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Assessment of the impact of binder grade on the laboratory performance of fiber reinforced asphalt mixtures

Ali Raza Khan [a,*], Ayman Ali [a], Harshdutta Pandya [a], Ahmad Alfalah [a], Yusuf Mehta [a], Mohamed Elshaer [b], Christopher Decarlo [c]

[a] Center for Research and Education in Advanced Transportation Engineering Systems (CREATES), United States
[b] Research Civil Engineer, US Army Corps of Engineers, Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory (CRREL), United States
[c] Mine Engineer, US Aggregates, United States

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ABSTRACT

This study aims to evaluate the impact of different fiber types and binder modifications on the volumetric properties and performance (rutting and cracking) of fiber-reinforced asphalt mixtures (FRAM). Four types of fibers (carbon, fiberglass, basalt, and polyolefin/aramid (PFA) mix) and two binder performance grades (PG 58–28 unmodified and PG 76–22 polymer modified) were used to produce a total of ten asphalt mixtures (two control and eight FRAM). All fibers were introduced at the manufacturer-recommended dosages (i.e., carbon, fiberglass, basalt: at 0.16%, and PFA: at 0.05%) by mix weight. The mix design and volumetrics properties were examined to assess the impact of FRAM on volumetric properties of modified and unmodified binders. Mix characteristics, durability, rutting, and cracking performances were also evaluated by performing several tests, including dynamic modulus test |E*|, Cantabro loss, Asphalt pavement Analyzer (APA), Flow Number (FN), and Indirect Tensile Asphalt Cracking Test (IDEAL-CT). Mix design results showed that FRAM at 0.16% dosage increased the air voids of the unmodified binder (PG58-28). PFA fibers did not have an impact on air voids or volumetric properties of the asphalt mix regardless of modification. Performance results showed that FRAM were highly durable than control mix, but durability is significant for polymer modified binder (PG76-22). Furthermore, only PFA reinforced mixtures showed better rutting resistance for both modified and unmodified binders. The addition of fibers did not show any impact on cracking performance of modified and unmodified binder prepared asphalt mix. Finally, PFA reinforced mix also indicated higher fracture toughness (G_f) and carbon fibers improved the ductility of asphalt mix.

1. Introduction

Asphalt concrete is widely used in the road building industry because of its serviceability, low cost, low noise, and riding comfort characteristics [1]. Over time, different distresses, such as fatigue thermal cracking, and rutting; initiate and propagate; causing asphalt roadways to deteriorate. The use of performance-enhancing additives (e.g., polymers, rubber, plastics, etc.) in asphalt mixtures is considered an effective way to minimize such pavement distresses and extend the life of roadways [2–5]. In addition to these additives, the use of fibers is also proven to enhance the cracking and rutting performance of mixtures without affecting binder properties. Different types of fibers (i.e., carbon, basalt, fiber glass, brucite, aramid, and lignin) are currently used in the asphalt industry [6–10]. These fibers showed improved rutting and cracking performance. Fibers also help control binder drain down in open graded asphalt mixtures. In fact, several state departments of transportation (DOTs) in the United States (US) specify the use of synthetic fibers for the purpose of controlling drain down. In the case of dense graded asphalt mixtures, fibers are added to enhance laboratory performance [11]. In fact, Ge et al., [12] reported the benefits of fiber reinforced mixes in the laboratory and field too. However, due to the use of fibers, volumetric properties, such as air voids, exceed typical design limits; thus, requiring an assessment of the impact of fibers on volumetric-based asphalt mix designs.

Several research studies investigated different fiber types (e.g., polypropylene, glass, aramid, basalt, lignin, polyvinyl alcohol, acrylic,

* Corresponding author.
E-mail address: khanal88@rowan.edu (A.R. Khan).

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and polyester) as potential additives to enhance asphalt mixtures' performance [7,8,13–16]. Alfalah et al., [1] investigated the impact of four different fiber types (Carbon 0.16%, Basalt 0.16%, Glass 0.16%, Polyolefin/Aramid (PFA) 0.05%, by total mix weight) on the rutting and cracking performance of asphalt mixtures prepared using PG76-22. Alfalah et al., [1] reported that fiber-reinforced asphalt mixtures (FRAM) prepared at the manufacturer-recommended dosages did not have an impact on their volumetric properties (i.e., mix design requirements were satisfied without the need to change the binder content). Alfalah et al., [1] also reported that the use of carbon, basalt, and glass fibers at the selected dosages did not significantly improve cracking and rutting resistance. The FRAM produced using the PFA showed improvement in rutting resistance [1].

Enieb et al., [17] evaluated asphalt mixtures prepared using glass fibers added at 0.3% and 0.6% by total mix weight and a penetration graded 60/70 binder. The authors did not consider the effect of fibers on volumetrics. Enieb et al., [17] described that FRAM had higher Indirect Tensile Strength (ITS) and moisture damage resistance compared to unreinforced asphalt mixtures; thus, reporting that mixture fatigue life is significantly better due to the addition of glass fibers. The suitability of Basalt fiber lengths (3 mm,6 mm,9 mm,12 mm,15 mm) for polymer modified (PG 76–22) was evaluated for mixes with different Nominal Maximum Aggregate Sizes (NMAS) (13.2 m, 19 mm, 26.5 mm) by Guo et al.,[18]. Results showed that Basalt fiber (0.3% dosage by total mix weight) affected mixes' air voids; requiring an increase of 0.1% in binder content (compared to control) to satisfy mix design requirements. Cracking and fatigue life was significantly enhanced at 6 mm, 9 mm and 12-mm fiber lengths for the 13.2, 19, and 26.5 mm NMAS mixes, respectively. All fiber lengths and NMAS showed consistent impact on tensile strength ratios (TSR%) (or moisture sensitivity) ranging from 80% to 90%. Guo et al.,reported that 6, 9, and 12 mm fiber lengths were feasible for NMAS 13.2 mm, 19 mm, and 26.5 mm, respectively. That is the case because these fiber lengths optimized performance at these NMAS.

Phan et al., [19] evaluated the laboratory performance of asphalt mixtures prepared using aramid fibers coated with either Sasobit or Paraffin wax. The binder grade used in this study was PG 64–22. Phan et al., [19] utilized wet (adding fibers into the mix when aggregates are fully coated with binder) and dry (adding fibers into the mix during mixing of binder and aggregates) methods to produce FRAM and ultimately determine their impact on mix performance. The increase in air voids for FRAM was significantly higher for the dry mixing method compared to the wet method. Therefore, the wet mixing method was utilized to fabricate performance samples. Phan et al., [19] reported that the use of Sasobit- and Paraffin-coated fibers significantly improved the cracking performance of asphalt mixtures; however, mixtures having Sasobit-coated fibers enhanced the cracking resistance by 20% compared to the control mix. The researchers also reported that both fiber types improved rutting resistance.

Motamedi et al., [20] evaluated the performance of asphalt mixtures produced using PFA fibers and PG 64–22 binder. This study evaluated fracture toughness at different temperatures and loading rates using edge-notched disc bend specimens. Motamedi et al., [20] reported that the fracture toughness of FRAM mixes increased with the decrease in temperatures from -5°C to -25 °C. That is the case when adding fibers at dosages ranging from 0.025% to 1% by mix weight. The same trend was observed with increasing the loading rate from 0.5 to 5.0 mm/min. Pei et al., [21] evaluated the impact of Basalt fiber diameter (7 μm, 13 μm, 25 μm) at a 0.3% dosage used in asphalt mixtures prepared with polymer modified PG 76–22 binder. The authors reported that air voids increased with the addition of fibers, and the optimum binder content for the FRAM mixes increased from 4.8% (control) to 5.1% (7 μm), 5.0% (13 μm), and 4.9% (25 μm). The cracking performance increased from 90 index points to 289, 162, and 122 for mixes with 7 μm, 13 μm, and 25 μm diameter fibers, respectively.

Considering the need for higher binder contents when producing FRAM, Alfalah et al., [10] conducted a study by adding different fibers (Carbon, Basalt, and Glass) in asphalt mixes prepared using a PG 76–22 binder. Alfalah et al., [10] observed that an increase in optimum binder content is needed to meet volumetric with higher fiber dosages. Therefore, performance was evaluated at optimum content and reduced (lower than optimum by 0.5% decrements) binder contents of all reinforced mixtures. The cracking performance of FRAM improved with the increase of binder contents and fiber dosage. However, the performance enhancement was due to the additional binder used in the FRAM mixes rather than the fibers [10].

In summary, the studies presented above indicate that the use of fibers, at mentioned dosages, for reinforcing HMA mixes might result in enhanced laboratory performance without considering the impact on volumetric properties. Other studies were also conducted to examine the impact of fiber thickness, length, and aggregate gradation on the performance of asphalt mixtures. However, most research studies concentrated on testing one or two fiber types simultaneously for a given binder grade. In addition, few studies compared the effect of different fiber types and binder grades on the design and performance of asphalt mixtures [22]. Therefore, further research is needed to fill this gap in knowledge and reach a consensus among researchers and manufacturers on the use of fibers in asphalt mixtures. The findings of this research will be valuable to state highway agencies interested in implementing FRAM.

2. Study objective

The goal of this study is to evaluate the impact of fiber type and binder modification (Performance Grade (PG)) on the mix design, on dynamic complex modulus, canrabro loss, and laboratory performance (rutting and cracking) of fiber reinforced asphalt mixtures.

3. Description of materials

One aggregate (diabase stone), two asphalt binders (polymer modified PG76-22 and unmodified PG58-28), and four different fiber types (carbon, basalt, fiberglass, and PFA) were used to produce asphalt mixtures for this study. A total of ten mixtures were produced: two unreinforced (control) mixes using the two binder grades, and eight FRAM. The control mixtures were prepared to meet the Federal Aviation Administration (FAA) requirements for a P-401 mix (i.e., 3.5 ±0.5% air voids, 50 design gyrations, and 15% minimum Void in Mineral Aggregate, VMA). The gradation and optimum binder contents for each of the control mixes are shown in Fig. 1. The four fibers (carbon, basalt, fiberglass, and PFA fibers) were selected because of their relatively high melting temperatures Table 1. It is noted; however, that the polyolefin in PFA had a lower melting point than the asphalt mixing temperature; thus, it melts into the asphalt binder. Extraction and recovery experiment test results showed that none of the fiber type have changed the performance grade of the binder. Table 1 presents the properties of all fibers used in this study. As shown in this table, carbon fibers had the least thickness and length, maximum tensile strength, and the greatest number of fibers at a given dosage and when compared to all other fibers. It is noted that the per ton cost of polymer modified (PG 76–22) binder and unmodified binder (PG 58–28) are 845 $/ton and 688 $/ton.

The FRAM mixes were produced by starting with the control mix designs and adding fibers, one fiber per mix, as reinforcement. The dosages of the different fibers were recommended by the fiber suppliers Table 1. A proportional mixing method (also known as "15 s dispersion" [1]) was used to produce loose fiber-reinforced mixes only for carbon, basalt, and fiberglass. This method involves adding the fibers into the mix in four equal-weight parts; every 15 s during mixing. The fibers are added into the mixing bowl after all aggregates were coated with asphalt binder. In general, the following steps were taken when producing fiber-reinforced mixtures for this study:

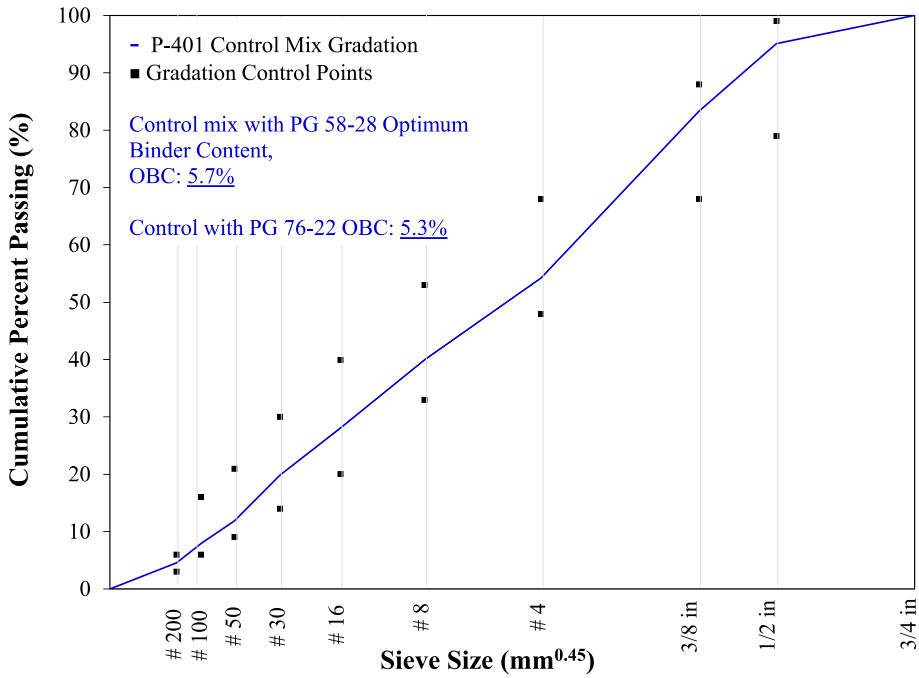

Fig. 1. Aggregate gradation and optimum binder for the PG76-22 and PG58-28 control mixtures.

Table 1
Properties of Fibers Used for P-401 Mix.

Fiber Property	Carbon	Basalt	Glass	PFA
Specific gravity	1.8	2.8	2.7	0.91/1.44
Tensile strength (MPa)	4137	2500	2000	483/3000
Length (mm)	6	9	12	19
Thickness (μm)	7.5	13	10	12
Acid/alkali resistance	inactive	inactive	inactive	Inactive
Decomposition temperature (°C)	500	>1500	>815	157/ >450
Melting temperature (°C)	1200	2500	1121	150/350
Price ($/lb)	3.02	4.10	3.02	6.75
Maximum recommended dosage *	0.16%	0.16%	0.16%	0.05%

* Recommended dosage was obtained from the manufacturer and is presented as a percentage of total mix weight.

- Mix preheated aggregates and binder until a full coating of aggregates (~30 s);
- Add the first portion of fibers into the bowl and mix for 15 s until all fibers are coated with the binder (~15 s);
- Repeat the previous step for the second and third portions of fibers. Mixing after the addition of a portion is continued for 15 s; and,
- Add the fourth portion of fibers into the bowl and mix for 60 s or until full coating of fibers and aggregates with binder (~total mixing time is approximately 3 min).

In the case of the PFA fiber, the mixing procedure used was the one recommended by the fiber supplier. The process involved dividing the aggregates batch into three equal parts and the aramid fibers into two equal parts. The first part of aggregates is placed into the mixing bowl, followed by the first half of the aramid fibers. The second part of aggregates with the other half of the aramid fibers are added into the mixing bowl. The third part of aggregates is then added to the mixing bowl followed by heated binder. The polyolefin portion of PFA is then placed to melt into the hot asphalt binder. The mixing of all components is then completed for a total time of three minutes.

4. Experimental program

A comprehensive testing program was designed for this study to evaluate the impact of fiber types and binder modification on the volumetric and mechanical properties and performance of asphalt mixtures. Fig. 2 presents this experimental program. As shown in this figure, the impact of binder modification (unmodified PG 76–22 and polymer modified PG 76–22) on the volumetric properties (or mix design) and mechanical performance of FRAM can be evaluated by comparing Mix Set 1 with Mix Set 2 and Mix Set 3 with Mix Set 4, respectively. Fig. 2 also shows that the impact of fiber type on performance is assessed by comparing the testing results obtained in either Mix Set 3 or Mix Set 4 to the control mixes' results; that is, keeping the binder grade "constant". The performance tests considered in this study (Fig. 2) are the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) for cracking performance, and the Asphalt Pavement Analyzer (APA) and Flow Number tests for rutting resistance. Performance interaction diagrams were developed for IDEAL-CT test parameters to characterize the toughness and ductility of mixes due to the addition of fibers. In addition, comparing test results from either Mix Set 3a or Mix Set 4a (Fig. 2) to the respective control mix results yields the impact of fiber type on the mechanical properties of FRAM. The mechanical properties of the control and FRAM mixes are evaluated using the Dynamic Complex Modulus (AASHTO T378) and the Cantabro Durability tests. A brief description of all the tests considered in the testing program are presented in the following subsections.

4.1. Indirect tension asphalt cracking test (IDEAL-CT, ASTM D8225)

The IDEAL-CT was conducted to evaluate the cracking performance of the control and FRAM mixes at intermediate temperatures (25 °C). For this study, samples were prepared using a Superpave Gyratory Compactor (SGC) to a height of 62 mm, a diameter of 150 mm, and a 7 ±0.5% target air voids level. During this test, mix samples are loaded at a rate of 50 mm/min until failure. Several cracking performance measures can be calculated using the load–displacement curves obtained from this test. These include fracture energy, crack propagation rate ($|m_{75}|$), ductility of a mix (l_{75}), strength to fracture (indirect tensile

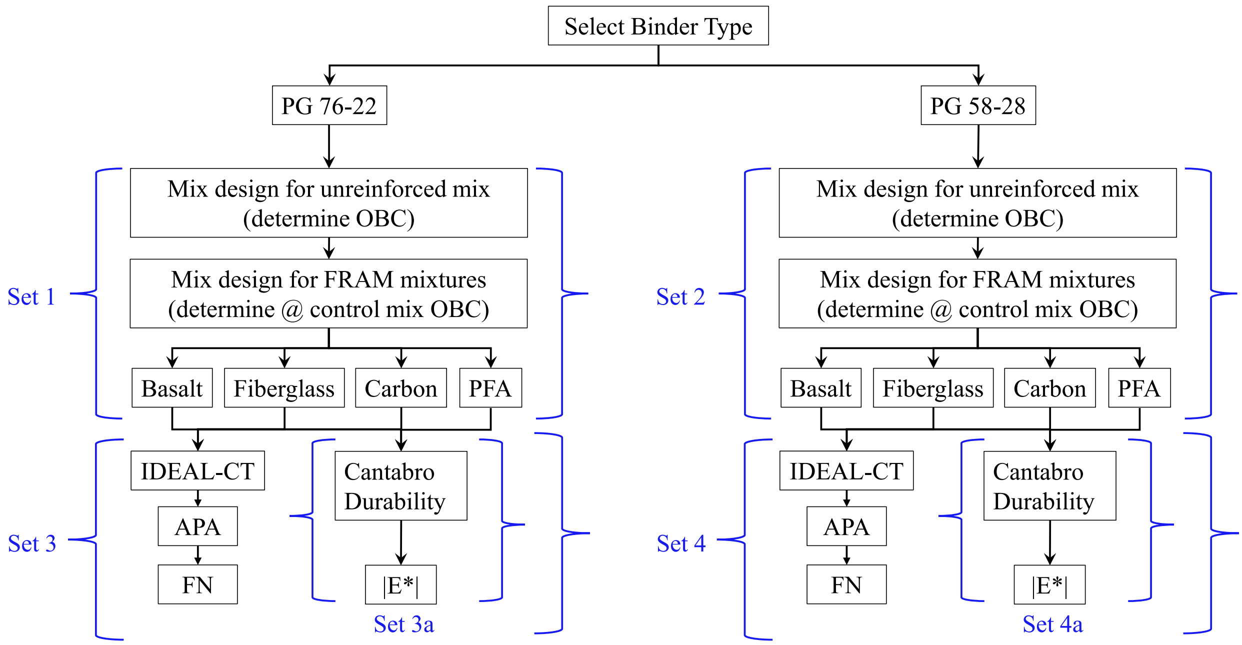

Fig. 2. Testing program for evaluating the impact of fiber type and binder grade on FRAM properties and performance.

strength or ITS), and Crack Tolerance Index (CT_{index}). Higher values of CT_{index}, fracture energy, and ITS indicate better cracking performance for asphalt mixtures. The formula for CT_{index} is shown in Equation (1).

$$CT_{index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D} \tag{1}$$

where, t is the average thickness (mm), G_f is the fracture energy (J/m^2), $|m_{75}|$ is the post-peak slope at 75% of peak load, l_{75} is the displacement of the post-peak load at 75%, and D is the diameter of the sample. The fracture energy (G_f) was computed by calculating the area under the load displacement curve normalized the sample dimension. It represents the energy that asphalt mix absorb during fracture.

4.2. Cantabro durability (AASHTO TP108)

The durability (resistance to breaking down) of asphalt and fiber reinforced mixtures was characterized according to the AASHTO TP 108 (Cantabro Loss test). Three replicates per mix were compacted to 115±5 mm height using the design gyrations (i.e., 50) in a SGC. In this test, one sample was subjected to 300 revolutions at a rotational speed ranging between 30 and 33 revolutions per minutes (RPM) in a Los Angeles Abrasion device. The percentage difference between the initial and final weights of the sample is calculated as the percentage loss (durability) of the asphalt mixture.

4.3. Asphalt pavement analyzer test (APA, AASHTO T340)

The APA test was conducted to assess the rutting susceptibility of the control and FRAM mixes according to the AASHTO T340. In this test, samples are preconditioned at testing temperature (64 °C for both PG76-22 and PG58-28) for a minimum of 6 h before testing. This test temperature was selected because it represents highs in New Jersey. Once the preconditioning time is complete, a vertical wheel load of 444.8 N is applied on a hose pressurized to 6.89 kPa and placed directly on top of the sample. The test is conducted for a total of 8000-wheel loading passes or until a maximum rut depth of 14.5 mm is reached. An average rut depth is usually reported for all replicates tested. Samples had a height of 75 mm, a diameter of 150 mm, and a 7±0.5% target air voids level.

4.4. Flow number (FN, AASHTO T378)

The FN test was used to evaluate the rutting susceptibility of asphalt mixtures at high temperatures (54 °C according to AASHTO T378). Three replicates were prepared at target air voids of 7±0.5% with a diameter of 100 mm and height of 150 mm. Haversine loading pulse with 0.1 s of loading followed by 0.9 s of rest was used to represent one loading cycle. This test was conducted until failure (i.e., 5% permanent strain). The number of cycles to failure is usually measured using the FN test.

4.5. Dynamic complex modulus test, (|E*|, AASHTO T378)

A dynamic modulus test was conducted to characterize the linear viscoelastic behavior of the control and FRAM mixtures. The test was performed according to AASHTO T378 at four different temperatures: 4.4 °C, 21.1 °C, 37 °C, and 54 °C for PG 76–22. In the case of the mixes prepared using the PG 58–28 binder, testing was conducted at 4.4 °C, 21.1 °C, and 37 °C. It is noted that the 54 °C test temperature was excluded for these mixes because the mix was in a soft state and studs started falling off and that prevented the LVDTs from measuring macrostrains at that temperature (soft binder grade). A sinusoidal stress load at frequencies of 25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, and 0.1 Hz was applied while maintaining the strain level within the samples to lower than 150 με; keeping the samples in a linear viscoelastic range. The master curve was plotted against reference Three replicates were tested of 100 mm diameter and 150 mm height to meet a target air voids level of 7±0.5%. The dynamic modulus |E*| was calculated by using equation (2). And the master curve was constructed to a reference temperature of (21.1C) by fitting the modulus values using sigmoidal function given in equation (3).

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{2}$$

where, σ_0 is the applied stress amplitude and ε_0 is the measured strain amplitude.

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(f_r)}} \tag{3}$$

where, $\delta, \alpha, \beta and \gamma$ are curve fitting parameter and f_r (Hz) is the reduced frequency.

5. Results and discussion

5.1. Impact of binder modification on volumetric properties of FRAM

Fig. 3 presents the volumetric mix design results for all mixtures. As can be seen from Fig. 3a, the control and FRAM mixes had similar rice specific gravity (maximum theoretical specific gravity, G_{mm}) regardless of the binder grade. This suggests that fibers did not have any impact on G_{mm} in a loose state. However, PFA FRAM shows slightly (≈0.3%) higher rice specific gravity compared to control mix for both PG grades. This was mainly attributed to the melted polyolefin, which in return may slightly change the properties of asphalt binder.

Fig. 3b and 3c present the bulk specific gravity (G_{mb}) for compacted samples and the air voids (AVC) of the control mix and FRAM asphalt mixtures, respectively. Carbon, basalt, and glass fibers reinforced mixtures had lower bulk specific gravities and higher air voids levels compared to control for unmodified PG58-28. The increased air voids indicate that higher binder content is required to satisfy the mix design air voids (3.5 ± 0.5%) requirements. The higher air voids are associated with the rebounding height of FRAM as observed by Alfalah et al., (10). Additionally, carbon, basalt and glass fibers had higher voids in mineral aggregates (VMA) as show in Fig. 3d. This indicates that voids in between aggregates had less binder to accommodate the voids. This also suggests that a higher binder content is required for these reinforced mixtures. Overall, these observations indicate that manufacturer recommended dosage (0.16%) does not have any impact on the volumetric properties of mixes prepared using polymer modified binder (PG 76–22); however, when using an unmodified binder to prepare FRAM, there was a significant impact on volumetrics. As such, it can be concluded that when using unmodified binders (PG58-28 in this study), it is essential to ensure that FRAM mixes are meeting design requirements.

5.2. Effect of fibers and binder modification on dynamic modulus and durability of FRAM

The dynamic modulus master curves for the control and FRAM mixes prepared using the unmodified PG 58–28 and polymer modified PG 76–22 binder grades are shown in Fig. 4(a) and 4(b), respectively. Dynamic modulus |E*| master curve was constructed to a reference temperature of 21.1 °C. High frequencies (left x-axis) in the master curve provide insights into cracking performance, and low frequencies (right x-axis) correspond to rutting performance.

Carbon, fiberglass, and Basalt fiber asphalt mixtures showed similar modulus values (Fig. 4a and 4b) to those obtained for the control mixes, irrespective of binder grade, and at both high and low frequencies. This indicates that the addition of these fibers did not show any considerable impact on cracking and rutting resistance. In contrast, PFA reinforced asphalt mixes for both binders showed higher |E*| values at low frequencies (Fig. 4a and 4b), compared to the control mix. It is believed that that polyolefin (PFA fiber) that melts in the asphalt binder during mixing of PFA reinforced mixes is the main reason for the change in |E*| values for these mixes. This observation also suggests that PFA modified asphalt mixtures had better rutting performance than the control and other FRAM mixes. This is the case for both type of mixtures prepared using modified and unmodified binders used in this study. However, all FRAMs exhibited similar trend for |E*| modulus values, indicating that

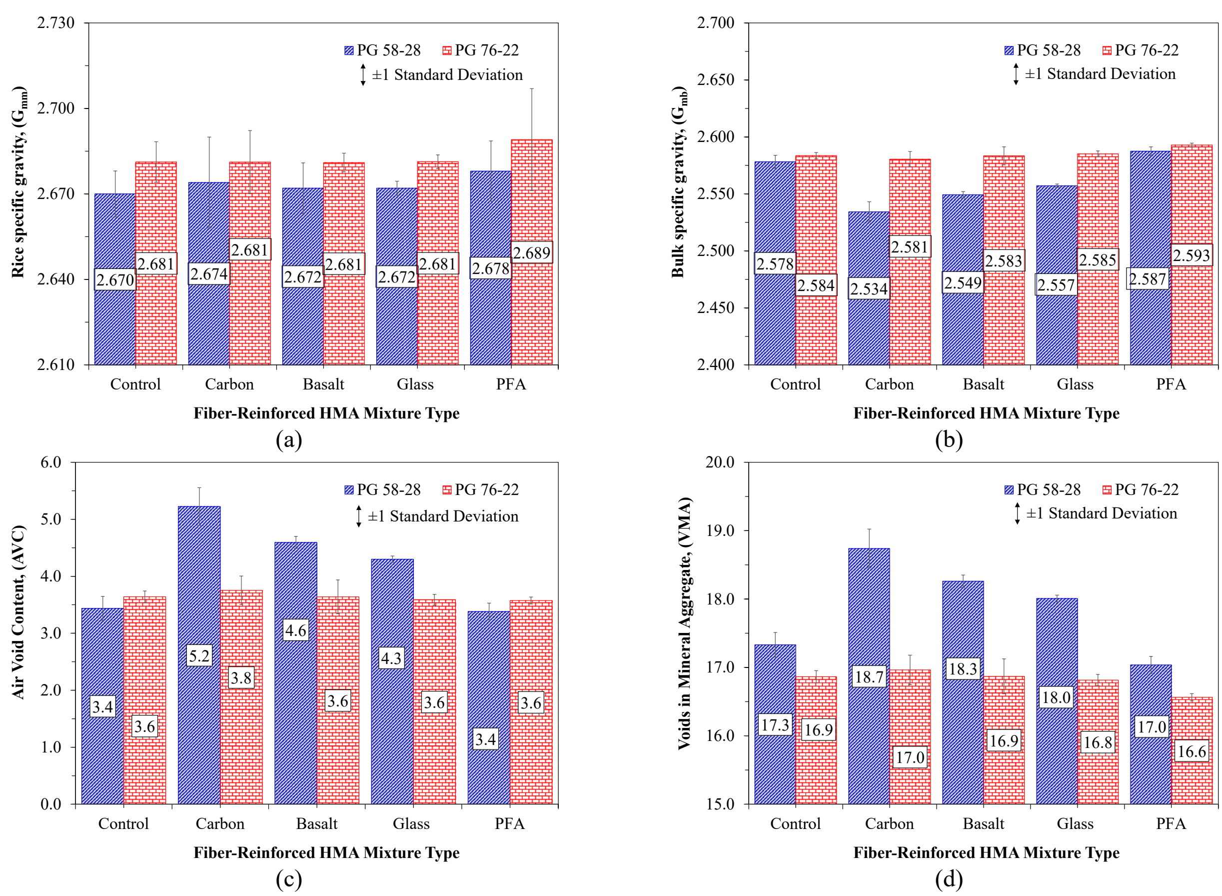

Fig. 3. Results for mix design of fiber reinforced asphalt mix (a) rice specific gravity, G_{mm} (b) bulk specific gravity, G_{mb} (c) air voids (d) voids in mineral aggregate, (VMA).

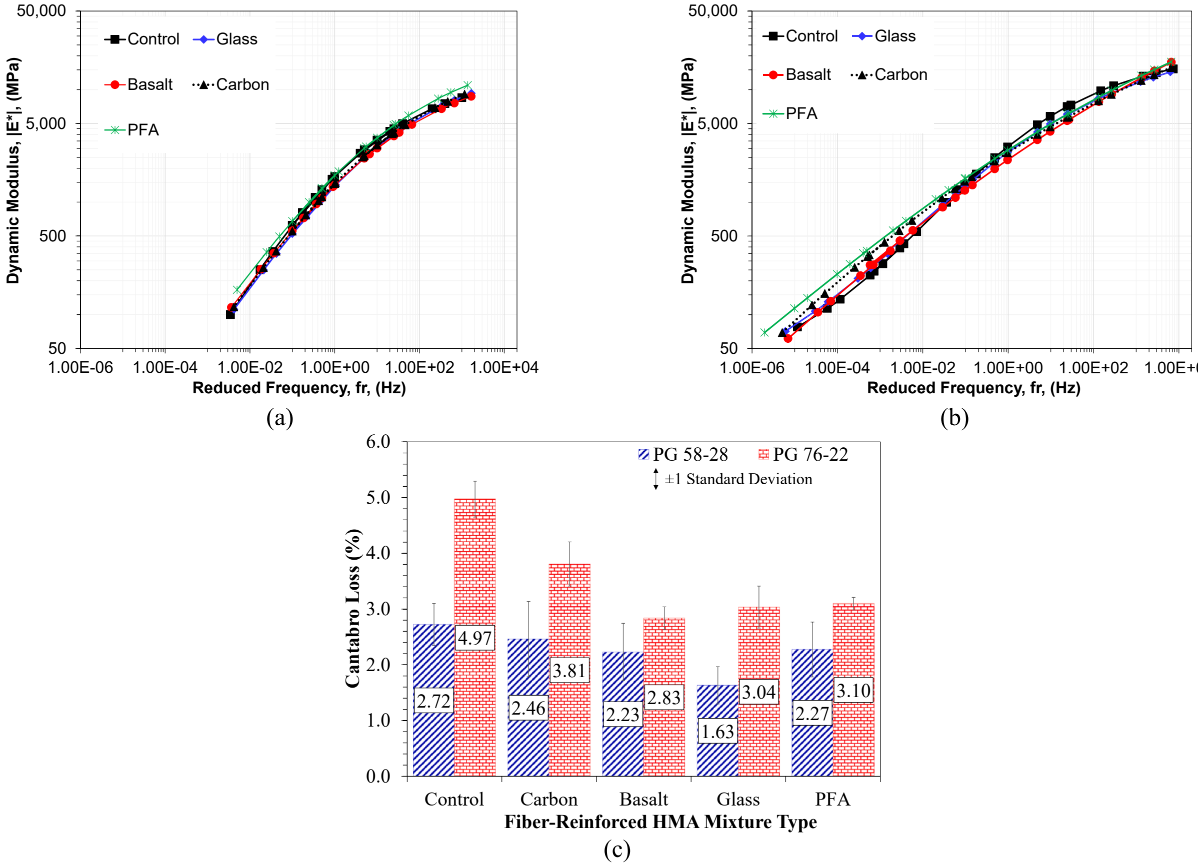

Fig. 4. Results of dynamic complex modulus, |E*|, master curve and cantabro durability (a) PG 58–28 (b) PG 76–22 (c) Cantabro durability.

binder grades did not show any considerable impact on dynamic modulus (|E*|) master curve.

The Cantabro durability test results are presented in Fig. 4c. Based on this test, all FRAM mixtures had lower Cantabro loss values than the control mixes for both binder types. This might be attributed to the strong bond between the fibers and binders. These observations indicate that FRAM mixes are less susceptible to breaking down when compared to unreinforced mixes. Among all fiber types, fiberglass and basalt reinforced mixtures showed the lowest Cantabro loss percentages; indicating that these mixes are more durable than other FRAM. Additionally, higher percentage loss values were observed for polymer modified (PG 76–22, stiffer) compared to unmodified (PG 58–28, softer). This was expected because softer binders can resist breaking down better than stiffer binders. Overall, fiber reinforcement improves the durability of the mix, and these findings also agree with the study by Yaro et al., [23].

5.3. *Effect of fiber type and binder modification on rutting performance of FRAM*

Rutting susceptibility of unreinforced (control) and fiber-reinforced mixtures was characterized by the APA and flow number (FN) tests, presented in Fig. 5a and 5b, respectively. Carbon, fiberglass, and basalt fibers reinforced mixtures showed similar (within ≈ 0.1 mm) APA rut depth for polymer modified PG76-22 compared to the control mix. In addition, control, and FRAM (carbon, fiberglass, and basalt mixtures) had the same rut depth measurements (within ≈ 1.1 mm) for the unmodified binder (Fig. 5a). This observation indicates that the addition of carbon, basalt, and fiberglass into asphalt mixture, regardless of binder modification, does not improve rutting resistance.

The rut depth values for PFA fibers, on average, were 28% and 21% less than the control mix for PG 58–28 and PG 76–22, respectively. The polyolefin melts into the binder and improves the rutting performance of the asphalt mix. This finding indicates that PFA fibers are highly effective in improving rutting resistance of asphalt mixes. These findings also agree with the |E*| test observations in which PFA fibers for both PG grades show higher modulus values at lower frequencies (Fig. 5a and 5b).

The control mix FN values (Fig. 5b) are similar than those for the carbon and basalt reinforced mixtures, regardless of binder grade. This suggests that the use of carbon and basalt fibers in asphalt mixes had the similar rutting performance. PFA reinforced mixture showed 156% and 2% higher values than the control mix for unmodified and polymer modified binders. This shows that PFA reinforced mix is highly effective for unmodified binders in rutting performance compared to the polymer modified binders. The PFA FN test findings for unmodified binder agree with the APA test results. Overall, however, considering the variability of samples, it appears that PFA fibers may not have an impact on the rutting performance (FN test results) of the polymer modified binder. Based on the rutting performance results, higher percentage improvements are observed for unmodified binder (softer), it suggests that addition of fibers is highly effective for unmodified binders compared to modified binders.

5.4. *Effect of binder modification and fiber type on strength and cracking resistance of FRAM*

The ITS and CT_{index} values for the control and fiber reinforced mixtures are presented in Fig. 6(a) and 6(b), respectively. As can be seen from Fig. 6(a), the ITS values for both control mixtures are similar to the carbon, fiberglass and basalt FRAM. This suggests that the addition of these fibers into asphalt mixes have no significant impact on tensile strength. Whereas PFA fibers showed higher ITS values (29% for unmodified PG 58–28 and 5% for polymer modified PG 76–22 compared to

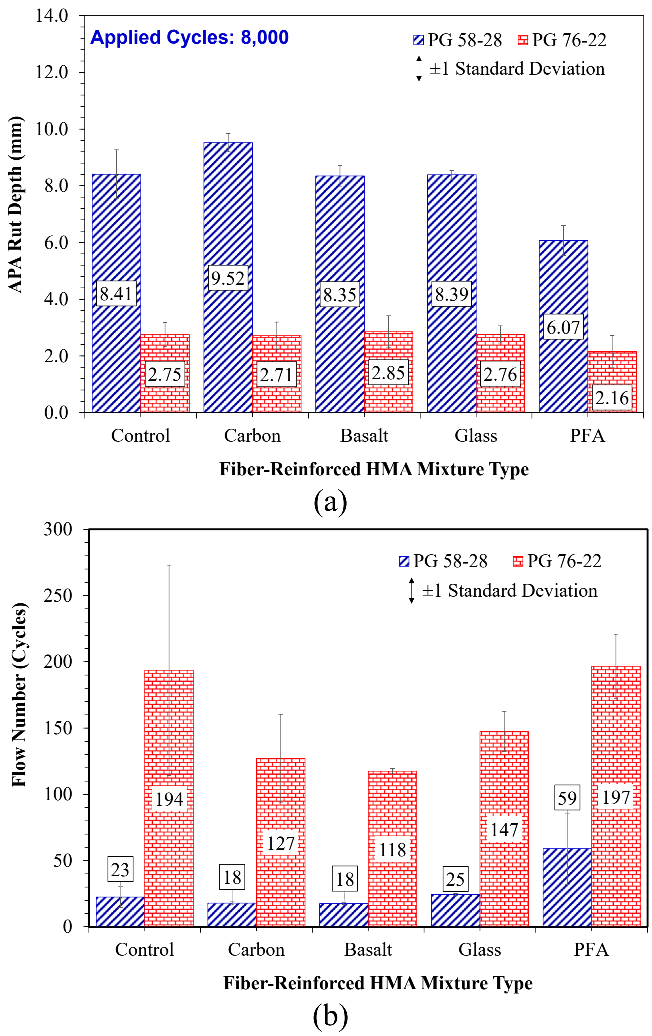

Fig. 5. Rutting performance (a) APA rut depth (b) FN test.

control), this suggests that PFA fibers might have a better ability to resist cracking.

It should be highlighted that ITS may not necessarily be a suitable indicator of cracking performance of asphalt concrete [24]. Fig. 6b shows that the carbon reinforced mixes (both binders) are the only mixes with a higher (on average by about 11%) CT_{index} when compared to the respective control mixes. It shows that the carbon fiber reinforced asphalt mixes have better cracking performance than the control mixes, regardless of binder type and modification. These observations may be associated with the strong bonding (adhesion) between the carbon fiber and asphalt binders. For the PFA-reinforced mix, the mix with the polymer modified binder had approximately 9.7% higher CT_{index} values than the control. However, the unmodified binder PFA mix had a 20% reduction in CT_{index} compared to control mix.These findings suggest that the use of PFA in asphalt mixes negatively impacts the cracking performance; especially when using unmodified binders. However, polymer modified mixtures did not showed any statistically significant improvement of the test results.

The cracking results were further evaluated using interaction diagrams with the goal of better understanding how the use of fibers affects the different IDEAL-CT performance measures (i.e., ITS, $|m_{75}|$, l_{75} and fracture energy, G_f). The interaction diagrams were developed by National Center for Asphalt Technology (NCAT). The diagrams were created by plotting the average G_f values on the y-axis and the ratio of l_{75} to $|m_{75}|$ on the x-axis. In general, G_f values provide insights into a mix's toughness while the $l_{75}/|m_{75}|$ ratio represents the relative ductility or brittleness of an asphalt mixture. Therefore, the increase in G_f and $l_{75}/|m_{75}|$ would yield higher CT_{index} values; thus, mixes with better cracking resistance. These mixes will usually be presented in the upper corner of the interaction charts. Each dotted contour line in the interaction charts represents identical CT_{index} values having different G_f and $l_{75}/|m_{75}|$ values. Fig. 6(c) shows the interaction charts for control and FRAM mixes prepared using the unmodified PG 58–28 asphalt binder. As shown in Fig. 6(c), PFA fibers had higher fracture energy and lower $l_{75}/|m_{75}|$ ratio compared to control and other fiber types. This observation indicates that PFA reinforced mixtures had higher toughness and lower ductility than those was obtained for control mix. The FRAM mixes prepared using basalt and fiberglass fibers had similar G_f and $l_{75}/|m_{75}|$ values to that of the control mix. This shows that these fibers neither improve the toughness nor the ductility of asphalt mix. Carbon fibers had lower G_f values and greater $l_{75}/|m_{75}|$ ratio than the control; indicating that this fiber type improved the ductility and reduced the toughness of the mixture. Fig. 6(d) illustrates the interaction chart of polymer modified PG 76–22. The results in this figure indicate that all fiber types had no impact either on G_f or $l_{75}/|m_{75}|$, and values were located between contours of 100 and 150.

Overall, the above-mentioned observations suggest that the addition of fibers into asphalt mixtures did not show any impact on IDEAL-CT performance measures when polymer modified binders are used. However, PFA fibers showed higher toughness and lower ductility, but carbon fibers improved the ductility of the mix for unmodified PG58-28.

6. Statistical analysis (ANOVA)

Statistical analyses were performed to determine the impact of fiber type and binder modification on performance improvement (control vs. fiber reinforcement). A multi-factor analysis of Variance (ANOVA) was performed with a Tukey's Honestly Significant Difference (HSD) post-hoc analysis at a 95% confidence level (or p-values $\leq$ 0.05). The HSD post-hoc analysis allows ~~for~~ a direct comparison of control and fiber-reinforced asphalt mix. The statistical significance of the impact of fiber type and binder grade on rutting (APA) and cracking (CT_{index}) is shown in.

As can be seen in Table 2, significant difference in results of different binder grades for rutting and cracking performance (p-value <0.001 for APA and CTindex) is observed. It indicates that both binder grade has a statistically significant different on the rutting and cracking results of FRAM mixes. Results in Table 2 also illustrate that the impact of fiber type is statistically significant on rutting performance (p-value <0.001), while the addition of different fibers did not show any statistically significant difference on cracking performance. This indicates that rutting performance enhanced significantly with addition of fibers. Post-Hoc analysis in this table indicates that PFA reinforced mixes shows significant improvement in rutting performance compared to control and other fiber types. Additionally, fiberglass reinforced mixture shows statistically significant difference (mean: 0.7087, p-value: 0.034) compared to carbon reinforced mixtures.

Table 2 CT_{index} post-hoc results shows that none of the fiber type showed statistically significant value compared to control and other fiber types. This suggests that addition of fibers into the asphalt mix did not have any impact on cracking performance regardless of fiber type.

7. Summary and conclusions

This paper presented a study aimed at evaluating the impact of fiber manufacturer recommended dosage on volumetric properties, mechanical properties, and performance of asphalt mix. Four different fiber types (carbon, basalt, fiberglass, and polyolefin/aramid PFA), two asphalt binders (polymer modified PG76-22 and unmodified PG58-28), and one aggregate type (diabase) were used to produce unreinforced and fiber reinforced mixtures. Carbon, basalt, and fiberglass were added to the mix at 0.16% dosage of total mix weight. A proportional mixing

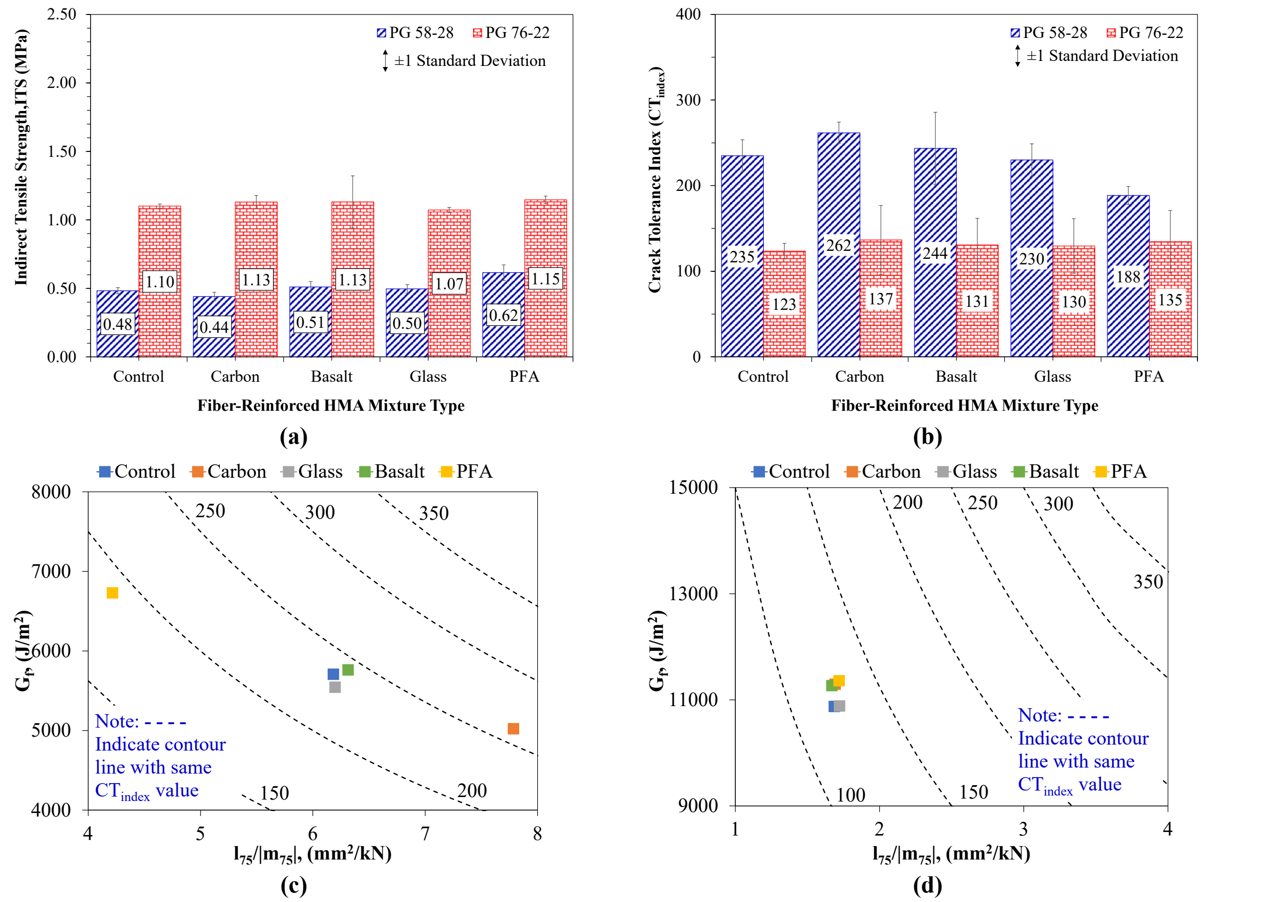

Fig. 6. Cracking performance of fiber reinforced mixtures and performance interaction chart (a) ITS (b) CT_{index} (c) G_f vs $l_{75}/|m_{75}|$ for PG 58–28 and (d) G_f vs $l_{75}/|m_{75}|$ for PG 76–22.

Table 2
Analysis of Variance (ANOVA) for Performance Test Results.

Factor	APA			CT_{index}	
	F-value	*p*-value		F-value	*p*-value
Fiber Type	21.465	**<0.001***		1.475	0.247
Binder Type	1456.226	**<0.001***		97.131	**<0.001***
Fiber Type* Binder Type	10.046	**<0.001***		1.524	0.233
Post-Hoc					
Fiber Type (I)	Fiber Type (J)	APA Mean Difference (I-J)	Sig. p-value	CTindex Mean Difference (I-J)	Sig. p-value
Control	Basalt	-0.0204	1.000	-7.3433	0.990
	Carbon	-0.4729	0.251	-19.9187	0.721
	Fiberglass	0.2358	0.826	-0.5781	1.000
	PFA	1.4663	<0.001*	17.7056	0.797
Basalt	Carbon	-0.2525	0.289	-12.5754	0.930
	Fiberglass	0.2562	0.779	6.7651	0.993
	PFA	1.4867	<0.001*	25.0489	0.528
Carbon	Fiberglass	0.7087	0.034*	19.3405	0.741
	PFA	1.9392	<0.001*	37.6243	0.165
Fiberglass	PFA	1.2304	<0.001*	18.2838	0.778

Note: *Statistically significant at confidence level of 95%.

method was adopted to prepare these mixes. PFA fibers were added at 0.05% dosage of total mix weight and mixed according to the method specified by the manufacturer. The mix characteristics, durability, resistance to rutting, and cracking performance were evaluated using the dynamic modulus test |E*|, Cantabro loss test, APA, FN, and IDEAL-CT test, respectively. The following conclusions were drawn based on the laboratory experimental results and subsequent statistical analyses:

- The manufacturer recommended fiber (carbon, basalt, and fiberglass) dosages (recommended dosage of 0.16%) impacted the volumetric properties (typically 0.9–1.8% higher AVC) for unmodified binder (PG 58–28) and required higher binder content. These fibers did not affect the volumetric properties of polymer modified binder (PG 76–22). PFA 0.05% reinforced mixes showed the same binder content as the control mix and consistent air voids, irrespective of the binder grade. Henceforth, to avoid mix design issues, the maximum threshold dosage (defined as the maximum dosage that had no mix design issues and maximize performance enhancement) was dependent on the selected grade of asphalt binder.
- The |E*| values for low temperature (higher frequencies) are the same for all FRAM types, showing equivalent cracking performance for control mix and fiber reinforced mixtures, irrespective of binder grades/ modification.
- The addition of PFA fibers into the asphalt mix showed higher |E*| modulus (∼35%) compared to control at a lower frequency, regardless of binder grade, indicating better rutting performance.
- Fiber reinforced asphalt mixtures significantly improved the durability of asphalt mixtures for polymer modified binders (PG 76–22) and showing 36% lower mass loss compared to control. Adding fibers into the asphalt mix did not impact the durability of an unmodified binders. The strong adhesion between fibers and polymer modified binders increase the resistance to breaking down compared to unmodified binder.

- In general, PFA fibers showed less (∼25% for both binders compared to control) rut depth and higher FN cycles (∼79% for both binders compared to control), indicating that PFA reinforced mixes are less susceptible to rutting. However, PFA mixtures are significantly more effective in terms of rutting resistance for unmodified binders (PG 58–28).
- Among all FRAM types, PFA-reinforced mixtures showed higher (29%) ITS values for a softer binder (PG 58–28) than the control mix, outperforming other fiber mixtures. It indicates that reinforcing asphalt mixtures with PFA fibers improved the tensile strength of softer binders.
- Carbon fibers showed higher (∼11%) CT_{index} values for both binder grades compared to control mixes. Statistically, the improvement was not significant. Hence, fibers' addition did not have any impact on asphalt cracking performance.
- Based on G_f, $l_{75}/|m_{75}|$, and CT_{index} interaction chart, FRAM prepared using polymer modified PG 76–22 neither increased the toughness nor the elasticity in comparison to control mix. In case of mixtures prepared using unmodified PG 58–28, PFA reinforcement improved mixture toughness (high G_f and low $l_{75}/|m_{75}|$), and the addition of carbon fibers showed higher elasticity ($l_{75}/|m_{75}|$) compared to the control mix.

It is recommended that future research explore the impacts of different fiber lengths and aging levels and aim to gain a better understanding of the role of fiber properties in HMA mixes. It is also recommended to evaluate the impact of aging on asphalt mixtures reinforced with fibers.

CRediT authorship contribution statement

Ali Raza Khan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Ayman Ali:** Conceptualization, Formal analysis, Methodology, Writing - review & editing. **Harshdutta Pandya:** Conceptualization, Formal analysis, Investigation. **Ahmad Alfalah:** Data curation, Investigation, Methodology. **Yusuf Mehta:** Funding acquisition, Supervision, Visualization, Writing – review & editing. **Mohamed Elshaer:** Formal analysis, Investigation, Writing - review & editing. **Christopher Decarlo:** Conceptualization, Data curation, Supervision, 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.

Data availability

Data will be made available on request.

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