Material and Structural Characterization of Fiber-reinforced Asphalt Pavements in Pennsylvania Using Forta Fiber Products

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Disclaimer

BACKGROUND

The pavement distresses impose maintenance and rehabilitation costs on road authorities. Improving the design protocols and quality of materials used in asphalt pavements leads to reduced maintenance and construction costs and helps to preserve the environment. To this end, reinforcing the asphalt mixtures using fibers is a promising solution. A homogeneous blend between fibers and other asphalt ingredients can improve the structural integrity of the asphalt mixtures to resist heavy loads in hot summers and offer crack-pinning ability in harsh winters. The fibers need to be chemically and physically compatible with the asphalt binder and aggregate. To address this concern, lab performance tests have been developed and used to evaluate the performance of asphalt mixtures by mimicking the field conditions. For a fiber product to be commercially competitive and recognized as a viable additive, the fiber-modified asphalt mixture needs to be examined using performance tests. Through this work, several performance tests were conducted on fiber-modified asphalt mixtures to assess the improvement level in performance. Enhanced pavement performance through additives such as fiber reduces maintenance costs due to the extended service life of the pavement. This research was undertaken through an agreement with Carnegie Mellon University to evaluate specifics fibers produced by Forta Corporation, a Pennsylvania based company. Forta has been one of the major players in providing fibers to the asphalt industry for use in the construction of asphalt mixtures.

OBJECTIVE AND SCOPE OF WORK

The objective of this work was to evaluate laboratory performance of asphalt concrete modified through fiber reinforcement. Fiber incorporation can result in lower thicknesses and/or longer service lives of the fiber-modified asphalts as compared to the control (without fiber) asphalt mixes. It was also the objective of this work to determine any changes in the asphalt binder performance grade as a result of replacing the regular polymer (virgin polyolefin) that accompanies the fiber in the asphalt mix with recycled plastic polymer (recycled polyolefin).

The work included two parts: 1) studying binders modified with the virgin polyolefin and recycled polyolefin, and 2) studying mixture performance characteristics when modified with fiber. The binder study included a complete battery of aging and rheological testing at high, intermediate, and low temperatures for grading the binder according to AASHTO M 320 specification. It also included testing the binder under multiple stress creep recovery (MSCR) to grade it under AASHTO M 332 specification before and after modification with polyolefin polymer.

The mixture performance testing included Hamburg Wheel Tracking (HWT), IDEAL-CT and IDEAL-RT. The HWT was used to evaluate the mixture for rutting and moisture damage. The IDEAL-CT was conducted at 25 ºC at various displacement rates to capture the effect of loading speed on the cracking response. The IDEAL-RT was conducted at high temperature to evaluate the rutting characteristics.

LITERATURE REVIEW

Asphalt mixtures are paramount in pavement construction, prevalent across highways to airfields due to their durability and noise-reducing properties. However, these mixtures often suffer from distresses exacerbated by increased traffic and environmental conditions, necessitating enhancements via additives which improve tensile and shear strength and reduce deformation risks. Researchers and practitioners have been diligently working toward enhancing the performance of asphalt pavements. A multitude of studies indicates that various additives such as polymers, fibers, anti-stripping agents, rubber, rejuvenators, and nanomaterials are incorporated into asphalt binders and mixtures. These additives are aimed at optimizing the overall efficacy and longevity of asphalt pavements.

The incorporation of fibers into asphalt mixtures serves to enhance their mechanical performance significantly. When fibers are integrated into asphalt mixtures, they serve as reinforcing materials, enhancing the cohesion of the mix. Fibers are mainly used to increase the mixture's resistance to deformations and cracks while improving its moisture resistance and freeze-thaw resilience. Fibers can also function as stabilizers, mitigating the drain-down effects in asphalt mixtures, particularly in Stone Matrix Asphalts (SMAs) and porous asphalt formulations, which are traditionally high in asphalt binder content. The relevant literature categorizes fibers as natural, synthetic, and waste-derived, each with specific properties influencing asphalt performance. Notably, the interaction of fibers with other modifiers creates synergistic effects that enhance the pavement's properties.

In asphalt road construction, the incorporation of fibers has been proved to be a viable method to enhance cracking performance. These fibers function as reinforcement elements within the asphalt matrix, serving to mitigate the propagation of cracks and improve the road's durability. When subjected to traffic-induced stresses and thermal cycling, the fibers restrain crack formation and reduce crack width, enhancing the road's resistance to reflective cracking, fatigue cracking, and thermal cracking. Furthermore, the fibers enhance the cohesion and tensile strength of the asphalt binder, thereby reducing susceptibility to moisture damage and promoting the overall longevity and structural integrity of asphalt pavements.

Natural Fibers: Including but not limited to bamboo, coconut, jute, and sisal, these fibers are sourced from plant materials and have historical precedence in construction. They offer environmental benefits but vary widely in effectiveness and durability based on their absorption and tensile properties.

Synthetic Fibers: These are manufactured fibers like polypropylene, polyester, and carbon fibers, known for their strength, stability, and resistance to environmental factors. Their use in asphalt mixtures leads to improved performance across various metrics, including stability and moisture resistance.

Waste-Derived Fibers: Utilizing recycled materials such as tire rubber, carpet residues, and even cigarette butts, waste-derived fibers contribute to sustainable construction practices by reducing landfill waste and enhancing asphalt mixture performance in specific applications.

The effectiveness of fibers is not only contingent on their properties but also on their interaction with other additives. This includes crumb rubber and polymers which, when combined with fibers, may further enhance the asphalt's resistance to various distresses. These combinations are crucial for tailoring asphalt mixtures to specific environmental conditions and loading scenarios.

The integration of fibers, especially from waste materials, presents a significant opportunity for advancing sustainable asphalt technologies. Future research is directed towards optimizing fiber content, studying the long-term effects of fibers in asphalt, and exploring new combinations of fibers and other eco-friendly materials to enhance pavement performance and sustainability.

There have been a number of studies dealing with the effect of fiber on the engineering properties of asphalt concrete and its performance. The fiber has not only been used in warm and hot mix asphalt but also in microsurfacing, seal coats, and cold mixes. However, its application in warm and hot mix is more widespread as compared to other applications. Application of fibers in microsurfacing could be found in reports by Solaimanian and Milander (2016), Solaimanian and Milander (2017), and Solaimanian et al. (2021). Usage in seal coating is covered in Solaimanian (2016). The work with Solaimanian and Milander (2020) with fiber modified cold asphalt mixes showed improved rutting resistance in Hamburg Wheet Tracking Device and improved fracture energy and flexibility from IDEAL-CT test when compared with no-fiber cold mixes (Figures 1 and 2).

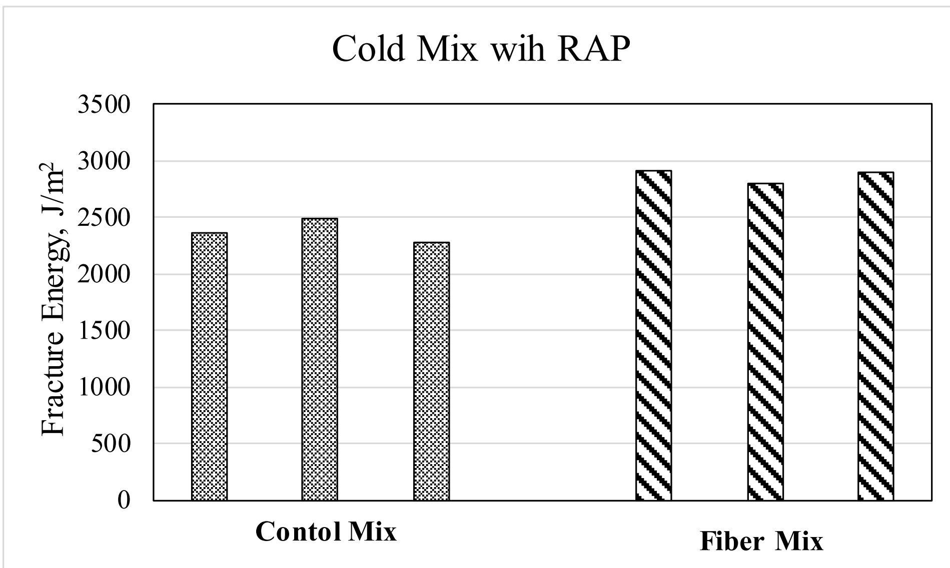

Figure 1 Comparison of Fracture Energy between Control Mix and Fiber Mix (Solaimanian & Milander, 2020)

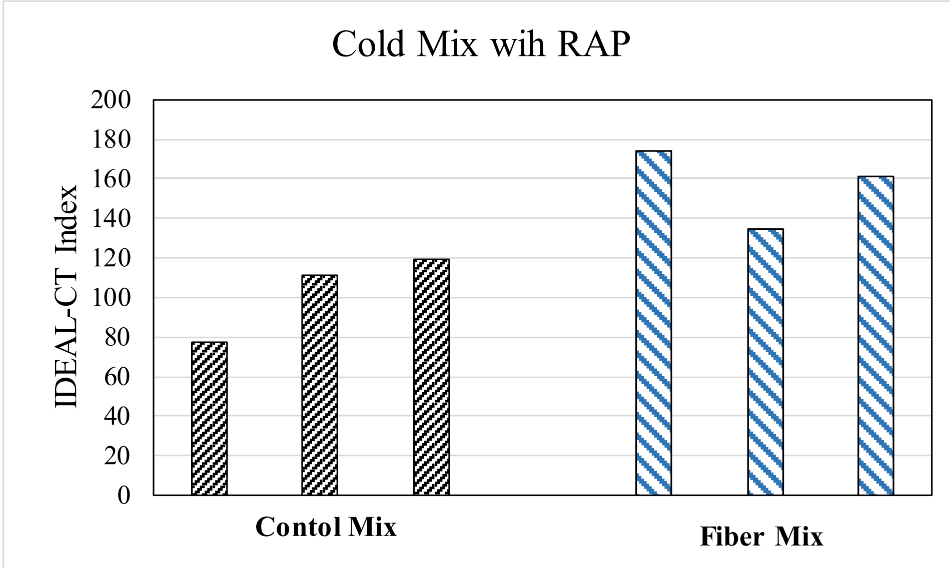

Figure 2 Comparison of IDEAL-CT Index between Control Mix and Fiber Mix (Solaimanian & Milander, 2020)

Carlo et al (2023) studied synthetic fibers at two dosage rates (0.05 and 0.10% by weight of the aggregate) with cold recycled asphalt mixtures. They noticed that there was no difference in the indirect tensile strength and stiffness between the control mix and the mix with 0.05% dosage rate but there was a substantial decrease of both properties at 0.1% dosage rate. The researcher also did repeated cycles of indirect tensile fatigue test and concluded improved fatigue life of the fiber modified cold recycled asphalt mixes compared with the control mix.

Using Model Mobile Load Simulator (MMLS3), Solaimanian and Milander (2015) found improved rutting resistance of the fiber-modified asphalt concrete compared with the control (no-fiber) mix. The accumulated rutting between 300,000 and 325,000 cycles of loading in MMLS3 was 5 mm for the slab made with fiber-reinforced asphalt compared with 10 mm for the control slab after adjusting for temperature variations.

Lee at al. (2005) studied the use of recycled carpet fibers on fracture energy of asphalt concrete. First, through the pull-out test, they determined the critical fiber embedded length to be 9.2 mm. Then, they used two lengths, 6 and 12 mm, and three volume fractions (0.25, 0.5, and 1%) in the asphalt mixture. Testing the specimens in the indirect tension test delivered 85% higher fracture energy than non-fiber reinforced specimens. Based on these results, the authors concluded potential for improved asphalt concrete fatigue life through the use of fibers.

Kaloush et al. (2010) studied laboratory performance of fiber-reinforced asphalt concrete through a variety of tests including triaxial shear strength, repeated load permanent deformation, dynamic modulus, flexural fatigue, and crack propagation. The researchers reported performance improvement across the board from these tests compared to the control mix: better resistance to shear deformation, lower permanent deformation, higher dynamic modulus, improved cracking resistance at low strain levels, higher strength and facture energy, and finally higher resistance to crack propagation.

In a similar study, Karanam and Underwood (2024) evaluated characteristics and performance of fiber-modified asphalt mixes. The researchers conducted engineering tests using Asphalt Mixture Performance Tester (AMPT) and captured properties such as dynamic modulus, stress sweep rutting, and cyclic fatigue resistance. They used the properties in the FlexPAVE™ software and made a prediction of performance to compare between the control (no-fiber) asphalt mixes and fiber-reinforced asphalt mixes. Their conclusion was that the fiber-reinforces asphalt mixes could enhance the fatigue resistance of the mix and provide better resistance to damage growth. Their prediction models indicated longer term performance of fiber-reinforced mixes compared with the control mixes.

EXPERIMENT PLAN

General

With the project goal in mind, a feasible experimental plan was developed to include laboratory tests on both asphalt binders and mixtures. To characterize the interactions between asphalt binders and fibers and to capture the performance at low and high temperatures, rheological and multi-stress creep recovery (MSCR) tests were conducted using a dynamic shear rheometer (DSR) and bending beam rheometer (BBR). Following binder characterization, testing of asphalt concrete mixtures was conducted to obtain engineering properties of the mixtures. Several performance tests were conducted on asphalt concrete specimens. The tests included Hamburg wheel tracking, IDEAL-CT, and IDEAL-RT tests. The IDEAL-CT tests were conducted at different displacement rates to determine the appropriate loading speed at which the effect of fiber reinforcement can be demonstrated. Table 1 indicates the testing matrix for this research.

Table 1 Variables included in the experimental plan.

Parameter	Number of Specimens	Description
Performance Test	3	HWT, IDEAL-CT and IDEAL-RT
Loading Rate	4	50, 30, 25, and 1 mm/min
Mixture	2	Fiber-modified, and control
Temperature	3	25, 50, and 54 °C depending on the test type
Aramid Fiber + Polyolefin	2	Virgin and recycled

The research team procured the raw materials needed to complete the experimental plan proposed for this study. The material collection included the aggregates, liquid binder, reclaimed asphalt pavement (RAP), and fibers. A total of 64 gyratory compacted specimens were prepared to complete the required performance test. The aggregates and RAP were received from local asphalt plants. The aramid fiber and the polyolefin polymers (both virgin and recycled) were provided by Forta Corporation. Before the mixing process started, the research team obtained the instructions from Forta and followed these instructions in preparing the specimens.

Materials and Mix Design

Virgin Binder Sources

The asphalt binder PG 64S-28 from United Refineries was used to prepare all asphalt mixture specimens.

Aggregate Sources

One type of virgin aggregate was included in the study. It was a limestone aggregate from an approved local quarry source in Pennsylvania.

Antistripping Agent

The liquid antistripping agent used in this work was from Ingevity, promoted under the term J1.

RAP

Material from a single RAP source was used for the mixture study. The gradation of the RAP before and after oven-burn extraction is provided in Figure 3.

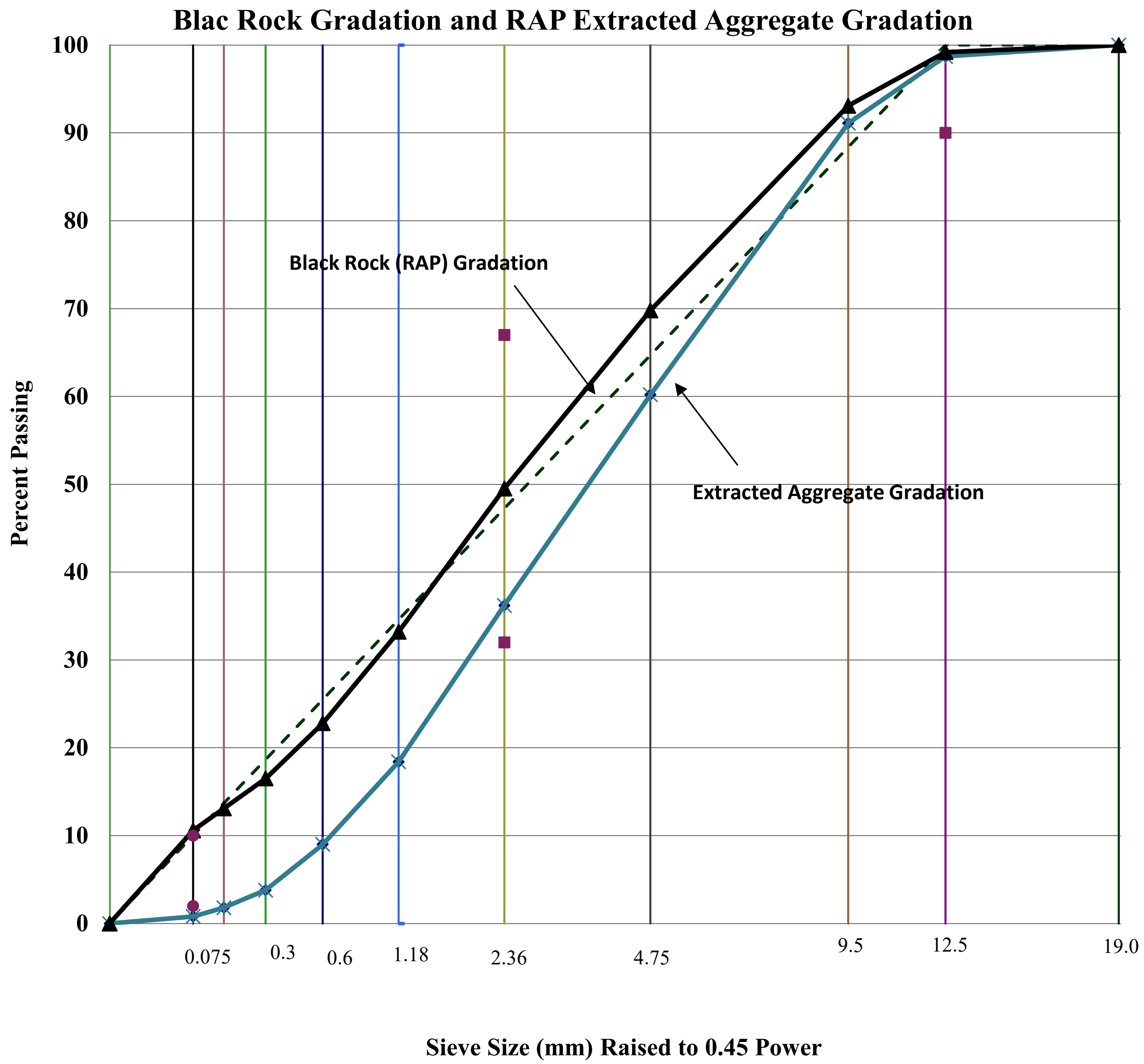

Figure 3 Particle size distribution for RAP (black rock) and RAP-extracted aggregate

Mix Design

A dense graded 9.5 mm Superpave mix with 15% RAP was used throughout the research. Gradation of the combined aggregate is presented in Figure 4 .

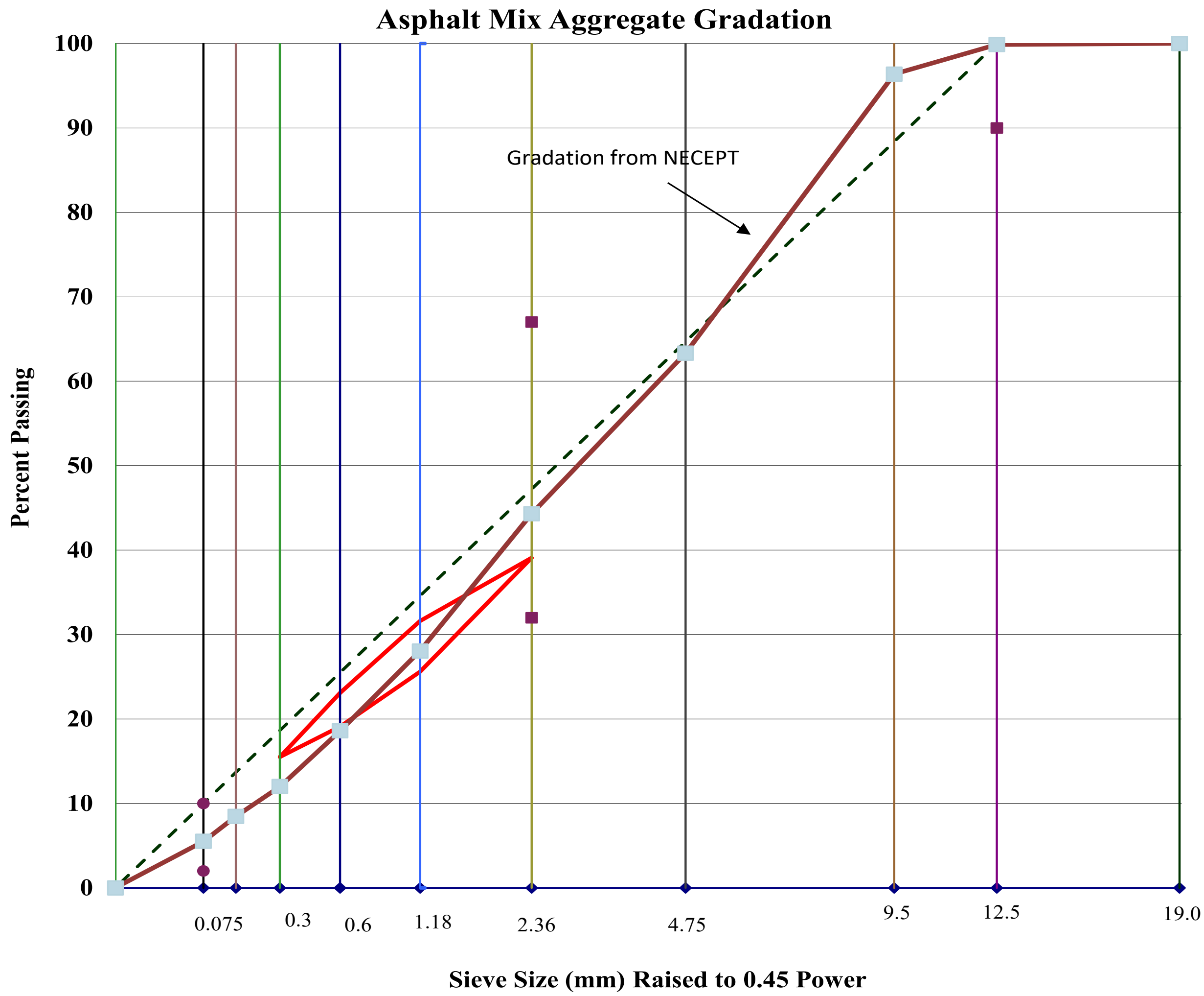

Figure 4 The aggregate gradation used for the 9.5-mix of this research

Preparation of Fiber-Modified Specimens for Binder Rheological Testing

This study included investigating the effect of the polyolefin polymer on the binder performance grade. A virgin PG 64S-22 binder was selected for this purpose. This is the same binder that was used to prepare asphalt mixture specimens for performance testing. The procedure followed in preparation of the modified binder is explained subsequently.

The binder was heated in the oven at 135 ºC until fluid enough to pour. A calculated amount of antistrip Evotherm J1 was placed in an empty can at a dosage rate of 0.25% by mass of the binder.

During the time, the binder was being heated in the oven, the virgin and recycled plastics (polyolefin) were weighed. The plastics were weighed in proportion to the same weight used in the asphalt mixture specimens of both IDEAL and Hamburg test specimens. When the binder was heated thoroughly, it was weighed into cans containing the antistrip agent. Immediately after weighing the binder into each can, the virgin and recycled polymers were slowly added and stirred with a spatula until fully blended. The blending process took less than 2 minutes. After blending the plastics, some of the binder was short-term aged using the rolling thin film oven (RTFOT) and some was long-term aged for 20 hours using the pressure aging vessel (PAV). The prepared binder samples were tested in the dynamic shear rheometer and bending beam rheometer for determination of the grade in the DSR and BBR.

Preparation of Specimens for Mixture Performance Testing

Mix preparation instructions were provided by Forta Corporation. The instructions included the process of incorporating the aramid fiber and the polyolefin polymer into the aggregate blend and mixing with the binder. The binders were heated in an oven at 150 °C and the virgin aggregates were heated in an oven at 160 °C before mixing. The asphalt loose mixtures were prepared with and without fiber and polyolefin polymer. The specimens without fiber were used as control mixtures. The prepared asphalt mixtures were cured in an oven for 2 hours at 150 °C before compaction. Before preparation of the compacted specimens for performance testing, the mix design was verified at 75 gyrations. For IDEAL-CT and Hamburg test specimens, the asphalt mixtures were cured in an oven for 4 hours at 135 °C, then heated to 150 °C for 1 hour before compaction.

All specimens were cylindrical and compacted using a Superpave gyratory compactor (SGC). The performance test specimens were prepared in the disk-shaped geometry, 150 mm in diameter and 60±2 mm thick. For both Hamburg wheel tracking and IDEAL-CT test, the specimens were prepared at 7.0±0.5%. For IDEAL-CT index test, the target air void was 5.5±0.5%.

Incorporating Fiber and Polymer into the Mixture

For laboratory mixing and compaction of both IDEAL and Hamburg specimens, the following steps were taken for preparation, mixing and compaction. The Laboratory Sample Mixing Guide provided by Forta was slightly altered as needed after the initial set of specimens were made. The amount of fiber in the asphalt mixture was 0.0066% and the amount of the polyolefin polymer was 0.0434% , by the weight of the mix. The total was 0.05% by weight of the asphalt mix. That translates into one pound of the combined fiber and polymer in one ton of the asphalt mix during field production.

The mass of material needed for a typical IDEAL-CT or HWT specimen is roughly 2,400 grams. The first specimen for performance testing was prepared in the presence of the Forta representative. The following are the steps for batching and preparation of the test specimens.

- The aramid fiber was weighed into two separate containers, half of the sample weight in each container. The total aramid weight per specimen was 0.17 grams (hence, 0.085 grams of aramid in each container). A weight of 1.101 grams polyolefin polymer was weighed into a single container for mixing and preparing each specimen. The fiber and polymer were weighed out according to the percentages given by Forta.
- The aggregate batches were weighed into coarse and fine trays, one tray of coarse and one tray of fine for each test specimen. The coarse portion contained all aggregate retained on the 2.36-mm sieve, while the fine portion contained all aggregate passing the 2.3-6mm sieve. This asphalt mix contained 15% RAP. The RAP was also split into two contained, one for the RAP retained on the 2.36-mm sieve and the other for the RAP passing the 2.36-mm sieve.
- After all of the necessary containers were prepared and weighed, they were placed in the oven at 156 °C, i.e., 6°C higher than typical mixing temperature. This increase was to compensate for heat lost while adding fibers. The aggregate trays were heated in the oven overnight to bring the aggregate to the proper mixing temperature.
- Approximately 1 hour before mixing, the binder with the required amount of antistrip was heated in the oven to mixing temperature.
- During this time of heating the binder, the mixing bucket and other necessary mixing tools were heated to the mixing temperature.
- Approximately 30 minutes before mixing, the trays of RAP were heated in the oven at 110°C for 30 minutes each before mixing.
- After the binder reached the mixing temperature, the coarse aggregate and coarse RAP were added to the mixing bucket in layers, with each layer being 1/3 of the coarse material. After placing the first layer of coarse aggregate, half of the aramid fibers were added. This step was followed by placing the second layer of coarse aggregate and the coarse RAP. Afterwards, the second half of the aramid fibers was added, and followed by the final layer of the coarse aggregate and coarse RAP.
- After adding the coarse material and aramid fibers, a crater was formed in the middle of the aggregates, using caution not to stir the fiber and aggregates.
- The addition of the binder was then added to the crater formed in the aggregates.
- After adding the binder, the polymer was added to the mixing bucket, sprinkling them directly onto the binder.
- The coarse material in the bucket was then mixed for roughly two minutes.
- The fine aggregates and fine RAP were then added to the mixing bucket. The material was then mixed for an additional 3 minutes to ensure proper blending.

- After mixing, the entire material was transferred to a conditioning tray, making sure all of the material from within the mixing bucket was transferred to the tray. The tray was then placed in an oven at 135°C for 2 hours of conditioning.
- After 2 hours of conditioning, the material was transferred into another oven at 145°C, the compaction temperature for this asphalt mixture. The tray was in this oven for an additional one hour before compaction of the asphalt mixture.
- These steps were followed for each additional test specimen that was prepared and compacted in the laboratory.
- After compaction of each test specimen, they were cooled to room temperature and then tested for their air voids.
- After testing for air voids, each specimen was then air dried in front of a fan for an additional 24 hours to ensure the specimen was dry before testing.

Description of Performance Tests

After completion of mix design verification, specimens were prepared using the Superpave gyratory compactor to conduct performance tests following the preceding detailed process. The tests included the Hamburg wheel tracking (HWT) test and indirect tensile asphalt cracking test (IDEAL-CT).

HWT

AASHTO T 324 was followed for testing the mix resistance to moisture damage and rutting under wheel tracking. Testing was conducted on specimens when submerged in water at 50 °C and subjected to 20,000 wheel passes. Replicate specimens were prepared using the gyratory compactor. The specimens were trimmed at the sides and were paired to deliver the required track. Two tracks were generated out of four compacted specimens (Figure 5).

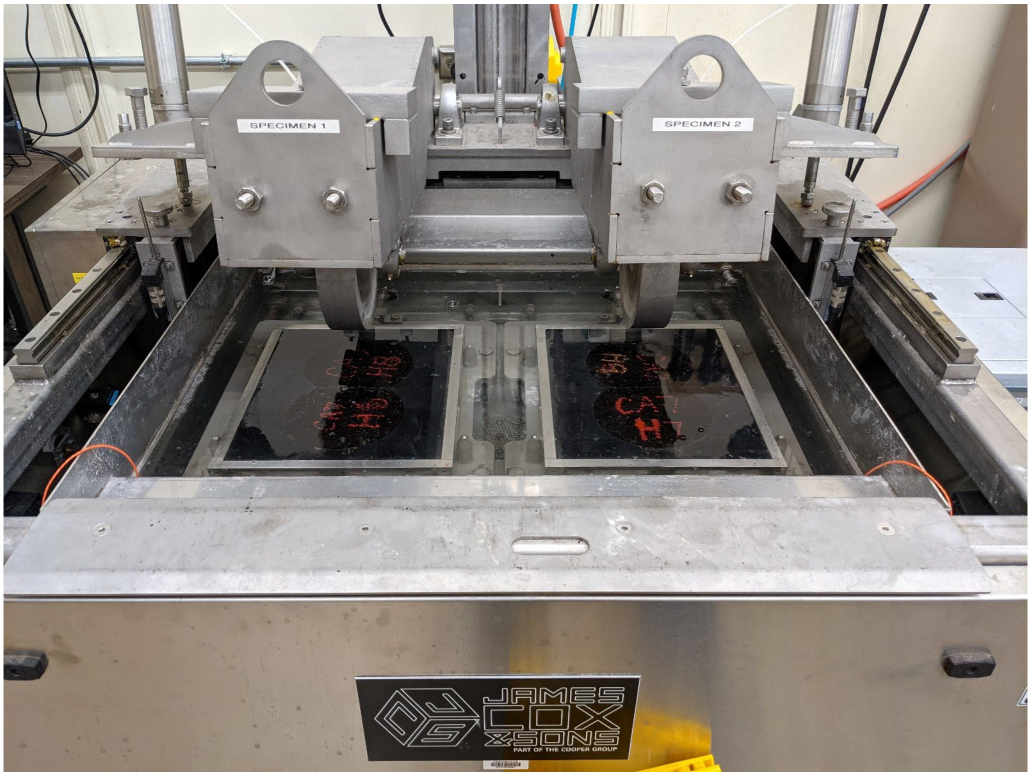

Figure 5. Setup for Hamburg wheel tracking.

The graph of a typical deformation-time curve delivers three segments: initial (primary) creep, secondary creep, and tertiary creep (Figure 6). The initial creep defines the early stage of deformation, which typically occurs within a limited number of cycles. The secondary creep is a more stable part of deformation, which defines the progress of rutting with an increasing number of passes linearly and typically carries a significantly larger number of cycles compared with the initial creep. Finally, the tertiary creep begins when the mix has become unstable as moisture damage takes effect and shows a significant rate of deformation as time progresses. In this report, the point of intersection of the slopes from secondary and tertiary creeps is defined as the inflection point for tertiary creep, or the stripping inflection point (SIP). There are several distinguishing parameters that can be derived from the HWT test and used in this research: maximum rut depth (i.e., rut depth at the highest number of wheel passes), SIP, ratio of stripping slope (or tertiary creep slope) to secondary creep slope, number of wheel passes to reach 12.5 mm of rut depth, rut depth after completion of 10,000 wheel passes, and finally the stripping slope in terms of rut depth for 1,000 wheel passes. All of these parameters have been extracted from the test results and are presented in this report.

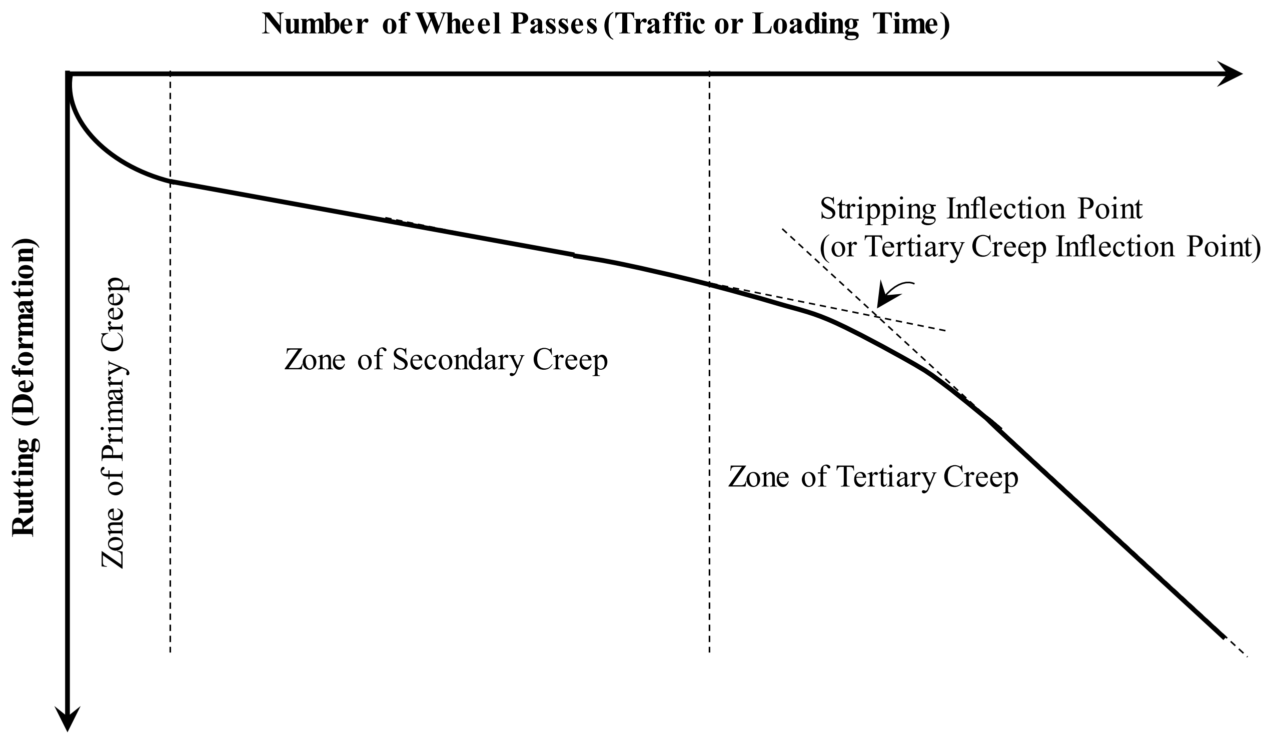

Figure 6. Different creep zones for a typical load-deformation test.

<u>*IDEAL-CT*</u>

This cracking test was conducted according to ASTM D8225-19, using a displacement rate of 50 mm/min and a 25 °C test temperature. For this study, specimens were also prepared and tested at slower displacement rates (30 mm/min, 25 mm/min, and 1 mm/min). Slower rates were used as the fiber may show its benefit in crack resistance at these lower rates of straining.

The test setup and the corresponding response are presented in Figures 7 and 8, respectively. Based on the load-displacement curve, several engineering parameters are derived, including the pre-peak and post-peak modulus, fracture energy, and peak load. The work of fracture divided by the slope of the post-peak curve at 75% of the peak load and multiplied by the extension at 75% of peak load gives the cracking index (Equations 1 and 2).

$$CT_{Index} = \frac{G_f}{\frac{P}{l}} \times \left(\frac{l_{75}}{D}\right) \tag{1}$$

$$\frac{P}{l} = |m_{75}| = \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \tag{2}$$

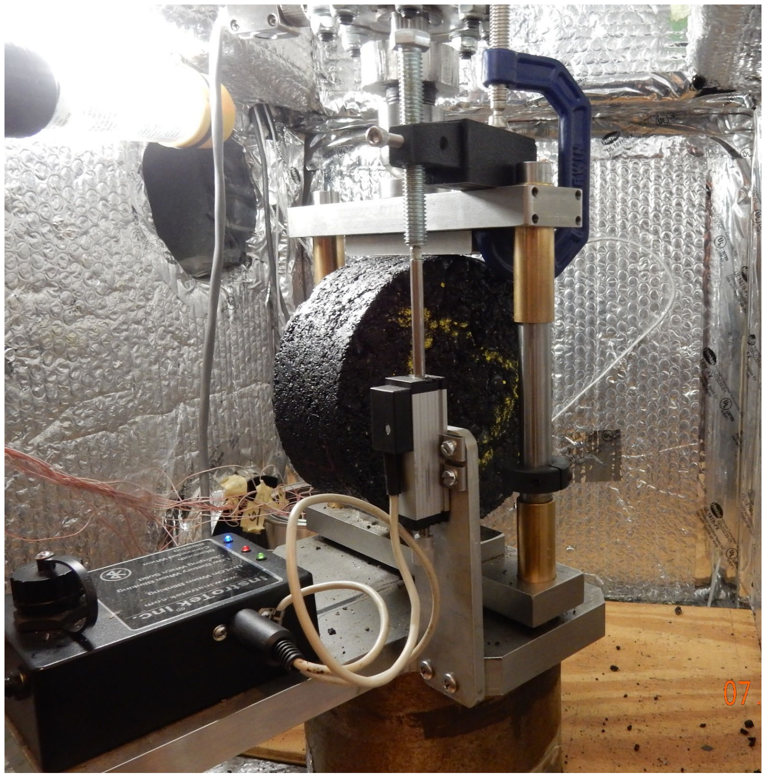

Figure 7. A picture of the IDEAL-CT test setup.

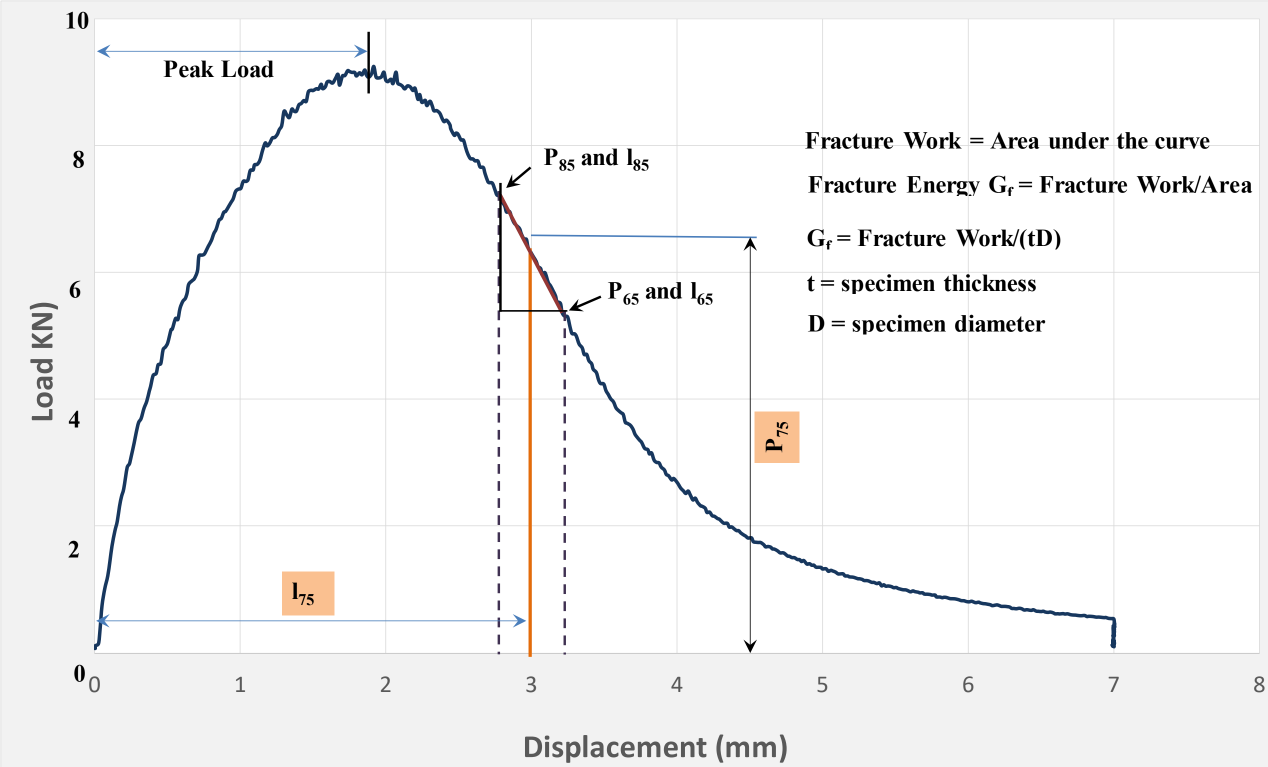

Figure 8. Load-displacement curve from a typical IDEAL-CT test.

IDEAL-RT

This test is promoted to capture the rutting potential of asphalt mixtures (Figure 9). The same equipment used in IDEAL-CT is used for this test except the supporting jig is different to force a specific shear stress path within the specimen. The specimen used for this testing has exactly the same geometry as the specimen used for IDEAL-CT testing. The test typically takes about 2 minutes to complete. Further characteristics of this test are provided below, and computations are conducted using equations 3 and 4.

- Test Standard: ASTM D8360-22 Displacement rate: 50 ± 2.0 mm/minute
- Sampling Rate: Min. 40 data points/second
- Test Temperature: 50 ± 15 °C

$$\tau_f = 0.356 \times \frac{P_{max}}{t \times w} \quad (3)$$

$$RT_{index} = 6.618 \times 10^{-5} \frac{\tau_f}{1\,Pa} \quad (4)$$

Where

T_f = shear strength (Pa)
P_{max} = maximum load (N)
T=specimen thickness (m), and
W = width of upper loading strip (=0.0191 m)
RT_{index} = rutting tolerance potential

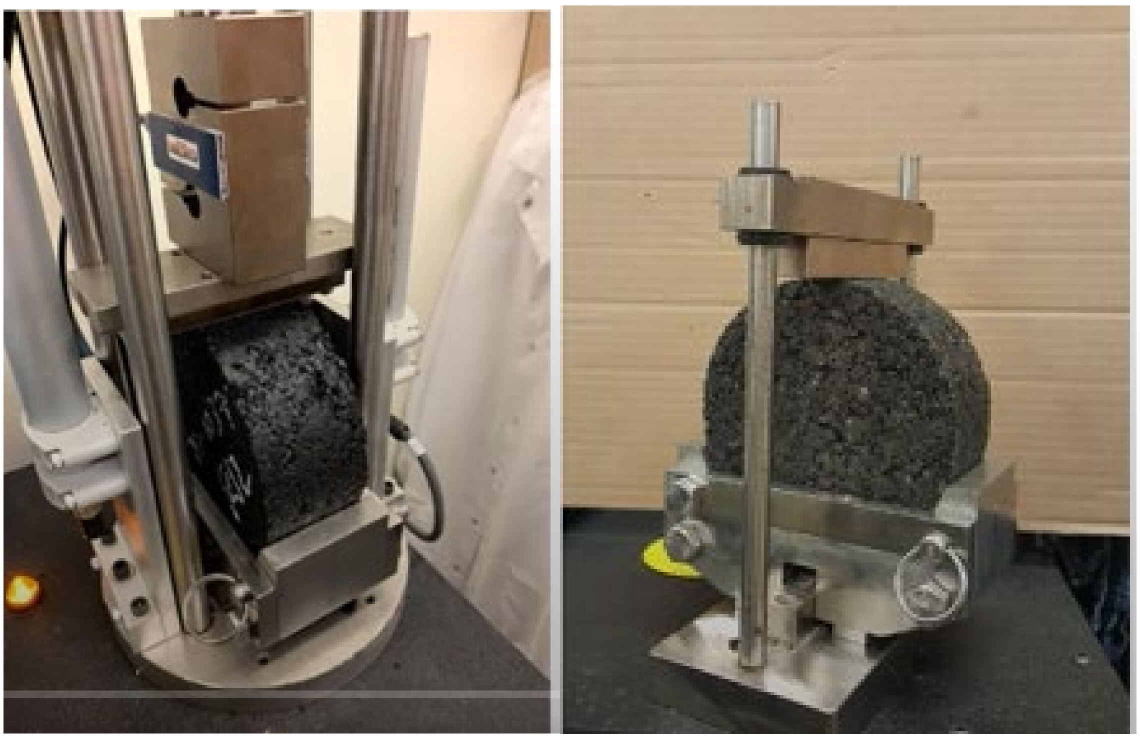

Figure 9 Equipment for IDEAL-RT Testing

ANALYSIS OF BINDER CHARACTERISTICS

High and Intermediate Temperature Grades

It is important to highlight that the objective of binder grade evaluation was simply to determine the change in grade if the original polymer is replaced by recycled polymer. Details of how the polymer was incorporated into the binder was discussed previously. It is also important to remind the reader that in this study no fiber was incorporated into the binder, and only the virgin polyolefin polymer or recycled polymer was introduced into the binder.

The performance grade of the tested binders at high and intermediate temperature are shown in Figures 10 and 11, respectively. For high temperature grade, the continuous grade of the binder is shown for both unaged and RTFO aged material. It can be seen that for high temperature grade the control binder, the binder with virgin polymer, and the binder with the recycled polymer yield similar results. For the RTFO (short-term) aged binder, the polymer and recycled plastic deliver similar results, but higher continuous grade compared with the control binder. In general, it is safe to conclude that if the virgin polymer is replaced by recycled polymer at the dosage rate recommended by Forta, the behavior and grade of the binder is not altered. At the intermediate test temperature, the results are comparable across all binders, and no difference is observed between the impact of virgin polymer and recycled polymer.

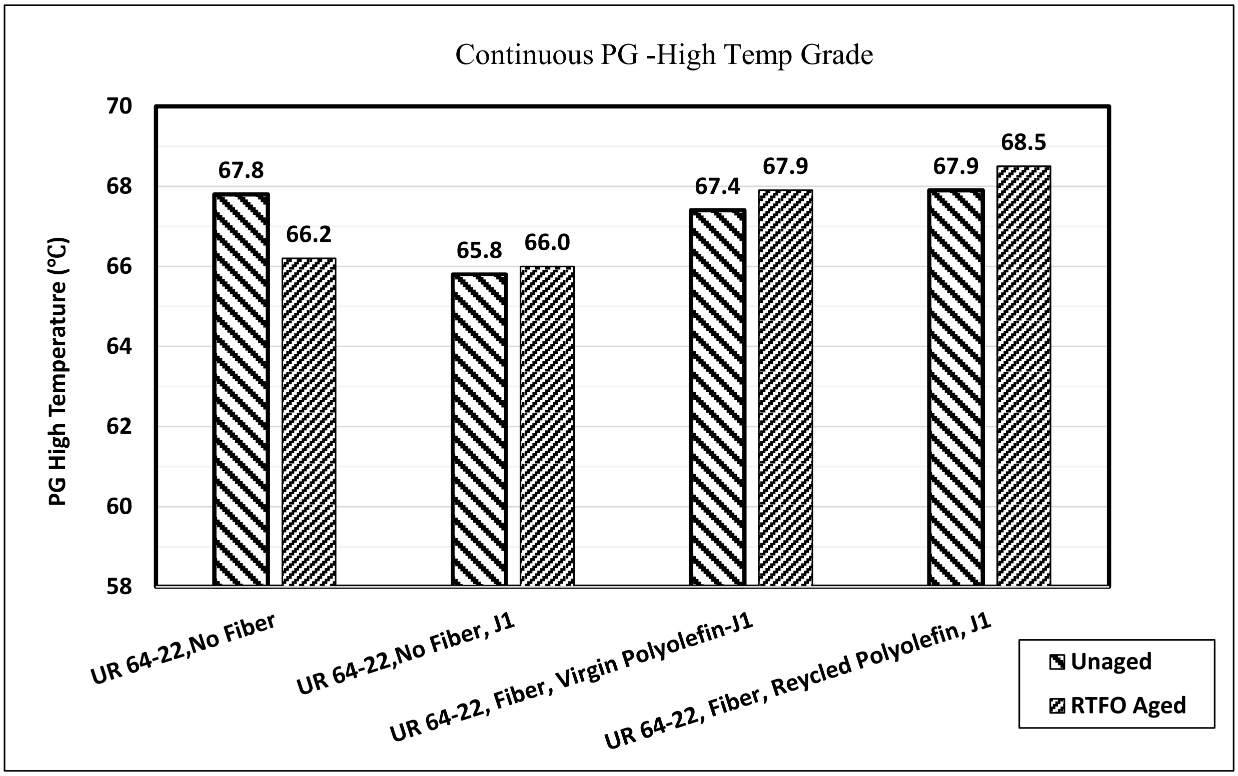

Figure 10 High temperature performance grade of the modified and plastic modified binders

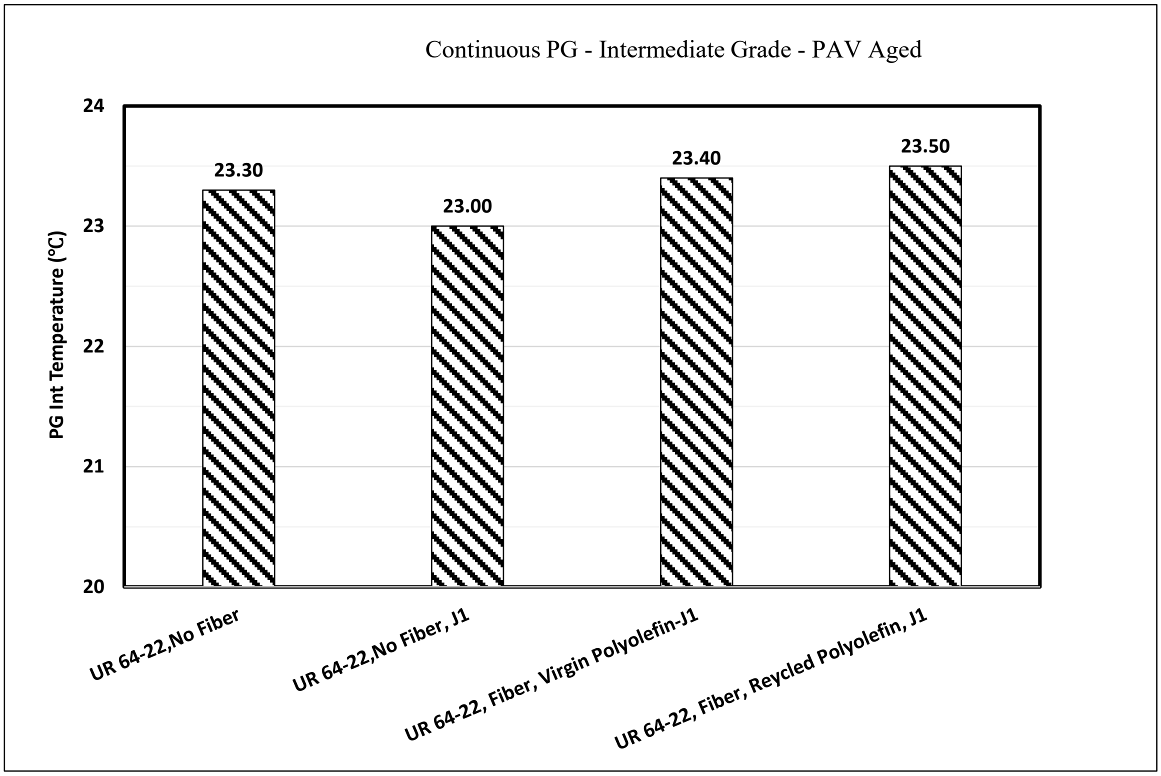

Figure 11 Intermediate temperature performance grade of the control and plastic modified binders

In addition to rheological testing for binder grading based on AASHTO M 320, the multiple stress creep recovery (MSCR) was conducted for binder grading based on AASHTO M 332. An interesting observation from this test is that the modified binders deliver a lower creep compliance (Jnr) compared to the control binder when tested at 64 ºC (Figure 12) . This is an indication of the stiffening effect of the modification, a positive improvement at high temperature. However, in terms of nominal grading, all binders can be classified as PG 64S-22. There is also no considerable difference between the effect of the original polymer and recycled polymer on the creep compliance Jnr. Finally, for all binders, the stress sensitivity is well below the threshold value of 75%, indicating that the asphalt binder will not get into a sudden failure mode at high stress levels or high temperatures (Figure 13). It should be noted that some have questioned validity of the stress sensitivity as calculated from the MSCR test and have not found it correlated to field performance.

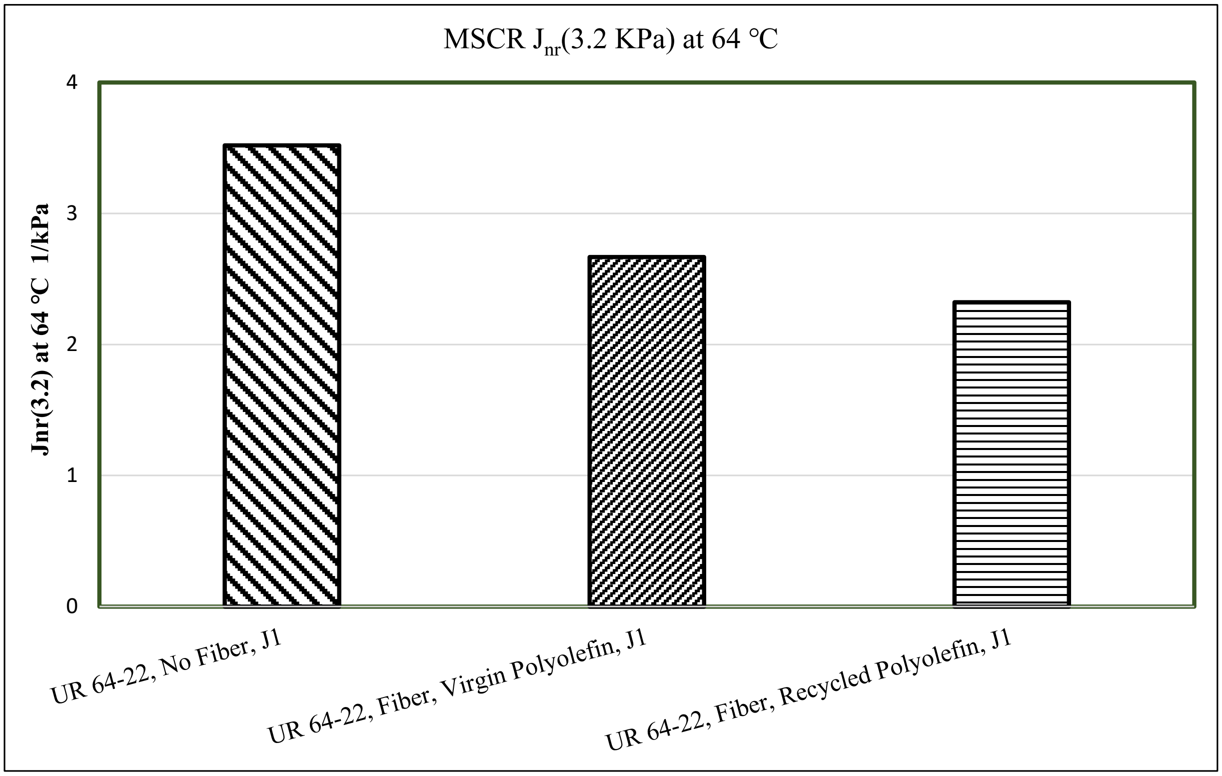

Figure 12 Creep compliance of the control and plastic modified binders

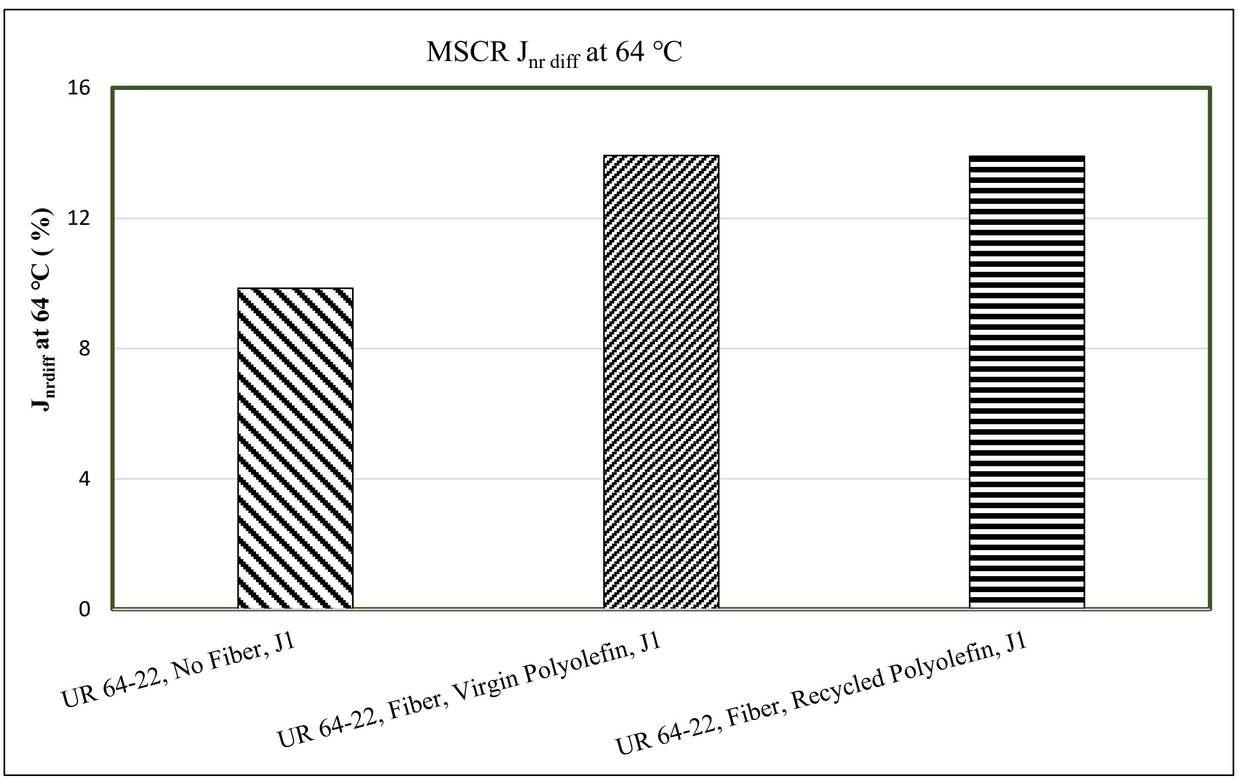

Figure 13 stress sensitivity based on creep compliance different

Low-Temperature Binder Grade and ΔT_c

The low temperature binder grade is presented in Figure 14. One can see the continuous low temperature grade manifesting a slight increase of almost 0.5 ºC for the modified binder compared to the control binder. This slight change is true regardless of whether the grading is based on the low temperature stiffness S or based on the relaxation parameter m, but all binders are graded as PG 64S-22. Another observation is that there is not much difference between the virgin polymer and the recycled polymer in terms of the impact on stiffness or relaxation parameter, even though considering the m value, one could say that the recycled polymer is showing a slightly better performance.

The threshold criteria for grade determination are the temperatures at which the binder stiffness (S) equals 300 MPa and the creep rate (relaxation parameter m) equals 0.3. These temperatures define the low-temperature grade of the binder as required by governing specifications (for example, AASHTO M 320). To establish critical temperatures for limiting values of stiffness and creep rate, the bending beam rheometer test (AASHTO T 313) must be conducted at least two temperatures. Ideally, these two temperatures bracket the threshold value of 300 MPa for S and 0.3 for *m* so that the critical temperatures are calculated through interpolation.

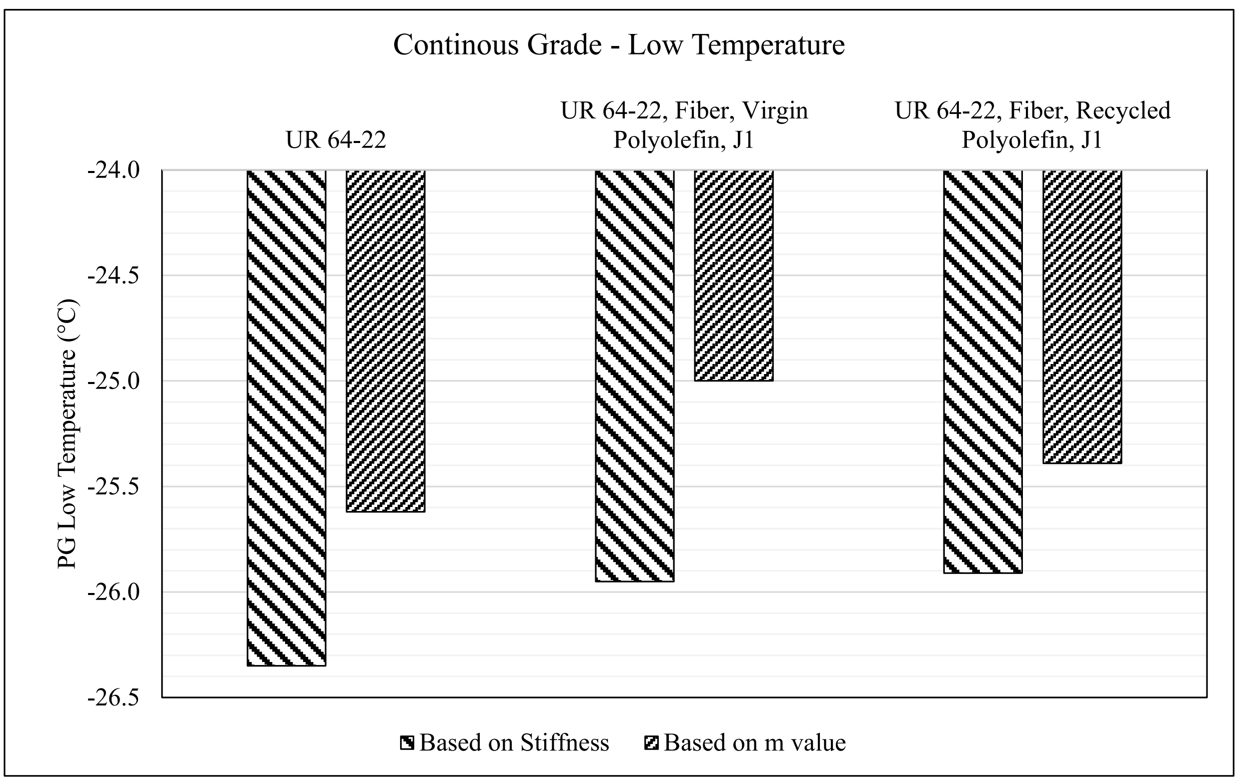

Figure 14 Low temperature grade of the control and plastic modified binders

Delta T_c (ΔT_c) is a binder parameter related to durability and cracking potential of asphalt mixture. It is defined as the difference between two critical cracking temperatures: one associated with stiffness and the other with relaxation parameter (or creep rate). Once the critical temperatures are established, ΔT_c is calculated using Equation 4.

$$\Delta T_c = T_{c,S} - T_{c,m} \tag{4}$$

Where

$T_{c,S}$ = critical cracking temperature to satisfy stiffness threshold value of 300 MPa
$T_{c,m}$= critical cracking temperature to satisfy stiffness creep rate value of 0.3

The low-temperature performance grade of the binder is decided by the larger number between $T_{c,S}$ and $T_{c,m}$. For example, if $T_{c,S}$ = -26.2 °C and $T_{c,m}$ = -23.7 °C, then the binder grade is established as -23.7 °C. Positive values of ΔT_c indicate that the binder cracking potential is governed by creep stiffness, while negative values indicate that the binder cracking potential is governed by the creep rate. In general, as ΔT_c becomes more negative, the binder is perceived to be more prone to cracking. Most of the states that have adopted ΔT_c as a specification parameter have set the threshold value at -5 °C (i.e., ΔT_c must not drop below -5 °C).

As seen in Figure 15, an increase of about 0.2 ºC in ΔTc is observed in the binder modified with the original polymer and a reduction of about 0.2 ºC is noted for the binder modified with the recycled plastic. One could argue that the recycled plastic shows a better performance compared with the original polymer but one should also consider the fact that all values shown in this figure are greater than -1.0 ºC and are acceptable values.

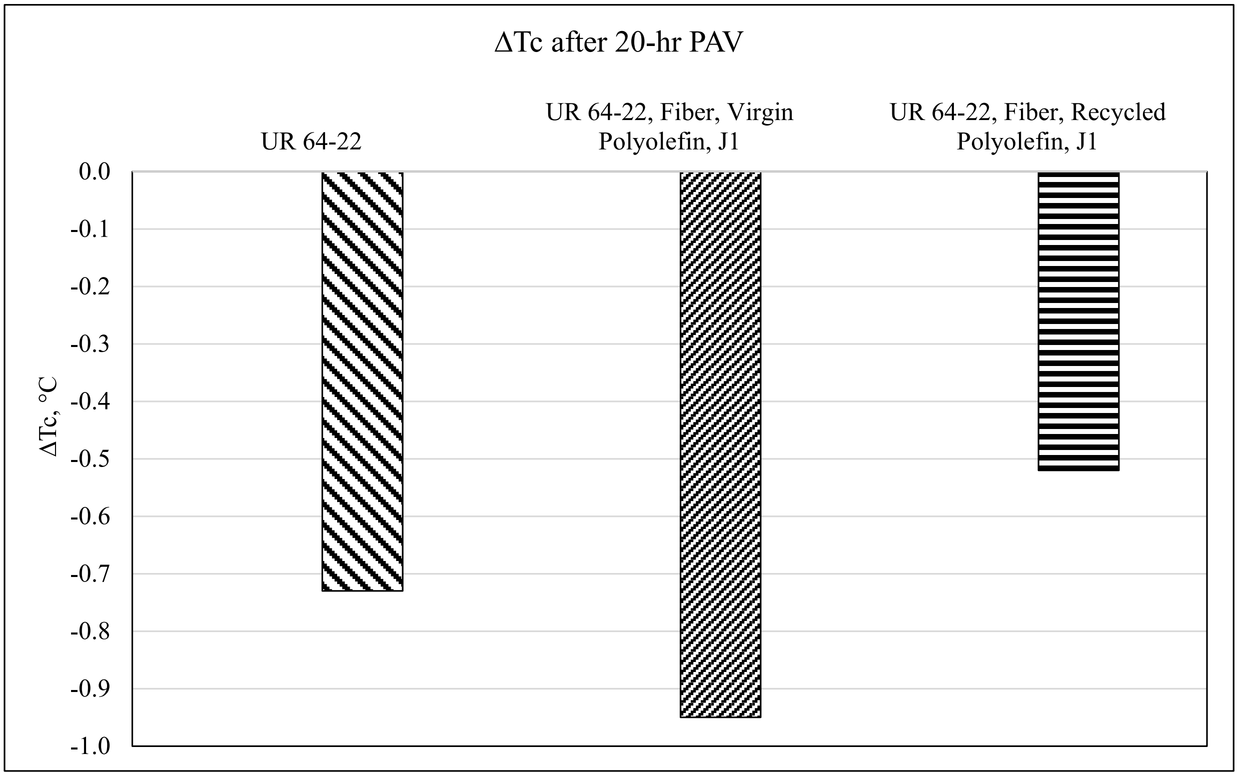

Figure 15 ΔTc for control and plastic modified binders

ANALYSIS OF MIXTURE CHARACTERISTICS

The focus of this chapter will be on discussion and analysis of data generated from mixture performance tests. These include mainly the results from Hamburg wheel tracking and indirect tensile asphalt cracking test.

Hamburg Wheel Tracking (HWT) Test Results

The Hamburg wheel tracking was conducted on two tracks: track 1 included the asphalt mix with fiber and the virgin polymer and track 2 included the asphalt mix with fiber and recycled polymer. One can see in Figure 16 that both tracks exhibited excellent performance, with maximum rut depth of 3 to 3.5 mm in both cases. The experiment indicates that replacement of the virgin polymer with the recycled plastic does not adversely affect performance of the mix in terms of resistance to rutting and moisture damage. Detailed information is provided in Table 2. Comparison is also made between these two mixes and the control mix with no fiber (Table 2 and Figure 17). No significant difference is observed between the performance of the mixes in HWT.

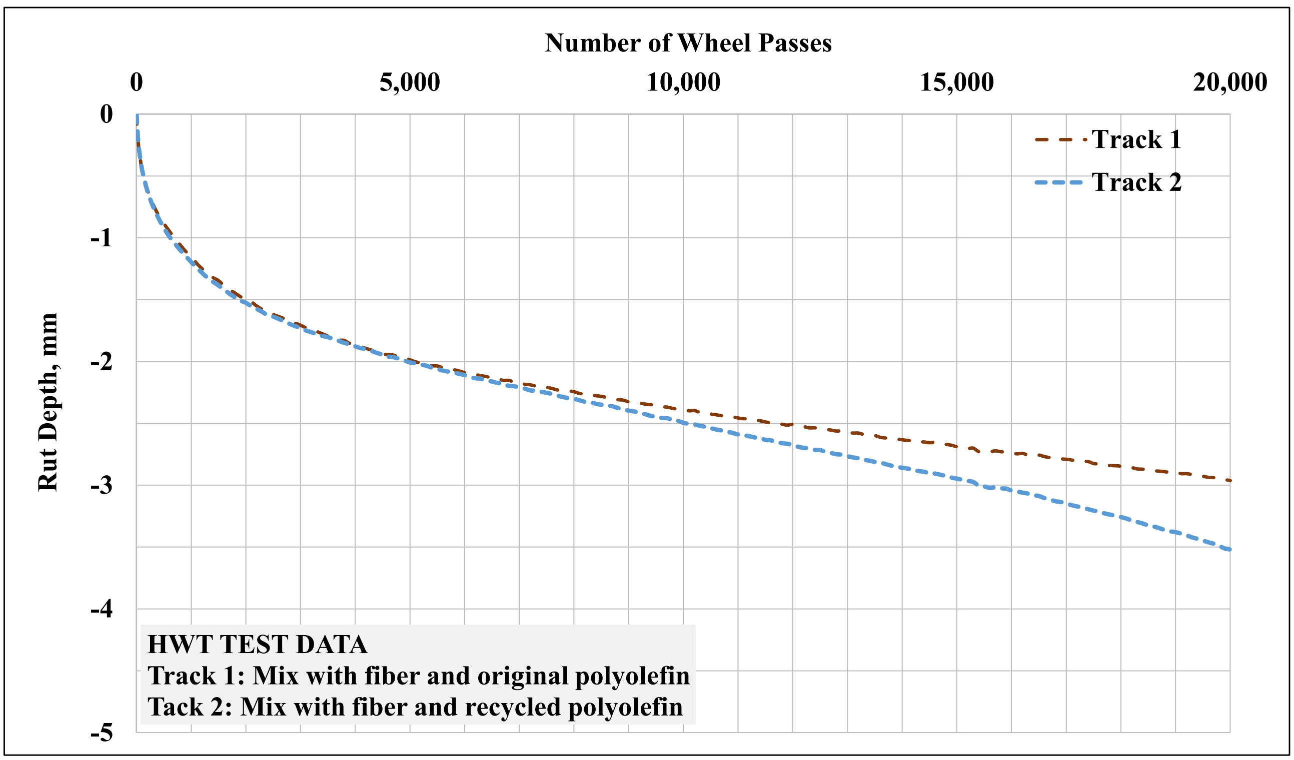

Figure 16 Rutting measured in the HWT test as a function of number of wheel passes

Table 2 Summary of Results from HWT Test
Track 1: Fiber + Original Polymer, Track 2: Fiber + Recycled Plastic

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	17,776	NA
Ratio of the slope (strip/creep)	1.00	1.43	1.22
Max Rut Depth (mm)	-2.96	-3.52	-3.24
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	142,991	68,458	105,725
No. of Passes to 12.5 mm rut depth	186,717	87,140	136,929
Rut depth at 10,000 passes, mm	-2.38	-2.50	-2.44
Creep Slope (mm/1000 passes)	0.06	0.09	0.08
Stripping Slope (mm/1000 passes)	NA	0.13	NA

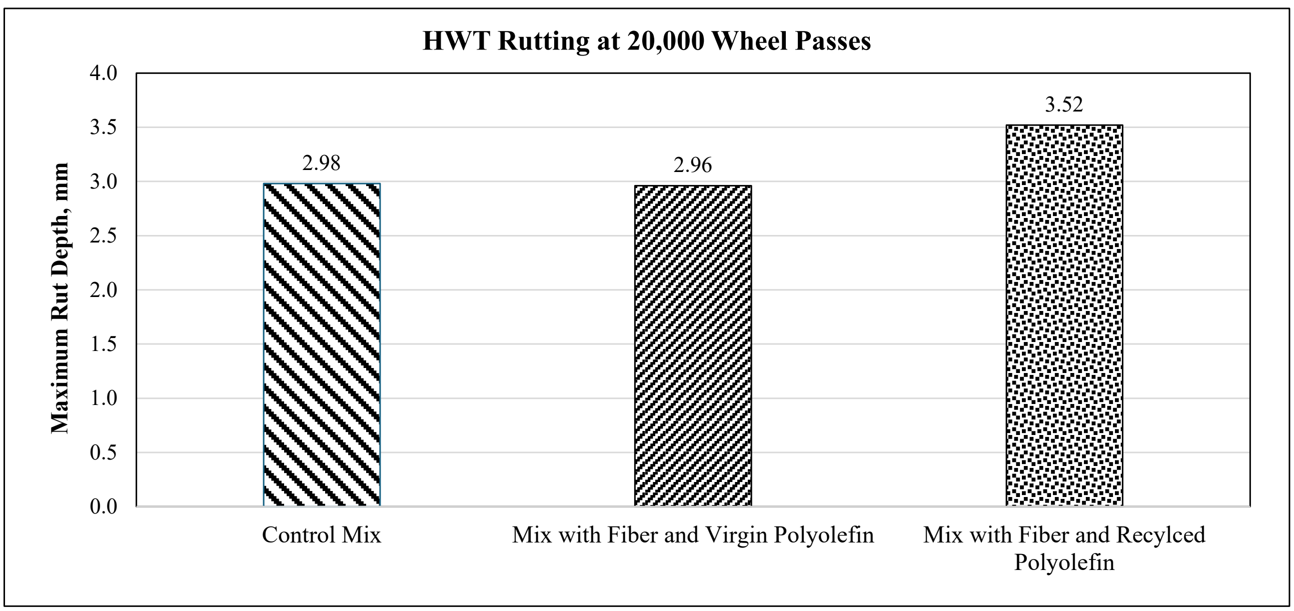

Figure 17. rut depth for excellent rut-resistant mixes in the Hamburg wheel tracking device

IDEAL-CT Test Results

IDEAL-CT testing was conducted more extensively compared with the HWT. True benefit of fiber in improving the fatigue resistance of the asphalt mix may be better observed when the IDEAL-CT test is conducted at lower displacement rates rather than the standard rate of 50 mm/min. Testing was conducted at four different displacement rates: 50 mm/min, 30 mm/min, 25 mm/min, and 1 mm/min. The control mix was tested at all four rates. The mix containing fiber and virgin polyolefin was tested at all rates except 1 mm/min. For evaluating how the recycled polyolefin compares with the virgin polymer in terms of its effect on the IDEAL-CT index, the mix with fiber and recycled polymer was tested at 50 mm/min and 30 mm/min. An example of load-displacement curve is shown in Figure 18. The figure shows four replicates of the same mix, and excellent closeness of the behavior among the four replicates. The graph indicates the high quality of mixture production and testing as the replicates deliver a very low coefficient of variability (COV =11.1%). Detailed results for all specimens of each group are presented in the appendix to this report.

Figure 19 demonstrates how the IDEAL-CT index varies as a function of displacement rate for different materials. The companion graph of Figure 18 exhibits the indirect tensile strength, i.e., the peak stress at the time of macrocrack. In general, as the specimens are loaded at a lower speed, the IDEAL-CT index and the tensile strength are both reduced. Of Course, this phenomenon is not observed for all cases. One can see that the fiber mix provided a higher index compared to the control mix at both 50 mm/min and 30 mm/min, but a lower index at 25 mm/min. However, the overall average increase of index for the fiber mix compared with the control mix is almost 27 percent at 50 mm/min and 47% at 30 mm/min whereas the average decrease is only about 17% at 25 mm/min. One can also see that the combination of aramid fiber and recycled polyolefin polymer delivers almost the same level of index and strength as the combination of aramid fiber with the virgin polyolefin in the asphalt mix.

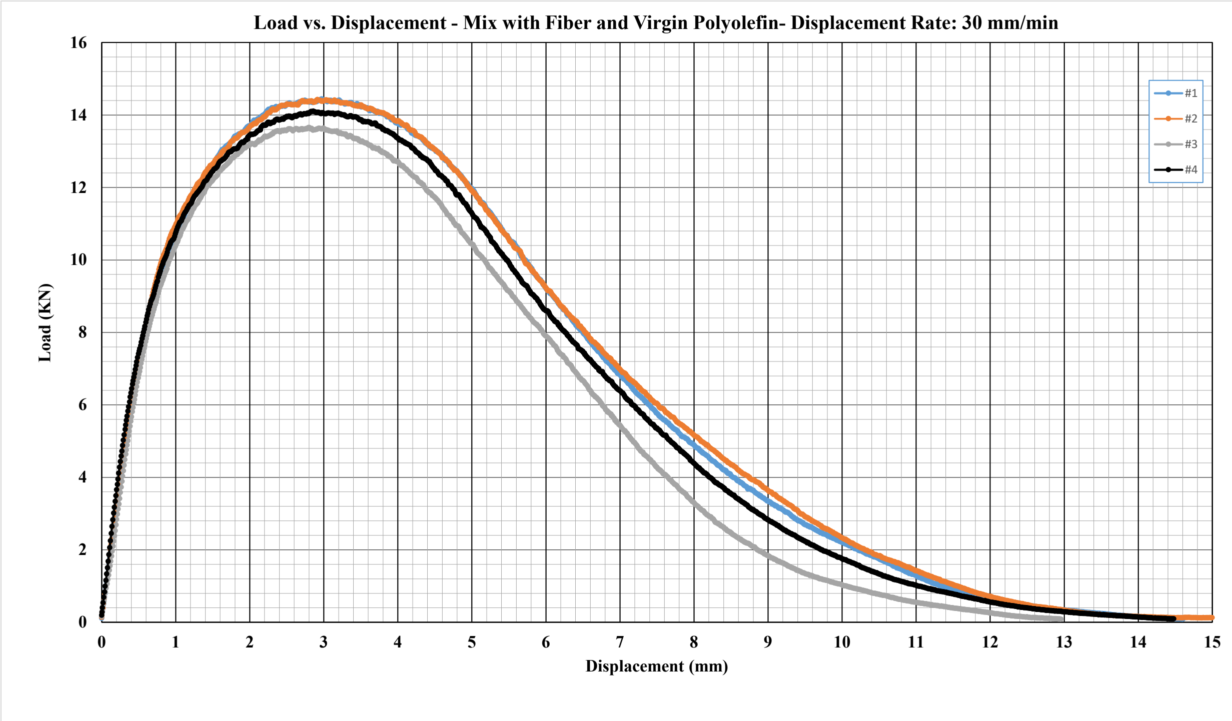

Figure 18 Load-Displacement graph for one of the mixes tested in IDEAL-CT

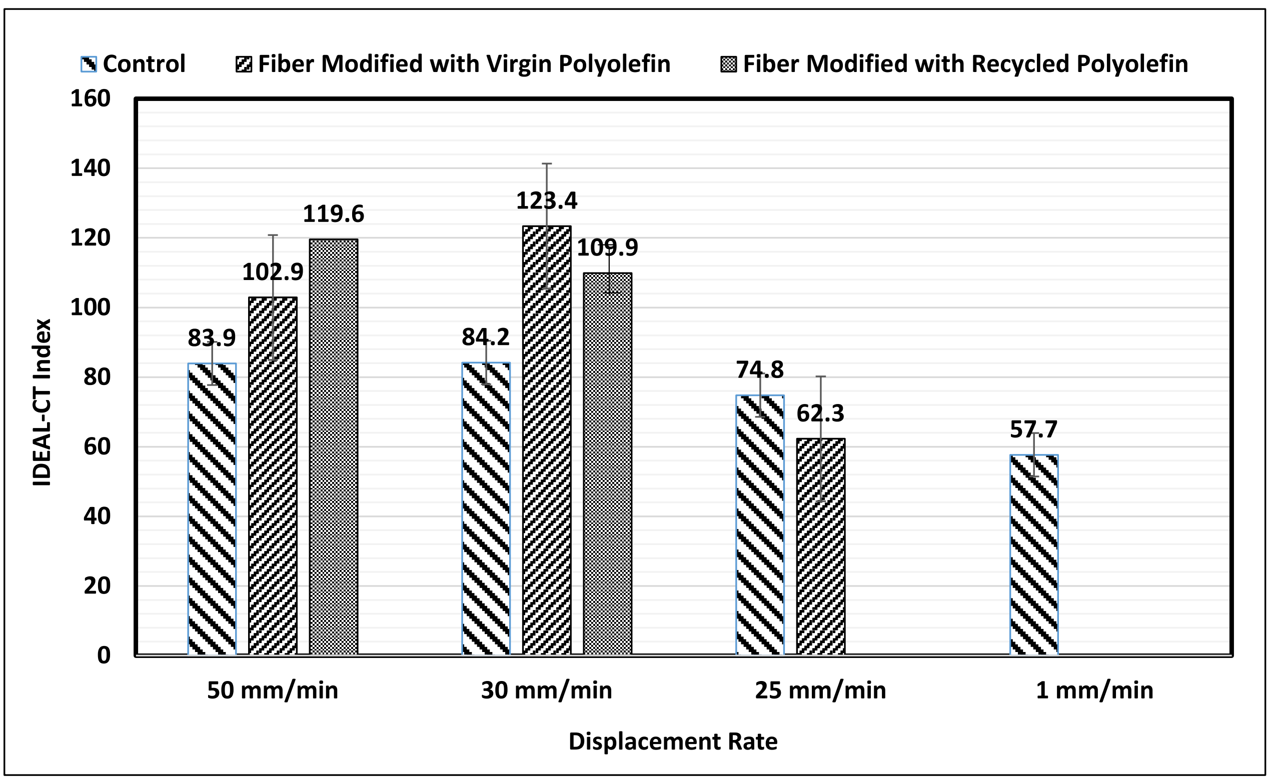

Figure 19 Effect of displacement rate on IDEAL-CT index for different types of mixes

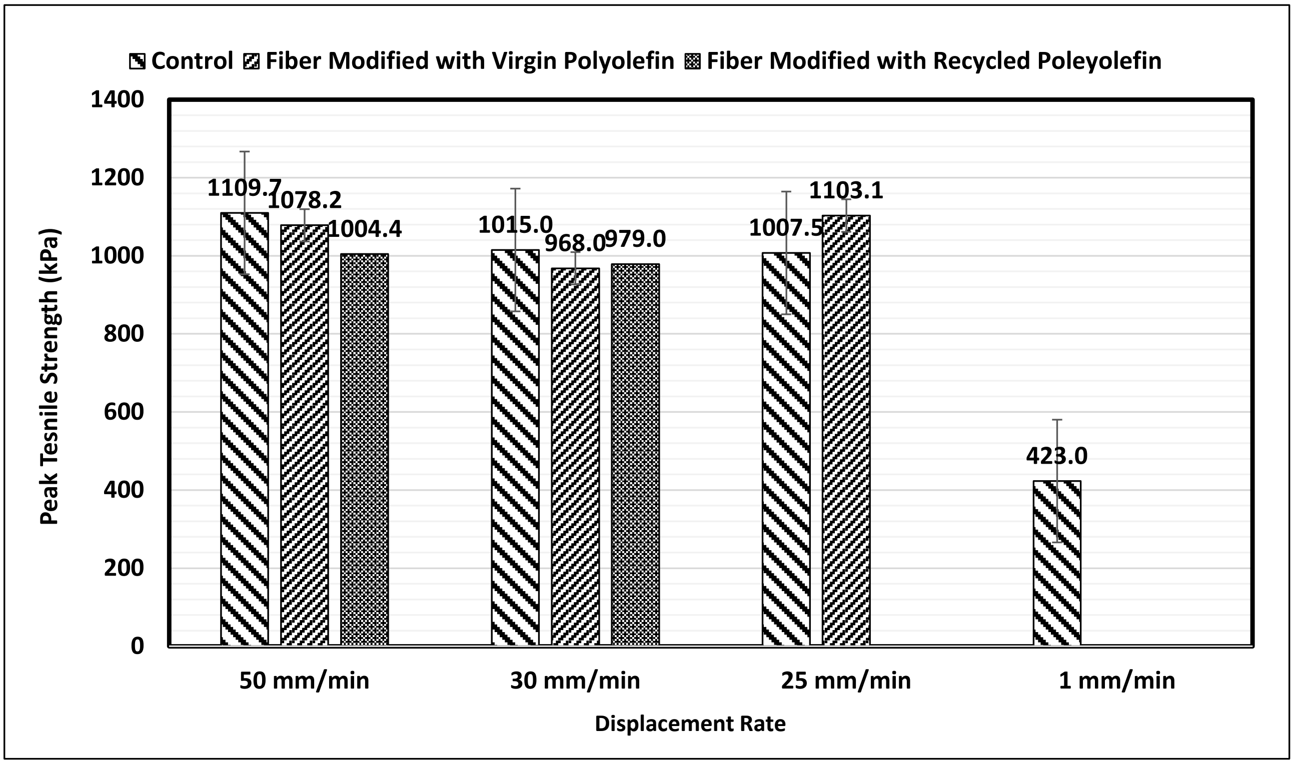

Figure 20 Effect of displacement rate on indirect tensile strength for different types of mixes

IDEAL-RT Test Results

The test was explained previously and is proposed as a tool for capturing the rutting resistance of the asphalt mix and its resistance to shear stresses. The test was conducted on four replicates of the control mix and the fiber modified mix with the virgin polyolefin. It can be seen from Figure 19 that the fiber-modified mix provided a better shear resistance compared to the control mix. The difference, however, was not found to be statistically significant.

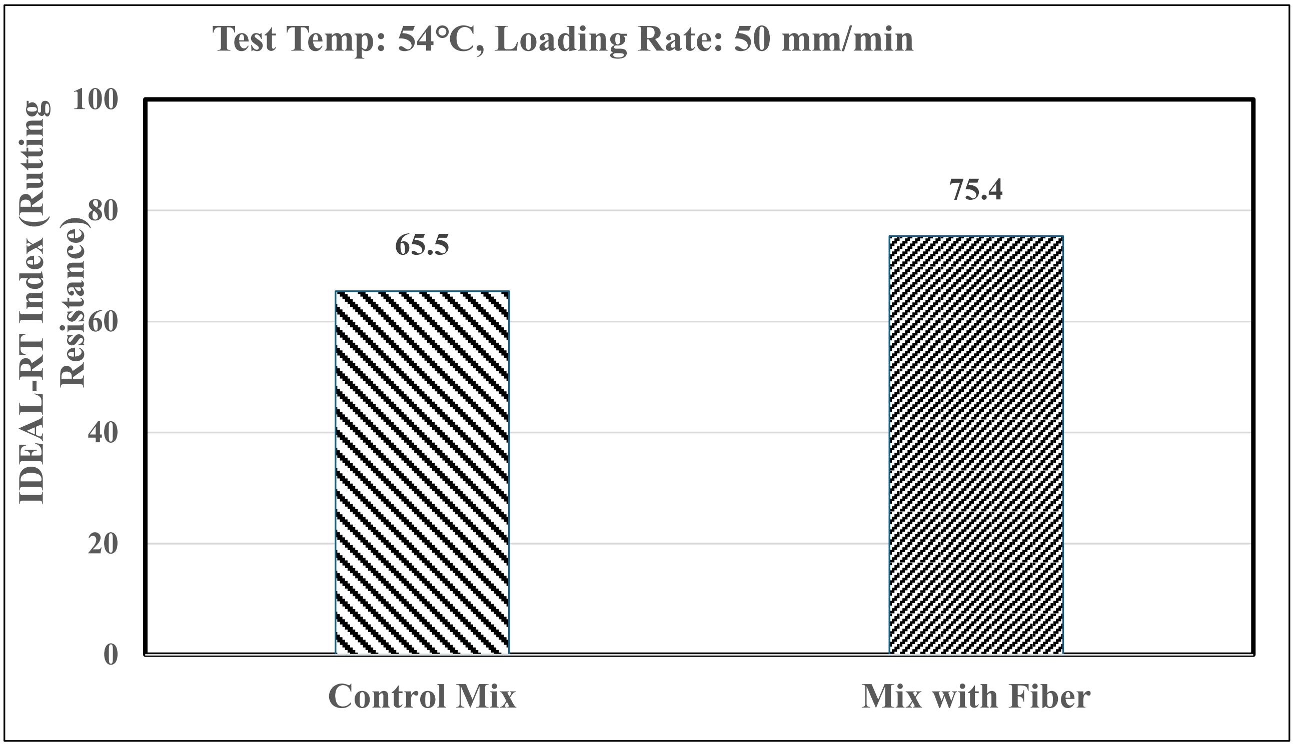

Figure 21 Rut resistance measured through IDEAL-RT for control and fiber modified mix

SUMMARY

A laboratory investigation was undertaken to evaluate the performance of fiber modified asphalt mixtures using a set of mechanical tests. The selected tests were the Hamburg wheel tracking, IDEAL-CT, and IDEAL-RT. The study also included investigating the impact of replacing the polymer carrier of the fiber with recycled polymer. The fiber, the virgin polymer, and the recycled polymer were all provided by Forta Corporation. The applicable dosage rate for each of these ingredients was also provided by Forta.

Rheological testing of unaged, short-term aged, and long-term aged binders with and without polymer modification was conducted and the performance grade of each of the binders was determined. The HWT test was used with a control and a fiber-modified mix. The IDEAL-CT test was applied to the control mix, the mix with fiber and the virgin polymer, and the mix with fiber and recycled polymer. Some of the mixes for IDEAL-CT determination were tested at a range of displacement rates. Finally, the IDEAL-RT was applied to the control mix and the mix with fiber and polymer.

CONCLUSIONS

The binder study revealed that modification of the binder with virgin or recycled polymer did not change the nominal grade of the binder. All binders were graded as PG 64S-22. There was a slight stiffening effect of the polymer on the binder, but no difference was found between the virgin polymer and recycled polymer in terms of impact on the rheological properties. There was a slight improvement in ΔTc when the recycled polymer replaced the virgin polymer in the binder.

Both the control and fiber modified asphalt mixes exhibited excellent performance in HWT, with the maximum rut depth under 3 mm after 20,000 wheel passes. The DEAL-CT results showed an increase in the cracking index for the fiber modified mixture compared with the control mixture when tested at 50 mm/min and 30 mm/min displacement rates, but not at the rate of 25 mm/min. The overall average increase of index for the fiber mix compared with the control mix was almost 27 percent at 50 mm/min and 47% at 30 mm/min. In general, lower testing speed resulted in lower IDEAL-CT index. While differences among IDEAL-CT values were seen among various mixtures, no considerable difference was observed for the indirect tensile strength among different mixes at the same displacement rate. The fiber modified mix with the recycled polymer showed a slight decrease in IDEAL-CT index but the difference was not significant. Finally, the IDEAL-RT test indicated improvement in rutting resistance of the fiber modified mixture compared with the control mix.

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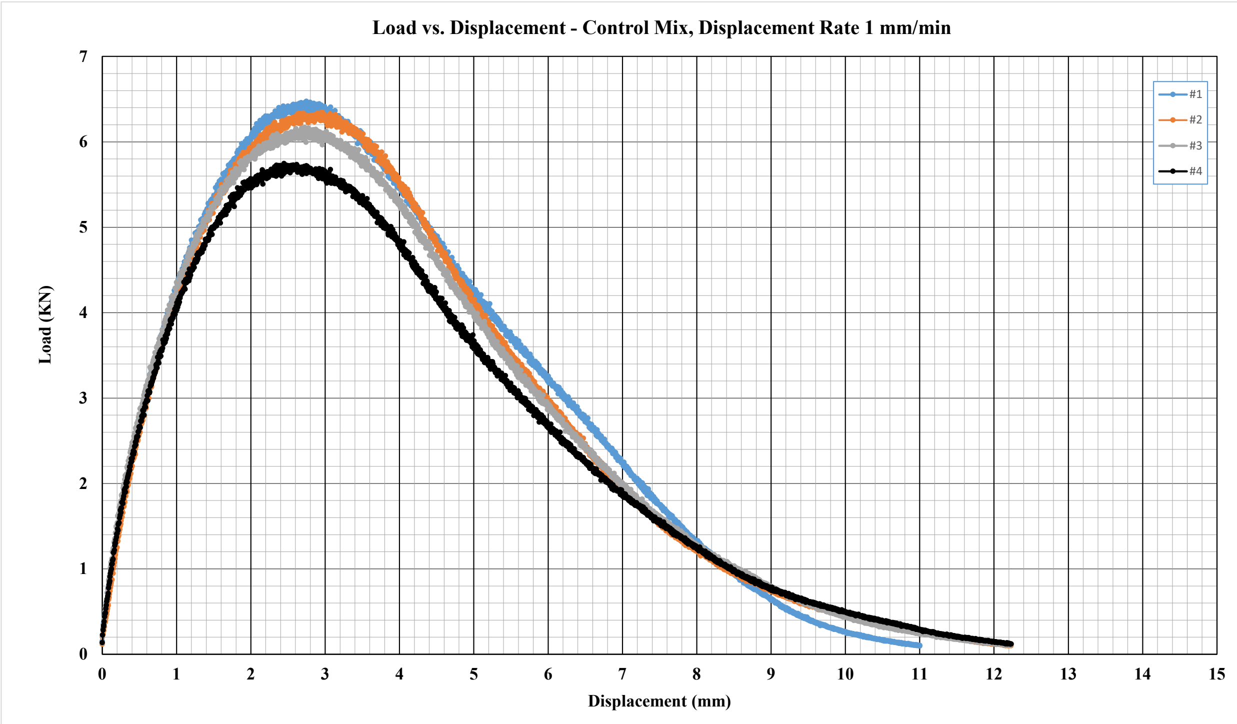
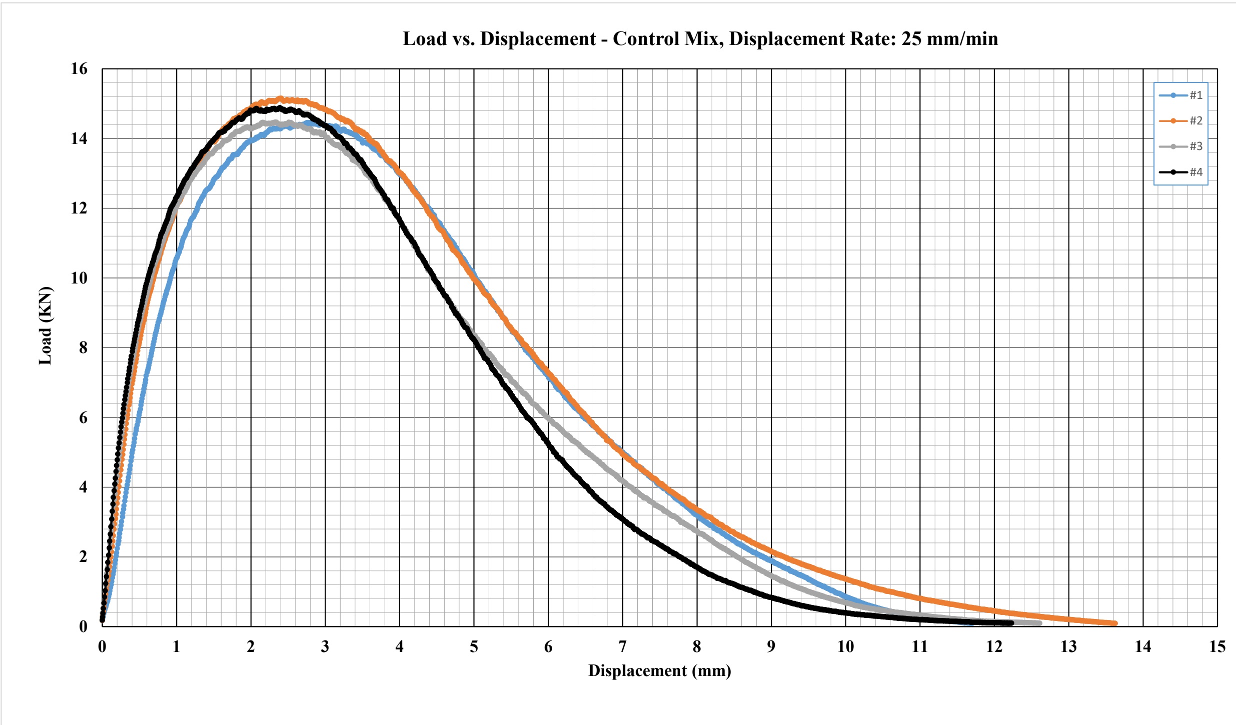
APPENDIX

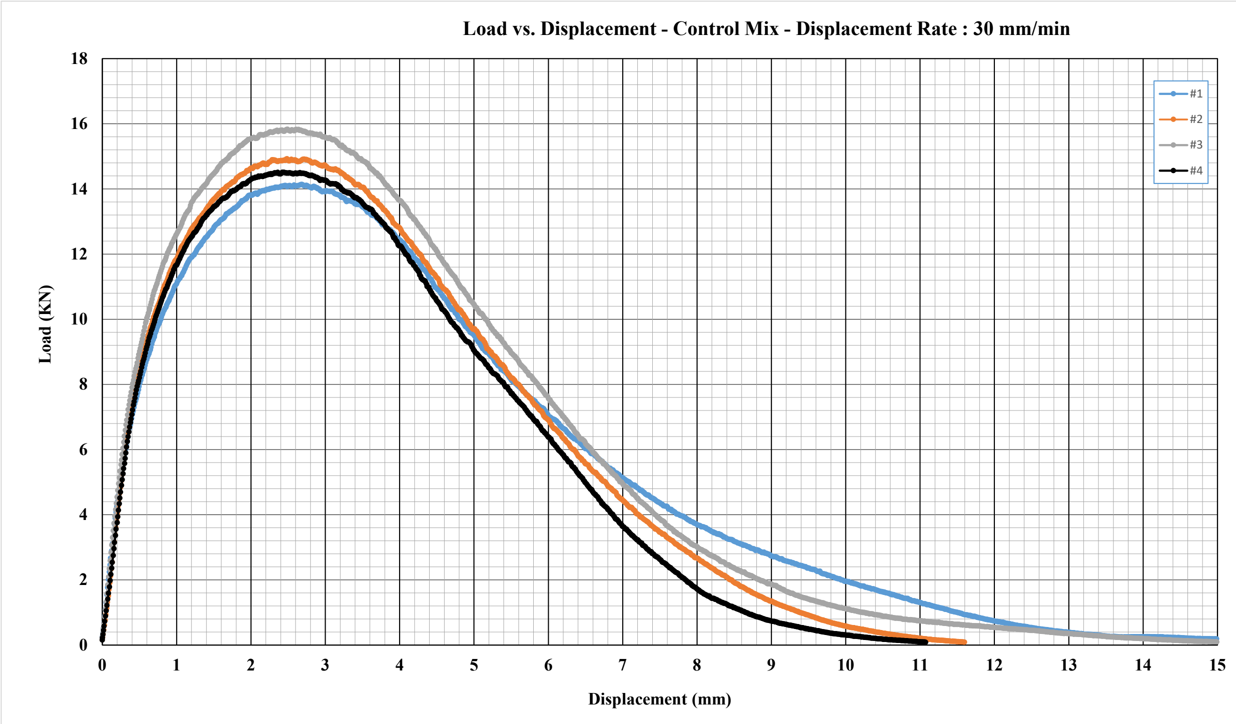
Detailed Data from IDEAL-CT Tests at Different Displacement Rates



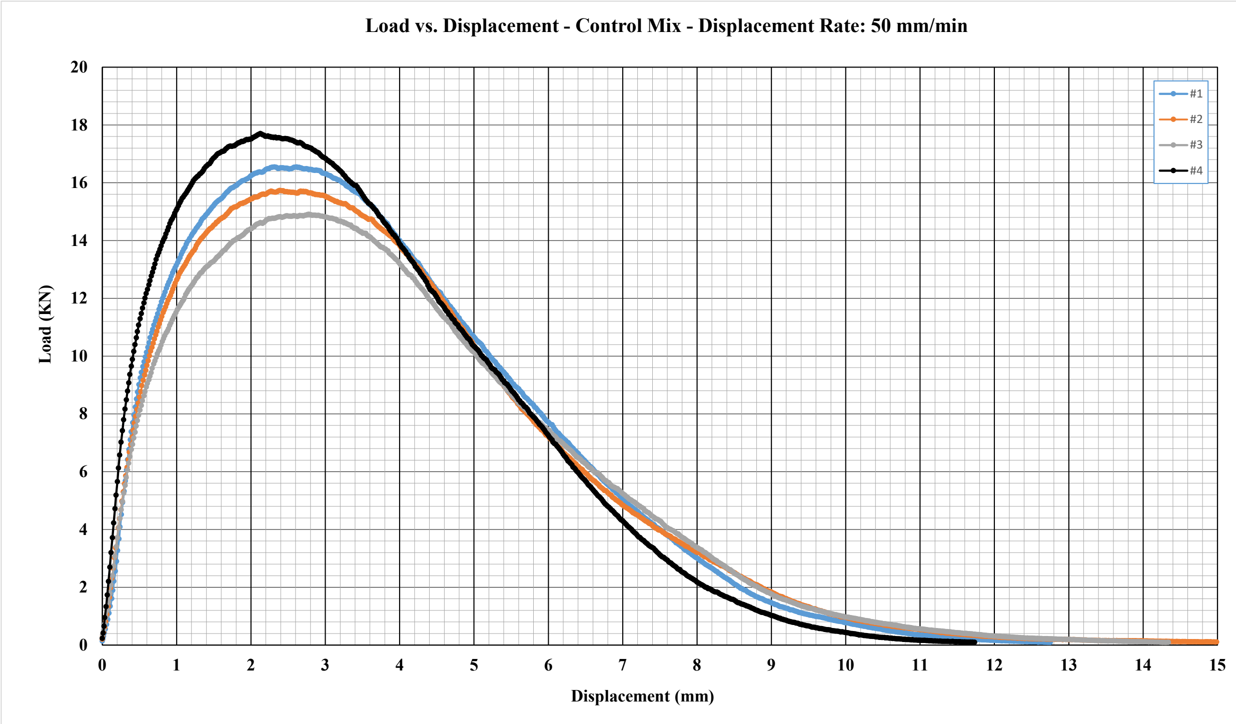
Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	6.474	33.9	3636.7	88.5	442.5	2.7	4.5	-1.23
IDEAL 2	6.347	26.6	2865.1	62.2	434.5	3.0	4.5	-1.39
IDEAL 3	6.168	24.0	2585.7	57.7	422.2	2.7	4.5	-1.34
IDEAL 4	5.746	19.9	2133.3	22.4	392.7	2.4	4.3	-2.76
Average	**6.184**	**26.1**	**2805.2**	**57.7**	**423.0**	**2.72**	**4.4**	**-1.68**
Stand. Dev.	**0.318**	**5.9**	**631.0**	**27.2**	**21.8**	**0.21**	**0.07**	**0.73**
Coef. of Var.	**5.1**	**22.5**	**22.5**	**47.1**	**5.2**	**7.8**	**1.7**	**43.3**



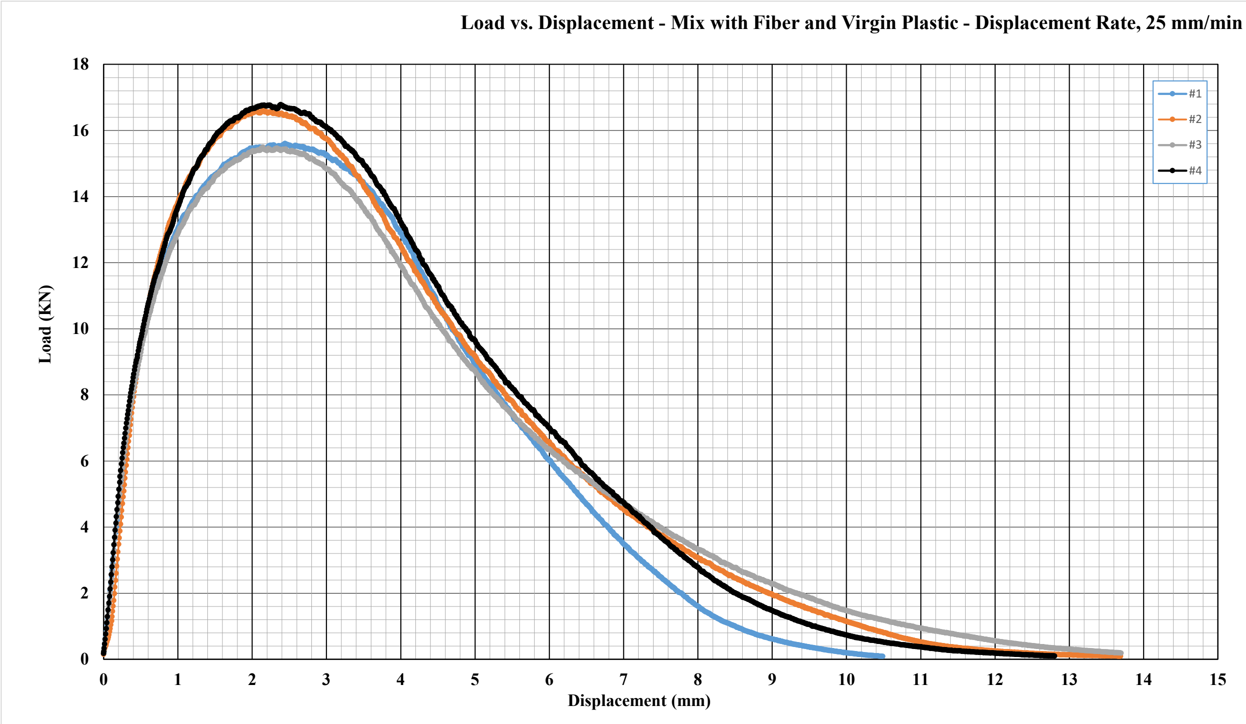
Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	14.456	81.3	8729.1	90.5	988.0	2.8	4.8	-3.07
IDEAL 2	15.155	81.5	8747.9	86.1	1035.7	2.4	4.6	-3.09
IDEAL 3	14.472	72.4	7776.7	64.3	989.1	2.3	4.2	-3.41
IDEAL 4	14.885	68.6	7369.4	58.3	1017.3	2.4	4.1	-3.49
Average	**14.742**	**76.0**	**8155.8**	**74.8**	**1007.5**	**2.47**	**4.4**	**-3.26**
Stand. Dev.	**0.339**	**6.5**	**693.2**	**15.9**	**23.2**	**0.20**	**0.29**	**0.22**
Coef. of Var.	**2.3**	**8.5**	**8.5**	**21.3**	**2.3**	**8.0**	**6.6**	**6.7**



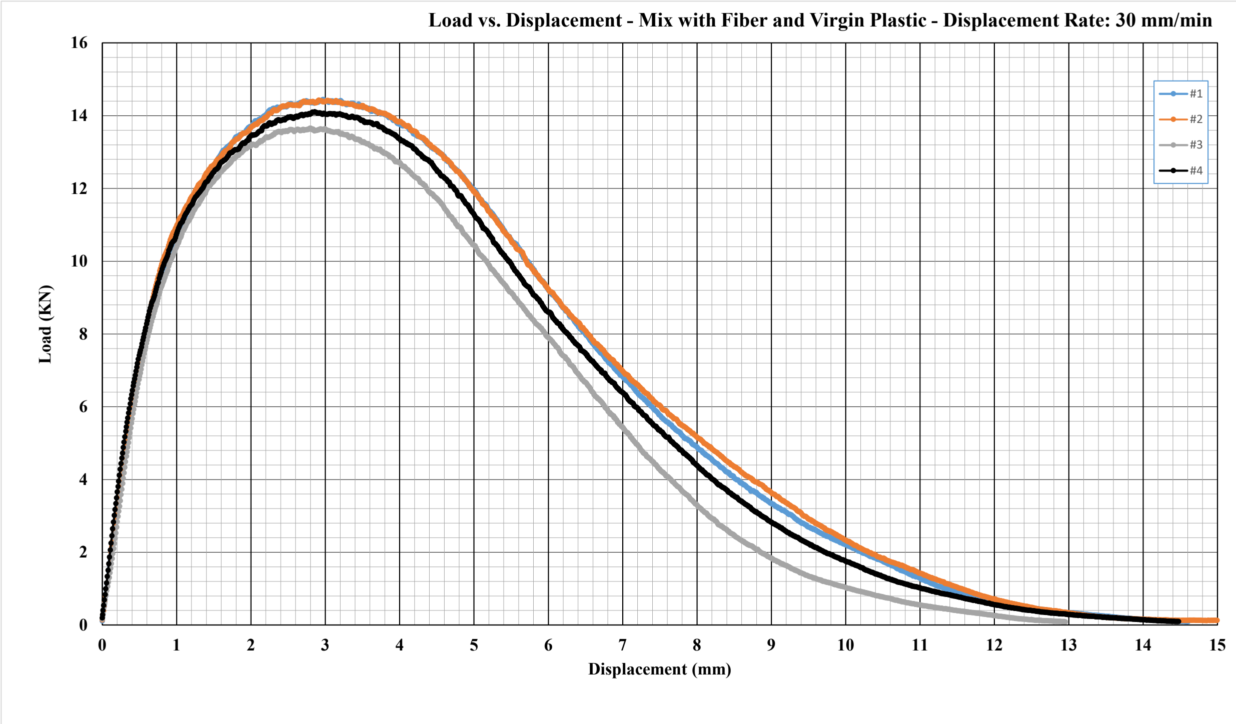
Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	14.138	86.2	9256.7	93.9	966.2	2.7	4.6	-3.04
IDEAL 2	14.926	81.3	8710.5	84.6	1018.5	2.5	4.5	-3.12
IDEAL 3	15.830	86.5	9284.3	86.6	1081.9	2.5	4.6	-3.26
IDEAL 4	14.513	74.1	7969.6	71.7	993.5	2.4	4.4	-3.27
Average	**14.852**	**82.0**	**8805.3**	**84.2**	**1015.0**	**2.52**	**4.5**	**-3.17**
Stand. Dev.	**0.727**	**5.8**	**616.6**	**9.3**	**49.4**	**0.12**	**0.09**	**0.11**
Coef. of Var.	**4.9**	**7.1**	**7.0**	**11.0**	**4.9**	**4.6**	**1.9**	**3.5**



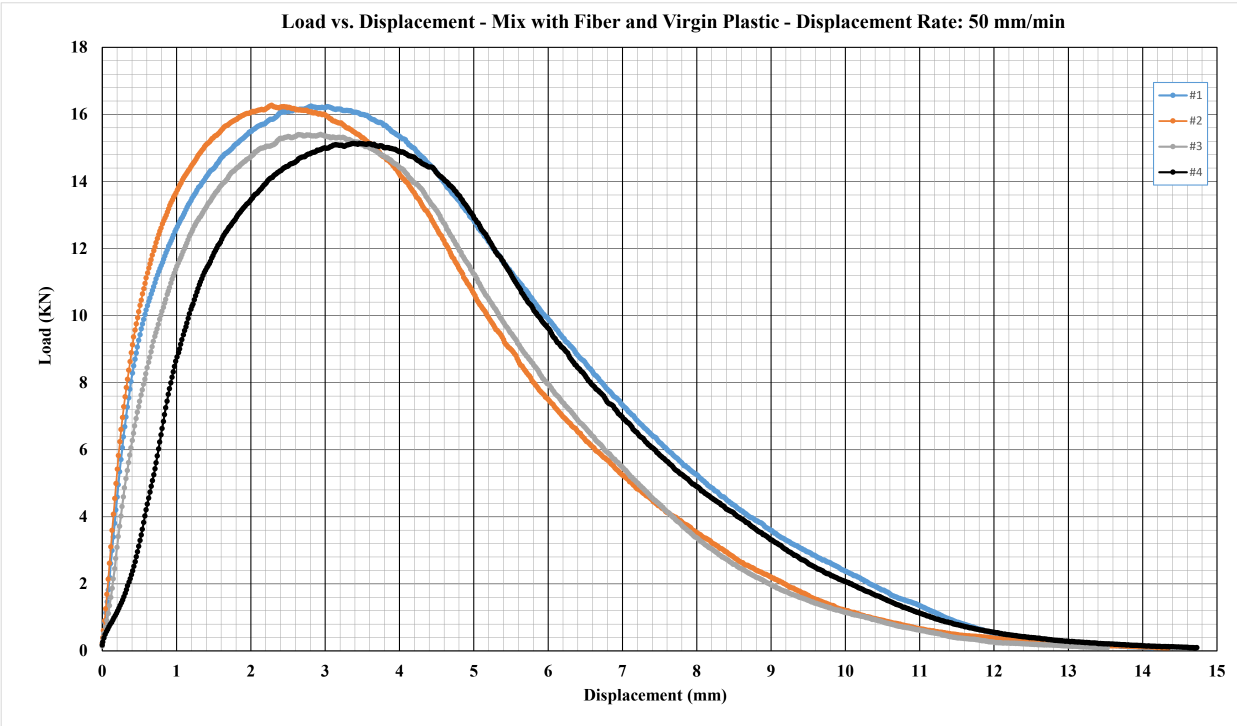
Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	16.547	90.7	9739.9	86.1	1130.9	2.6	4.4	-3.36
IDEAL 2	15.733	88.9	9541.9	82.2	1075.2	2.4	4.6	-3.57
IDEAL 3	14.911	85.8	9210.4	90.9	1019.1	2.8	4.6	-3.14
IDEAL 4	17.703	91.8	9889.8	76.5	1213.8	2.1	4.2	-3.58
Average	**16.224**	**89.3**	**9595.5**	**83.9**	**1109.7**	**2.48**	**4.5**	**-3.41**
Stand. Dev.	**1.191**	**2.6**	**293.6**	**6.1**	**83.0**	**0.28**	**0.22**	**0.21**
Coef. of Var.	**7.3**	**3.0**	**3.1**	**7.3**	**7.5**	**11.4**	**4.9**	**6.1**



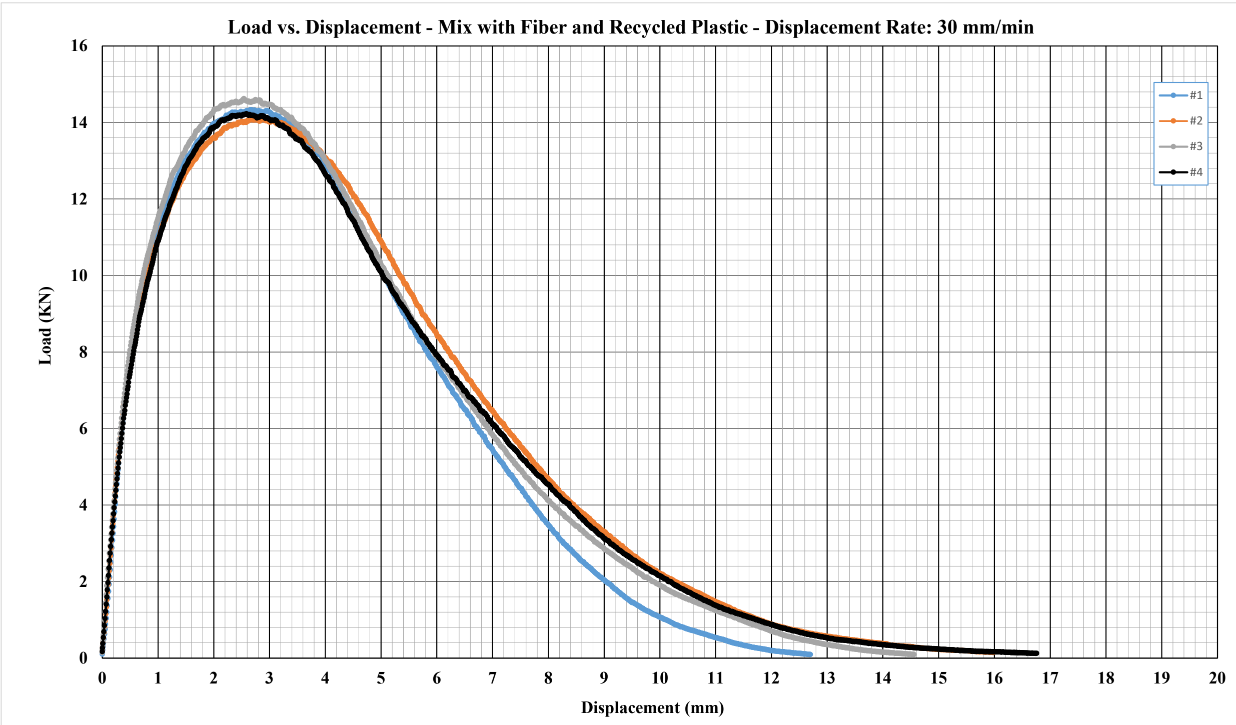
Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	15.608	79.7	8553.5	59.3	1066.7	2.4	4.3	-4.12
IDEAL 2	16.597	83.1	8917.2	64.9	1134.3	2.2	4.0	-3.68
IDEAL 3	15.495	76.6	8240.6	63.9	1060.7	2.1	4.1	-3.50
IDEAL 4	16.784	78.5	8452.2	61.0	1150.8	2.4	4.2	-3.83
Average	**16.121**	**79.5**	**8540.9**	**62.3**	**1103.1**	**2.28**	**4.1**	**-3.78**
Stand. Dev.	**0.664**	**2.7**	**282.7**	**2.6**	**46.1**	**0.15**	**0.12**	**0.26**
Coef. of Var.	**4.1**	**3.4**	**3.3**	**4.2**	**4.2**	**6.8**	**2.8**	**7.0**



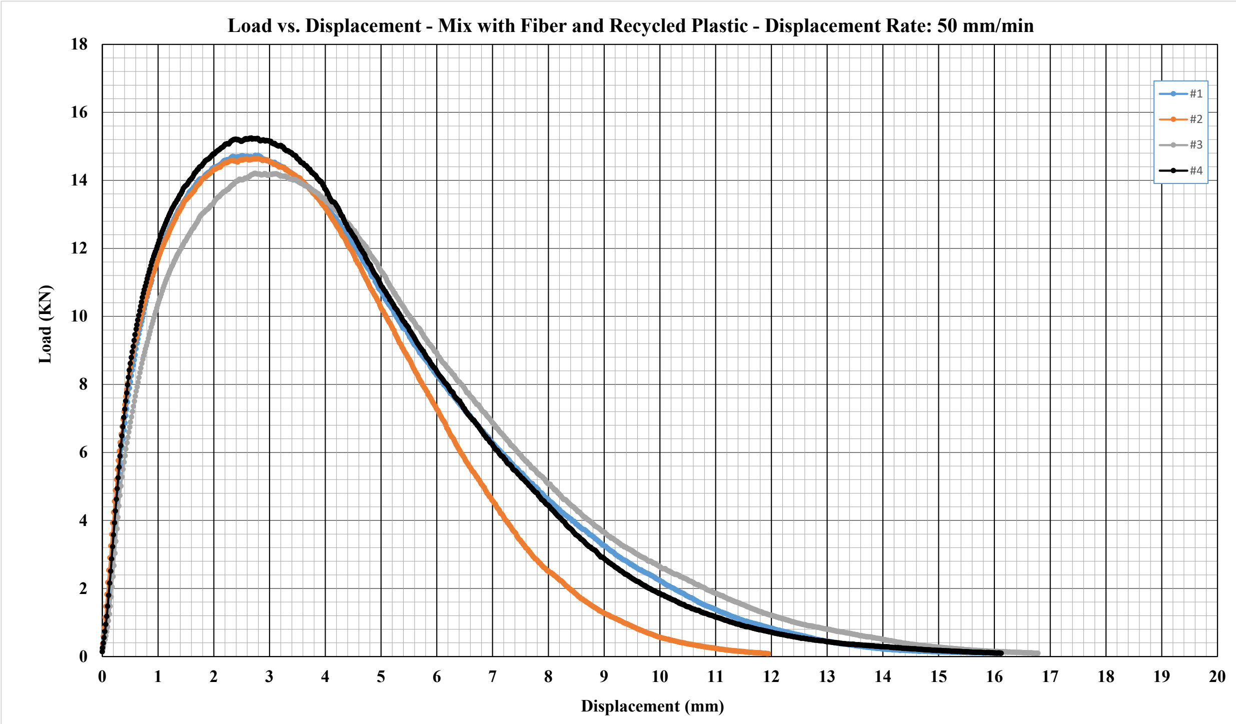
Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	14.442	95.1	10209.6	136.3	987.0	3.0	5.4	-2.70
IDEAL 2	14.428	92.5	9926.6	134.1	986.1	2.9	5.4	-2.67
IDEAL 3	13.655	79.1	8507.8	110.4	934.7	2.8	5.1	-2.60
IDEAL 4	14.106	81.0	8698.8	112.7	964.1	2.9	5.3	-2.71
Average	**14.158**	**86.9**	**9335.7**	**123.4**	**968.0**	**2.89**	**5.3**	**-2.67**
Stand. Dev.	**0.369**	**8.0**	**857.1**	**13.7**	**24.6**	**0.08**	**0.16**	**0.05**
Coef. of Var.	**2.6**	**9.2**	**9.2**	**11.1**	**2.5**	**2.7**	**3.1**	**1.9**



Specimen	Peak Load (KN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	16.245	105.4	11330.1	133.1	1112.0	2.8	5.2	-2.95
IDEAL 2	16.274	94.2	10115.0	84.7	1112.2	2.3	4.6	-3.67
IDEAL 3	15.404	89.6	9623.8	83.9	1052.8	2.9	4.9	-3.76
IDEAL 4	15.133	93.8	10084.8	109.9	1035.9	3.5	5.5	-3.34
Average	**15.764**	**95.8**	**10288.4**	**102.9**	**1078.2**	**2.87**	**5.0**	**-3.43**
Stand. Dev.	**0.583**	**6.7**	**729.9**	**23.5**	**39.7**	**0.48**	**0.37**	**0.37**
Coef. of Var.	**3.7**	**7.0**	**7.1**	**22.8**	**3.7**	**16.9**	**7.4**	**10.7**



Specimen	Peak Load (kN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)
IDEAL 1	14.333	84.6	9,080.9	99.6	979.6	2.7	4.8	-2.9
IDEAL 2	14.117	88.4	9,487.3	130.2	964.8	2.9	5.1	-2.5
IDEAL 3	14.621	83.9	9,002.2	104.7	999.3	2.5	4.8	-2.7
IDEAL 4	14.229	78.8	8,461.6	105.1	972.5	2.6	4.8	-2.6
Average	**14.325**	**83.9**	**9,008.0**	**109.9**	**979.0**	**2.7**	**4.9**	**-2.68**
Stand. Dev.	**0.216**	**3.9**	**421.8**	**13.8**	**14.8**	**0.15**	**0.18**	**0.19**
Coef. of Var.	**1.5**	**4.7**	**4.7**	**12.5**	**1.5**	**5.5**	**3.6**	**7.1**



Specimen	Peak Load (kN)	Work of Fracture (J)	Fracture Energy (J/m2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Displ. at Peak Load (mm)	Post Peak Displ. at 75% Peak Load (mm)	Post Peak Tangential Slope at 75% Peak Load (kN/mm)	Post Peak Tangential Slope at 75% Peak Load (N/m)
IDEAL 1	14.738	94.1	10,098.7	127.2	1,007.2	2.7	4.9	-2.6	-2,587,884
IDEAL 2	14.639	82.5	8,856.6	91.6	1,000.5	2.8	4.8	-3.1	-3,075,420
IDEAL 3	14.208	95.5	10,236.4	143.5	969.5	2.7	5.2	-2.5	-2,503,612
IDEAL 4	15.247	94.4	10,121.0	116.0	1,040.4	2.7	4.8	-2.8	-2,807,919
Average	**14.708**	**91.6**	**9,828.2**	**119.6**	**1,004.4**	**2.7**	**4.9**	**-2.74**	-2,743,709
Stand. Dev.	**0.427**	**6.1**	**650.5**	**21.8**	**29.1**	**0.05**	**0.22**	**0.26**	255,658
Coef. of Var.	**2.9**	**6.7**	**6.6**	**18.2**	**2.9**	**1.8**	**4.5**	**9.3**	9.3

PENNSYLVANIA MANUFACTURING INNOVATION PROGRAM

INTERIM AND FINAL PROJECT REPORTS

Reports are ***limited to two pages.*** Information will be included in the program update to the PA Department of Community and Economic Development (DCED).

i) Complete/update the project participants in items #2 and #3 if necessary.

ii) Provide a brief description of the technical accomplishments of the project for the reporting period in item #4. Relate these accomplishments to the PMIP goals of addressing immediate industry challenges and/or developing new technologies/processes to meet industry needs and enhancing economic development.

For the *final* report, please include one figure that conveys a key aspect of the technical outcome of the project in item #4. This description should be suitable for public dissemination to a lay audience.

Indicate Type of Report:

Final Project Report

Section A: Project Accomplishments

1. **Project Title: Material and Structural Characterization of Fiber-reinforced Asphalt Pavements in Pennsylvania Using Forta Fiber Products**

2. **Research Team: Mansour Solaimanian, Behnam Jahangiri, Xiaogang Guo, Scott Milander, Ali Sahraei Joubani**

Research Team	Name	Email Address
Principal Investigator	Mansour Solaimanian	msol@psu.edu
Graduate Student	Ali Sahraei Joubani	
(Graduate Student)		
Undergraduate Student	Benjamin Allbaugh	

3. **Industry Project Participants with contact information:**

Industry Partner	Industry Contact Name	Mailing Address	Email Address
Forta Corporation	Scott Nazar	100 Forta Dr., Grove City, PA 16127	snazar@fortacorp.com

4. Results of the Project:

A laboratory investigation was undertaken to evaluate the performance of fiber modified asphalt mixtures using a set of mechanical tests. The selected tests were the Hamburg wheel tracking, IDEAL-CT, and IDEAL-RT. The study also included investigating the impact of replacing the polymer carrier of the fiber with recycled polymer. The fiber, the virgin polymer, and the recycled polymer were all provided by Forta Corporation. Rheological testing of unaged, short-term aged, and long-term aged binders with and without polymer modification was conducted and the performance grade of each of the binders was determined. The HWT test was used with a control and a fiber-modified mix. The IDEAL-CT test was applied to the control mix, the mix with fiber and the virgin polymer, and the mix with fiber and recycled polymer. Some of the mixes for IDEAL-CT determination were tested at a range of displacement rates. Finally, the IDEAL-RT was applied to the control mix and the mix with fiber and polymer.

The binder study revealed that modification of the binder with virgin or recycled polymer did not change the nominal grade of the binder. All binders were graded as PG 64S-22. There was a slight stiffening effect of the polymer on the binder, but no difference was found between the virgin polymer and recycled polymer in terms of impact on the rheological properties. There was a slight improvement in DTc when the recycled polymer replaced the virgin polymer in the binder.

Both the control and fiber modified asphalt mixes exhibited excellent performance in HWT, with the maximum rut depth under 3 mm after 20,000 wheel passes. The DEAL-CT results showed an increase in the cracking resistance for the fiber modified mixture compared with the control mixture when tested at 50 mm/min and 30 mm/min displacement rates, but not at the rate of 25 mm/min. In general, lower testing speed resulted in lower IDEAL-CT index. While differences among IDEAL-CT values were seen among various mixtures, no considerable difference was observed for the indirect tensile strength among different mixes at the same displacement rate. This is an indication of improving the mix asphalt mix flexibility without compromising the mix strength. Figure 1 presents how the mix flexibility is improved through the use of fiber at various displacement rates. Finally, the IDEAL-RT test indicated improvement in rutting resistance of the fiber modified mixture compared with the control mix. The overall conclusion from this study was that improved performance of the asphalt mix is obtained through the use of fibers in the mix. The improved performance could potentially reduce the life cycle cost.

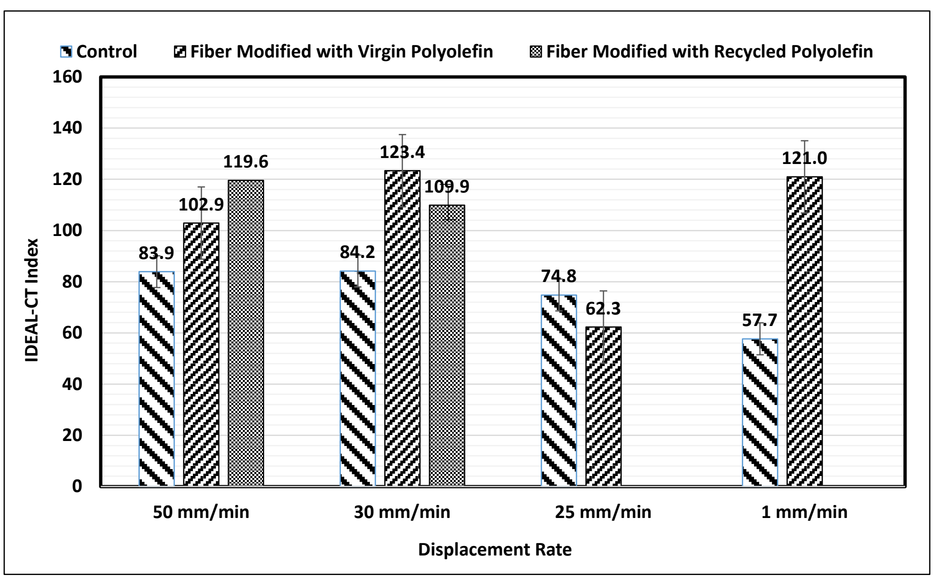


Figure 1 Effect of fibers on the asphalt mix flexibility at different displacement rates