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Effect of treated fibers on performance of asphalt mixture

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HIGHLIGHTS

- Surface treatment was developed incorporating aramid fiber and warm-mix additive.
- The wet method at high speed could mitigate adverse mixing effects.
- Treated fibers improved the performance of asphalt mixture.
- Warm-mix additive coated fiber outperformed other reinforced fibers.

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ABSTRACT

In this study, a fiber surface treatment (coating technique) was developed using paraffin wax and warm-mix additive (WMA) to enhance fiber's distribution throughout the asphalt mixture. Three types of fiber were examined, including WMA coated fiber, wax coated fiber, and uncoated fiber. The performance of fiber-reinforced mixtures was investigated by indirect tensile asphalt cracking test (IDEAL- CT), dynamic modulus, flow number, and overlay testing. Two mixing methods (e.g., dry and wet) were employed to determine the best mixing method. The promising results indicated the potential of incorporating warm-mix additive and fiber. Although Tukey-Kramer statistical analysis showed no significant difference between wet and dry mixing methods, the wet mixing method was recommended to mitigate the adverse mixing effects (e.g., fiber clustering, fiber sticking on the mixer). The insignificant difference between wax-coated fiber and uncoated fiber mixtures indicated the critical impact of coating materials on performance of reinforced asphalt mixture. Finally, mixtures containing 0.05% of WMA coated fiber suggest potential improvement in the performance of asphalt mixture, such as enhancing the cracking tolerance index (CT_{Index}), prolonging fatigue life, and exhibiting good resistance rutting.

1. Introduction

Owing to excellent performances (e.g., pavement smoothness, driving safety), asphalt concrete is widely applied on highways or urban roads. In the United States, over ninety-four percent of roads have been paved by asphalt concrete [1]. This composite material consists of coarse aggregate, fine aggregate, asphalt binder, additives, and air void. Due to excessive traffic loads and environmental factors, asphalt pavements deteriorate their properties early before the design life [2]. Therefore, the enhancement of asphalt concrete performance is one of the hot topics to attract scientists and engineers [3]. Many researchers have proved the effect of reinforced-fiber in asphalt mixture. For instance, Wu et al. pointed out that dynamic modulus has improved by containing 0.3% of cellulose fiber [4]. Putman and Amirkhanian found that the utilization of waste fiber could enhance moisture susceptibility of asphalt mixture [5]. Polypropylene fiber increased asphalt concrete life under repeated creep testing [6] and reduced the reflective cracking [7]. Healing performance asphalt concrete was affected by fiber's properties (e.g., fiber content, fiber type) [8,9]. In general, the containing fiber can increase the performance and durability of asphalt pavements.

Aramid fiber has been widely used to improve asphalt concrete performance due to the high tensile strength and thermal stability. The research done by Klinsky et al. pointed out that aramid fiber provided a three-dimensional reinforcement network to the asphalt mixture [10]. In this research, the addition of 0.05% fiber by weight of total mixture showed an increase of 15% and 30% in resilient modulus and dynamic modulus, respectively. It's well known that fiber properties (e.g., diameter, length, distribution, and orientation in a mixture) are the key factors that influence the performance of fiber-reinforced mixture [11]. The mixing

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method and fiber surface treatment play a significant role, as well. Abtahi et al. recommended that two mixing techniques (e.g., dry and wet mixing) are often used to incorporate fiber in asphalt mixture [12]. Besides, the coating technique commonly uses to treat the surface of the fiber. The coating treatment helps fiber reduce static, which affects the mixing process. Excess static can make mixing difficult [13]. Nowadays, aramid fibers are commonly coated by a thin paraffin wax membrane to mitigate the clustering phenomenon. The fiber clustering can reduce the mechanical properties of fiber modified asphalt mixture. Therefore, this research aims to improve the homogenous distribution of aramid fiber throughout the HMA mixture.

The fiber-reinforced mixture's mechanical properties are examined by indirect tensile asphalt cracking test (IDEAL-CT), dynamic modulus, flow number, and overlay testing (OT). The IDEAL-CT provides a method to evaluate load–displacement behavior at 25 °C. Besides, the cracking tolerance index (CT_{Index}) was defined as the cracking resistance of asphalt mixture [14]. The larger CT_{Index}, the lower the crack growth rate is. The dynamic modulus and flow number test provide stiffness and rutting resistance of asphalt mixture, respectively, while OT estimates a fiber-reinforced mixture's reflective cracking.

In this study, a new coating technique was developed in laboratory conditions. Three types of fiber were utilized in the series of samples. First, the WAX fiber was covered by the paraffin wax. Second, WMA fiber was coated by warm-mix additives. Finally, UNC fiber (uncoated fiber) stands for fiber without surface treatment. The properties of coated fiber were examined by diameter, core–shell ration, and morphology. All reinforced fibers had a length of 19 mm and a 0.05% content by the mixture's weight. Two mixing techniques (e.g., dry and wet mixing) were employed to find the best mixing methods. Regarding the mechanical properties of fiber-reinforced asphalt mixture, the IDEAL-CT test, the dynamic modulus test, flow number test, and OT were used to examine cracking resistance, stiffness, rutting, and reflection cracking, respectively. This research indicates a better understanding of treated fiber on the performance of fiber-reinforced asphalt mixtures.

2. Materials and methods

2.1. Materials

The aggregates, including coarse, fine, and mineral filler, were made from limestone. Table 1 shows the size gradation of the aggregate used in making samples. The PG 64–22 binder was used in this research. Fig. 1 illustrates three types of fiber. First, wax coated fiber, is inspired based on the technical properties of wax coated aramid fiber products available in the market. The wax coated fiber was covered with a thin layer of paraffin wax. Second, WMA coated fiber was produced by aramid fiber and coating of warm-mix additive in the laboratory. Finally, uncoated fiber was made from pure aramid fiber. All types of reinforced fiber had a length of 19 mm. The basic properties of materials can be referenced in Table 2.

2.2. Laboratory coating process

The core–shell ratio was designed by 50:50 (calculated by weight). This ratio is suggested based on the trial test, which showed the desired durability. The coating layer thickness was computed based on the annular (as shown in Fig. 2a). The outer radius is the radius of coated fiber, while the inner radius is the radius of the pure fiber bundle. The following steps were applied in the coating process (Fig. 2b):

a) Coating material was placed in the oven to reach a liquid state.
b) The pure fiber bundle was guided in a coating room with the output diameter equal to the coated diameter.
c) Liquid coating material was carefully poured into a coating room, heated by the glass alcohol burner.
d) The coated fiber was slowly pulled out with a velocity of 5 mm/s.
e) Finally, the coated fiber was conditioned at room temperature for three hours before cutting into small pieces with 19 mm in length.

2.3. Asphalt mixture preparation

Hot Mix Asphalt mixtures were adopted to conduct a series of experiments. According to the Superpave Mix Design method, all asphalt mixtures were prepared with optimum asphalt content of 5.4% [15]. The containing 0.05% fiber by weight of mixture was used to reinforce asphalt mixture [16]. Fig. 3 shows the research flowchart. After producing WMA coated fiber and evaluation on the mixing method, the best-mixed method was chosen to conduct a series of samples. The Superpave Gyration Compactor is used to compact asphalt samples to the designed air voids of 7 ± 0.5%. Four asphalt mixtures were developed to evaluate the effect of fiber on the properties of asphalt concrete. These mixtures included the CTR mixture (without fiber), WAX mixture (with wax coated fiber), WMA mixture (with warm-mix additive coated fiber), and UNC mixture (with uncoated fiber). Each mixture was prepared three replicates for average.

2.4. Test methods

2.4.1. Determination of WMA coated fiber basic properties

Wax coated fiber and WMA coated were developed in the laboratory condition. The fiber diameter was determined by a ruler with an accurate of 0.01 mm (Fig. 4a). The average fiber diameter was computed by nominal distribution. Also, the core–shell ratio was determined using the following steps. A coated fiber dosage (W_b) was placed in an oven with a temperature of 140 °C (Fig. 4b). Based on the team's experiment, the fiber weight was unchanged after three hours in the oven. The core–shell ratio was calculated by Eq. (1). The W_a, $W_b - W_a$ were denoted as core (fiber) and shell (coating material), respectively.

$$r = \frac{W_b - W_a}{W_a} \quad (1)$$

where,

r: core–shell ratio,
W_b: weight of coated fiber before heating,
W_a: weight of coated fiber after heating.

2.4.2. Mixing methods

The effect of mixing type was analyzed using two mixing techniques (e.g., dry and wet) [12]. In the dry process, fiber was mixed

Table 1
Size gradation of aggregate.

Sieve size (mm)	19	12.5	9.5	4.75	2.36	0.6	0.3	0.15	0.075
Percent passing (%)	100	98	86	60	45	23	14	8	3

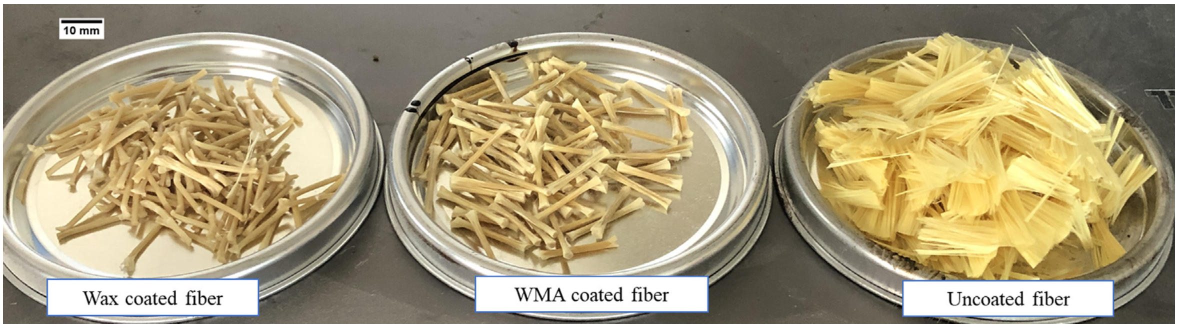

Fig. 1. Fibers used in this study.

Table 2
Material properties.

Materials	Properties	Values	Specification
Bitumen	Density (g/cm^3)	1.02	–
	Penetration (25 °C, 5 s, 0.1 mm)	70	60–100
	Softening point (°C)	48	47
Uncoated fiber	Density (g/cm^3)	1.44	1.40–1.45
	Average length (mm)	19 ± 1	–
	Equivalent diameter (μm)	12	–
	Tensile strength (MPa)	2900	–
Paraffin wax	Density	0.84	–
	Melting point (°C)	65	-
Warm-mix additive	Density (g/cm^3)	0.95	ASTM D792
	Viscosity at 140 °C (cps)	200 ± 40	ASTM D4402
	Penetration (25 °C, 5 s, 0.1 mm)	72	AASHTO T 49
	Melting point (°C)	140	–

with hot aggregates thoroughly for 90 s. Then, bitumen was added and mixed for 90 s. In the wet process, binder and aggregates were mixed for 60 s. Then asphalt mixture was mixed with 50% fiber for 60 s. Finally, the remaining fiber was added and mixed for 60 s. The mixing process was performed at 160 °C. The samples were compacted to reach air voids of 4 ± 0.5% at a temperature of 140 °C. Besides, the Tukey-Kramer (T-K) statistical analysis was employed to find the difference between two mixing methods in terms of IDEAL-CT. The T-K produce is based on calculating confidence intervals for the difference between each pair of averages (μ). Each confidence interval is examined to determine if it includes zero. If the interval does not include zero, the two means are significant difference, and vice versa the including zero of interval indicates the two means are not significant difference [17].

2.4.3. IDEAL-CT

The IDEAL – CT evaluates the cracking resistance of asphalt concrete. The cylindrical samples in this test were compacted using Superpave Gyratory Compactor with a diameter of 150 mm and a height of 62 mm. The DTS-30 (Dynamic testing system-30 kN) machine was employed to conduct IDEAL-CT (Fig. 5a). Test specimens were conditioned in a chamber at 25 °C for two hours before testing. A vertical force was applied across the specimen's diameter with a constant loading rate of 50 mm/min. Load and displacement were then monitored and recorded throughout the testing process. Fujie et al. developed a cracking tolerance index (CT_{Index}) that is computed by load versus displacement graph [14]. The CT_{Index} is calculated by Eq. (2). The PPP_{75} (75% post peak-load point) and its slope ($|m_{75}|$) were illustrated in Fig. 5b. Also, indirect tensile strength (ITS) was calculated by Eq. (3).

$$CT_{Index} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \quad (2)$$

where,

$m_{75} = \left|\frac{P_{85}-P_{65}}{l_{85}-l_{65}}\right|$, slope at 75% PPP
G_f(J/mm^2), fracture energy,
l_{65}, l_{75}, l_{85}(mm), displacement at 65%, 75%, 85% PPL,
P_{65}, P_{75}, P_{85}(N), load at 65%, 75%, 85% PPL,
D(mm), diameter of specimen.

$$ITS = \frac{2P}{\pi Dt} \quad (3)$$

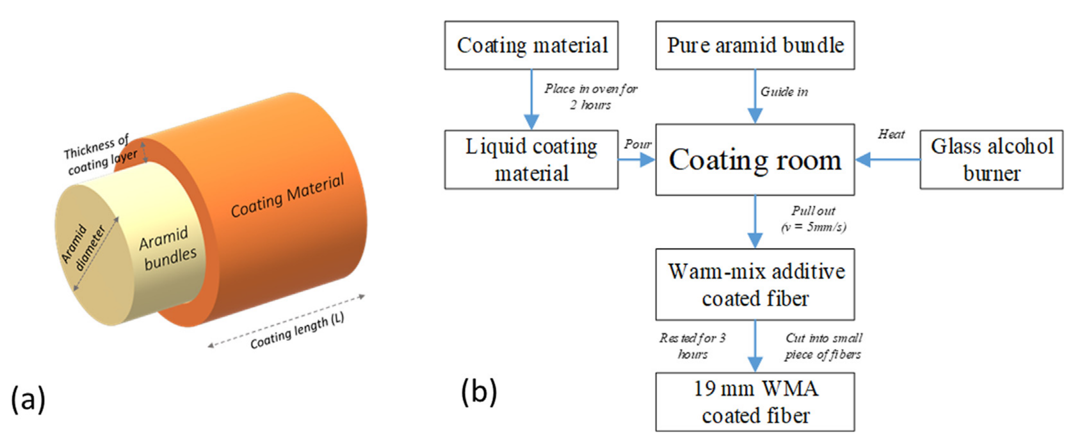

Fig. 2. Coated fiber (a), laboratory coating process (b).

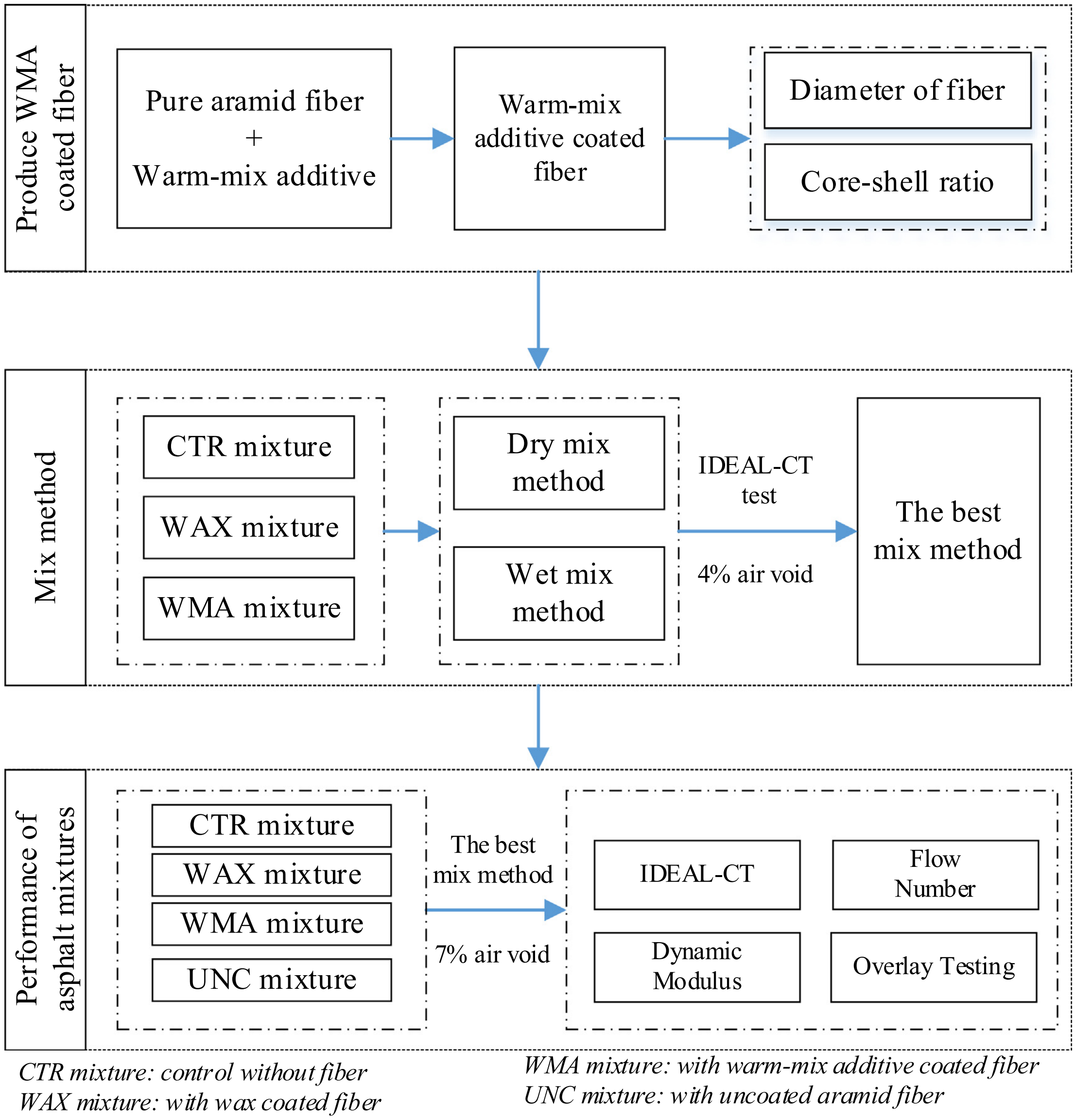

Fig. 3. Research flow chart.

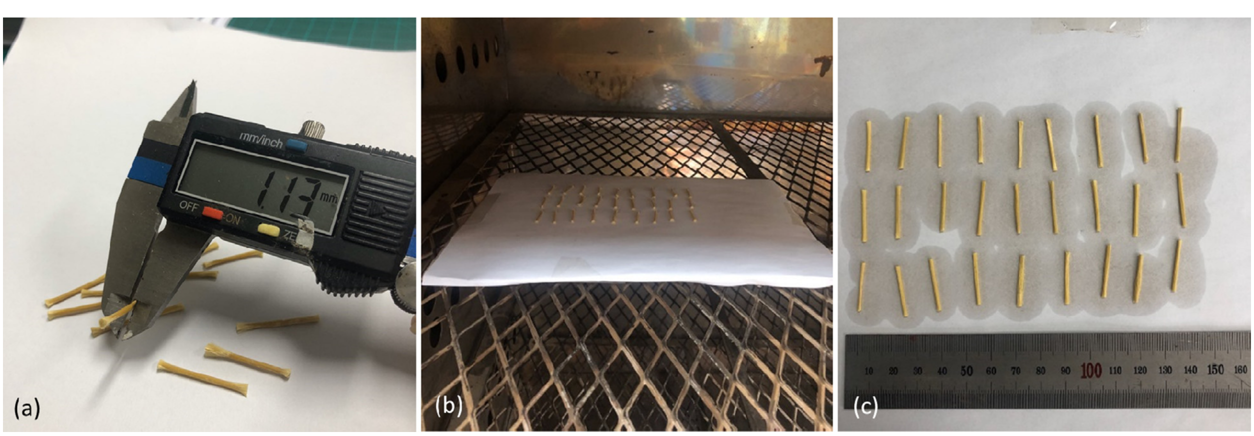

Fig. 4. Diameter of WMA fiber (a), fiber before heating (b), and fiber after heating (c).

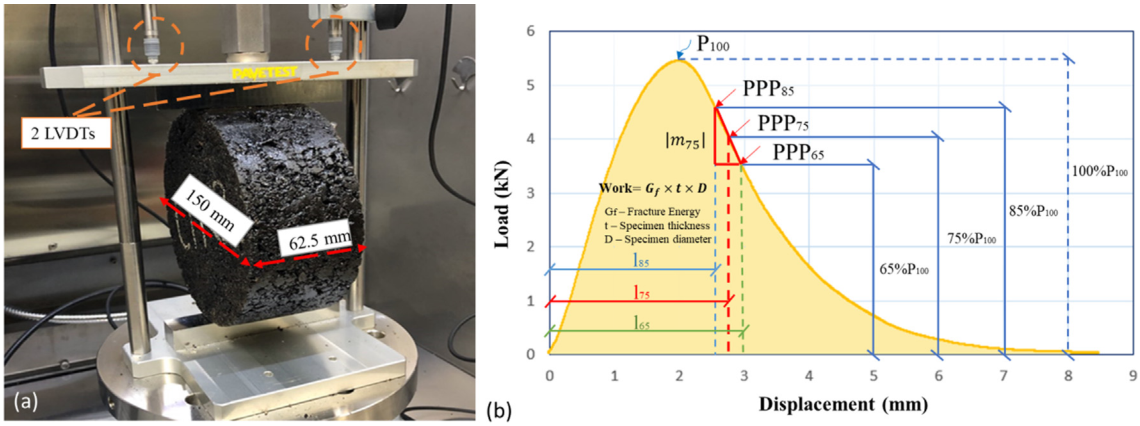

Fig. 5. IDEAL-CT test setup (a), load-displacement of test sample (b).

where,

ITS (MPa), indirect tensile strength,
P(N), peak load,
D(mm), diameter of sample,
t (mm). thickness of sample.

2.4.4. Dynamic modulus

The DTS-30 machine was employed to conduct the dynamic modulus test. The cylindrical samples were prepared with 100 mm in diameter, 150 mm in height, and air void of 7 ± 1% (Fig. 5b). Four temperatures (e.g., −10, 4, 21, and 37 °C) were selected in test produce according with AASHTO TP T342-11 [18]. The specimen was conditioned at the test temperature for at least three hours to obtain the uniform temperature distribution throughout the specimen. The samples were subjected to six different loading frequencies (e.g., 25, 10, 5, 1, 0.5, and 0.1 Hz) for each testing temperature. During the test, sinusoidal axial compressive stress was imposed on samples [19]. The dynamic modulus ($|E^*|$) was computed by Eq. (4) [20]. Furthermore, the master curves were constructed using the principle of time–temperature superposition. The temperature of 21 °C was selected as a reference temperature. The master curves were obtained by fitting using a sigmoid function, as shown in Eq. (5) [21].

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{4}$$

where

σ_0(MPa), applied stress amplitude,
ε_0, measured strain amplitude.

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(f_r)}} \tag{5}$$

where

$\delta, \alpha, \beta, \gamma$: curve fitting parameters,
f_r, (Hz): reduced frequency.

2.4.5. Flow number

The flow number (FN) test is a type of creep test to determine the permanent deformation characteristic. The FN test was carried out at 50 °C using three replicates for each mixture. The samples had a 100 mm in diameter, 150 mm in height, and 7 ± 1% air voids (Fig. 6b). The test was conducted under the condition of unconfined pressure and 0.7 MPa compressive stress. The testing chamber was set to equilibrate at the testing temperature for at least one hour. One loading cycle consisted of 0.1 s load period and 0.9 s rest period [22]. The load was terminated at 10,000 cycles or reaching five percent of permanent strain [23]. MATLAB's curve fitting [24] was employed to obtain FN based on the Francken model (Eq. (6)). The FN is the number of cycles where the second derivative changes from negative to positive (Eq. (7)) [25].

$$\varepsilon_p = A(n^B) + C(e^{Dn} - 1) \tag{6}$$

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{B-2} + CD\varepsilon^{Dn} \tag{7}$$

where,

ε, (%): permanent strain
n: number of cycles
A, B, C, D: fitting parameters

2.4.6. Overlay testing

The overlay test has shown to properly characterize asphalt mixes based on fatigue cracking resistance potential [26]. This test is conducted to simulate the propagation of reflective cracking in the laboratory over time by the effect of repeated load. Fig. 7 illustrates the preparation of the OT specimen. A 150 mm cylindrical sample was cut to achieve 75 mm in width and 38 mm in thickness (Fig. 7d). A two-part epoxy with an adhesive tensile shear strength of 15 N/mm^2 was used to glue a sample onto the OT plate. The glued sample was cured at room temperature and pressed by 4.5 kg steel solid for 12 h (Fig. 7e) [27]. The OT test was carried out at 25 ± 0.5 °C temperature. One OT cycle consisted of 5 s loading and 5 s unloading. The maximum opening displacement was controlled at 0.62 mm under the loading rate of 0.1 Hz. The test was terminated when reaching of 85% reduction from peak load. In this test, the crack resistance potential of asphalt mixture was considered as the number of load cycles to crack failure. The higher the number of load cycles is the better of fatigue cracking resistance. Besides, crack initiation and crack rate index can be obtained from the OT machine [28]. The crack initiation is defined as the cracking phenomenon before obtaining peak load of the first cycle. The crack rate index is defined as the velocity of crack propagation. The greater crack rate index indicates faster crack propagation.

3. Results and discussion

3.1. Properties of WMA coated fiber

The diameter distribution of WMA coated fiber is shown in Fig. 8a. The majority of fiber diameters were distributed in a range

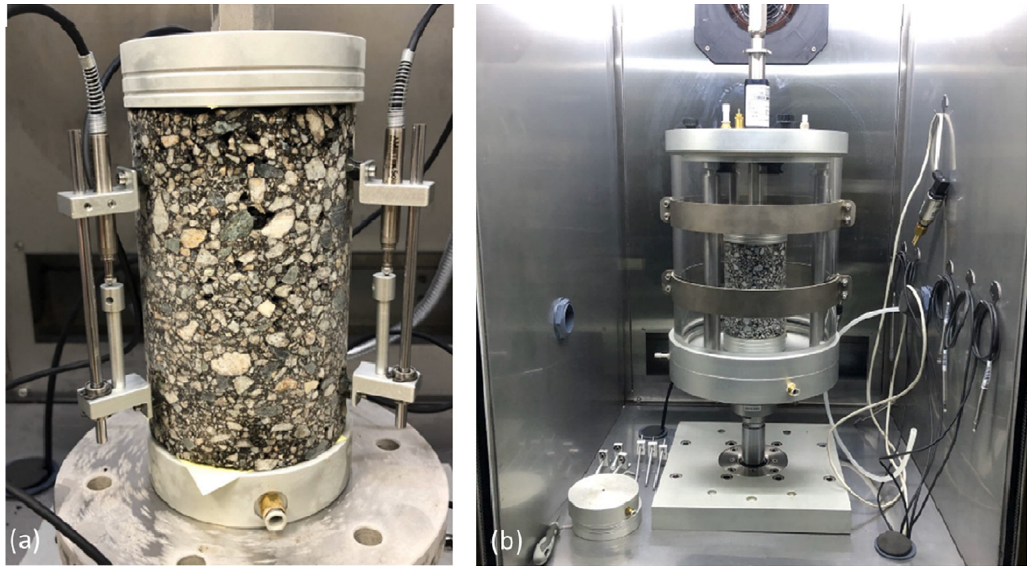

Fig. 6. Dynamic modulus test (a) and unconfined flow number test (b).

Fig. 7. OT sample preparation.

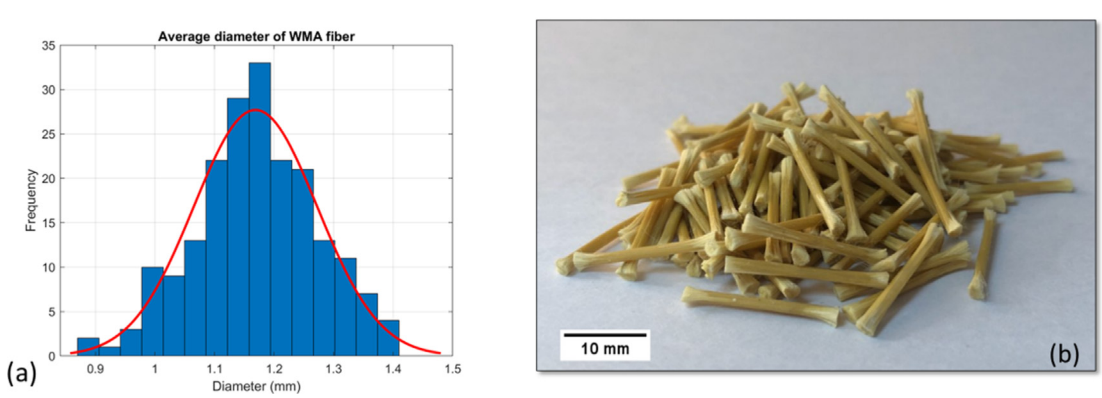

Fig. 8. Diameter of WMA coated fiber (a), morphology of WMA coated fiber (b).

of 1.1–1.2 mm. The average diameter was approximately 1.16 mm. The morphology of WMA coated fiber is shown in Fig. 8b. Moreover, and core/shell ratio was approximately 46:54 compared to the initial design of 50:50. The lower measured ratio may be attributed to the error of the experiment in laboratory conditions.

3.2. Mixing methods

Under the material placement step and high rotation speed in the dry mixing process, the microfiber flew in the air, then stuck into the mixing pot. This phenomenon may cause a loss of fiber content (Fig. 9a). In contrast, the wet mixing method could prevent this phenomenon. Based on the author's experiment, mixing fiber and aggregate at low speed caused more clustering fiber and sticking on the mixer than high speed (Fig. 9b). Therefore, the authors recommended mixing fiber and aggregate at high speed to prevent the negative fiber distribution phenomenon.

The use of coated fiber (e.g., WAX coated fiber and WMA coated fiber) helped fiber efficiently distribute in the asphalt mixture, which prohibits the clustering issue. Because the coating layer of treated fiber can reduce the connection to each other; once mixing, the coated fiber would efficiently distribute in the asphalt mixture. The coated layer was melted under the high mixing temperature and fiber released to the surrounding environment. However, it is noticed that the wax-coated fibers sometimes present a poor distribution of fibers (Fig. 9c). This may be due to production error; whiles WMA coated fiber is strictly controlled.

Table 3 shows the air void of fiber-reinforced asphalt mixtures. Mixtures containing fiber showed a slightly higher air void than the CTR mixture. This may be due to the reducing viscosity effect of binder [29]. Regarding compaction property, the mixing method showed a negligible impact on the number of gyrations. Asphalt mixture having the wet mixing method showed a slightly higher CT_{Index} than that of the dry mixing method. However, statistical results showed no significant difference between the wet and the dry mixing methods (Table 4). Meanwhiles, the effect of fiber types (e.g., WAX, WMA, UNC) was a significant difference. It can be concluded that the mixing methods had a slight impact on the properties of the asphalt mixture (e.g., air voids, compaction energy). Therefore, the wet mixing technique was used to reduce negative effects.

Table 3
Properties of asphalt mixture based on mix method.

Mixtures	Avg. G_{mb}	Avg. G_{mm}	Air voids (%)	No. gyrations	CT_{Index}
CTR (No Fiber)	2.371	2.469	3.97	161	84
WAX-dry	2.373	2.478	4.23	205	122
WAX-wet	2.373	2.475	4.12	197	138
WMA-dry	2.372	2.479	4.33	206	165
WMA-wet	2.369	2.471	4.12	192	172

Note: WAX-dry: wax coated fiber with dry mix method, WMA-wet: warm-mix additive coated fiber with wet mix method.

Table 4
Multiple comparisons by T-K procedure (studentized q = 0.05).

Comparisons	T-K interval		Conclusions
	Lower value	Higher value	
CTR to WMA-dry	−96.948	−43.199	Significantly different
CTR to WMA-wet	−110.024	−56.276	Significantly different
CTR to WAX - dry	−54.318	−0.569	Significantly different
CTR to WAX - wet	−70.008	−16.259	Significantly different
WMA-dry to WMA-wet	−39.951	13.798	Not Significant
WMA-dry to WAX-dry	15.756	69.504	Significantly different
WMA-dry to WAX-wet	0.066	53.814	Significantly different
WMA-wet to WAX-dry	28.832	82.581	Significantly different
WMA-wet to WAX-wet	13.142	66.891	Significantly different
WAX-dry to WAX-wet	−42.564	11.184	Not Significant

3.3. IDEAL-CT

Fig. 10 shows that mixtures containing fiber acquired a higher in both CT_{Index} and ITS than the control mixture. The WMA mixture gained the highest CT_{Index} and ITS, which were 149.69 and 1.62 MPa, respectively. Meanwhile, the CTR mixture presented the lowest value in both CT_{Index} and ITS. The fiber contribution was evident in the peak strength, which indicated by indirect tensile strength [30]. Referred to Eq. (2), the CT_{Index} is the reverse proportion with 75% post-peak slope ($|m_{75}|$), revealing the importance of slope formation. The lower CT_{Index} value indicated a higher $|m_{75}|$value. The fiber-reinforced mixtures obtained a lower slope value than the CTR mixture. This is because the fiber can hold samples together under crack propagation. As shown in Fig. 10b, fiber-reinforced mixtures gained a better ductile behavior than the CTR mixture. This property of fiber mixture strongly reduced the 75% PPP slope value, establishing a greater CT_{Index}.

Moreover, the WMA coated fiber presented an approximate 20% greater than wax-coated fiber in terms of CT_{Index}. This may be due to the warm-mix additive that can improve the performance of the asphalt mixture. Meanwhile, the main role of paraffin wax only covered fiber. The T-K analysis results showed no significant difference between the WAX and the UNC mixture (Table 5). This again confirmed the negligible impact of paraffin wax on the enhancement of CT_{Index}.

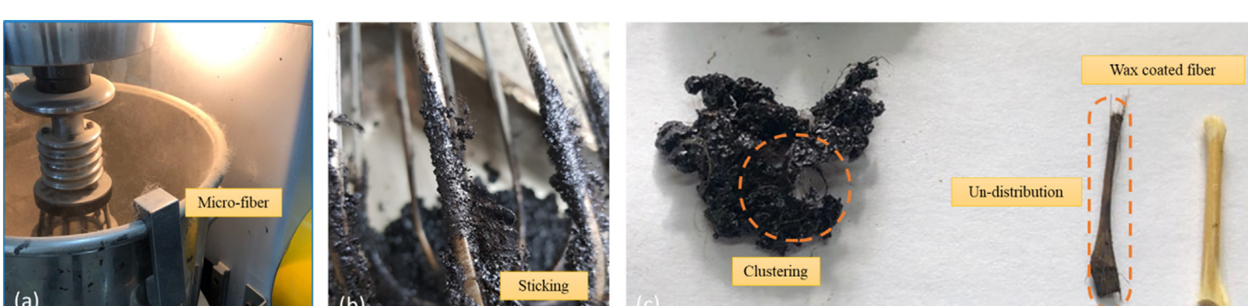

Fig. 9. Fibers stick on mixing pot (a), fibers stick on mixer (b), fiber clustering and un-distribution (c).

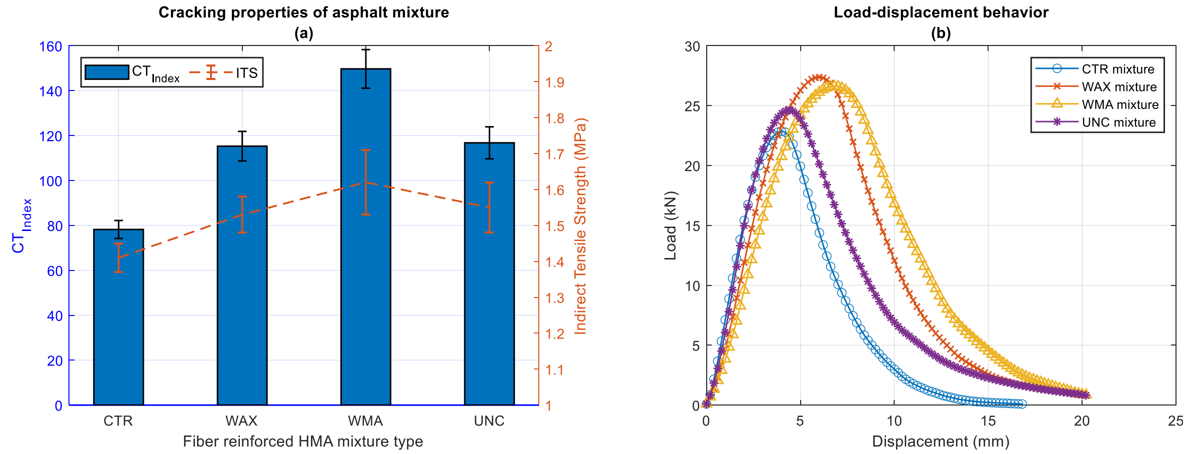

Fig. 10. IDEAL-CT results (a), load–displacement behavior (b).

Table 5
IDEAL-CT multiple comparisons by T-K procedure (studentized q = 0.05).

Comparisons	T-K interval		Conclusions
	Lower value	Higher value	
CTR to WAX	−54.991	−19.198	Significantly different
CTR to WMA	−89.405	−71.509	Significantly different
CTR to UNC	−56.476	−20.683	Significantly different
WAX to WMA	−52.311	−16.518	Significantly different
WAX to UNC	−19.381	16.411	Not Significant
WMA to UNC	15.033	50.826	Significantly different

3.4. Dynamic modulus

Fig. 11a illustrates dynamic modulus master curves of asphalt mixture at 21 °C. Overall, fiber-reinforced mixtures obtained a higher dynamic modulus than that of the CTR mixture. The aggregates and fiber structure mainly dominated the elastic behavior of the asphalt mixture. Hence, the addition of fiber improved the structure of the asphalt mixture [31]. The increment in dynamic modulus was evident at high temperatures or low frequencies. Additionally, fiber-reinforced mixtures and CTR mixture presented a relative equivalent value at the lower temperature or extremely high frequencies. The softening effect at high temperatures may lead to this result. Also, Fig. 11b shows a direct comparison of dynamic modulus at the frequency of 10 Hz. It is observed that the modulus of fiber-reinforced mixtures was higher than the CTR mixture at all temperatures. The WMA mixture presented the highest values than others, especially at the higher temperature (e.g., 21 °C, 37 °C). It can be concluded that the addition of WMA coated fiber produced some stiffening effect at high temperatures.

3.5. Flow number

Fig. 12a shows a permanent strain versus the number of load cycles. Overall, adding fiber improved resistance to permanent deformation. The WMA mixture's load number was double than that of the CTR mixture. The flow number is defined as the point in the permanent strain curve, where the rate accumulation of permanent strain reaches a minimum value and then increases rapidly [10]. Among the three types of fiber, the WMA mixture presented the highest flow number, reached 426 cycles. Meanwhile, the CTR mixture only withstands in 294 cycles. Statistical analysis showed no significant difference between the WAX and the UNC mixture (Table 6). Validating the mixtures in this experiment, the flow number of mixtures should have a minimum of 300 cycles, according to AASHTO – T 378-17 [23]. The results from Table 7 show that the flow number of fiber-reinforced mixtures were higher than the

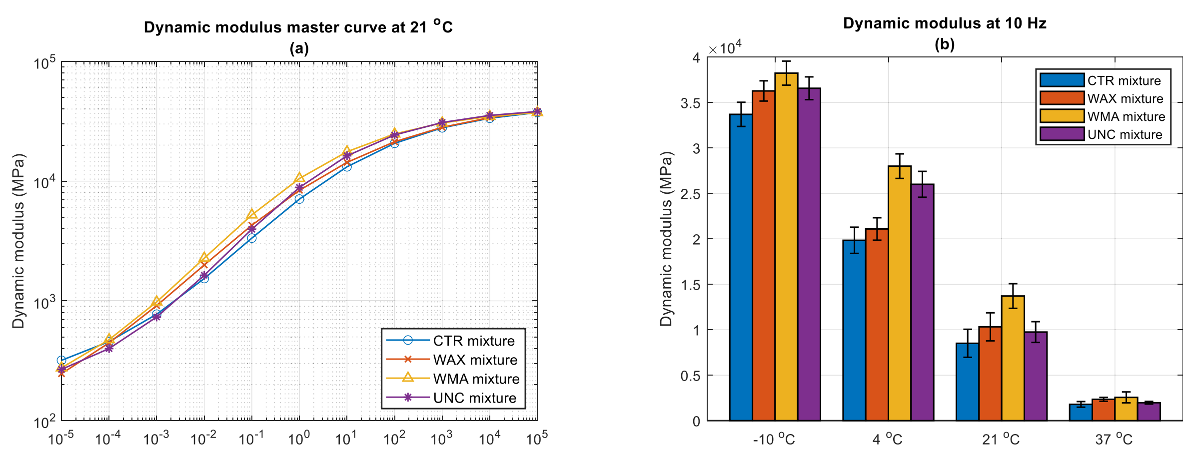

Fig. 11. Dynamic master curves (a) and measured dynamic values at 10 Hz (b).

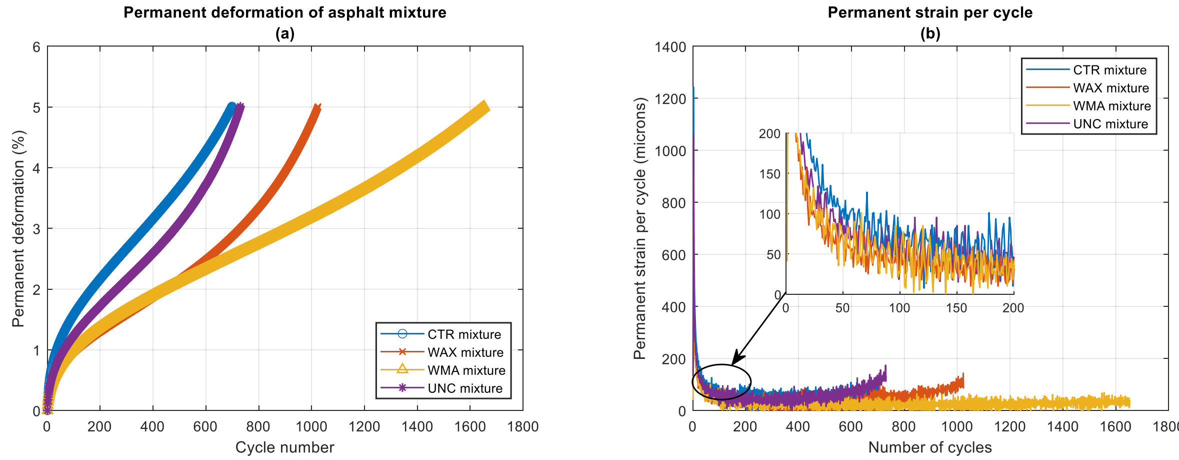

Fig. 12. Accumulated permanent strain (a), strain rate per cycle (b).

Table 6
Flow number multiple comparisons by T-K procedure (studentized q = 0.05).

Comparisons	T-K interval		Conclusions
	Lower value	Higher value	
CTR to WAX	−101.121	−21.546	Significantly different
CTR to WMA	−180.454	−140.667	Significantly different
CTR to UNC	−82.454	−2.879	Significantly different
WAX to WMA	−119.121	−39.546	Significantly different
WAX to UNC	−21.121	58.454	Not Significant
WMA to UNC	58.212	137.788	Significantly different

minimum of the requirement. Besides, the strain rate per cycle is shown in Fig. 12b. The lower strain rate per cycle leads to a greater flow number. The CTR and the UNC mixture showed a similar strain rate per cycle, while the WMA mixture presented the lowest strain rate. Finally, the reinforcement of fiber in the asphalt mixture could lead to better asphalt pavement resistance to rutting.

3.6. Overlay testing

Table 8 exhibits the OT test results from the cyclic fatigue loading. As discussed in the IDEAL-CT section, the WMA mixture had a greater CT_{Index} and ITS, which could influence fatigue cracking resistance. Compared to other mixtures, the WMA mixtures having 429 OT cycles dominates the remained mixtures. The CTR mixture showed the lowest value of OT cycles, which gained 219 cycles to reach an 85% load drop. Besides, the WAX and the UNC mixture presented an insignificant difference (Table 9). This may be due to coating material (e.g., paraffin wax) that did not improve the asphalt mixture's performance. Also, the COV of 30% was used as a threshold to obtain an accurate representation of the material property [26]. The results from Table 8 show that the COV of all three samples was lower than the criteria.

The critical fracture energy again confirmed the improvement in the tensile strength of the reinforced-fiber mixture. The critical fracture energy of fiber-reinforced mixtures was approximately

Table 9
OT number multiple comparisons by T-K procedure (studentized q = 0.05).

Comparisons	T-K interval		Conclusions
	Lower value	Higher value	
CTR to WAX	−121.886	−28.781	Significantly different
CTR to WMA	−251.219	−204.667	Significantly different
CTR to UNC	−100.552	−7.448	Significantly different
WAX to WMA	−175.886	−82.781	Significantly different
WAX to UNC	−25.219	67.886	Not Significant
WMA to UNC	104.114	197.219	Significantly different

Table 7
Flow number of fiber-reinforced asphalt mixture.

Mixtures	Flow number		Cycles to 5% permanent deformation	Francken model parameters			
	Average	Std. Dev.		A	B	C	D
CTR	294	10.3	699	0.1442	0.4600	0.0456	0.0052
WAX	347	15.6	1024	0.1340	0.4163	0.0863	0.0033
WMA	426	13.2	1653	0.1071	0.4472	0.0345	0.0037
UNC	329	17.3	731	0.2097	0.4298	0.1093	0.0038

Table 8
Summary results of OT test.

Mixture	OT cycle number			Critical fracture energy, G_c			Crack rate index, C_i		
	Average	Std. Dev.	COV	Average	Std. Dev.	COV	Average	Std. Dev.	COV
CTR	219	12.5	15.9	253.5	9.8	13.2%	0.309	0.014	2.6%
WAX	291	15.3	10.4	338.3	12.1	11.9%	0.258	0.008	3.5%
WMA	429	15.4	8.5	355.5	13.9	9.7%	0.234	0.010	2.9%
UNC	279	18.2	13.0	331.3	12.5	10.4%	0.252	0.012	2.6%

30% greater than that of the control mixture (Table 8). The fiber distributions in asphalt mixture can improve the connection between aggregates, which leads to higher fracture energy to obtain the peak load. Also, containing fiber has shown improvement in crack resistance. The rack rate index (C_i) is defined as the crack propagation of asphalt mixture. The higher C_i, the faster crack propagation is. The WMA mixture acquired the lowest C_i value (e.g., 0.252), indicating the best cracking resistance. Meanwhile, the CTR mixture (C_i = 0.309) presented a faster crack propagation.

4. Conclusions

The laboratory test results in this study showed that the containing treated fiber improves the asphalt mixture's performance. The following key findings and conclusions can be drawn:

- The surface treatment may help coated fibers reduce connection to each other, which improves the homogenous distribution of fiber throughout the asphalt mixture.
- The WMA coated fiber in this study had a core–shell ratio of 46:54 compared to the designed 50:50 ratio and a diameter of 1.16 mm. The incorporation of WMA and fiber helps the WMA fiber outperform other fibers in terms of mechanical properties.
- The wet mixing process at high mixing speed was used to mitigate fiber loss and adverse effects (e.g., fiber clustering, sticking issue on the mixer).
- The insignificant difference between the WAX mixture and the UNC mixture indicated a notable impact of coating material on improving asphalt performance.
- The addition of fibers in the asphalt mixture improved both CT_{Index} and indirect tensile strength. Fiber-reinforced samples generated better ductile behavior than that of without fiber.
- Although the reinforced-fiber effect could be negligible at low temperatures or high frequencies, fiber addition produced some stiffening effect at high temperatures (e.g., 37 °C).
- The use of fiber in asphalt mixtures contributes to stronger asphalt pavement resistance to rutting. HMA having proper fiber content gained lower accumulated permanent settlement and higher flow number, indicating a better mix of stability against shear deformation compared to the control mixture.

In general, asphalt mixture containing treated fiber, especially warm-mix additive coated fiber (WMA coated fiber), showed promising results to enhance its mechanical properties. It should be noted that more analysis of the microstructure of WMA coated fiber, different core/shell ratios, and fiber's distribution in asphalt mixture should be carried out in further research.

CRediT authorship contribution statement

Tam Minh Phan: Methodology, Validation, Data curation, Writing - review & editing, Writing - original draft. **Son Ngoc Nguyen:** Validation, Data curation, Writing - review & editing, Writing - original draft. **Chang-Bae Seo:** Validation. **Dae-Wook Park:** Methodology, Validation, Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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