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# Laboratory Evaluation of the Mechanical Properties of Asphalt Concrete Reinforced with Aramid Synthetic Fibers

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PROJECT: EFFECT OF ACE FIBERS ON ASPHALT MIX PERFORMANCE

**PREPARED FOR:**

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14. ABSTRACT

The research project presented in this report evaluates the effects that the addition of aramid fibers has on the mechanical properties of a dense-graded mix frequently used in California, a Superpave mix with 19 mm (3/4 in.) nominal maximum aggregate size, 15 percent reclaimed asphalt pavement (RAP) content, and PG 64-10 binder. A fiber-reinforced asphalt concrete (FRAC) was prepared by adding aramid fibers at a rate of 0.013 percent of total mix weight. The mechanical properties of the two mixes, original and FRAC, were determined in the laboratory. Based on laboratory testing, adding the fibers improved fatigue resistance of the original mix at high strain levels considerably. It also improved rutting resistance while only changing the stiffness a little. The added fibers did not negatively impact the compactability of the mix nor did it seem to change the mix volumetrics. The laboratory testing results indicate that adding aramid fibers would be of greatest value where asphalt is subjected to high strain levels, such as in overlays of jointed concrete pavements or in pavements with considerable cracking. This study did not consider any occupational health risks, environmental risks or cost considerations, effects on constructability (particularly compaction) in the field, or what effects added fibers might have on the ability to recycle fiber-reinforced asphalt pavement.

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It is recommended that the addition of aramid fibers be considered for applications where asphalt is subjected to high strain levels, such as overlays of jointed concrete pavements or pavements with considerable cracking.

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# DISCLAIMER



# ACKNOWLEDGMENTS

The research presented in this report was funded by Surface Tech. This support is greatly appreciated. Surface Tech also donated the aramid fibers (ACE XP Polymer Fiber™) used in this experiment. Asphalt mixes were produced and donated by Teichert Materials. The technical contributions from Dr. Joe Dennis (Surface Tech) and Dr. Phillip Blankenship are acknowledged and greatly appreciated.

# PROJECT OBJECTIVES

The goals of the research presented in this report are to determine how the addition of synthetic fibers to an asphalt mix typically used in California would impact the mix's mechanical performance, and, based on that impact, to recommend potential applications for the resulting fiber-reinforced asphalt concrete. This research is expected to contribute to filling a knowledge gap about how synthetic fibers can help improve the mechanical performance of typical California asphalt mixes.

# EXECUTIVE SUMMARY

The practice of using fibers to reinforce asphalt mixes has been around for decades. The goal of adding the fibers to dense-graded asphalt mixes is to improve the mixes' mechanical performance. Typically, synthetic polymer fibers are used for this purpose, and the resulting asphalt mix is referred to as *fiber-reinforced asphalt concrete* (FRAC).

Numerous experimental studies have shown that adding synthetic polymer fibers to dense-graded mixes can improve their mechanical performance, particularly with regard to rutting and fatigue resistance. Those studies' findings about improved FRAC performance raise the question: How much the mechanical performance of a dense-graded mix produced in large quantities in California could be improved with the addition of synthetic fibers? The research presented in this report is intended to contribute to answering that question.

The reference mix selected for this study was a Superpave mix with 19 mm (3/4 in.) nominal maximum aggregate size, 15 percent reclaimed asphalt pavement (RAP) content, and PG 64-10 binder. Aramid fibers, 0.013 percent over the weight of the mix (2.1 ounces per ton of mix), were added to the reference mix to produce a FRAC. Both the original mix and the FRAC were mixed in a plant. Test specimens were prepared in the laboratory.

Laboratory testing was conducted to determine the two mixes' stiffness, rutting resistance, and fatigue resistance. Based on the production quality control and the laboratory testing results, a number of conclusions were drawn regarding the aramid fibers' impact on the mechanical properties of the original asphalt mix.

- Dynamic modulus testing conducted in flexural mode between 10 and 30°C (50 and 86°F) and in compression mode between 4 and 40°C (39 and 104°F) indicated that the stiffness of the original mix was not impacted considerably by the added fibers.
- Four-point bending fatigue testing conducted at 20°C (68°F) indicated that the fibers considerably improved the fatigue life of the original mix at high strain levels. Fatigue life increased 90 and 200 percent, respectively, at 600 and 900 με (peak-to-peak strain). Conversely, no effect was observed at intermediate strain levels (300 and 400 με).
- Repeated load testing conducted with the asphalt mixture performance tester (AMPT) indicated that the added fibers improved the original mix's rutting resistance. With aramid fibers added, the number of load repetitions to reach 5 percent permanent deformation increased 46 and 18 percent, respectively, at 45 and 55°C (113 and 131°F).
- Adding the fibers to the original mix did not impact its compactability in the laboratory and did not seem to change its volumetrics.

Overall, adding the aramid fibers resulted in two improvements to the mechanical properties of the asphalt mix. The first was an increase in fatigue resistance at high strain levels, and the second was an increase in rutting resistance. At the same time, addition of fibers did not seem to produce any negative impacts on the asphalt mix's constructability or its volumetrics properties. Together, these three outcomes indicate that, based on the mechanical properties considered in this study, the applications that might most benefit from aramid fiber addition are those where asphalt is subjected to high strain levels, such as in overlays of jointed concrete pavements or overlays of pavements with considerable cracking.

It is recommended that field evaluation be conducted to assess the potential of aramid fibers to improve the reflective cracking resistance of dense-graded mixes. It is also recommended that future work consider any occupational health risks, environmental risks, cost considerations, and effects on constructability (particularly compaction) in the field, as well as any impacts on the future recyclability of fiber-reinforced asphalt concrete.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Asphalt concrete |
| AMPT | Asphalt mixture performance tester |
| FRAC | Fiber-reinforced asphalt concrete |
| 4PB | Four-point bending |
| NCHRP | National Cooperative Highway Research Program |
| OGFC | Open-graded friction course |
| RAP | Reclaimed asphalt pavement |
| SMA | Stone matrix asphalt |

# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| In | inches | 25.4 | Millimeters | mm |
| Ft | feet | 0.305 | Meters | m |
| Yd | yards | 0.914 | Meters | m |
| Mi | miles | 1.61 | Kilometers | Km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | Square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | Square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | Square meters | $m^2$ |
| ac | acres | 0.405 | Hectares | ha |
| $mi^2$ | square miles | 2.59 | Square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | Milliliters | mL |
| gal | gallons | 3.785 | Liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | Grams | g |
| lb | pounds | 0.454 | Kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9<br>or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | Lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | Newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | Kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | Inches | in |
| m | meters | 3.28 | Feet | ft |
| m | meters | 1.09 | Yards | yd |
| km | kilometers | 0.621 | Miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | Hectares | 2.47 | Acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | Milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | Gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | Ounces | oz |
| kg | kilograms | 2.202 | Pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | Poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

# 1 INTRODUCTION

## 1.1 Background

Fibers have been used to reinforce asphalt mixes for decades. A 2014 survey conducted as part of the development of NCHRP Synthesis 475, "Fiber Additives in Asphalt Mixtures," revealed that 30 out of 48 US states allow or require the use of fibers in some asphalt mixes *(1)*. The survey revealed that the most common application of fibers is for preventing asphalt binder draindown in stone matrix asphalt (SMA) and open-graded friction courses (OGFC). These two mix types are prone to asphalt binder draindown because they have a gapped or open aggregate gradation and a high asphalt binder content, and the cellulose or mineral fibers are used to prevent the draindown. The survey also revealed that the second most common application of the fibers is in dense-graded mixes. When added to these mixes, the fibers improve the mechanical performance. Synthetic fibers are typically used in this second application, and the resulting asphalt mix type is referred to as *fiber-reinforced asphalt concrete* (FRAC). Note that these synthetic polymer fibers should not be confused with cellulose fibers, which are more common. The polymer fibers are engineered to improve the mixture performance.

Numerous experimental studies have shown that the addition of synthetic polymer fibers can improve the mechanical performance of dense-graded mixes with unmodified asphalt *(1-11)*. Typical fiber doses range from 0.3 to 0.7 percent of the weight of the mix. Overall, laboratory and field studies generally tend to show an improvement in a mix's rutting and fatigue resistance, and an improvement in an asphalt mix's resistance to reflective cracking. The outcomes of the experimental studies are not consistent regarding the fibers' effects on asphalt mix stiffness. Conclusions from some of the experimental studies are listed below:

- Galinsky reported that use of a FRAC overlay on a severely cracked concrete pavement resulted in much less cracking (less than 50 percent) and much less severe cracking than in a reference section where the asphalt concrete was mixed without fibers *(2)*. The fiber use also resulted in a considerable improvement in asphalt rutting performance.
- Huang and White showed that synthetic fibers increased the laboratory fatigue life (flexural beam testing) of a conventional asphalt concrete by a factor of two *(3)*. In this particular case, adding the fibers also reduced the asphalt mix stiffness.
- Kaloush et al. conducted a comprehensive laboratory mechanical characterization of a FRAC and its unreinforced counterpart *(4)*. Testing results indicated that the fiber-reinforced mix showed considerably improved rutting and thermal cracking performance compared with the original mix. The mix stiffness increased due to the added fibers and the increase was larger at high than at low temperatures. The fibers' effects on flexural beam fatigue life were temperature-dependent: at 4°C (40°F), fatigue life improved

considerably (by a factor of 10) due to the addition of the fibers; however, the fibers did not impact fatigue life at 21°C (70°F) considerably.

- Xu et al. compared the laboratory performance of a FRAC with the performance of the original dense-graded mix *(5)*. The fibers included mineral and synthetic types. In this case, the fibers improved the rutting resistance, fatigue life, and toughness of the original mix considerably although the improvement was larger for the synthetic than for the mineral fibers.

Because of the increase in resistance to reflective cracking, FRAC has been used frequently for overlays of severely distressed concrete and asphalt pavements *(1)*. In these particular applications, FRAC performance has been shown to be comparable to the performance of asphalt concrete with polymer-modified binders. Conclusions from some experimental field studies are listed below:

- McDaniel and Shah conducted a field evaluation of alternative methods for improving asphalt mix rutting and cracking performance *(6)*. The alternatives included addition of synthetic fibers and polymer modification of the asphalt binder. Although all the resulting mixes presented similar good rutting performance, they also presented remarkable differences in terms of cracking performance. The fiber-reinforced asphalt mix showed better cracking performance than the original mix but did not match the performance of the polymer-modified binder mixes.
- Maurer and Malasheskie studied different options for preventing reflective cracking *(7)*. The options included use of fabric interlayer, stress-absorbing membrane interlayer, and FRAC. The FRAC mix presented the best reflective cracking performance in the field (a greater than 50 percent reduction compared to the reference mix).
- Anderson et al. studied different options for preventing rutting in asphalt concrete overlays *(8)*. The options included use of FRAC and polymer-modified asphalt concrete, and all the mixes performed well in terms of rutting in the field. In terms of fatigue and top-down cracking, the performance of the FRAC mix matched the performance of the mixes with polymer-modified binder.
- Gibson et al. *(9)* and Kutay et al. *(10)* evaluated the performance of a number of asphalt mixes under full-scale accelerated pavement testing with the Accelerated Loading Facility. The mixes included polymer-modified binders, rubberized binders, and synthetic polyester fibers. The fibers did not impact the rutting performance of the original mix but improved fatigue performance considerably. In fact, the fatigue performance of the FRAC mix was better than the fatigue performance of the mixes with polymer-modified binder. Furthermore, once fatigue microcracks appeared in the FRAC, they did not coalesce into larger cracks as occurred in the other mixes.

The design of asphalt mixes intended to reduce environmental asphalt paving's impacts, including warm mix technologies and high reclaimed asphalt pavement (RAP) content, is another field where synthetic fiber application can be relevant. For example, Giustozzi et al. showed that the proper addition of additives, polymer, and fibers improved the mechanical performance of a warm mix asphalt with 40 percent RAP *(11)* considerably.

Overall, experimental studies indicate that the addition of fibers seldom impacted asphalt mix mechanical performance negatively. Nonetheless, a number of studies showed that adding fibers either made compaction more difficult or increased the air-void content of the compacted mix *(3,12,13)*, which would be expected to reduce fatigue and reflective cracking performance in the field. One experimental laboratory study showed that synthetic fibers improved mix indirect tensile strength considerably although the improvement was only marginal after freezing and thawing *(5)*, an outcome attributed to the higher air-void content of the FRAC compared to the original mix.

Based on the literature review conducted in this research project, polyester, polypropylene, and aramid are the most common fibers in FRAC. These three are synthetic polymers. It would be difficult to determine if the three different synthetic materials produce different results in the asphalt mix because most of the experimental studies focused on a very limited number of mixes and fibers.

Because a number of studies verified the FRAC's good mechanical performance, a question has been raised about how much the addition of synthetic fibers would improve the mechanical performance of a dense-graded mix being produced in large quantities in California. This question is particularly interesting because of challenges the California road network currently faces, which includes the need to constantly meet increased user-demand with limited resources, the use of increasing amounts of reclaimed asphalt pavement, and the increasing need for asphalt overlays that must meet high mechanical standards. Unfortunately, there are several reasons that make it difficult to answer this question based on current state of the art. First, most of the experimental studies were based on a limited number of mixes and fibers, which makes it hard to extrapolate the results to other mixes. Second, outcomes from adding the fibers differed considerably from one experiment to another. And finally, to date, a fundamental understanding of the interaction between the fibers and the asphalt mix has not been achieved.

## 1.2 Project Objective

The goal of the research presented in this report is to determine how the addition of synthetic fibers would impact the mechanical performance of an example asphalt mix being used in California and, based on that impact, to identify potential applications for the resulting fiber-reinforced asphalt concrete. The study's objectives do not include testing or any consideration of occupational health risks, environmental risks, or cost considerations;

effects on constructability (particularly compaction) in the field; or the effects of added fibers on the ability to reclaim asphalt pavement that has fibers in it.

### 1.3 Scope

Due to time and budget limitations, this research study focused on a unique fiber type and a unique asphalt mix. The fiber material is *aramid,* a synthetic polymer of aromatic polyamides. Aramid fibers are a class of heat-resistant and strong synthetic fibers *(14)*. The results of this study should not be extrapolated beyond the use of this fiber and the fiber dimensions.

This study used one dense-graded asphalt mix, a Superpave dense-graded mix with 19 mm (3/4 in.) nominal maximum aggregate size, 15 percent RAP content, PG 64-10 binder, and siliceous aggregates. This mix type is commonly used in California.

# 2 EXPERIMENTAL DESIGN

## 2.1 Materials

### *2.1.1 Fibers*

The aramid name refers to "aromatic polyamide." The chain molecules in these fibers are highly oriented along the fiber axis and, as a result, a higher proportion of the chemical bonds contributes to the fiber's strength than in many other synthetic fibers *(14)*. Because of its high strength, the aramid fibers are used in ballistic protection, in heat and cut protection, in the automotive industry, in ropes and cables, in conveyor belts, and in other applications where high fiber strength is required *(15)*. Based on the manufacturer's specifications, this fiber's tensile strength is greater than 2,700 MPa (400,000 psi) (that is, around five times the strength of ASTM A36 structural steel). Table 2.1 includes the technical specifications of the fibers used in this particular research, as reported by the manufacturer. The material safety datasheet can be downloaded from manufacturer's web site *(16)*. Figure 2.1 includes pictures of the aramid fibers, and Figure 2.2 includes a picture of loose asphalt mix reinforced with aramid fibers.

**Table 2.1. Technical Specifications of ACE XP Polymer Fiber™ Aramid Fibers**

| Material Property | Measure |
|---|---|
| Material | Para-Aramid Fiber (50 – 52% by weight) |
| Form | Filament yarn |
| Tensile strength | > 2.758 GPa (400,000 psi) |
| Elongation at break | < 4.4% |
| Modulus | > 95 GPa (13.8 mill. psi) |
| Specific gravity | 1.44-1.45 (g/cm$^3$) |
| Decomposition temperature | > 427°C (800°F) |
| Treatment type | Sasobit® Wax (48 – 50% by weight) |
| Treatment melting temperature | > 77°C (170°F) |
| Length | 38 mm (1.5 in.) |
| Appearance/handling | Free-flowing coated fiber/Bundles (visual) |

*Note:* data source is Reference *(15).*

**Figure 2.1: Aramid fibers (left) and fiber bundles (right).**

**Figure 2.2: Asphalt mix reinforced with aramid fibers.**

### *2.1.2 Mixes*

As explained in the introduction, the mix selected for this study is a Caltrans Superpave dense-graded mix with 19 mm (3/4 in.) nominal maximum aggregate size, 15 percent RAP content, PG 64-10 binder, and siliceous aggregates. The design asphalt binder content is 4.9 percent (over total weight of mix). The target aggregate gradation is presented in Figure 2.3 together with results from the quality control testing conducted during field production verification.

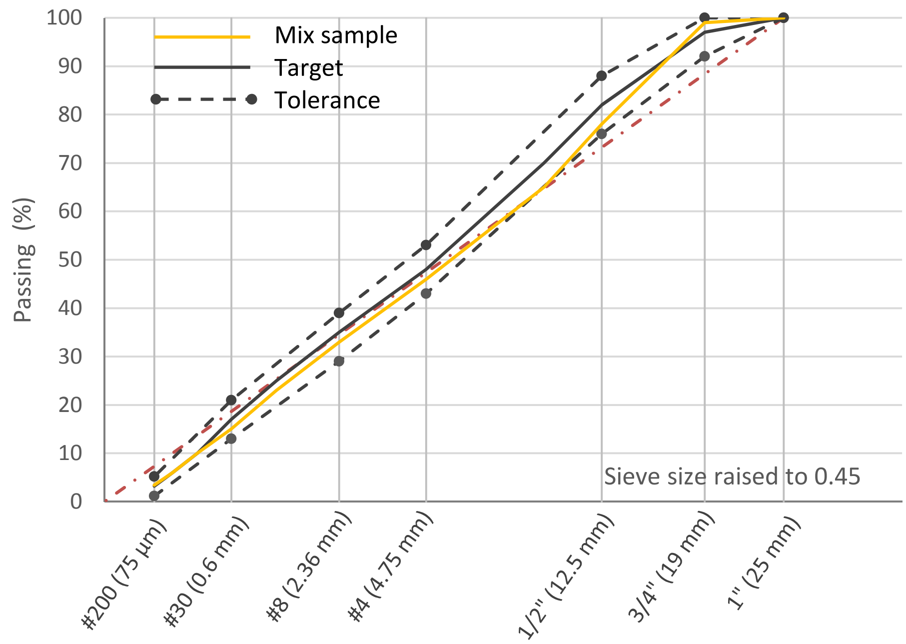


**Figure 2.3: Mix gradation.**

No specific mix design was conducted for the fiber-reinforced asphalt concrete (FRAC). Based on recommendations of the aramid fiber's producer, the fiber dose was 0.013 percent of the total mix weight. This dose corresponds to 4.2 ounces of aramid fibers with wax coating (2.1 ounces of aramid fiber) per ton of mix. The two mixes, the original asphalt concrete and the FRAC, differed only in the addition of fibers, with no change in mixture volumetrics. All the other job mix formula properties were the same, including aggregate gradation and asphalt binder content.

Both the original asphalt concrete and the FRAC were produced in the plant. Although producing an asphalt mix with fibers in the laboratory is an alternative, doing so would introduce uncertainty in the representativeness of the material produced. Loose mix samples were taken from the plant and then compacted in the laboratory to produce test specimens.

As explained in the introduction, a number of studies showed that the addition of fibers either made the compaction more difficult or increased the compacted mix's air-void content *(3,12,13)*. In this particular case, the addition of fibers did not seem to negatively impact mix compactability. The quality control conducted during field production verification resulted in very similar air-void contents for the two mixes: 3.5 percent (original mix) and 3.85 percent (FRAC). These air-void content values were based on gyratory specimens compacted at 85 (Ndes) gyrations. The addition of fibers did not seem to negatively impact the FRAC mix's moisture sensitivity since the indirect tensile strength ratio (AASHTO T 283) was very similar in the two mixes: 94 and 92 percent for the original mix and the FRAC, respectively. The two mixes' maximum relative density was also very similar: 2.477 (original mix) and 2.487 (FRAC). In summary, adding fibers to the original mix did not impact its compactability in the laboratory and did not seem to change its volumetrics. This outcome is likely related to the relatively low fiber dose, which was much lower than the doses typically used with other synthetic fibers.

## 2.2 Tests Conducted

A comprehensive laboratory characterization of the two mixes' mechanical properties was conducted. The characterization's goal was to determine the fundamental properties that can be directly related to performance: stiffness, rutting resistance, and fatigue resistance. The characterization included the variables and tests listed below:

- Flexural fatigue resistance, based on the four-point bending (4PB) fatigue test (ASTM D8237-18 and AASHTO T 321-14). Test temperature and frequency were, respectively, 20°C (68°F) and 10 Hz. Testing was conducted under sinusoidal controlled displacement.
- Flexural stiffness, based on the four-point bending frequency sweep test (ASTM D7460-10 and AASHTO T 321-14). Test temperature and frequency ranges were, respectively, 10 to 30°C (50 to 86°F) and 0.01 to 15 Hz.
- Stiffness and rutting resistance, based on dynamic modulus and repeated load triaxial testing using the asphalt mixture performance tester (AMPT, AASHTO T 378-17). Test temperature and frequency ranges for the stiffness tests were, respectively, 4 to 40°C (39 to 104°F) and 0.1 to 25 Hz. Rutting resistance was determined with unconfined repeated loading test at 45 and 55°C (113 and 131°F).

All test specimens were compacted to 6±0.5 percent air-void contents, which were determined following AASHTO T 331-13 (Corelok). Beams were cut from slabs that were compacted with a rolling wheel compactor (Figure 2.4). The compaction of the fiber-reinforced asphalt did not seem to differ from the compaction of the original mix. The same number of rolling wheel passes were applied to the two mixes in order to achieve the target air-void content.


**Figure 2.4: Rolling wheel compaction.**

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# 3 RESULTS AND DISCUSSION

The dynamic modulus of the two asphalt mixes, the original asphalt concrete (AC) and the fiber-reinforced asphalt concrete (FRAC), is shown in Figure 3.1 (4PB test) and Figure 3.2 (AMPT test). Based on these figures, the addition of the fibers did not impact mix stiffness at intermediate and low temperatures, although it produced some stiffening effect at high temperatures (see Figure 3.2, 40°C/104°F tests). The increase in stiffness at high temperatures is expected to help the FRAC mix resist rutting.

As explained in the introduction, laboratory studies showed contradictory results on the effect that adding synthetic fibers has on asphalt mix stiffness. Some laboratory studies—such as the one conducted by Huang and White *(3)*—indicated a drop in stiffness, while others—such as the study conducted by Kaloush et al. *(4)*—showed the opposite. It should be noted that Huang and White used polypropylene fibers while Kaloush et al. used a combination of polypropylene and aramid fibers. The Kaloush et al. study indicated that the stiffening effect was larger at high than at low temperatures, an outcome that agrees with the results shown Figure 3.2.

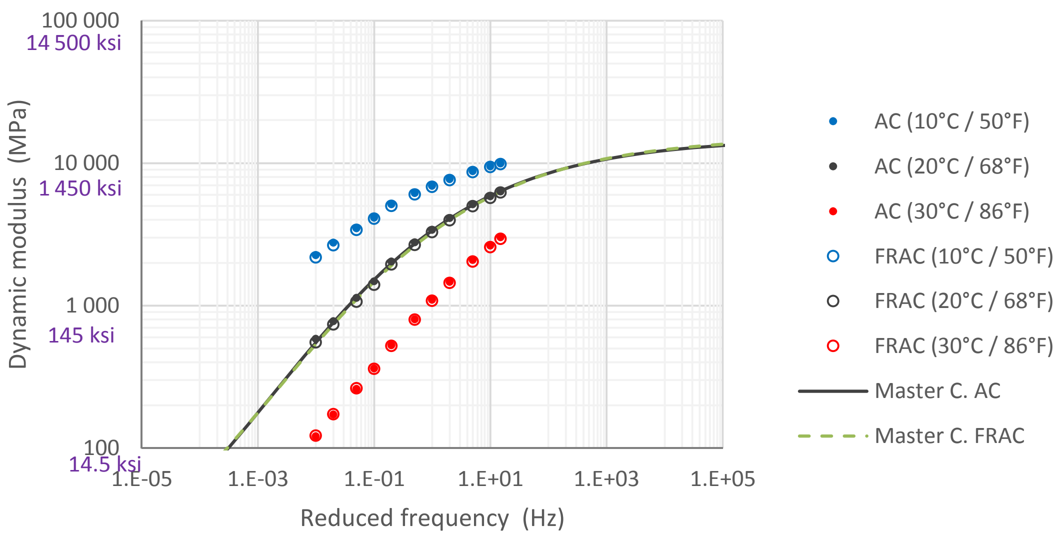



**Figure 3.1: Stiffness of the asphalt mixes (4PB flexural beam test).**

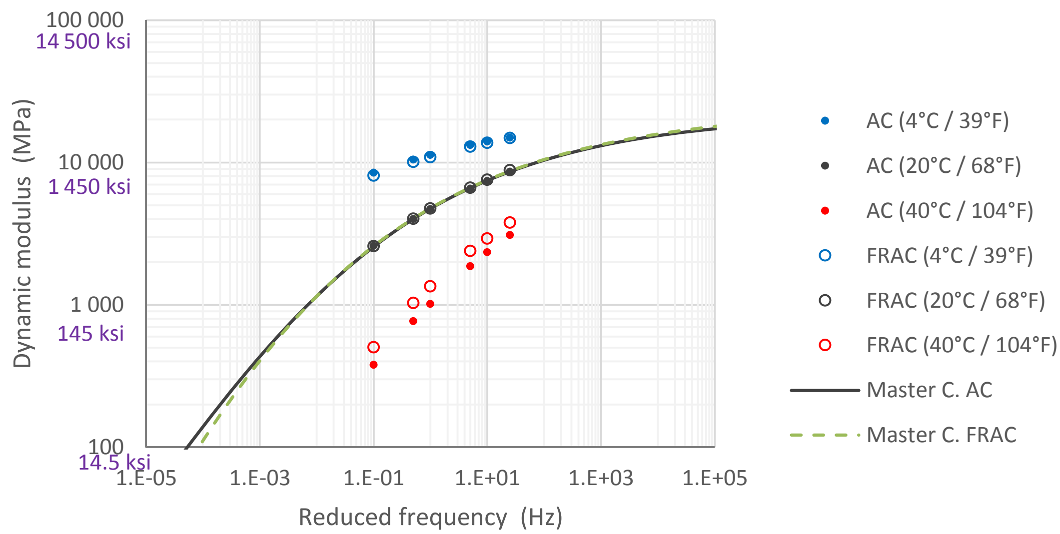
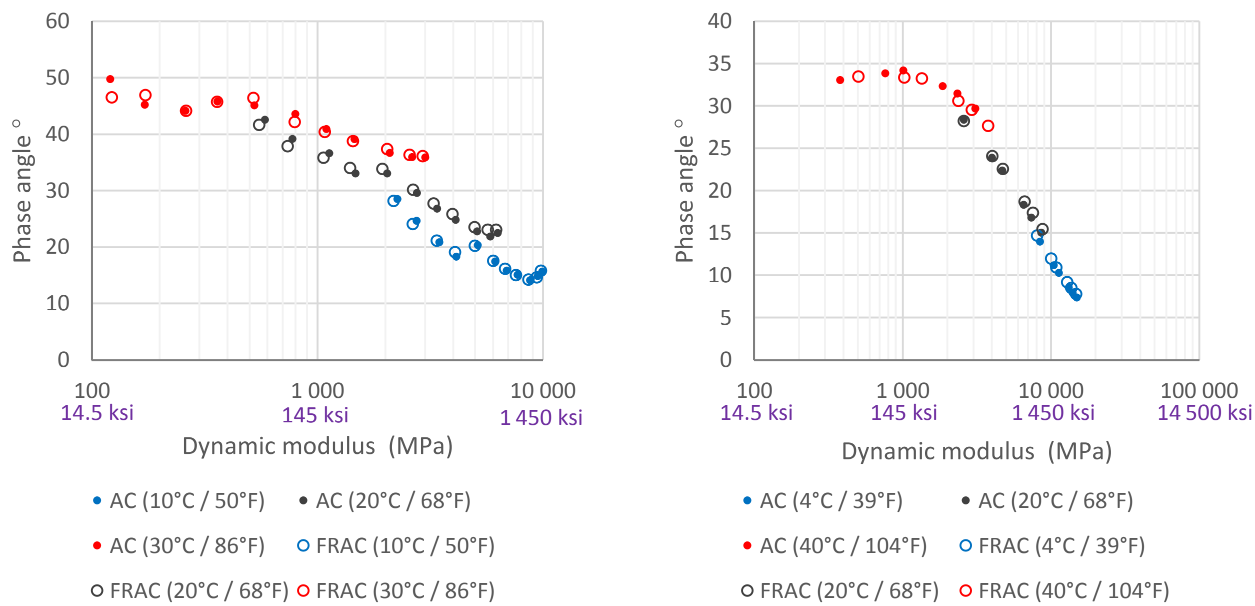



**Figure 3.2: Stiffness of the asphalt mixes (AMPT test).**

Addition of the fibers did not seem to impact the phase angle of the asphalt mix. When plotted in Black space (dynamic modulus versus phase angle), the original mix and the FRAC seemed to follow the same pattern (Figure 3.3).




**4PB testing (flexural)** **AMPT testing (compressive)**

**Figure 3.3: Stiffness of the asphalt mixes in the Black space.**

Three strain levels were initially applied in order to test the two mixes' fatigue resistance: 300, 400, and 600 με (peak to peak). At the two lower strain levels, 300 and 400 με, the fibers did not seem to impact the asphalt mix's fatigue life. However, Figure 3.4 shows that at the 600 με strain level, addition of the fibers resulted in a 90 percent increase in fatigue life. After these results were obtained, a decision was made to conduct additional testing at 900 με to verify that the impact on fatigue resistance was strain-dependent. This additional testing confirmed the strain sensitivity of the fibers' reinforcing effect: at 900 με, addition of the fibers resulted in a 200 percent increase in asphalt mix fatigue life. A strain level as high as this may occur in asphalt overlays of jointed concrete pavements or on overlays of pavements with considerable cracking *(17-19)*. Importantly, this indicates that the addition of the aramid fibers to the asphalt mix should provide improved resistance to cracking when subjected to high strains in the field as seen in reflective cracking.

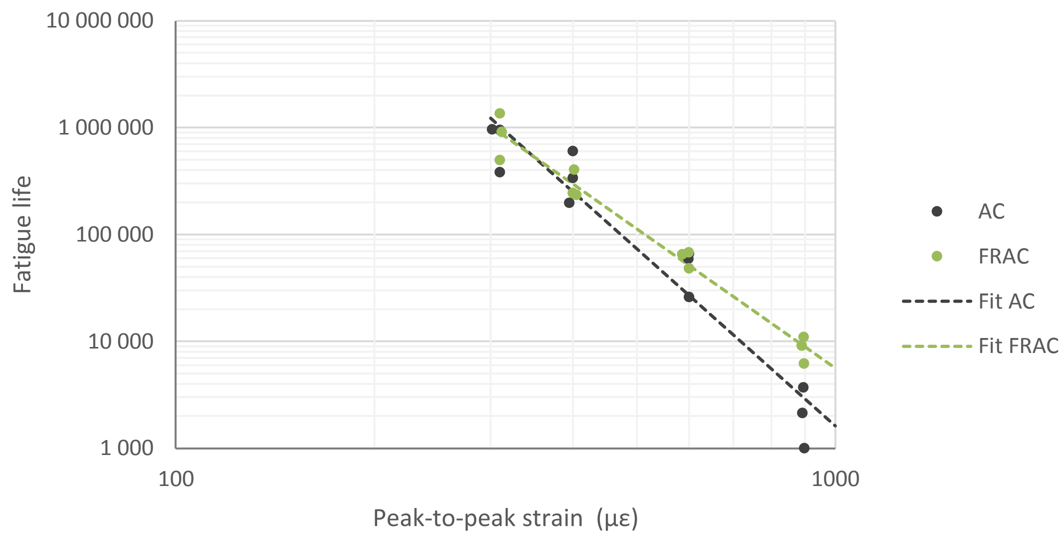



**Figure 3.4: Fatigue resistance of the asphalt mixes (4PB flexural beam testing, 20°C/68°F and 10 Hz).**

Because adding the fibers impacted the fatigue resistance at high strain levels considerably, a decision was made to test the original mix and the FRAC in semicircular bending following the Illinois Flexibility Index Test (AASHTO TP-124). Two parameters are determined from this test: the fracture energy and the flexibility index *(20)*. However, the results from this testing were not sensitive to the fibers' reinforcing effect.

The strain sensitivity of the stiffness of the two asphalt mixes was evaluated based on the stiffness measured at Cycle 50 of the 4PB fatigue tests. The results are presented in Figure 3.5. As this figure shows, the two mixes presented little strain sensitivity since the stiffness did not change much with the strain level. Again, the addition of the fibers did not seem to impact asphalt mix stiffness at intermediate temperatures since similar stiffness values were obtained for the two mixes.

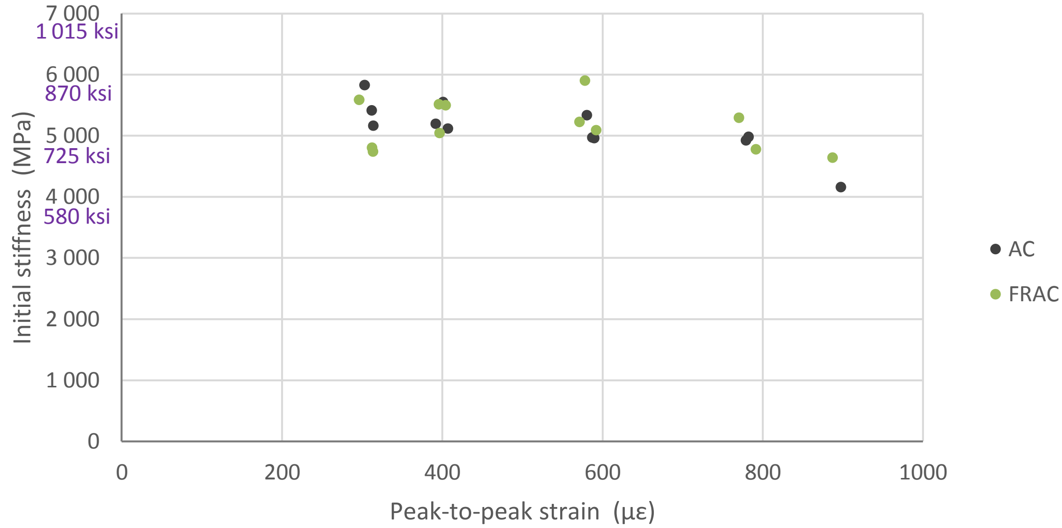
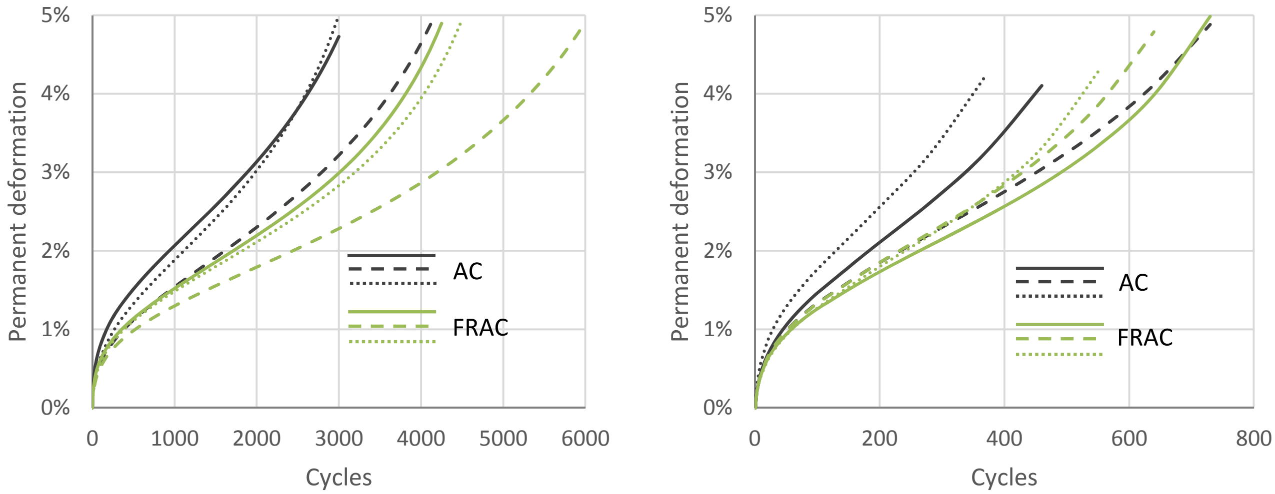



**Figure 3.5: Strain sensitivity of the stiffness of the asphalt mixes (4PB flexural beam testing, 20°C/68°F and 10 Hz).**

The mixes' resistance to permanent deformation was tested with the unconfined repeated loading test at 45 and 55°C (113 and 131°F). The results are shown in Figure 3.6. Adding the fibers increased the mix's resistance to permanent deformation considerably. At 45°C (113°F), the number of load repetitions to reach 5 percent permanent deformation increased 46 percent (FRAC versus the original mix), while the increase was 18 percent at 55°C (131°F). The fact that the increase was larger at 45°C than at 55°C may be related to the stronger adhesion between the fibers and binder at 45°C compared to 55°C.

Overall, the addition of the aramid fibers resulted in two improvements in the mechanical properties of the asphalt mix. The first was the increase in fatigue resistance at high strain levels. The second was the increase in rutting resistance. At the same time, the addition of the aramid fibers did not seem to produce any negative impact on asphalt mix constructability or volumetric properties. Together these outcomes indicate that, based on the mechanical properties considered in this study, the best use of FRAC is in applications where the asphalt is subjected to high strain levels, such as overlays of jointed concrete pavements or overlays for pavements with considerable cracking.




**45°C (113°F)** **55°C (131°F)**

**Figure 3.6: Permanent deformation of the asphalt mixes (AMPT repeated loading testing).**

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# 4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The laboratory research project presented in this report shows the effects that adding aramid fibers has on the mechanical properties of a dense-graded mix used in California, a Superpave mix with 19 mm (3/4 in.) nominal maximum aggregate size, 15 percent RAP content, and PG 64-10 binder. The aramid fibers, 0.013 percent of the total weight of the mix, were added to a reference mix to produce a fiber-reinforced asphalt concrete (FRAC). Both original mix and the FRAC were mixed at the plant and sampled to prepare testing specimens in the laboratory. Laboratory testing was conducted to determine the two mixes' stiffness, rutting resistance, and fatigue resistance. Based on production quality control and the laboratory testing results, a number of conclusions were drawn regarding the impact of the aramid fibers on the mechanical properties of the original asphalt mix.

- Dynamic modulus testing conducted in flexural mode between 10 and 30°C (50 and 86°F) and in compression mode between 4 and 40°C (39 and 104°F) indicated that the stiffness of the original mix was not impacted considerably by the addition of the fibers.
- Four-point bending fatigue testing conducted at 20°C (68°F) indicated that the fibers considerably improved the fatigue life of the original mix at high strain levels. Fatigue life increased 90 and 200 percent, respectively, at 600 and 900 $\mu\varepsilon$ (peak-to-peak strain). Conversely, no effect was observed at intermediate strain levels (300 and 400 $\mu\varepsilon$).
- Repeated load testing conducted with the AMPT indicated that the addition of the fibers improved the rutting resistance of the original mix. The number of load repetitions to reach 5 percent permanent deformation increased 46 and 18 percent, respectively, at 45 and 55°C (113 and 131°F).
- Adding fibers to the original mix did not impact its compactability in the laboratory and did not seem to change its volumetrics.

Based on the results of the laboratory testing, it appears that applications that might benefit the most from the addition of aramid fibers are those where the asphalt is subjected to high strain levels, such as in overlays of jointed concrete pavements or overlays of pavements with considerable cracking.

It is recommended that field evaluation be conducted in order to assess the potential of the aramid fibers to improve the reflective cracking resistance of dense-graded mixes. It is also recommended that future work consider any occupational health risks, environmental risks, cost considerations, and effects on constructability (particularly compaction) in the field, as well as on the ability to reclaim fiber-reinforced asphalt concrete in the future.

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