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Case study

Reuse of carbon fiber composite materials in porous hot mix asphalt to enhance strength and durability

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ABSTRACT

Porous hot mix asphalt (PHMA) allows runoff to infiltrate through the pavement. Cured carbon fiber composite materials (CCFCM)s from aerospace production lines were ground into three size groups (Fine, Medium, and Large) and reused as reinforcement agents for PHMA in comparison to commercial synthetic fiber. The Fine CCFCMs premixed with liquid asphalt binder performed the best to reinforce PHMA in terms of indirect tensile strength and cracking resistance at both 25 °C and −10 °C. The addition of fine CCFCMs and synthetic fibers reduced the porosity by 17% and infiltration rate by up to 20%, while both fibers showed to prevent draindown of asphalt binder at an elevated temperature. The PHMA reinforced with the Fine CCFCMs performed the best in rutting resistance.

1. Introduction

One of the main challenges associated with traditional impermeable pavement structures is runoff control. A poorly designed stormwater system can result in water pooling in unwanted areas, flash flooding, and hydroplaning [1]. The extent of negative effect from this phenomenon can range from minor inconvenience on low-traffic volume roads to fatal accidents on highways or interstates [2]. Use of porous hot mix asphalt (PHMA) can be an effective solution for stormwater management [3].

To allow runoff to infiltrate through the pavement and into the subsurface or the underlying drainage system, PHMA is designed with high air void in the mixture. Despite the advantage of discharging runoff, high air void in the mixture results in reduced strength and durability when compared to a dense-graded hot mix asphalt (HMA). Therefore, porous asphalt is commonly used for parking lots, low-volume roads and trails [4]. Adjusting the mix design of PHMA, such as controlling the angularity of the aggregate, use of different types and contents of the binder, or change in aggregate gradation, may improve the mechanical properties. However, the sole method of an improved mix design will be limited in improving the mechanical properties, especially during winter conditions when the mixture becomes brittle and is prone to a higher rate of raveling [5]. The use of additives, such as cellulose or synthetic fibers in the mixture, is another approach towards improving the strength and durability of PHMA mixture [6]. Using fibers will manipulate the viscoelasticity of the asphalt mixture and can improve the dynamic modulus, moisture susceptibility, creep compliance, rutting resistance, and freeze-thaw resistance [7]. Furthermore, the indirect tensile strength of PHMA can improve more than 60% at 25 °C with the inclusion of fibers [8].

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The innovation of this study is to reinforce PHMA by using fiber-shaped reinforcement processed from the excess cured carbon fiber composite materials (CCFCMs) from the aerospace industry. This is a composite material, which contains carbon fibers embedded in an epoxy matrix [9] and is readily available from the industrial waste stream and byproducts from many other industries such as renewable energy and automotive [10]. The processed CCFCMs have been tested to show the enhancement of the physical and mechanical properties for pervious concrete [9,11]. In this study, the effect of the addition of CCFCMs in comparison to commercial synthetic fibers as reinforcing elements in PHMA was evaluated. The origin of CCFCM is from plane manufacturing lines. CCFCM can be recycled using thermal or chemical recycling processing, but these methods use a high amount of energy and the recycled product will be high priced yet low-quality material [10]. In this study, a mechanical downsizing method followed by screening to produce a value-add reinforcement agent for PHMA mixtures. The cost of ground CCFCM was estimated to be substantially lower than recycled CCFCM from thermo-chemical recycling methods ($5/kg compared to $13-19/kg) [12].

The main objective of this study was to examine the effect of different size groups of recycled CCFCM fibers for their ability to enhance the various mechanical properties of the PHMA mixtures while maintaining the infiltration performance. The best performing CCFCM size group was identified based on the mechanical properties obtained from the indirect tensile test conducted at 25 °C and −10 °C. Subsequently, the PHMA reinforced with the best performing CCFCM size was evaluated in terms of infiltration rate, draindown resistance, abrasion resistance, and rutting resistance, and compared with the control and synthetic fiber reinforced PHMA mixtures.

2. Materials and methods

2.1. Materials

2.1.1. Mix design of control PHMA

Information regarding the asphalt binder used in the study is shown in Table 1. Polymer modified binders are required to be used in PHMA for added strength [13]. The target air void of the PHMA was 20% which was achieved by 75 gyration effort in the compactor. The minimum required infiltration rate is 254 cm/hr (100 in/hr) [14]. The mixing and compaction temperatures ranged from 164.4 to 170.6 °C, and 152.8–157.2 °C, respectively, based on the recommendation of the asphalt binder supplier, US Oil and Refining. The temperature-viscosity chart is shown in Fig. 1, provided in the Job Mix Formula.

Fig. 2 shows the gradation of the aggregate used in the study. Approximately, 70% of the aggregate falls in the 4.75–12.5 mm size range with a low amount of fines (2.3%) passing 0.075 mm sieve size to generate an open-graded mix for high infiltration rates. Based on the surface area factor shown by others [15], the calculated surface area of this aggregate gradation is 2.24 m^2/kg and the binder film thickness without considering binder absorption is 26.2 microns, based on 6% asphalt content by the weight of dry aggregate. The higher binder film thickness is designed in this PHMA is to provide better performance in terms of durability and resistance to raveling and aging.

2.1.2. Cured composite carbon Fiber materials (CCFCMs)

Originated from the production lines of Boeing, CCFCMs were received as plate pieces and were processed into three sizes of fiber-shaped reinforcing elements (Fine, Medium and Large) by milling and screening through three sieve sizes: 0.841 mm, 2 mm, and 3.35 mm [11]. Note that after grinding each recycled fiber maintains its composite nature of several carbon fibers embedded in the epoxy matrix in contrast to individual carbon fibers. The mean diameters of the Fine, Medium and Large CCFCMs were 0.33 mm, 0.81 mm, and 1.67 mm, respectively. The mean length for the Fine, Medium and Large CCFCMs were 2.85 mm, 11.63 mm, and 20.20 mm, respectively. The dimensional properties of the three processed CCFCMs are shown in Table 2 and Fig. 3.

The dosage of CCFCMs used to reinforce PHMA was 0.05% of the total mixture weight, which was selected based on the common dosage of commercial fibers used in the dense HMAs [16,17] corresponding PHMA reinforced with Fine, Medium, and Large CCFCMs are referred to as F-C-PHMA, M-C-PHMA, and L-C-PHMA, respectively. Before mixing, CCFCMs were heated with the batched aggregates for 2 h at the mixing temperature and then mixed with asphalt binder at the desired dosage. In addition to the three mixtures above, pre-mixing of the Fine CCFCMs with the heated liquid state binder was used to assess the influence of the mixing sequence on the properties of the mixtures, and this mixture is labeled as pre-mixed Fine CCFCMs PHMA (PF-C-PHMA).

Table 1
Asphalt Binder Information.

Category	Value
Asphalt Binder Grade	PG 70-22ER
Asphalt Content (% Dry Aggregate)	6.0%
Mixing Temperature Range	164.4 to 170.6 °C
Compaction Temperature Range	152.8 to 157.2 °C
Anti-Strip Amount (%Wt. of Asphalt Binder)	0.50%

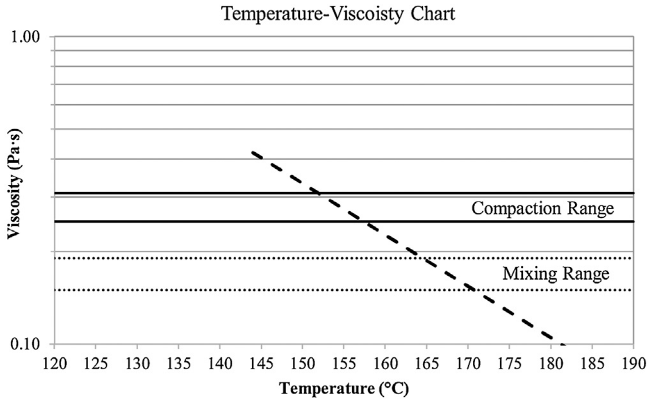

Fig. 1. Temperature – Viscosity Chart of the polymer-modified asphalt binder with a grade PG 70-22ER (Reproduced based on the Job Mix Formula).

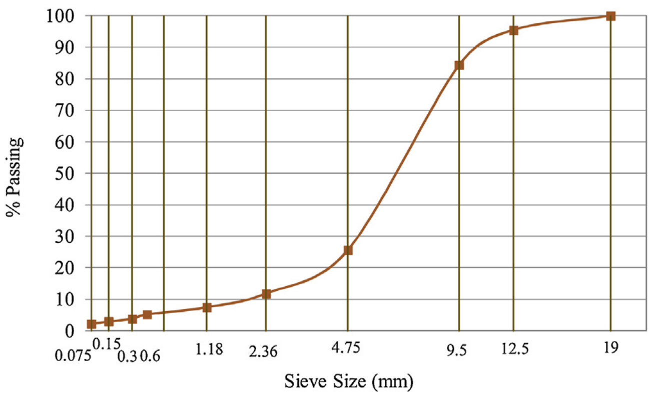

Fig. 2. Gradation of Aggregate used in PHMA.

Table 2
Dimensional Properties of CCFCM Used in the Study.

Geometric Parameter/Category		Fine	Medium	Large
Mean Diameter (*d*)		0.33 mm	0.81 mm	1.67 mm
Mean Length (*l*)		2.85 mm	11.63 mm	20.20 mm
Aspect Ratio (*l*/*d*)	Minimum	1.08	1.14	1.10
	Maximum	32.23	60.25	45.08
	Mean	8.51	14.29	12.09

2.1.3. Commercial synthetic fibers

A commercial synthetic fiber product by Forta-Fi®, which is composed of a mix of aramid and polyolefin fibers [18], was used in this study as a comparison measure. Aramid fibers are string-like materials that could latch on heated aggregates to increase tensile strength and reduce cracking. Polyolefin fibers are sheet-like materials that could melt into the heated binder and increase the stiffness of the mixture to enhance the durability [19]. The PHMA with synthetic fiber reinforcement is referred to as Syn-F-PHMA and the dosage used is the same as the CCFCM dosage in PHMA.

To maintain the proportion of aramid and polyolefin fibers at an equal rate that represents the production in the field, the fibers were separated individually and weighed 0.025% based on the total mixture for each type of fiber, yielding 0.05% of synthetic fiber dosage per total weight. The aramid fibers were dispersed using the compressed air to ensure that mixing of fiber with aggregate and binders are homogenous. To avoid clumping of the aramids during the mixing stage, they were included in the aggregate in small portions at a time. Polyolefin fibers were added after pouring the desired amount of liquid binder in the mixture, and they can melt into the binder due to the elevated temperature. This process was done inside the mixing bucket immediately before mixing of all the materials, including heated aggregates, binders, and fibers. After thoroughly mixing the materials, the clumping of aramid fibers was observed. Therefore, during the preparation of the

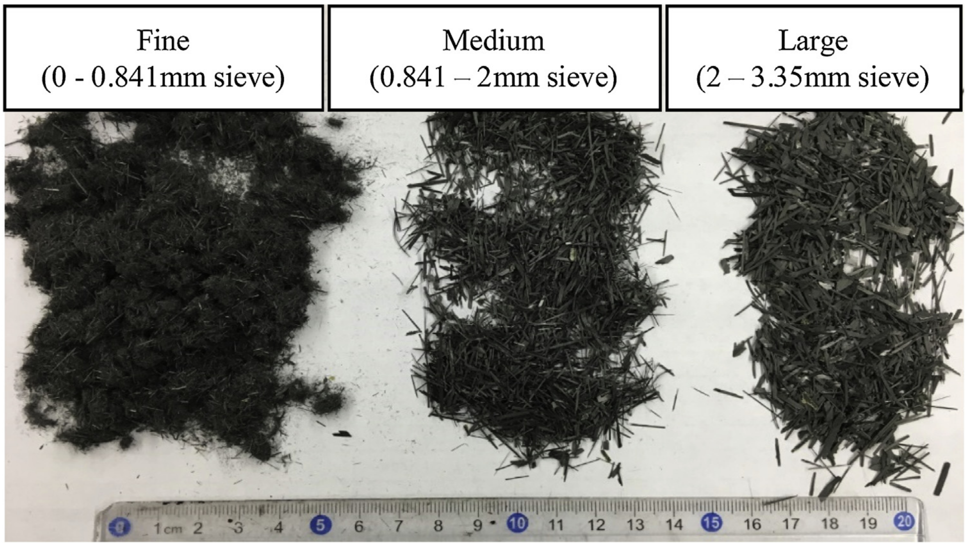

Fig. 3. Processed CCFCMs in Three Size groups: Fine, Medium, and Large.

mixture aged for 2 h to reach the compaction temperature, the fiber clumps in the loose mixture were separated once again for a homogenous and uniform mixture. The synthetic fibers by Forta-Fi® have been studied extensively in dense-graded HMA [20,21], but their benefits to PHMA has been rarely studied.

2.2. Test methods

Tests used in this study for evaluating the different properties of the PHMA mixtures are summarized in Table 3. All tests, except for the draindown effect and Hamburg Wheel Tracking Test (HWTT), were conducted on three samples. The draindown effect was conducted twice as only a small variation was observed while the resulted values were in small percentages. Four specimens were prepared for the HWTT test, as shown in Fig. 6.

2.2.1. Volumetric and infiltration analysis

The properties determined by volumetric analysis, including air void [22] and porosity [23] are highly related to the infiltration performance of the PHMA [24]. Since the main function of PHMA is to provide a drainage system for runoff, infiltration rate testing is conducted using a modified method for the laboratory compacted specimen following ASTM C1701, which is originally designed for the field infiltration testing [25]. The specimen was confined around the sides using shrink-wrap, as shown in Fig. 4, to keep the water flow in the vertical direction. The time was measured between the first contact of water with the top surface of the specimen and when the 1-liter water completely drained from the top surface to maintain a constant flow rate, the water level during the testing was maintained between 10 and 15 mm. The targeted minimum infiltration rate is 254 cm/hr (100 in/hr).

One of the concerns during the construction of PHMA is the draindown of the asphalt to the bottom of PHMA, resulting in segregation of the asphalt content in the mixture. Draindown may occur during the silo storage, transportation in the truck, and the waiting period between placement and compaction. Loose asphalt mixture was placed in a steel mesh basket in the oven at 140 °C and 130 °C, as mentioned in the mix design provided by the local asphalt provider. Materials were placed in the oven for an hour while some of the materials dropped through the mesh. Percentage of dropped materials with respect to the initial mass shall be less than 0.3% [26]. Though the testing was completed at both temperatures, the draindown values at the higher temperature, 140 °C, were already within the specification. A lower draindown value was observed for the testing at 130 °C. Thus, only the result conducted at 140 °C is reported.

Table 3
Conducted Tests and Obtained Properties.

Conducted Test	Obtained Properties
Volumetric Analysis (ASTM D3203, ASTM C1754)	Air Void and Porosity
Infiltration Rate (ASTM C1701)	Infiltration Performance
Draindown Effect (ASTM D6390)	Draindown Effect
Indirect Tensile (IDT) Test at 25 °C (AASHTO T283) and −10 °C (AASHTO T322)	IDT Strength, Cracking Resistance, and Ductility
Cantabro Abrasion (ASTM C1747)	Durability
Hamburg Wheel Tracking Test (AASHTO T324)	Rutting Resistance

Fig. 4. Infiltration Rate Testing in Laboratory.

2.2.2. Mechanical properties

Mixture strength and ductility, cracking resistance, permanent deformation, and durability of PHMA were evaluated by indirect tensile (IDT) test at 25 °C and −10 °C following AASHTO T283-14 [27] and AASHTO T322-07 [28], Hamburg Wheel Tracking Test using AASHTO T324-14 [29], Cantabro abrasion using ASTM C174 [30].

A constant loading rate of 50.8 mm/min or 12.5 mm/min was applied during IDT testing at 25 °C or −10 °C, respectively, and the set up for the test is shown in Fig. 5. For both tests, pre-loading of 20 N was applied prior to conducting the test to avoid damage from a shock load. The test was conducted until the post-peak load drops below 200 N, or a complete failure was observed. The load-displacement curve, as shown in Fig. 5, was constructed to evaluate the mechanical properties of the mixtures. Strength, cracking resistance, and ductility was obtained through the peak load, fracture work density (FWD), and vertical failure deformation (VFD), respectively. Fracture work is the required energy to cause a complete failure of the specimen and is divided by the volume of the specimen to obtain FWD (unit: kPa). The VFD (unit: mm) is the displacement at peak load and represents the ductility of the specimen [31].

Cantabro test was conducted inside a drum, revolving at 33 rotations per minute. Mass losses at 100, 200, and 300 revolutions were recorded. The maximum allowable mass loss after 300 revolutions was 20% of the initial mass [32]. A smaller mass loss indicates a higher abrasion resistance and is interpreted as an indicator of the durability.

The Hamburg wheel track test (HWTT) was conducted on two 62.5 mm thick specimens while submerged under water at 50 °C. Since the PHMA has higher designed air voids (>>7%), the samples were prepared by adjusting the weights to achieve 62.5 mm in height under 75 gyrations. For the PHMA, it was difficult to observe the stripping inflection point, since water can drain off from the mixtures quickly and the severity of permanent deformation happened gradually in this test. Therefore, the rut depth evolution with the number of cycles are reported. The set-up for HWTT before and after testing are shown in Fig. 6 (a) and (b).

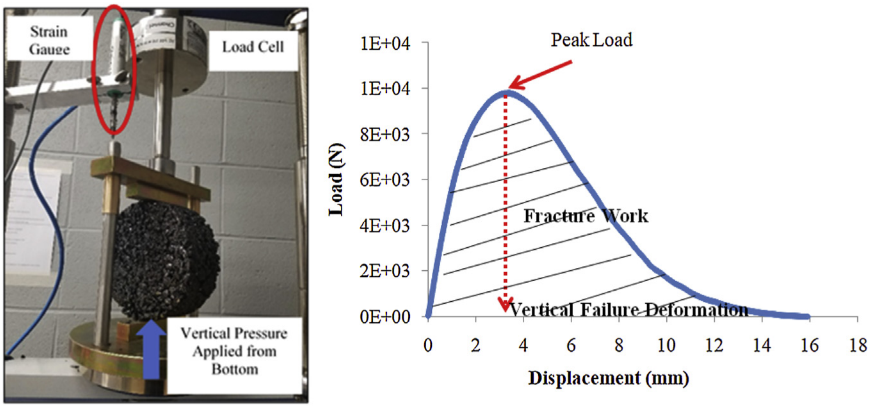

Fig. 5. IDT Test Set-up and Typical Load-Displacement Curve in IDT Test.

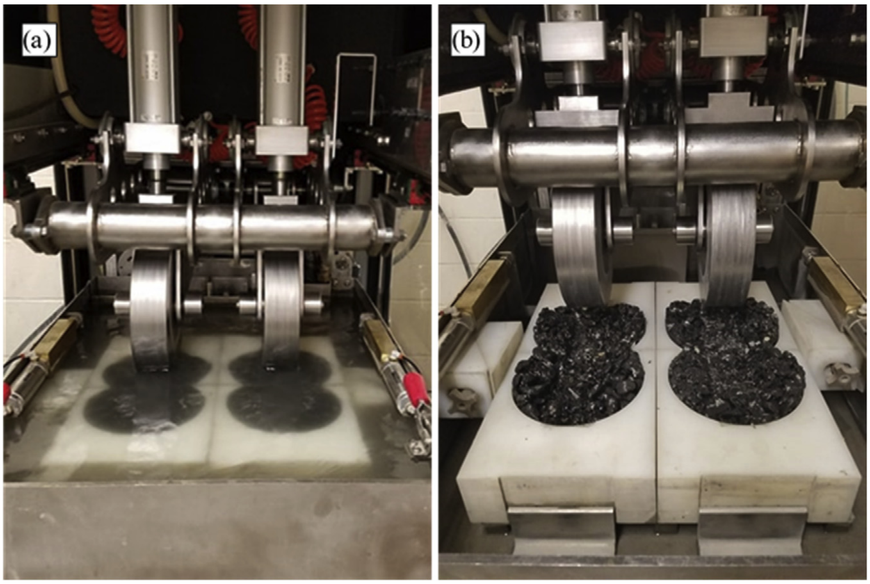

Fig. 6. HWTT Setup: (a) Samples Submerged Under Water Before Testing and (b) Samples after Reaching 12.5 mm Failure Rut Depth.

3. Test results and discussions

3.1. IDT test results at 25 °C

The results of IDT testing, including IDT strength, fracture work density (FWD), and vertical failure deformation (VFD), are shown in Fig. 7 for all six mixtures. Paired *t*-test was conducted using a 95% confidence interval ($\alpha = 0.05$) to distinguish any significant improvement and the p-values are shown in Table 4. The PF-C-PHMA showed a statistically significant improvement in IDT strength and fracture work density (33% higher than the Control PHMA), but a lower ductility was observed for PF-C-PHMA. The Medium and Large CCFCMs did not improve the IDT strength significantly, but all PHMAs reinforced by fibers have higher cracking resistance with high average values of fracture work density. The synthetic fibers improved the ductility of PHMA and resulted in a similar fracture work density with the premixed fine CCFCMs.

3.2. IDT test results at −10 °C

The results of IDT testing at −10 °C are shown in Fig. 8 and the p-value for statistical comparison for the six mixtures are shown in Table 5. Strength results showed a similar trend to the results at 25 °C, where PF-C-PHMA showed a statistically significant improvement in IDT strength, followed by the F-C-PHMA with a 26% increase in IDT strength. Different trends were observed in FWD in comparison to the results at 25 °C testing, where M-C-PHMA showed the most improvement in FWD (59% increase), followed by the Syn-F-PHMA (41% increase). Furthermore, M-C-PHMA also showed the most improvement in VFD (13%), but a significant increase was observed only for Syn-F-PHMA with 10% improvement.

From the results of the IDT tests, the Fine CCFCMs increased the strength of PHMA in both forms of F-C-PHMA and PF-C-PHMA, but compromised ductility as the peak load was achieved at a lower deformation. This indicated that the Fine CCFCMs, that contain carbon-based powder and short length fiber, could stiffen the mixture.

On the other hand, the M-C-PHMA showed higher, yet non-significant results for FWD and VFD at −10 °C, which indicated that string-shaped Medium CCFCMs could increase the ductility and crack resistance of PHMA. This is similar to the function of string-shaped Aramid fibers in commercial synthetic fiber products [19]. However, the addition of Large CCFCMs did not show significant improvements in IDT strength at either testing temperatures, which implies that the aspect ratio of the string-shaped reinforcement element is critical to the performance of PHMA. Overall, the results of the Medium and Large sizes of CCFCMs did not significantly affect the mechanical properties of the mixtures. Therefore, further testing was performed for Control PHMA, PF-C-PHMA, and Syn-F-PHMA by volumetric analysis, infiltration performance, draindown, and abrasion and rutting resistance.

3.3. Volumetric analysis

The air void and porosity testing results of the selected mixtures are shown in Fig. 9 (a) and (b), respectively. While the target values for air void is between 16% and 22%, the results exceeded the upper boundary slightly. The control PHMA showed the highest air void of 24.6% while the Syn-F-PHMA showed the lowest (22.8%), but the differences were marginal.

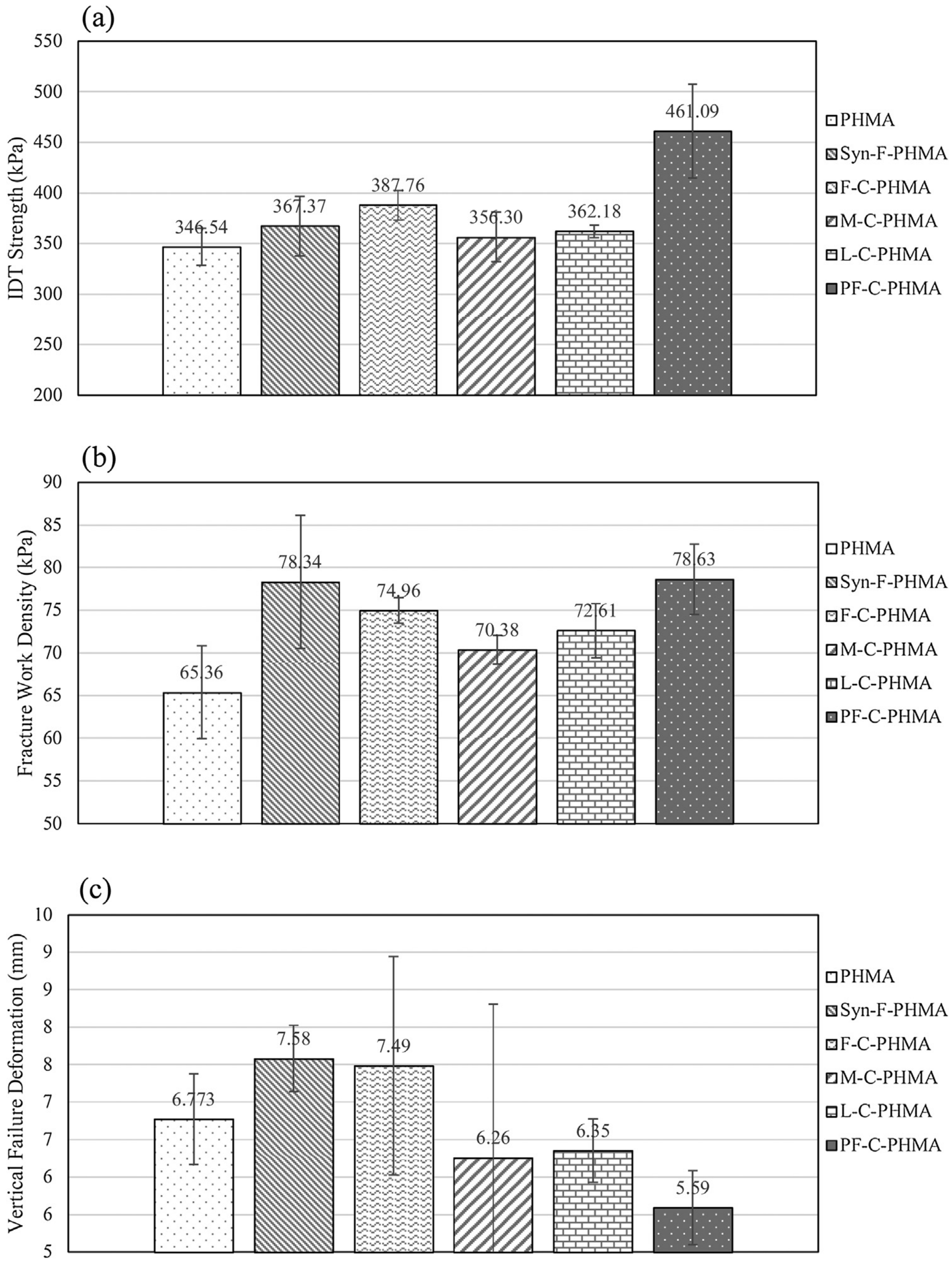

Fig. 7. IDT Test Results at 25°C; (a) Strength, (b) Cracking Resistance, (c) Ductility.

Table 4
P-Values from Statistical Analysis of PHMA Mixtures at 25°C.

Mixture Test Parameter	Syn-F-PHMA	F-C-PHMA	M-C-PHMA	L-C-PHMA	PF-C-PHMA
IDT Strength	0.091	0.095	0.361	0.191	0.010
FWD	0.077	0.032	0.072	0.047	0.006
VFD	0.156	0.359	0.378	0.137	0.097

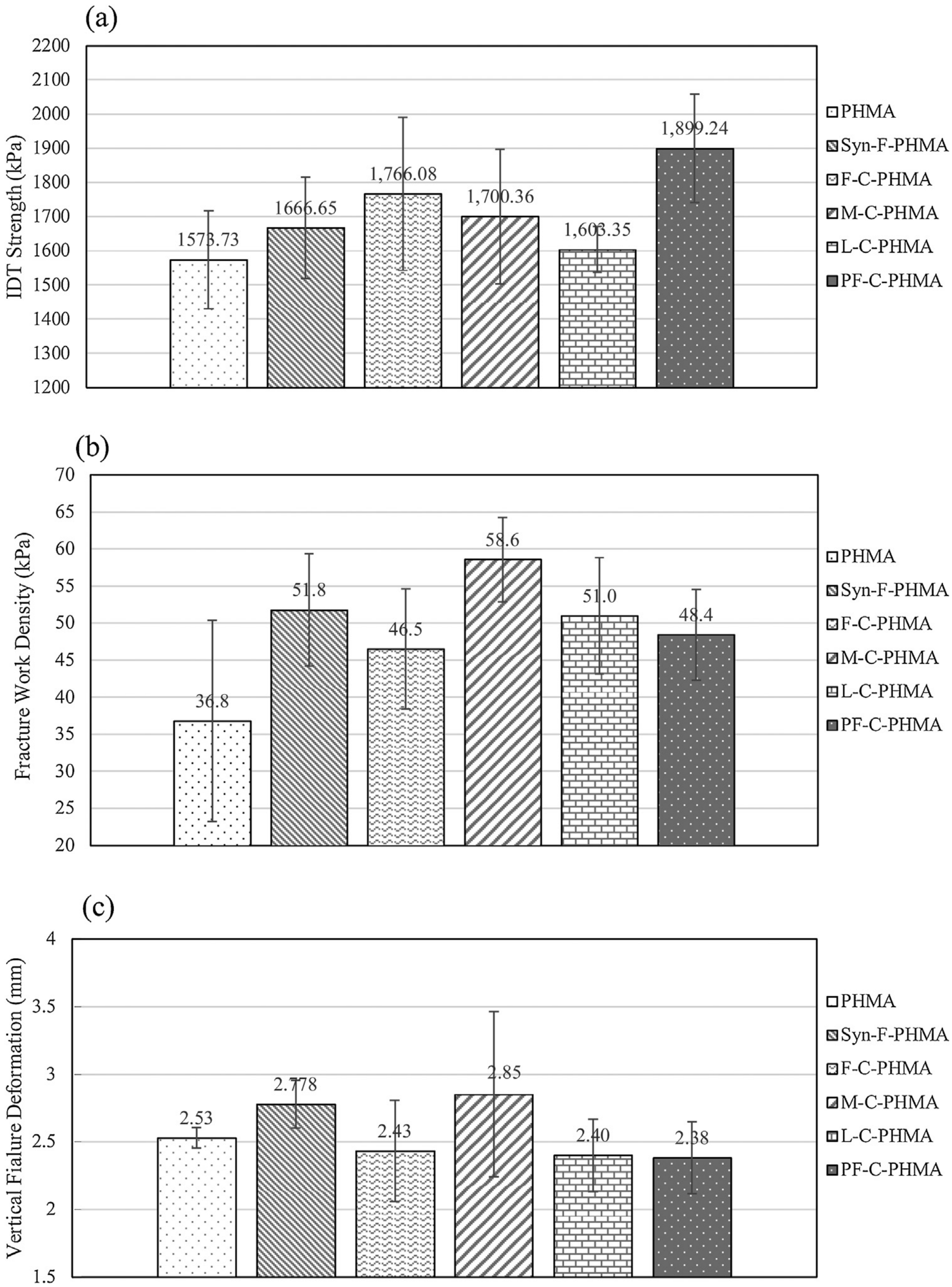

Fig. 8. IDT Test Results at -10°C: (a) Strength, (b) Cracking Resistance, (c) Ductility.

Table 5
P-values from the Statistical Analysis of PHMA Mixtures at −10°C.

Mixture Test Parameter	Syn-F-PHMA	F-C-PHMA	M-C-PHMA	L-C-PHMA	PF-C-PHMA
IDT Strength	0.304	0.230	0.286	0.415	0.014
FWD	0.172	0.046	0.086	0.091	0.161
VFD	0.028	0.337	0.234	0.289	0.236

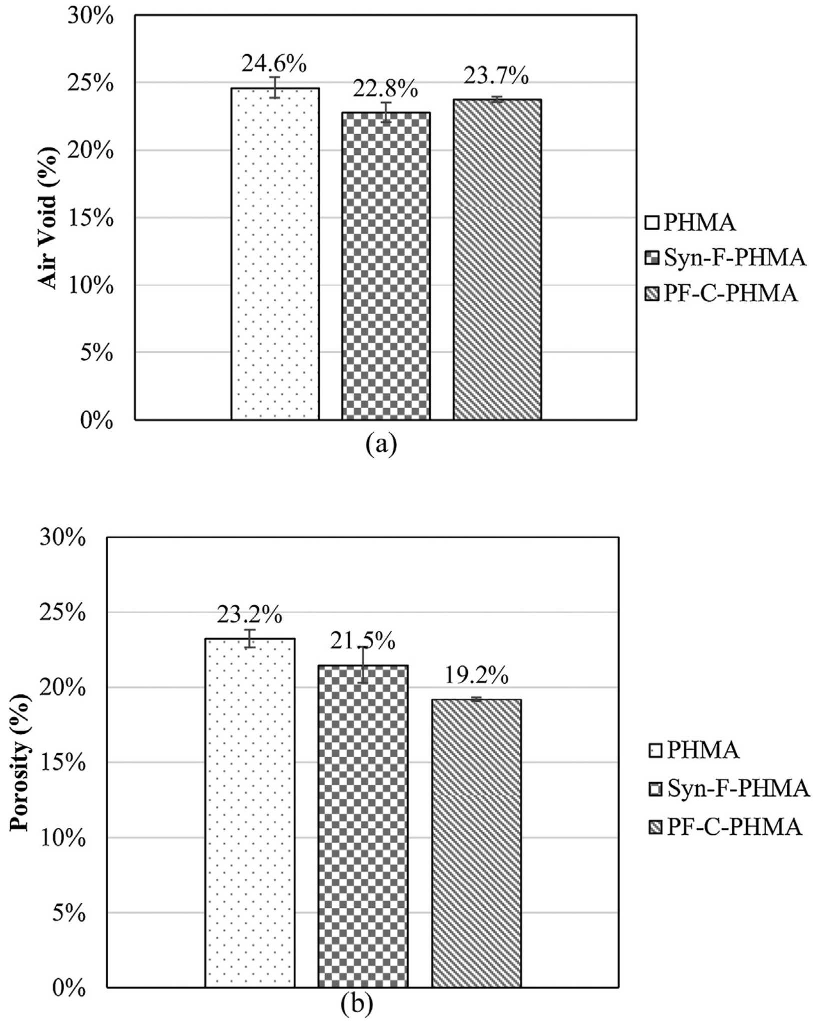

Fig. 9. (a) Air Void and (b) Porosity Results.

Although the total air voids in the specimen were similar, the interconnected voids, also known as the effective voids or porosity, showed a different trend. Fig. 9(b) shows that the Control PHMA had the highest porosity (23.2%), while the Syn-F-PHMA and PF-C-PHMA had a slightly lower porosity of 21.5% and 19.2%, respectively. The addition of fibers, either synthetic fiber or fine CCFCMs in PHMA, could reduce the interconnected voids in the PHMA.

3.4. Infiltration performance

The infiltration rate is an important criterion in designing the PHMA mixture. Fig. 10 shows the results of the infiltration rate of the mixtures. The best performance was observed in the Control PHMA with 873.60 cm/hr and the lower infiltration rates were observed in Syn-F-PHMA (657.74 cm/hr) and PF-C-PHMA (697.14 cm/hr), but they are all well above the threshold value of 254 cm/hr. Since the infiltration rate is highly influenced by porosity [24], the reductions of the infiltration rate were expected in the Syn-F-PHMA and PF-C-PHMA due to the reduction of the porosity. Again, the string-like aramid fibers in the synthetic fibers and short length fiber in the Fine CCFCMs may narrow the pores and lengthen the flow path in the PHMA mixture, thus leading to a reduction of porosity and infiltration.

3.5. Draindown

Draindown of the liquid binder at an elevated temperature can cause the produced PHMA becoming inhomogeneous in asphalt content. As shown in Fig. 11, the Control PHMA showed the highest draindown value of 0.25%, which is close but lower to the specification value of 0.3%. The inclusion of the Fine CCFCMs and the synthetic fiber can significantly reduce the draindown. While the aramid fibers in the synthetic fiber can reduce the infiltration rate, it can effectively prevent

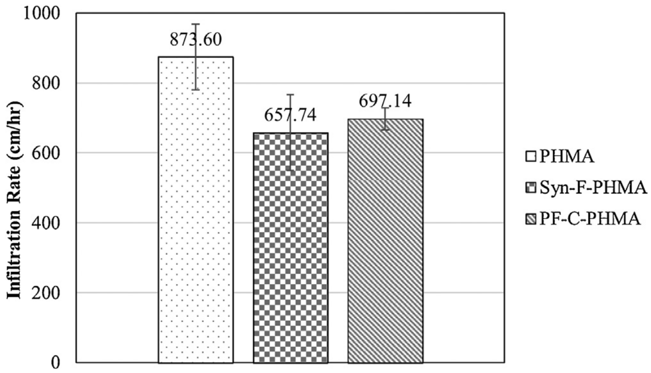

Fig. 10. Infiltration Rates of Control PHMA, Syn-F-PHMA, and PF-C-PHMA.

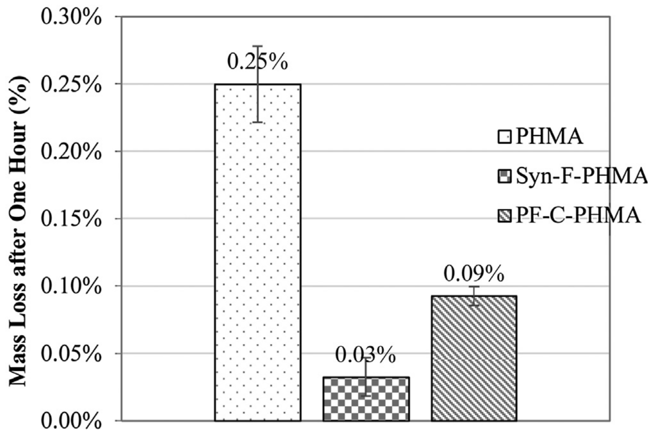

Fig. 11. Draindown Results at 140°C.

the binders from draining down. As a result, the mass loss due to draindown was the lowest in Syn-F-PHMA (0.03%). Similarly, the short length fibers in Fine CCFCMs increase the draindown resistance of the mixture. Though the draindown resistance of PF-C-PHMA was slightly less than Syn-F-PHMA, both mixtures performed better than the Control PHMA. With the use of either element, the adverse draindown effect shall not be a concern during the construction practice.

3.6. Cantabro abrasion

Since the degradation and raveling of PHMA are often observed where individual aggregates become separated from the pavement [33], the Cantabro tests were conducted to evaluate the PHMAs' resistance to degradation. Fig. 12 shows the Cantabro test result for the Control PHMA after 100, 200, and 300 revolutions. As seen in Fig. 13, the mass loss of Syn-F-PHMA and PF-C-PHMA were comparable with the Control PHMA, and all mixtures were within the specification with less than 20% mass loss after 300 revolutions. It can be concluded that neither synthetic fiber nor Fine CCFCM affected the abrasion resistance of the PHMA. The possible explanation is that the mass losses due to abrasions in Cantabro test were only observed at the edges of the gyratory samples as shown in Fig. 12, where the fibers may not take effect to increase the bond between aggregate particles at these edges.

3.7. Hamburg wheel tracking test (HWTT)

Fig. 14 shows the rut depth evolution with the number of wheel passes (cycles) determined in the HWTT. A moderate variation in results was observed since the tested samples have higher air voids. The use of Fine CCFCMs showed an improved rutting resistance (22%) compared to the Control PHMA, while Syn-F-PHMA performed similarly to the Control PHMA. Again, the carbon-based powder in the Fine CCFCMs increased the stiffness of the binder and the existence of short length fibers in PHMA is beneficial to bond aggregates together. Rutting resistance is an important performance criterion for PHMA as they are often used for parking lot and low-traffic roads [34]. Pavements in those locations are subjected to slow moving and turning vehicles, which will increase the potentials of vertical permanent deformation of the pavement [35]. Therefore, the HWTT result implies that incorporating Fine CCFCMs into PHMA is highly recommended.

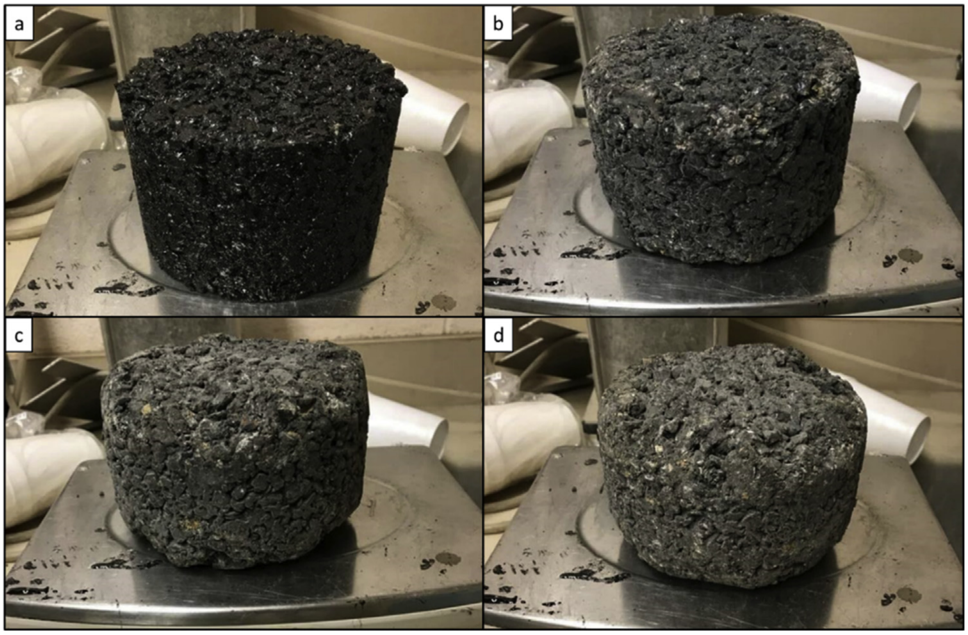

Fig. 12. Cantabro Abrasion of Control PHMA: (a) Initial, (b) After 100 Revolutions, (c) 200 Revolutions, and (d) 300 Revolutions.

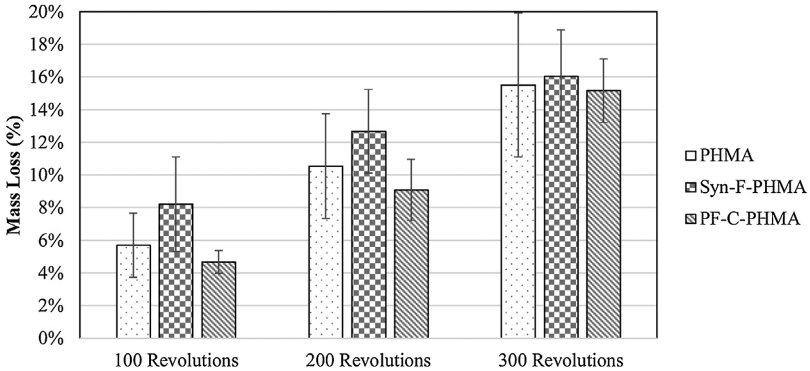

Fig. 13. Cantabro Abrasion Results for Every 100 Revolutions.

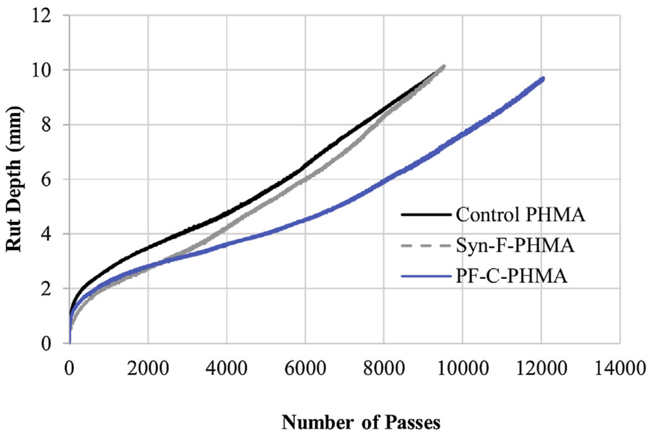

Fig. 14. Rut Depth (mm) in the Hamburg Wheel Tracking Test.

4. Conclusions

In this study, ground cured carbon fiber composite materials (CCFCMs) available as industrial waste was used as reinforcement in porous hot mix asphalt (PHMA). The CCFCMs were processed into three different size groups: Fine, Medium, and Large. First, the size effects of CCFCMs on the mechanical performance of PHMA were assessed based on the results of the indirect tensile (IDT) test at 25 °C and −10 °C. The best performing size group was then evaluated in terms of air voids and porosity, infiltration performance, draindown, Cantabro abrasion resistance, and rutting resistance. Also, the commercially ready synthetic fiber product, Forta-Fi®, was included in the study to compare with the effect of CCFCMs. The conclusions of the study are:

(1) The Fine CCFCMs that contain carbon-based powder and short length fibers premixed with liquid asphalt binder before mixing with aggregates (PF-C-PHMA) significantly increased the IDT strength of the PHMA mixture at both 25 °C and −10 °C, by 33% and 21%, respectively. The significant improvement was also observed in cracking resistance at 25 °C with 11% improvement.
(2) The inclusion of either Fine CCFCMs or synthetic fiber can prevent the draindown of asphalt binder at elevated temperature during the production; however, this practice can reduce the porosity of PHMA and result in a lower infiltration rate, yet all mixtures were still well above the required infiltrate rate of 254 cm/hr.
(3) The inclusion of either Fine CCFCMs or synthetic fibers in PHMA doesn't improve the Cantabro abrasion resistance. While the Fine CCFCMs improved the rutting resistance of PHMA by 22%.

Overall, the newly developed PHMA reinforced by the premixed Fine CCFCMs (PF-C-PHMA) showed similar performance with the PHMA reinforced by the synthetic fibers in terms of infiltration rate and draindown resistance, while PF-C-PHMA performed up to 20% better in mechanical properties in comparison to the control PHMA. The future work of using CCFCMs will focus on the plant production of CCFCMs reinforced PHMA mixtures. The effects of different aggregate types with different textures and shapes can change the dispersion or matrix of CCFCMs in PHMAs, which need to study separately from this study.

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