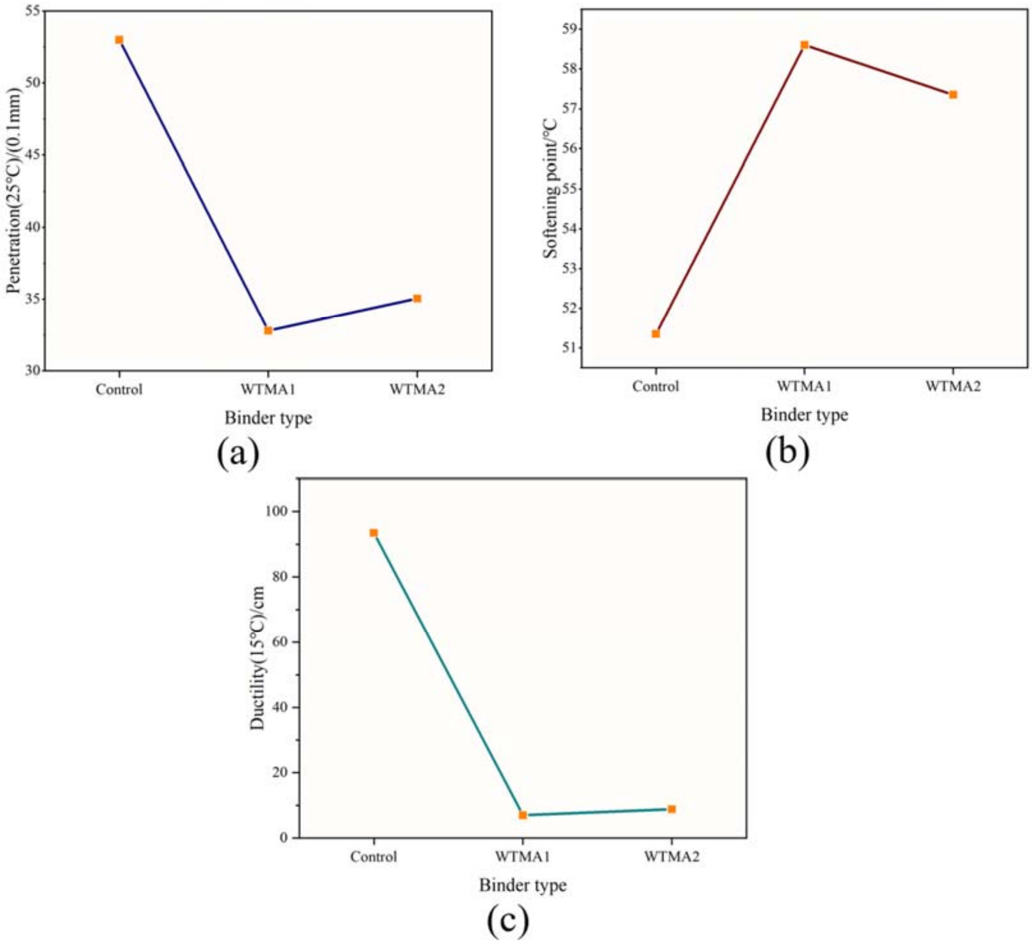


Fig. 7 Physical properties of asphalt binders: (a) penetration, (b)softening point, (c) ductility

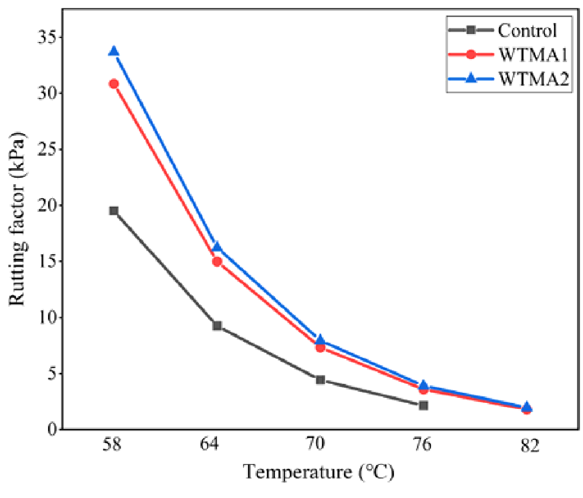


Fig. 8 Rutting factor (G*/sinδ) values of asphalt binders

The fatigue resistance factor values of all binders from 19 °C to 28 °C at PAV state are shown in Fig. 9. It can be seen that the G*sinδ values increase as the test temperature decreases regardless of binder type, which indicates that the lower the temperature, the greater the energy loss of the asphalt binder during the stress deformation process. Moreover, at a temperature of 25 °C, the fatigue resistance factor of the control binder met the required limit value (≤ 5000kPa), while those of WT binders exceeded. On the contrary, at 28 °C the modified binders met the required value. Furthermore, at 25 °C, the fatigue resistance factor value of the control binder increased after adding WTs, which means that the addition of WTs reduced the fatigue resistance factor value of control binders.

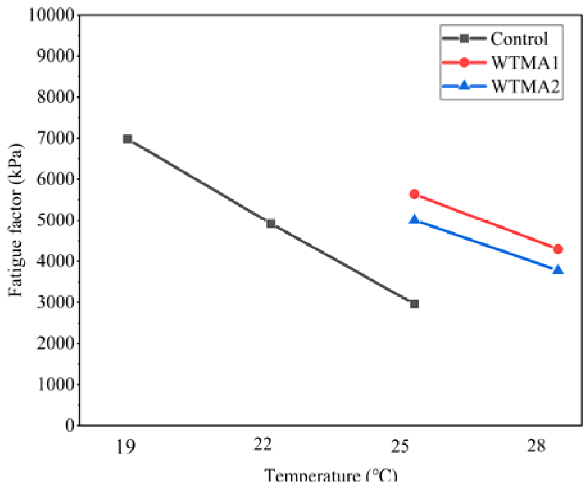


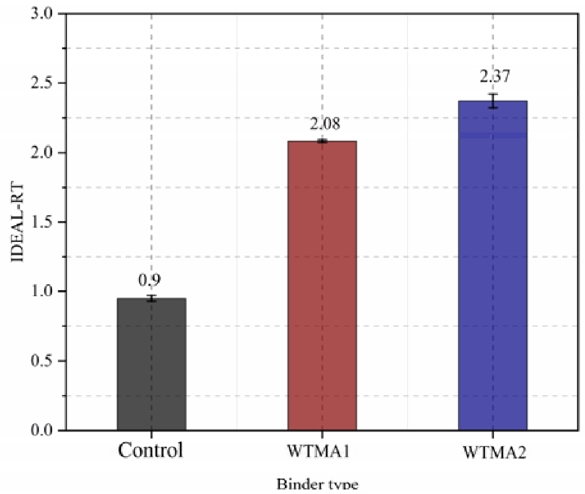
Fig. 9 Fatigue factor (G*·sinδ) values of asphalt binders

E. IDEAL-RT

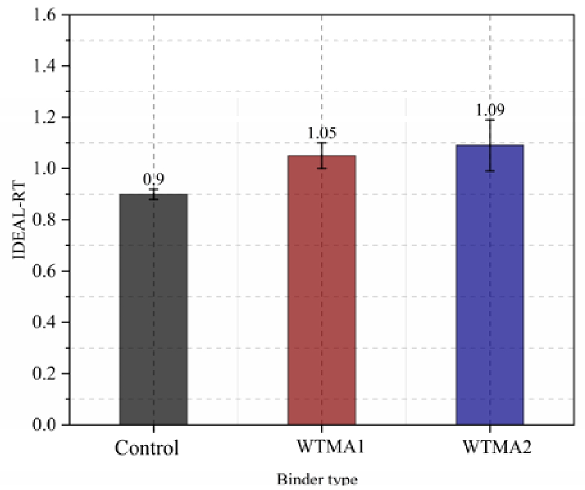
Fig. 10 shows the IDEAL-RT test result for control and modified mixtures at 50 °C. The higher the RT_{index} value, the better the rutting performance.

As can be seen in Fig. 10 (a), the RT_{index} is sensitive to the type of asphalt binder. Moreover, the RT_{index} values increased after WTs were added. Therefore, the addition of WT can effectively improve the rutting resistance of the asphalt mixture. In addition, the RT_{index} values of WT1 mixture were slightly higher.

Figs. 10 (a) and (b) showed that the WT-modified asphalt mixtures produced by the wet process had the highest RT_{index} compared to those produced by the dry process, which means the wet mixing process can maximize the improvement effect of the WT on the asphalt mixture. This is mainly because before mixing the mixture, the WT was added to the asphalt, and both mixed and sheared under high temperature using high-speed shearing machines, resulting in a good dispersion of toner particles in the mixtures. In summary, the mixing process can affect the RT_{index} value of the asphalt blends.



(a) Wet process



(b) Dry process

Fig. 10 RT_{index} values of asphalt mixtures

F. IDEAL-CT

The larger the CT_{index} value of the asphalt mixture during the entire cracking stages is, the greater the work required to fully crack the asphalt mixture. Fig. 11 shows the Ideal-CT test results of asphalt mixtures. According to Fig. 11, the use of WT reduced the binder's cracking resistance, as indicated by a lower CT_{index} value. The possibly reason is that the addition WT could increase the modulus and decrease the surface energy of the binder mixtures, lowering the cracking resistance of the asphalt mixture.

The results of the IDEAL-CT test were further processed by a statistical hypothesis t-test to evaluate the significance of the cracking tolerance index using a P-value. The P-value at the significance level of 0.05 was determined as 0.59, thus, it can be deduced that there is no significant difference in the CT_{index} values of the mixture before and after the addition of WTs.

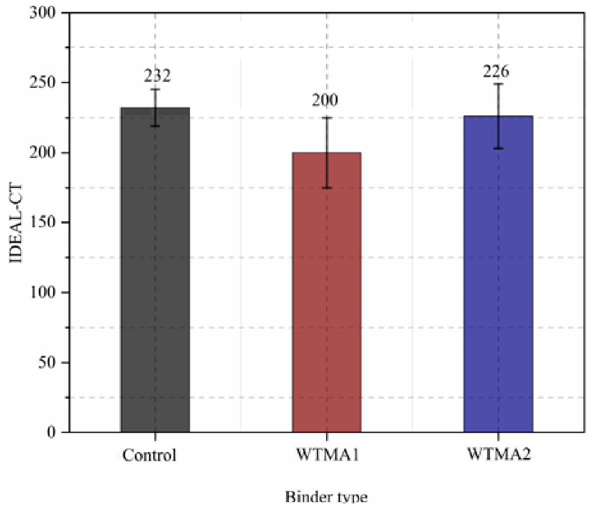


Fig. 11 CT_{index} values of asphalt mixtures (Wet process)

IV. CONCLUSION

This study investigated the physical and fatigue properties as well as rutting performance of asphalt binder containing two types of WT modifiers at a rate of 8%. Also, the IDEAL-CT and IDEAL-RT tests were conducted for all mixtures. Based on the research results, the following conclusions can be drawn:

- The addition of WTs increases the viscosity values at 135 °C. WTMA2 showed greater viscosity value than WTMA1. In other words, WTMA1 requires higher mixing and compaction temperatures during mixture production.
- With the addition of WT, the penetration and the ductility values of the control binder decreased, while the softening point values increased, regardless of the WT type.
- The $G^*\sin\delta$ test results demonstrate that the addition of WT s reduced the fatigue resistance of neat binder.
- Based on $G^*/\sin\delta$ results, it was found that the WT material can significantly improve the high-temperature performance of asphalt binder. However, their effects differed depending on the source of toner.
- The RT_{index} results indicate that using WTs as modifier improves the rutting resistance of the asphalt mixture. In

addition, the mixing process can affect the mixture properties. The wet process showed the highest RT_{index}.

- It was observed that the cracking resistance property of WT-modified asphalt mixtures could not be evaluated by CTindex.

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