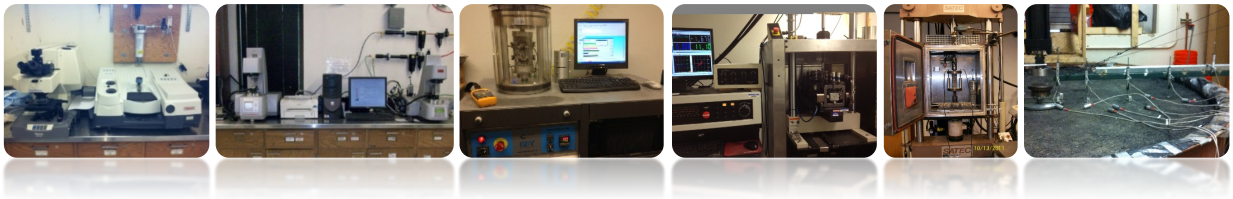

Evaluation of TechniSoil G5® Stabilized Aggregate Mixture

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The TechniSoil G5® stabilizer is a polymeric binder that can be used for binding aggregates together to create a stable surface mixture for roadways and parking lots. Polymer products are partially derived from renewable resources such as plants and animals and, with some exceptions, generally do not contain toxins or environmentally damaging substances. By using such polymer-based products, the use of toxic substances released to the environment can be reduced or eliminated and keep the world sustainable and green for future generation.

This report presents the results of a comprehensive laboratory evaluation program of a G5-stabilized aggregate mixture using the latest advancements in materials testing. Aggregates from Greenhorn were stabilized with TechniSoil G5® at a rate of 7.0% by dry weight of aggregates. The G5-stabilized aggregate mixture was evaluated for stiffness using the dynamic modulus (E*) test in accordance with AASHTO TP 79 and AASHTO PP 61, resistance to rutting using the flow number (FN) test in accordance with AASHTO TP 79, resistance to reflective cracking using the overlay tester (OT) in accordance with Tex-248-F, resistance to thermal cracking using the Uniaxial Thermal Stress and Strain Tester (UTSST) in accordance with an ASTM draft standard test method, and resistance to fatigue cracking using the flexural beam fatigue test in accordance with AASHTO T 321.

Based on the analysis of the data generated from the laboratory evaluation of the G5-stabilized aggregate mixture, the following conclusions can be drawn:

- The G5-stabilized aggregate mixture exhibited a viscoelastic behavior where the stiffness of the mixture depended on temperature and loading rate.
- The G5-stabilized aggregate mixture had higher moduli values and was more stable at low loading frequencies (representing slow moving traffic loads) and/or high temperatures when compared to a typical dense-grade hot-mix asphalt (HMA). This indicates a stable mixture in hot climates and at intersections on urban streets and on off-ramps.
- The G5-stabilized aggregate mixture resisted the tertiary flow at 60°C (140°F) after 20,000 loading cycles while maintaining the permanent axial strain below 0.20%; thus, super-exceeding the minimum flow number requirements for asphalt mixtures as specified in AASHTO TP 79. This indicates that the mixture will offer an excellent resistance to rutting at elevated temperatures and at intersections on urban streets and on off-ramps when used as a surface layer.
- The G5-stabilized aggregate mixture exhibited an excellent resistance to reflective cracking. The mixture did not reach failure in the Overlay Tester even after 9,000 loading cycles; thus, well exceeding the minimum number of cycles required for various types of asphalt mixtures as set forth by Texas Department of Transportation (TxDOT).
- The G5-stabilized aggregate mixture exhibited an excellent resistance to thermal cracking after long-term aging in a forced-draft oven for 5 days at 85°C (185°F). The mixture was able to resist a low temperature of -42°C (-43.6°F) without fracturing or developing any micro cracks in the specimen while maintaining a high tensile strength.

- The G5®-stabilized aggregate mixture exhibited an excellent resistance to fatigue cracking at 21.1°C (70°F) after long-term aging. Given both, the state of strains under typical traffic loads and the extremely higher number of cycles to failure, the G5®-stabilized aggregate mixture is expected to perform extremely well in fatigue resistance as well.

In summary, the G5-stabilized aggregate mixture exhibited unique characteristics with superior performance at high, intermediate, and low temperatures suggesting a very good performance in the field when used as a surface course layer. The mixture may offer excellent alternatives when used as a surface layer in hot climate areas with heavy traffic and/or braking actions such as at traffic lights on urban streets and off-ramps. The mixture is also anticipated to perform very well when used in cold climates and/or on top of a cracked asphalt pavement due to its high resistance to reflective cracking and thermal cracking.

I. INTRODUCTION

This report summarizes the evaluation of a stabilized aggregate material using the TechniSoil G5® stabilizer conducted in the Pavement Engineering and Science laboratory at the University of Nevada, Reno (UNR). The TechniSoil G5® stabilizer, a new class of super polymers, is a quick curing liquid binder. Polymer products are partially derived from renewable resources such as plants and animals and, with some exceptions, generally do not contain toxins or environmentally damaging substances. By using such polymer-based products, the use of toxic substances released to the environment can be reduced or eliminated and keep the world sustainable and green for future generation.

In this study, the TechniSoil G5® was added to aggregate material from Greenhorn at a rate of 7.0% by dry weight of aggregates. Table 1 summarizes the gradations for the individual stockpiles as well as for the blend used in this study.

The latest technologies were used to evaluate the properties and characteristics of the G5-stabilized aggregate mixture that are critical to its resistance to the various distresses. The dynamic modulus test was used to evaluate the stiffness of the mixture to multiple loading rates and temperatures. Furthermore, the G5-stabilized aggregate mixture was evaluated to the following modes of pavement failure using the most widely accepted laboratory tests:

- Permanent deformation,
- reflective cracking,
- thermal cracking, and
- fatigue cracking.

Table 1. Gradation of Greenhorn Aggregate Stockpiles and Blend Aggregates.

Sieve Size	Test Method	Percent Passing			
		3/16 x 7/16 Crushed Aggregate	1/4 inch Washed Sand	Crushed Sand	Blend
Bin Percentages		5%	10%	85%	100%
1/2 inch (12.5 mm)	ASTM C-136 and California Test-202	100	100	100	100
3/8 inch (9.5 mm)		90	100	100	100
#4 (4.75 mm)		16	96	98	94
#8 (2.36 mm)		8	80	67	65
#16 (1.18 mm)		6	69	42	43
#30 (0.600 mm)		5	48	29	30
#50 (0.300 mm)		5	13	21	19
#100 (0.150 mm)		3	4	14	12
#200 (0.075 mm)		1.2	2	9.7	8.5

The G5-stabilized aggregate mixture was placed and compacted in a large slab in a controlled environment. Core samples were taken from the compacted slab and evaluated for dynamic Modulus, rutting resistance (permanent deformation), reflective cracking resistance, and thermal cracking resistance. Beam specimens were also cut out of a compacted slab for the evaluation of the mixture to fatigue cracking resistance.

The results for a typical dense-graded hot mix asphalt (HMA) were used in this study for reference purposes to demonstrate the behavior of the evaluated G5-stabilized aggregate mixture in comparison to that of a typical asphalt mixture. It should be recognized that the properties of

HMA mixtures vary significantly as a function of aggregate source, gradation and properties, volumetric properties of the mix, and the grade/modification of the asphalt binder. The permanent deformation and reflective cracking test results for the G5-stabilized aggregate mixture were also compared to well-established criteria for asphalt mixtures. The following summarizes all the results and findings from this study.

II. MODULUS PROPERTY OF PAVING MATERIALS

The fundamental definition of modulus is the relationship between the stress and strain of an engineering material. For linear elastic material such as Portland cement concrete mixtures the modulus is referred to as "elastic modulus." For other paving materials that are not completely linear elastic such as unbound granular and fine materials the modulus is referred to as "resilient modulus." The resilient modulus test for unbound granular and fine materials is conducted in the axial loading mode under triaxial conditions following AASHTO T 307. In the case of asphalt materials, the definition of modulus has changed through the years to reflect advances in the testing and analysis techniques. Up to the early 1990s, the diametral resilient modulus test was commonly used to evaluate the modulus of asphalt mixtures. The diametral test applies a compressive pulse load along the diametral axis of the sample at a single loading rate. In the late 1990s the technology of testing asphalt mixtures advanced to the measurement of the dynamic modulus to better represent the viscoelastic behavior of asphalt mixtures. The details of the Dynamic Modulus test are provided in the next section.

2.1. Dynamic Modulus Property

The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) uses the dynamic modulus (E*) master curve to evaluate the structural response of the asphalt pavement under various combinations of traffic loads, speed and environmental conditions. The E* property of an asphalt mixture is evaluated under various combinations of loading frequency and temperature in accordance with AASHTO TP 79 – "Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) using the Asphalt Mixture Performance Tester (AMPT)." Using the viscoelastic behavior of an asphalt mixture (i.e., interchangeability of the effect of loading rate and temperature), the master curve is developed in accordance with AASHTO PP 61 – "Developing Dynamic Modulus Master Curve for Hot Mix Asphalt (HMA) using the Asphalt Mixture Performance Tester (AMPT)." The dynamic modulus test is conducted on a 4.0-inch diameter by 6.0-inch height cylindrical specimen cored from the center of a sample compacted in the Superpave gyratory compactor (SGC). Figure 1 shows a picture of the AMPT equipment along with a typical E* master curve for an asphalt mixture. The E* property provides an indication on the general quality of an asphalt mixture.

The same AASHTO procedures for determining the E* for asphalt mixtures were used in this evaluation to measure the E* for the G5-stabilized aggregate mixture from Greenhorn. Figure 2 shows the G5-stabilized aggregate sample in the dynamic modulus testing set up. Figure 3 shows the E* property of the G5-stabilized aggregate mixture at various loading frequencies and temperatures. All test specimens were compacted to 12% ± 1% air voids. The bars in Figure 3b represent the average E* values while the whiskers on top of the bars represent the limits of the 95% confidence interval (CI) of the measured E* property. Overlapping of the confidence intervals implies the similarity in the measured E*.

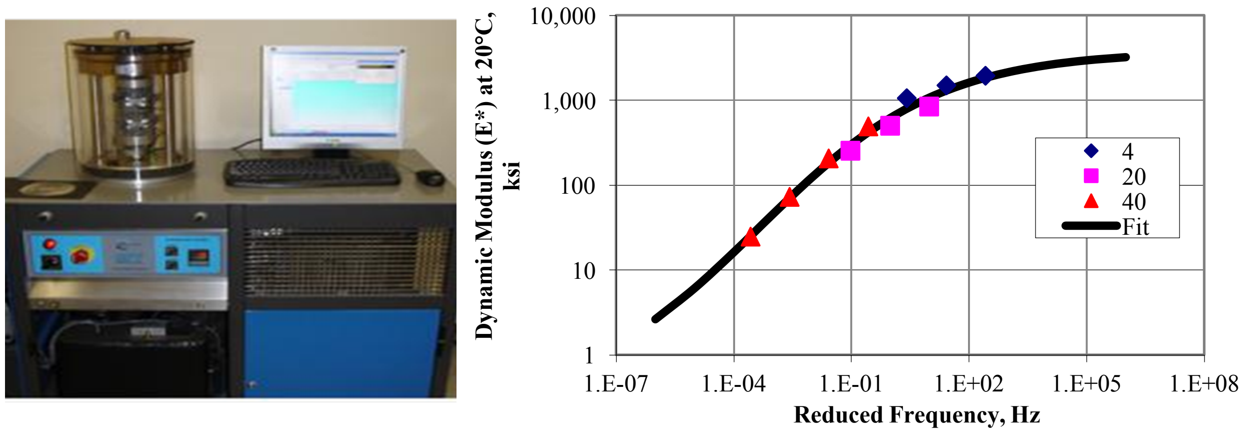


Figure 1. Asphalt mixture performance tester (AMPT) and a typical master curve for asphalt mixture.

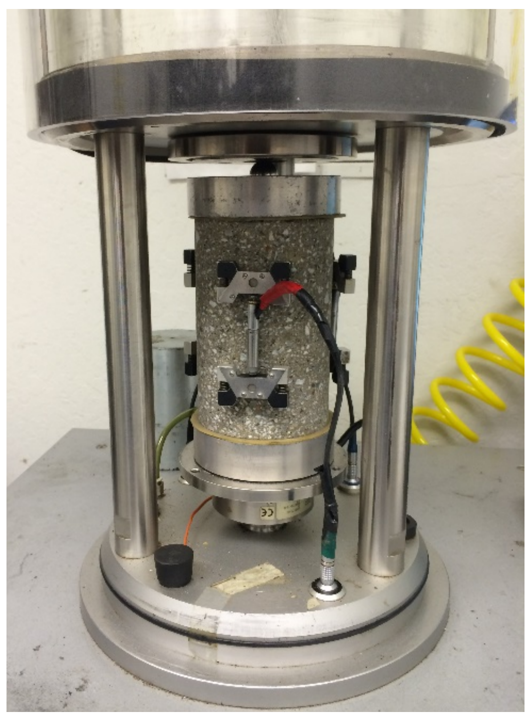
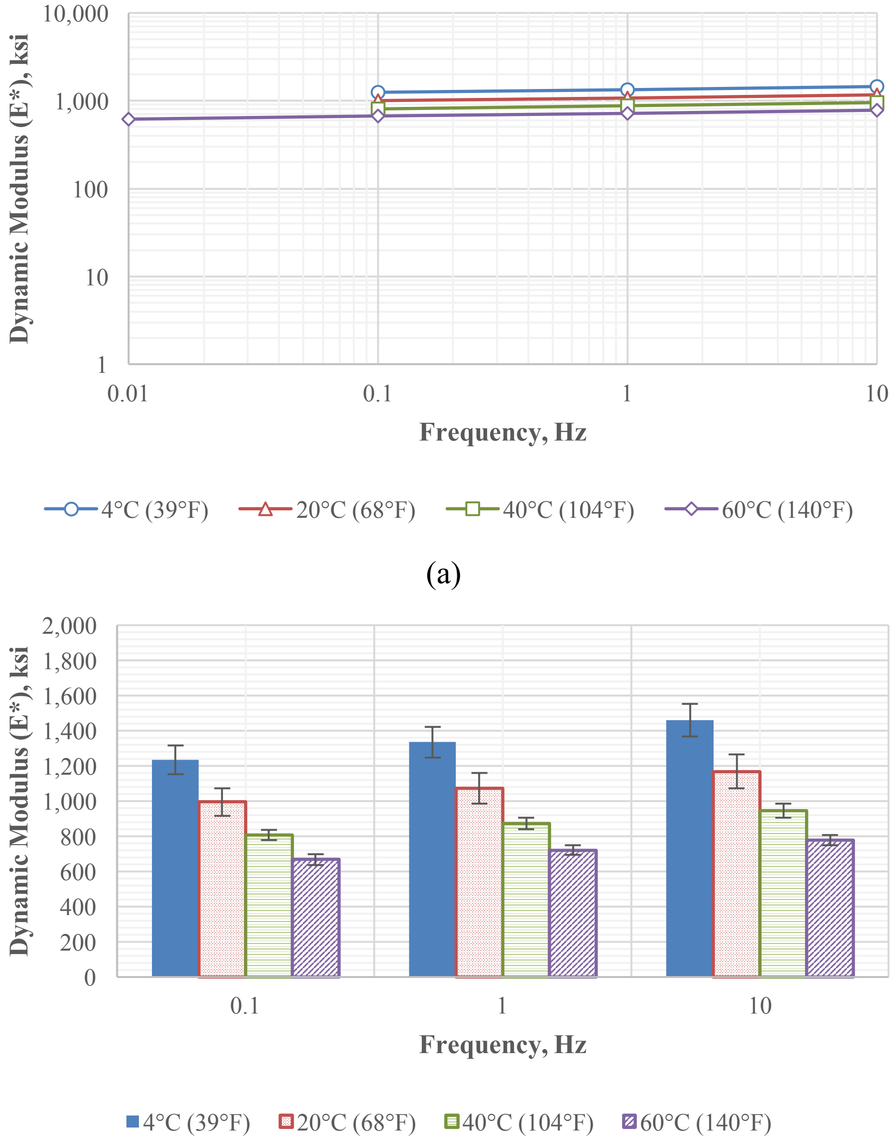


Figure 2. The G5-stabilized aggregate sample in the dynamic modulus testing set-up.

Figure 4 shows typical trends of E* data for a dense-graded HMA mixture compacted to 7% ± 1% air voids. In the case of the HMA mixture, the E* property decreases with increasing temperature and increases with increasing the frequency of loading which is an indication of a viscoelastic behavior. In general, a similar behavior was observed for the G5-stabilized aggregate mixture with the impact of frequency of loading on the E* property being to a lesser extent. This, in general, indicates that the G5-stabilized aggregate does also have a viscoelastic behavior and its stiffness can be represented by an E* master curve. Accordingly, Figure 5 and Figure 6 show the E* master curve for the G5-stabilized aggregate mixture and typical dense-graded HMA, respectively.



(b)

Figure 3. Dynamic modulus of the G5-stabilized aggregate mixture: (a) log-log scale; (b) normal scale (error bars represent the mean value plus or minus 95% confidence interval).

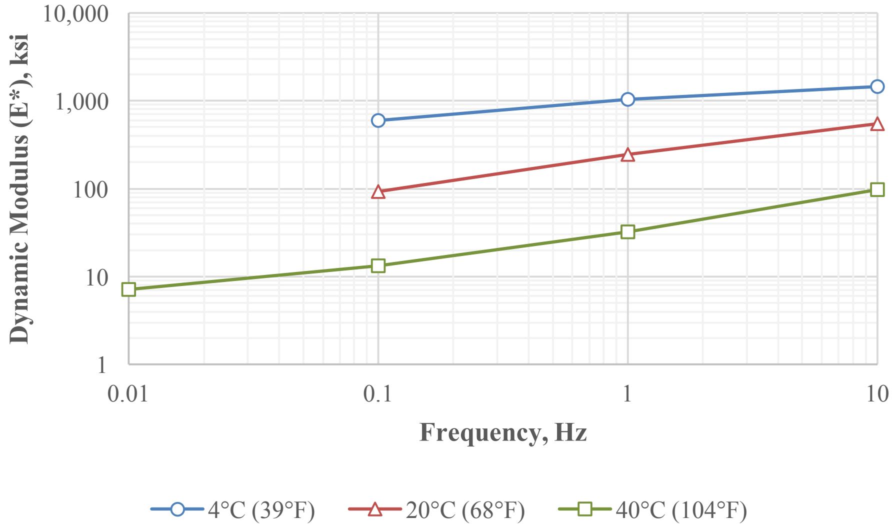


Figure 4. Typical dynamic modulus for HMA mixture.

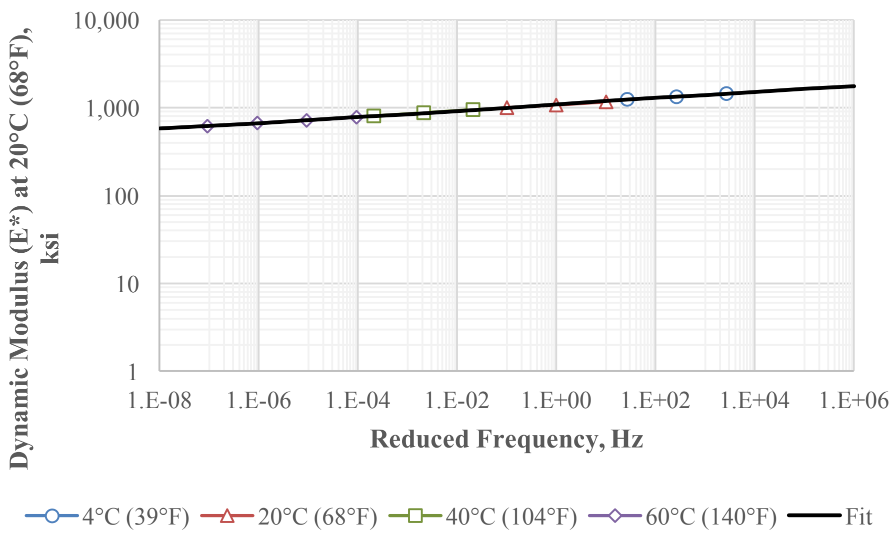


Figure 5. Dynamic modulus master curve for the G5-stabilized aggregate mixture.

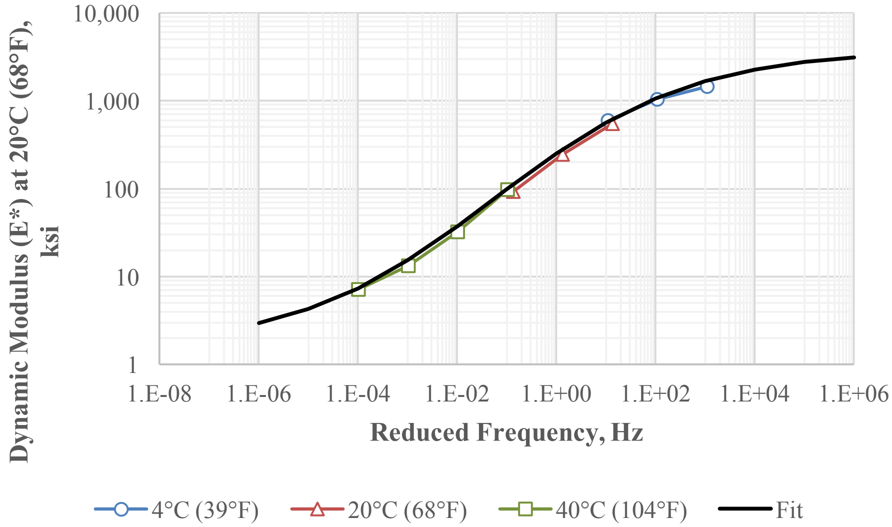


Figure 6. Typical dynamic modulus master curve for HMA mixture.

An examination of the data in Figure 3 to Figure 6 leads to the following conclusions. It should be noted that the E* property of the G5-stabilized aggregate mixture is anticipated to vary with any variation in the G5 binder content. It should also be kept in mind that the specimens for the G5-stabililzed aggregate mixture had an air void level significantly higher than the HMA specimens (on average 12% versus 7%).

- The G5-stabilized aggregate mixture exhibited a viscoelastic behavior which is attributed to the G5 stabilizing polymer. The impact of temperature on the E* property of the G5-stabilized aggregate mixture was significant (to a lesser extent for the loading frequency) with an increase in E* was observed with the decrease in temperature. Thus, the dynamic modulus (E*) master curve is suitable to evaluate the structural response of the G5-stabilized aggregate mixture under various combinations of traffic loads, speed and environmental conditions.
- The E* property of the G5-stabililzed aggregate mixture was found to be significantly higher than the E* for the typical dense-graded HMA; in particular, at low reduced frequencies (less than 0.01 Hz). Thus, indicating an excellent resistance for the G5-stabilized aggregate mixture for rutting and shoving in hot climates and at intersections on urban streets and on off-ramps.

III. RESISTANCE TO PERMANENT DEFORMATION

The resistance of the G5-stabilized aggregate mixture to permanent deformation was evaluated in accordance with AASHTO TP 79 test: "Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)." The flow number (FN) test consists of subjecting a 4-inch by 6-inch cylindrical sample at a specified temperature to a repeated axial compressive load pulse of 0.1 second loading and 0.9 second of rest period. All test specimens were compacted to 12% ± 1% air voids and tested unconfined by applying a vertical deviator stress of 87 psi (600 kPa). The resulting cumulative permanent axial strain is measured and plotted versus the number of load cycles. Figure 7 shows the G5-stabilized aggregate sample in the FN testing set up. Figure 8 shows the response of a typical dense-graded

HMA. The cumulative permanent strain can be defined by the primary, secondary, and tertiary zones. In the primary zone, the permanent strain increases rapidly but at a decreasing rate. In the secondary zone, the permanent strain rate maintains a constant value until it starts increasing in the tertiary creep zone. The point at which the tertiary flow starts is called the flow number (FN). In other words, the FN is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain. The higher the flow number (FN) value the better the resistance of the mixture to rutting (i.e., permanent deformation).

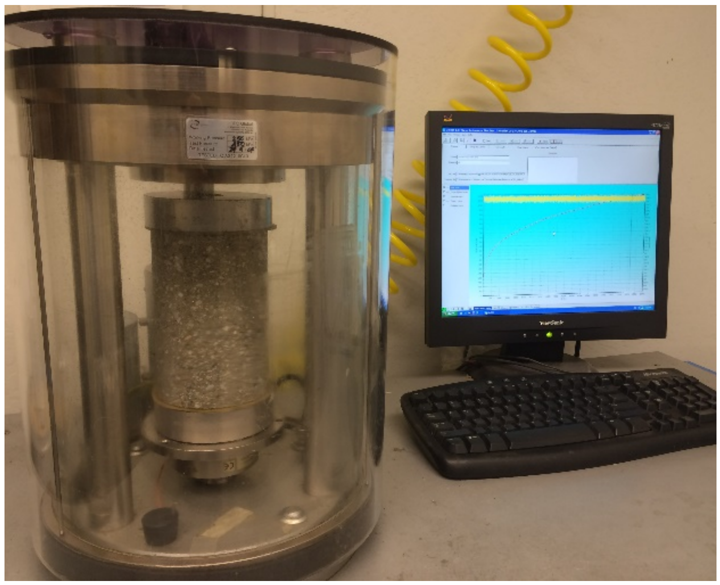


Figure 7. The G5-stabilized aggregate sample in the FN testing set-up

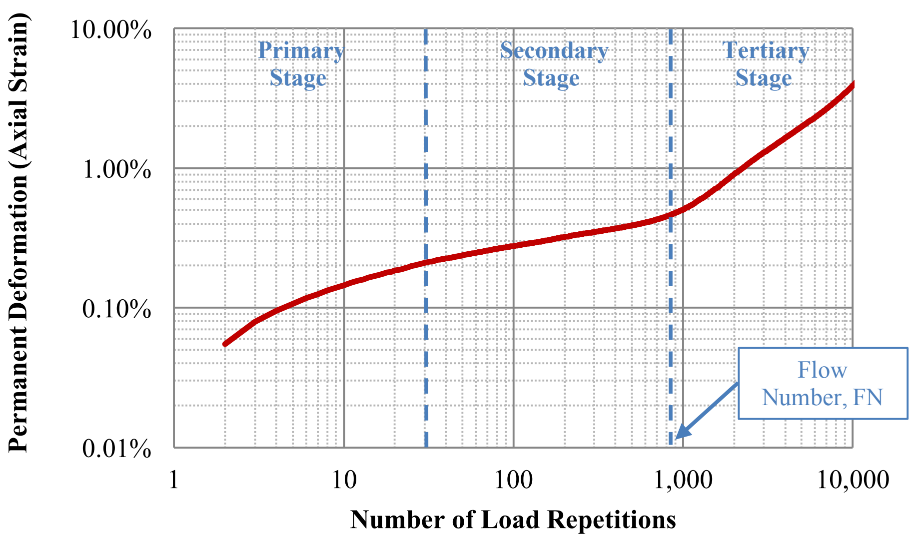


Figure 8. Typical permanent deformation curve for a dense-graded HMA mixture.

According to AASHTO TP 79-15, the flow number testing temperature is the high adjusted PG temperature determined using the LTPP Bind Version 3.1 software based on the project climatic data from the nearest weather station and using the evaluation parameters listed below:

- Design reliability = 50%,
- Target rut depth = 12.5 mm (0.50 inch),
- Adjustment for traffic loading and speed = 0.0, and
- Depth of layer = 20 mm (0.80 inch).

The flow number test was conducted on the compacted G5-stabilized aggregate mixture at 60°C (140°F). The selected testing temperature was the highest temperature that can be achieved in the AMPT machine. Figure 9 and Figure 10 Show the location of the various sections in the US with a high adjusted PG temperature of 58°C and 64°C (136.4 and 147.2°F) as determined using the LTPP Bind Version 3.1 software, respectively.

The flow number test results at 60°C (140°F) for the G5-stabilized aggregate mixture are shown in Figure 11. The minimum average flow number requirements for HMA as a function of traffic level are shown in Table 2 in accordance with AASHTO TP 79-15. A higher minimum FN is required for a higher traffic level. The data presented in Figure 11 show that no FN was observed for the evaluated G-5 stabilized aggregate mixture even after 20,000 cycles of load repetitions. Hence, super-exceeding the minimum FN requirements for HMA mixtures. Furthermore, the accumulated permanent axial strain remained minimal and below 0.20% at the end of the 20,000 cycles of load repetitions. Accordingly, the G5-stabilized aggregate mixture exhibited a superior and excellent resistance to permanent deformation (i.e., rutting). Thus, suggesting that the evaluated mixture can successfully withstand the high and heavy traffic in hot climates when used as a surface layer.

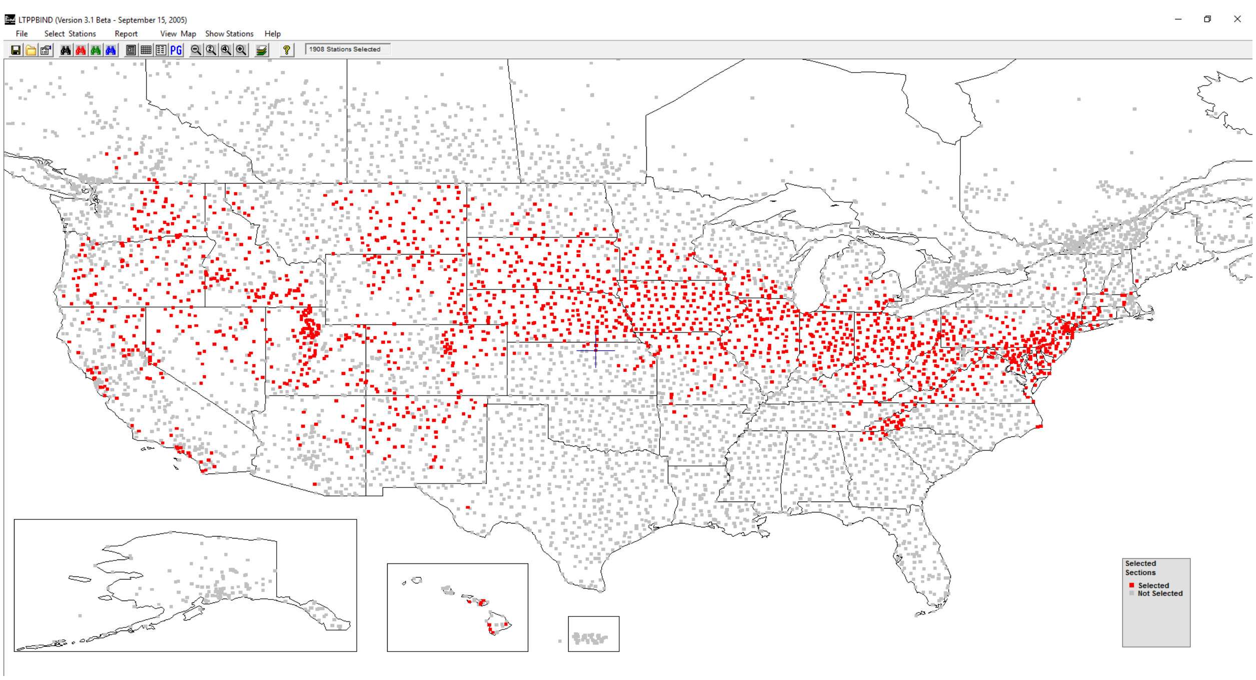


Figure 9. US map from LTTP Bind Version 3.1 software showing in red the sections with a high adjusted PG temperature of 58°C.

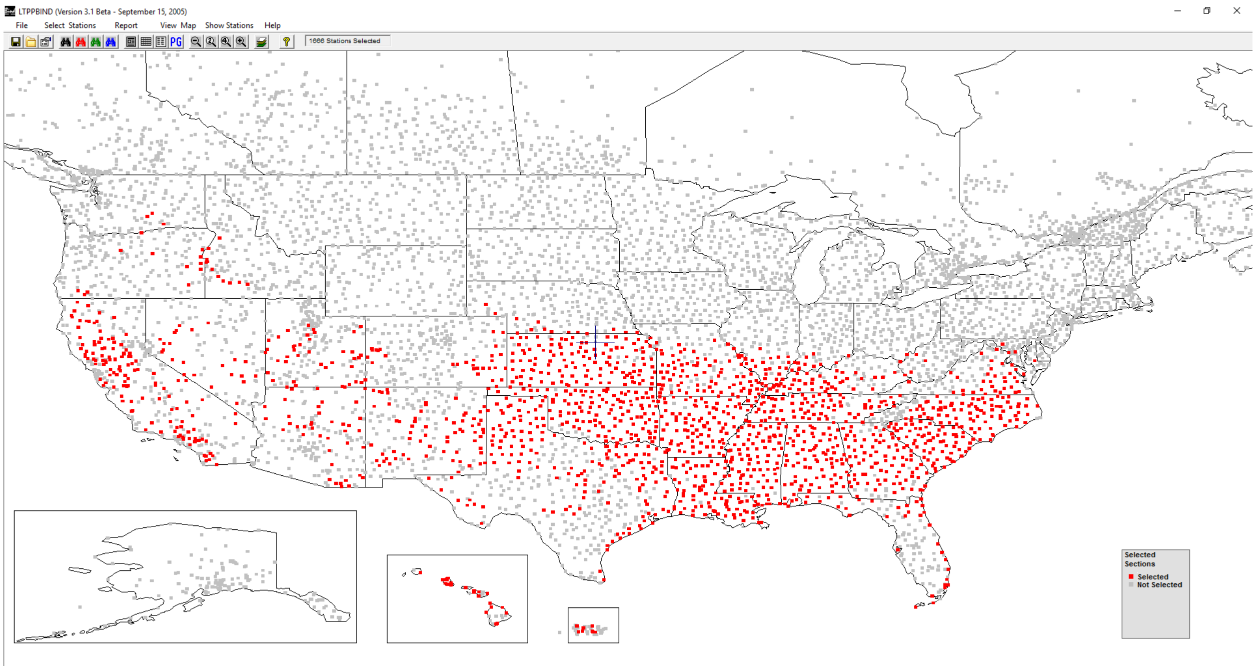


Figure 10. US map from LTTP Bind Version 3.1 software showing in red the sections with a high adjusted PG temperature of 64°C.

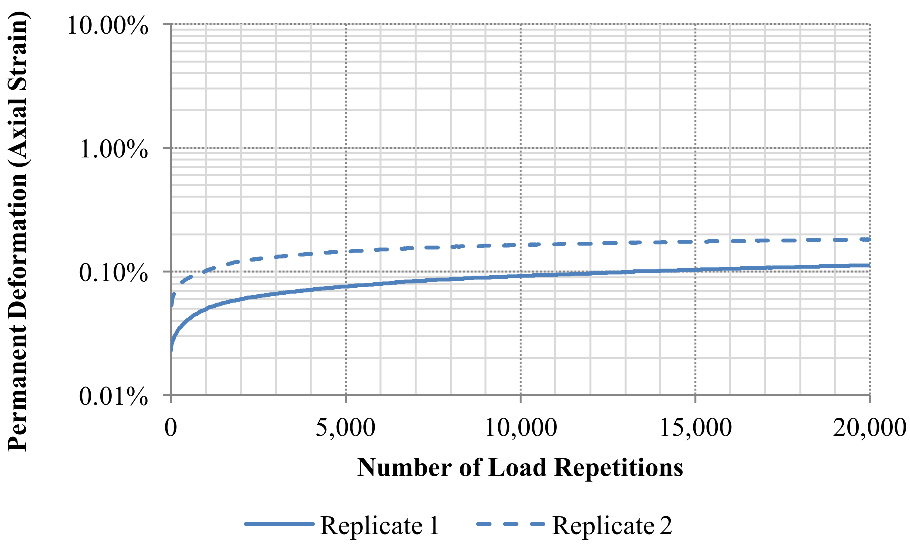


Figure 11. FN test results for the G5-stabilized aggregate mixture.

Table 2. Minimum Average Flow Number Requirements for HMA (AASHTO TP 79-15).[1]

Traffic Level, Million ESALs	**HMA Minimum Average Flow Number**
<3	--[2]
3 to <10	50
10 to <30	190
≥30	740

Notes:
[1] Minimum flow number values were established using the average of four specimens and the flow number test parameters in Table X2.3 of AASHTO TP 79-15.
[2] No minimum flow number requirement (flow number testing not required)

IV. RESISTANCE TO REFLECTIVE CRACKING

Pavement rehabilitation has become one of the most important issues facing many highway departments. One major type of distress influencing the life of an asphalt concrete overlay is reflective cracking. When overlays are placed over jointed or severely cracked existing rigid or flexible pavements, cracks will reflect to the surface in a relatively short period of time. Physical tearing of the overlay occurs because of movements under heavy wheel loads at joints and cracks in the underlying pavement layer. Therefore, the long-term performance of the overlay will depend on its ability to resist reflective cracking. Reflective cracking in the overlay allows water to percolate into pavement structure and weaken the supporting layers, hence contributing to several forms of pavement deterioration.

Numerous previous efforts have been exerted to reduce or prevent reflective cracking of asphalt overlays including the increase thickness of asphalt overlay, the use of stress absorbing membranes inter-layers, the use of fabrics and geotextiles membranes, and the fracturing of the existing concrete slabs. The basic principle of reflective cracking is that the tensile stresses at the interface of the crack and the new asphalt overlay are significantly increased due to the discontinuity at the tip of the crack. The developed tensile stresses rapidly exceed the tensile strength of the asphalt overlay and the crack forms at the interface and quickly propagate to the surface. Combating reflective cracking can be achieved by either one of the two approaches: a) reduce the magnitude of the tensile stresses at the crack-overlay interface or b) increase the tensile strength of the asphalt overlay.

The Overlay Tester (OT) was used to characterize the resistance of the G5-stabilized aggregate mixture to reflective cracking by subjecting a sample to repeated opening and closing movements in accordance with TxDOT Tex-248-F. The OT was specifically designed to simulate the horizontal opening and closing of joints and cracks that exist underneath a new overlay.

The OT test specimen consists of a 6-inch long by 3-inch wide and 1.5-inch thick sample. Once the specimen is prepared, it is glued on two metallic plates, one that is fixed and another one that is mobile to create the opening and closing simulation (Figure 12). The glued sample is conditioned inside the test chamber for a minimum of 2 hours at the testing temperature. The test is conducted in a controlled displacement mode until the failure occurs at a loading rate of one cycle per 10 seconds with a maximum displacement of 0.018 inch at the testing temperature of 10°C (50°F). Each cycle consists of 5 seconds of loading and 5 seconds of unloading. The cycles are applied until failure as defined by a drop of 93% of the maximum load measured on the first cycle. The OT will typically stop the test if this drop is not reached within 1,000 cycles.

Since 2013, the overlay test has been part of TxDOT specifications to determine the susceptibility of bituminous mixtures to fatigue or reflective cracking (Tex-248-F). Table 3 shows the minimum overlay tester requirements for asphalt mixtures implemented by TxDOT.

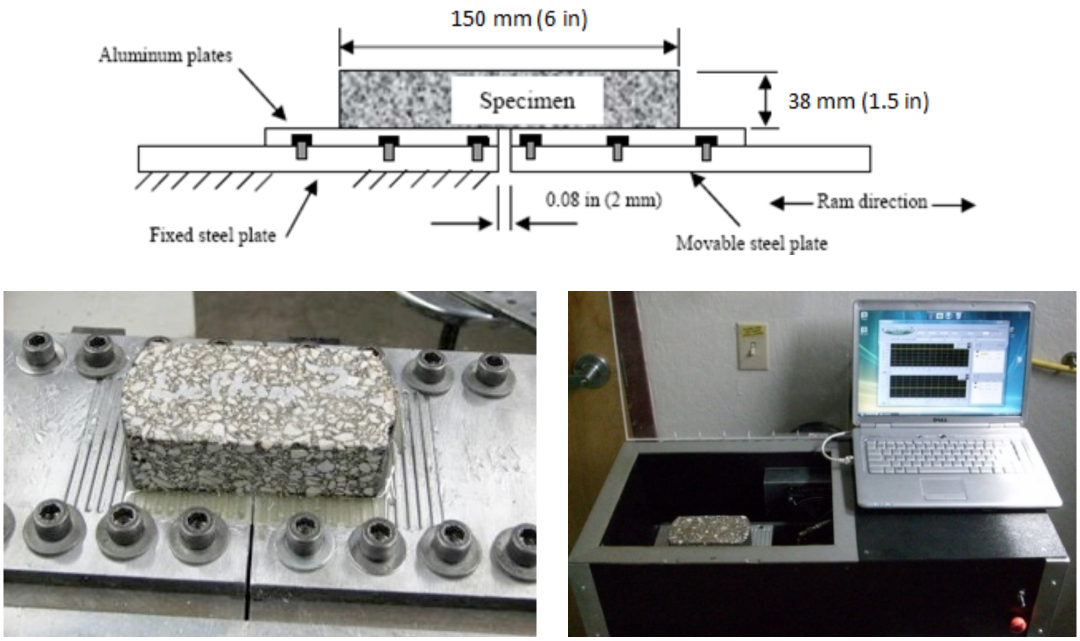


Figure 12. Schematic and photo of the TTI overlay tester.

Table 3. Minimum Overlay Test Requirements for Asphalt Mixtures (TxDOT, 2013).

Type of Mixture	Minimum Number of Cycles
Stone-Matrix Asphalt (SMA)	200
Fine-Graded Permeable Friction Course (PFC)	300
Thin Asphalt Overlay Mixture	500

Figure 13 shows the G5-stabilized aggregate sample in the AMPT overlay testing set up. Figure 14 shows the test results for the G5-stabilized aggregate mixture at 10°C (50°F). The data show that failure was not reached even after 9,000 loading cycles, hence exceeding the minimum numbers required for the various types of asphalt mixtures (Table 3). Accordingly, the evaluated G5-stabilized aggregate mixture is expected to have an excellent resistance to reflective cracking.

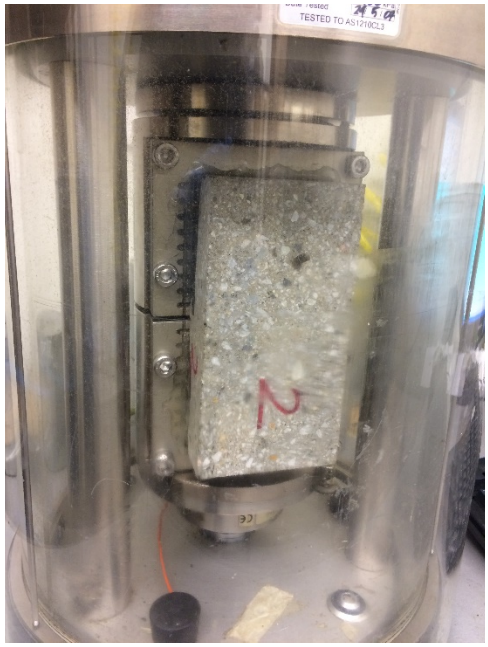


Figure 13. The G5-stabilized aggregate sample in the AMPT overlay testing set-up

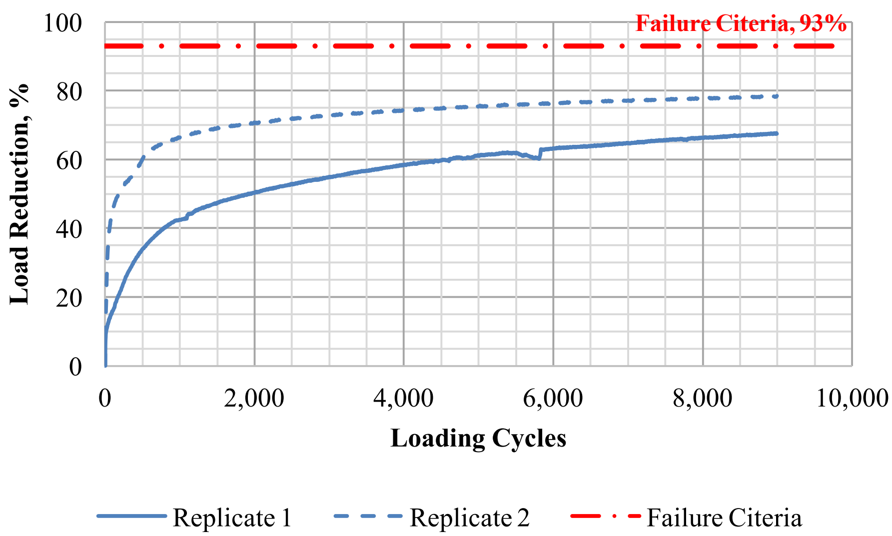


Figure 14. Reflective cracking test results at 10°C (50°F) for the G5-stabilized aggregate mixture.

V. RESISTANCE TO THERMAL CRACKING

Low temperature or thermal cracking is a frequent type of failure in asphalt pavements particularly in the cold regions or locations with high daily temperature fluctuation. The primary pattern of low temperature cracking is the "top-down" propagation of cracks through the depth of the asphalt layer in transverse direction. As the pavement temperature drops, tensile stresses are induced in the asphalt mixture due to the restrained contraction of asphalt layer. The initiation of low temperature cracking is associated with the induced tensile stress in asphalt mixture layer exceeding the tensile strength of the mixture. Accordingly, the performance of an asphalt pavement to low temperature cracking is highly dependent on the viscoelastic characteristics, thermal contraction coefficient, and fracture properties of the mixture.

In this study, the uniaxial thermal stress and strain tester (UTSST) was used to determine the low-temperature cracking resistance of the G5-stabilized aggregate mixture following the ASTM draft Standard Test Method for Determining Thermal Cracking Properties of Asphalt Mixtures through Measurement of Thermally Induced Stress and Strain.

The UTSST was developed by the research team at the University of Nevada, Reno by enhancing the thermal stress restrained specimen test (TSRST) (Alavi *et al.,* 2013; Hajj *et al*., 2013; Morian *et al*., 2014; Morian, 2014). The details of the UTSST set up are shown in Figure 15. Typical thermal stress and strain measurements from the UTSST for dense-graded HMA are shown in Figure 16a. The test cools down a 2.25-inch diameter by 5.50-inch height cylindrical specimen at a rate of 10°C/hour while restraining it from contracting. While the sample is being cooled down from 20°C, tensile stresses are generated due to the ends being restrained. The mixture would fracture as the internally generated stress exceeds its tensile strength. The temperature and stress at which fracture occurs are referred to as "fracture temperature" and "fracture stress", respectively, and represent the anticipated field temperature under which the pavement will experience thermal cracking.

During the cooling period, an added modular feature to the set-up allows for the measurement of the thermal coefficient of contraction from an unrestrained specimen concurrently with the stress measurements from the restrained specimen. The unrestrained specimen is made up of two 2.25 inch cylindrical specimens glued together using a thin layer of epoxy (Figure 15). The unrestraint specimen is placed on a frictionless roller stand to minimize friction and allow for the free shrinkage or expansion of the specimen during thermal loading. Two invar rods are glued to the ends of the specimen as LVDT targets. The invar rods extend out of the chamber to maintain the LVDTs near ambient temperature while the temperature of chamber is reduced. The invar rods are machined from specific types of alley which has a very low thermal coefficient of expansion (about 0.12×10-5 1/°C). During the test, the temperature was determined by measuring the surface of a dummy specimen.

The measured thermal build-up stress can be related to the corresponding measured thermal strain using the uniaxial constitutive equation for linear viscoelastic materials, i.e., Boltzmann equation (Christensen, 2003). These conditions are considered to be met for uniform and undamaged specimens.

By considering the synchronized thermal stress and thermal strain measurements, the UTSST modulus of an asphalt mixture at each temperature can be calculated from the discrete form of the Boltzmann equation as presented in Equation 1.

$$E(T(t_n)) = \frac{\left(\sigma_{Th}(t_{n+1}) - \sum_{i=2}^{n+1} E(t_{n+1}-t_i)\left(\varepsilon_{Th}(t_i) - \varepsilon_{Th}(t_{i-1})\right)\right)}{\varepsilon_{Th}(t_1)} \quad [1]$$

Five characteristic stages of material behavior are identified from the developed stiffness-temperature curve relationship and thermal build-up stress curve (Figure 16a and Figure 16b). A brief description for these behaviors is listed below.

- **Viscous softening:** From this stage the relaxation modulus of the asphalt mixture increases rapidly with decreasing temperature.

- **Viscous-glassy transition:** At this stage the glassy properties of the material overcome the viscous properties.
- **Glassy hardening:** At this stage the behavior of the material is pure glassy.
- **Crack initiation:** In this stage micro-cracks occur in the specimen due to the induced thermal stresses when the material behavior is glassy.
- **Fracture:** At this stage the asphalt mixture specimen breaks due to the propagation of micro-cracks by the induced thermal stresses, i.e. macro failure.

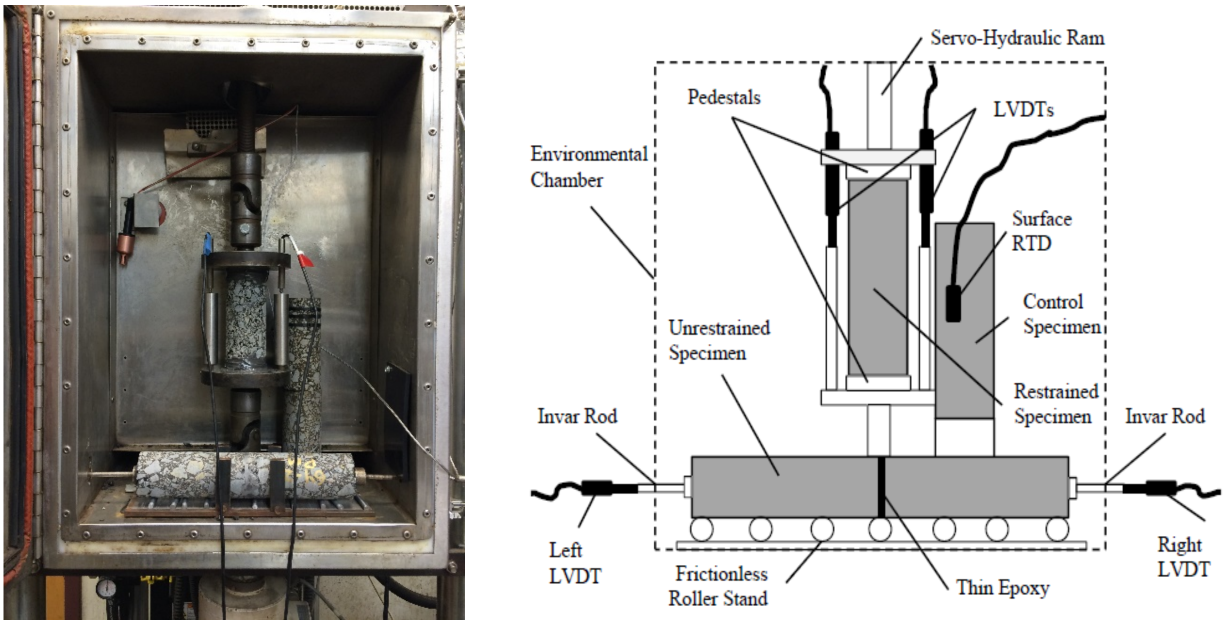
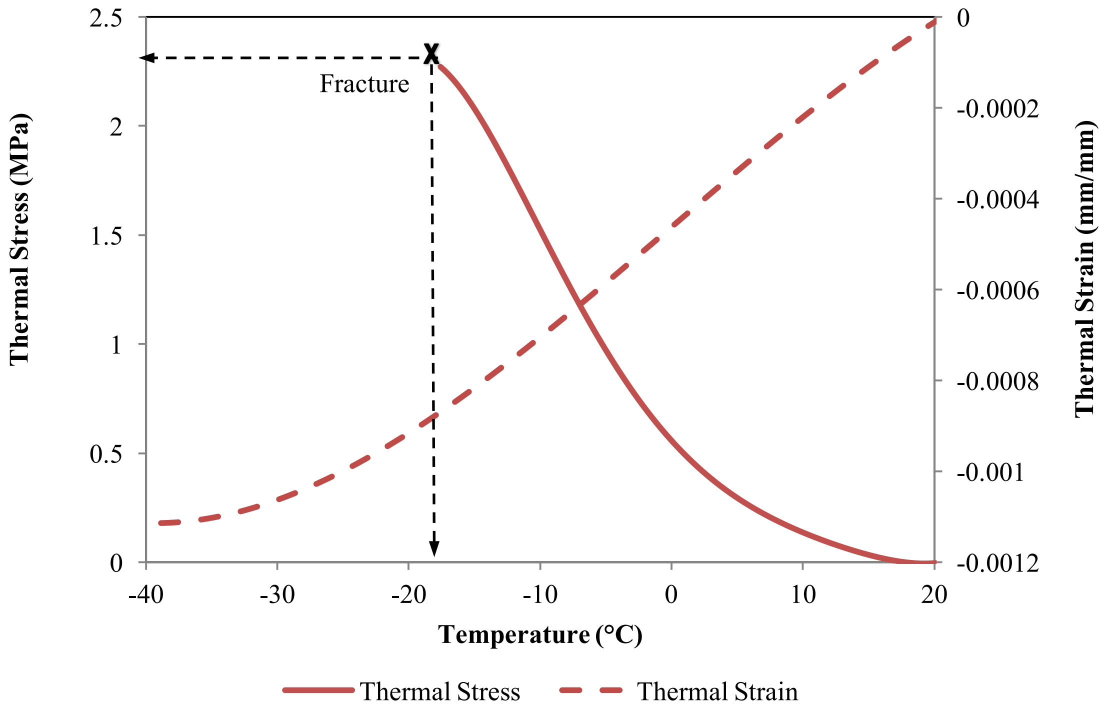
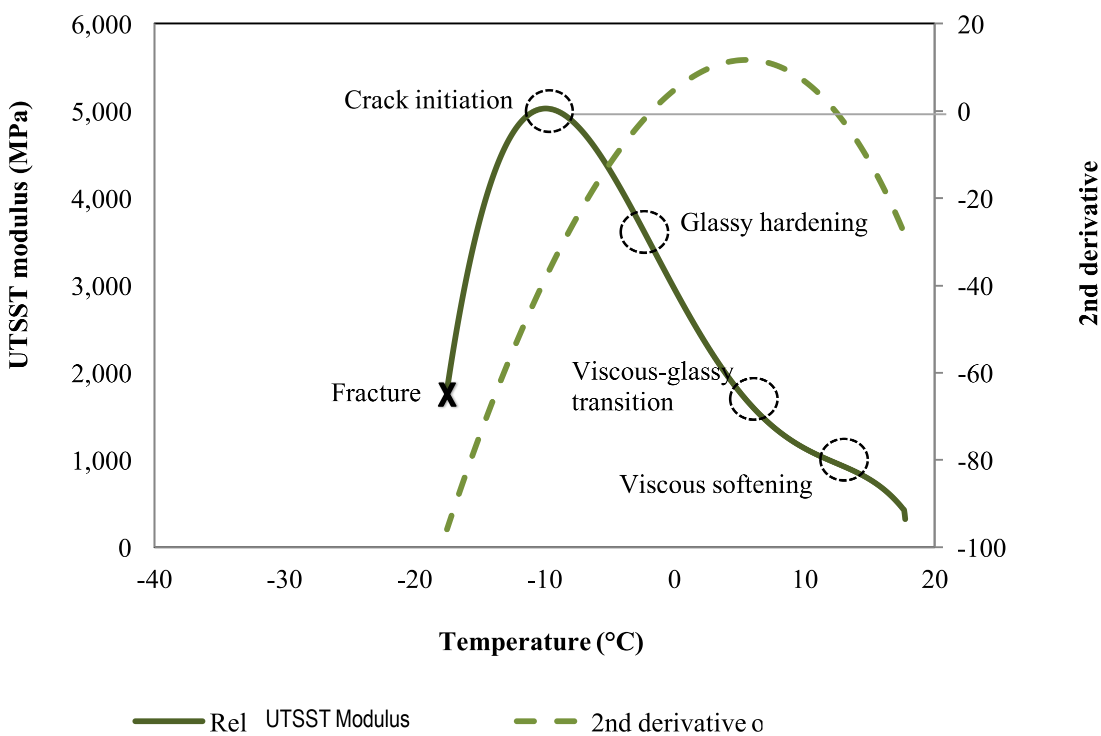


Figure 15. Uniaxial thermal stress and strain test (UTSST) set-up for HMA.



(a)



(b)

Figure 16. (a) Measured thermal stress and strain; (b) Calculated UTSST modulus for a typical HMA and Associated Characteristic Stages

The compacted cylindrical specimens of the G5-stabilized aggregate mixture were long-term aged for 5 days at 85°C (185°F) in accordance with AASHTO R 30 to simulate the long-term aging properties of the mixture in the field when thermal cracking becomes critical. Figure 17 to Figure 19 show the UTSST test results for the G5-stabilized aggregate mixture as well as for a typical dense-grade HMA. Table 4 summarizes the calculated thermos-viscoelastic properties. It should be noted that the evaluated G5-stabilzed aggregate mixture did not fracture or reach the crack initiation stage even after experiencing a temperature as low as -42°C (-43.6°F) (the test was manually stopped after reaching the equipment low temperature limit); thus indicating a superior resistance to thermal cracking. The data also show that the G5-stabilzed aggregate mixture exhibited a higher thermal stress build-up than the typical HMA at all temperatures indicating a high tensile strength for the G5-stabilzed aggregate mixture. Furthermore, the G5-stabilzed aggregate mixture had a higher modulus than the typical HMA down to about a temperature of -15°C (5°F) below which the mixture exhibited a lower modulus than HMA; thus indicating a better mixture behavior at colder temperatures.

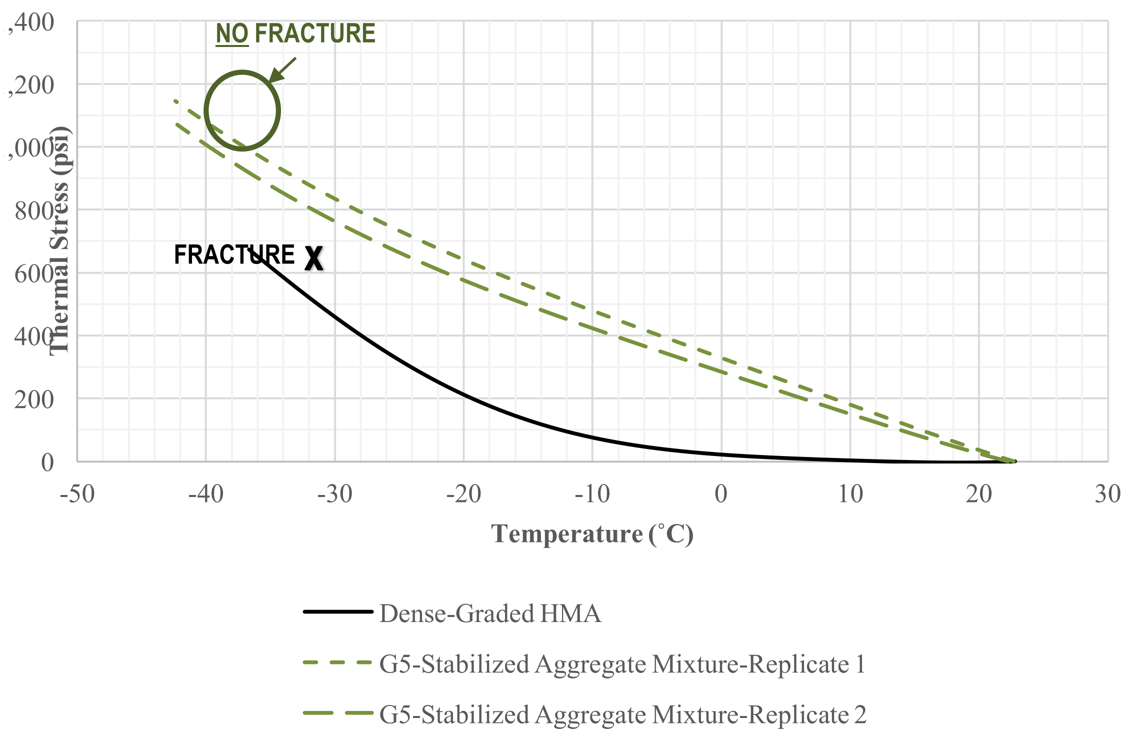


Figure 17. UTSST thermal stress build-up as a function of temperature for the G5-stabilized aggregate mixture and a typical dense-graded HMA.

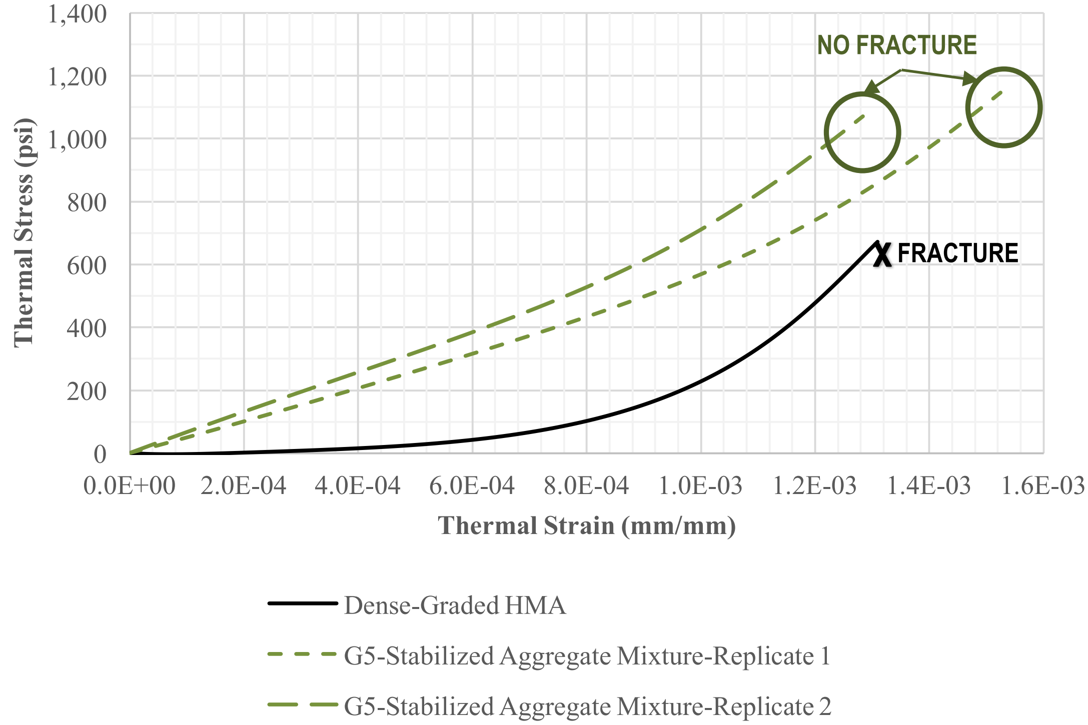


Figure 18. UTSST thermal stress versus thermal strain for the G5-stabilized aggregate mixture and a typical dense-graded HMA.

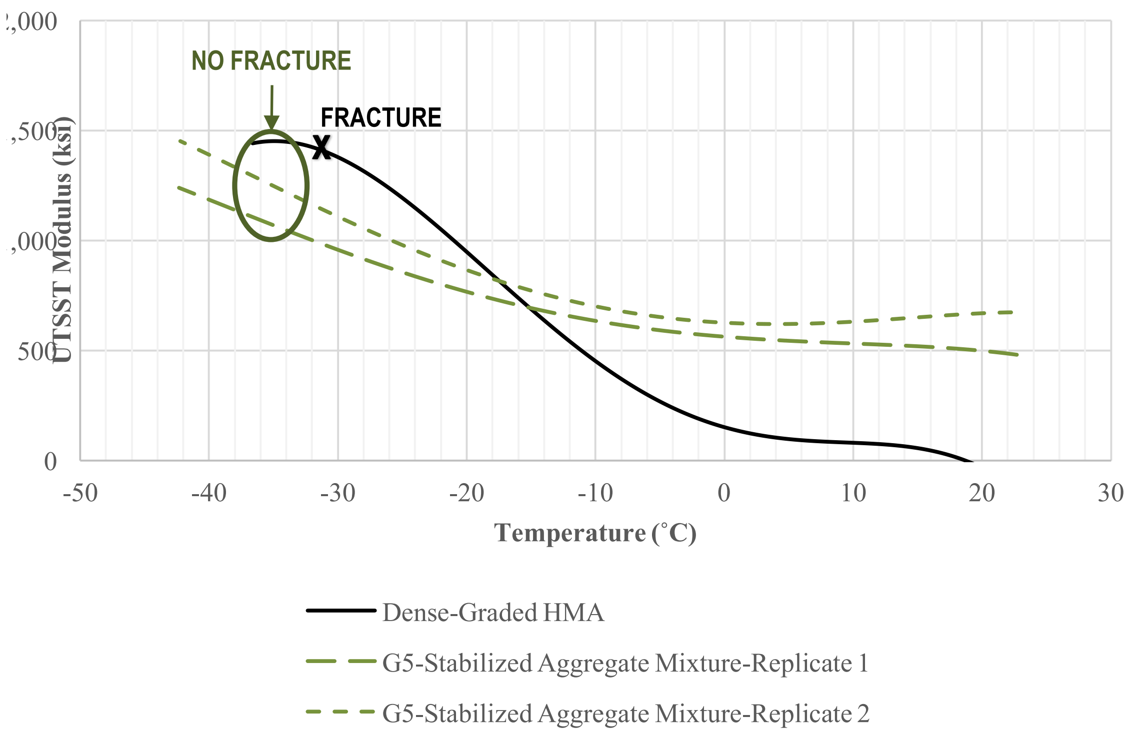


Figure 19. UTSST Modulus for the G5-stabilized aggregate mixture and a typical dense-graded HMA.

Table 4. Average Thermo-Viscoelastic Properties of the G5-Stabilized Aggregate Mixture and a Typical Dense-Graded HMA.

Mixture	Property	$E_{(UTSST)}$, ksi (MPa)	Temperature, ˚C (˚F)	Thermal Stress, psi (kPa)	Thermal Strain, inch/inch
G5-Stabilized Aggregate	Viscous Softening	591 (4,072)	12.4 (54.3)	134 (921)	2.41E-04
	Viscous-Glassy Transition	689 (4,750)	-11.9 (10.6)	481 (3,318)	8.09E-04
	Glassy Hardening	1,224 (8,437)	-37.7 (-35.9)	981 (6,762)	1.31E-03
	Crack Initiation	N/A[1]	<-42.0 (-43.6)	N/A[1]	N/A[1]
	Fracture	N/A[1]	<-42.0 (-43.6)	N/A[1]	N/A[1]
Dense-Graded HMA	Viscous Softening	81 (560)	9.4 (48.9)	4 (26)	2.43E-04
	Viscous-Glassy Transition	224 (1,543)	-3.5 (25.7)	34 (233)	5.55E-04
	Glassy Hardening	856 (5,899)	-18.3 (-0.9)	181 (1,245)	9.40E-04
	Crack Initiation	1450 (9,997)	-34.9 (-30.8)	616 (4,247)	1.28E-03
	Fracture	1440 (9,928)	-36.6 (-33.9)	672 (4,633)	1.31E-03

Notes:
[1] No measurements were reported since specimens did not reach fracture nor the crack initiation stage.

VI. RESISTANCE TO FATIGUE CRACKING

The resistance of the G5-stabilized mixture to fatigue cracking was evaluated using the flexural beam fatigue test AASHTO T 321: "Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending." The 2.0×2.5×15 inch (50×64×380 mm) beam specimen is subjected to a four-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the center portion of the specimen. In this study, constant strain tests were conducted at different strain levels; using a repeated haversine load at a frequency of 10 Hz, and a temperature of 21.1°C (70°F). The test Specimens with air voids of 12±1% percent were long-term aged for 5 days at 85°C (185°F) in a forced-draft oven in accordance with AASHTO R 30. The fatigue cracking performance model shown in equation below was derived for the evaluated G5®-stabilized aggregate mixture.

$$N_f = k_{f1}\left(\frac{1}{\varepsilon_t}\right)^{k_{f2}} \qquad [2]$$

Where, N_f is the fatigue life (number of load repetitions to fatigue damage), ε_t is the applied tensile strain, k_{f1} and k_{f2} are experimentally determined coefficients. The mixtures for the flexural beam fatigue test were long-term aged prior to testing since fatigue cracking is a later pavement life failure (i.e., after 5 years). Figure 20 shows a picture of the flexural beam fatigue testing equipment.

Figure 21 the fatigue relationship for the G5®-stabilized aggregate mixture along with a typical dense-graded HMA. Table 5 compares the fatigue relationship parameters (k_{f1} and k_{f2}) between the G5-stabilized aggregate mixture and a typical dense-graded HMA. Figure 21 shows that if the beam fatigue test samples are subjected to 750µstrain of tensile strain, they will fail after 82 million cycles for the G5-stabilized aggregate mixture while it is only 28,706 for a typical dense-graded HMA. It is also reminded that the fatigue performance of a dense-graded HMA changes drastically with aggregate gradation, asphalt binder grade, and mixture volumetrics. In summary, the evaluated G5®-stabilized aggregate mixture is expected to have an excellent resistance to fatigue cracking.

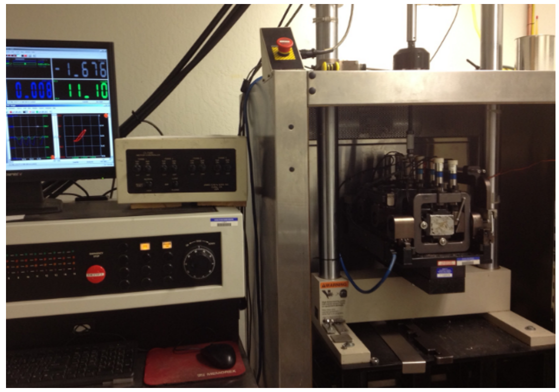


Figure 20. Flexural beam fatigue test setup.

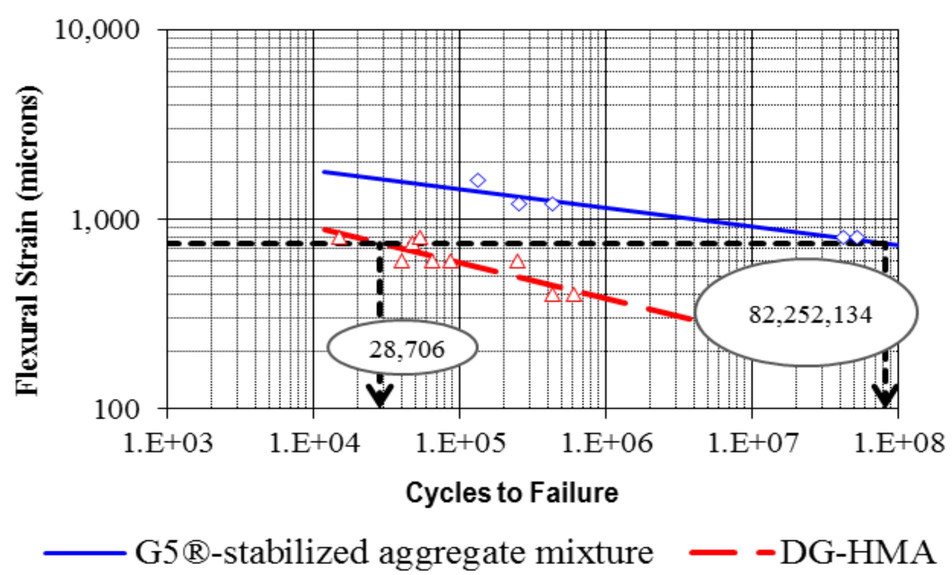


Figure 21. Flexural beam fatigue test setup.

Table 5. Fatigue Performance Model Parameters of the G5-Stabilized Aggregate Mixture and a Typical Dense-Graded HMA.

Property	G5®-stabilized agg. mixture	DG-HMA
Average air voids, %	12.0	6.7
Average flexural Stiffness, ksi	1,011	172
K_{f1}	1.527E-24	8.293E-13
K_{f2}	10.154	5.293

VII. SUMMARY AND CONCLUSION

In this study, an extensive laboratory evaluation of an aggregate stabilized with TechniSoil G5® polymer binder was conducted. The designed mixture was evaluated in terms of its dynamic modulus property, resistance to permanent deformation, and resistance to reflective, thermal, and fatigue cracking. Based on the analysis of the data generated in this study, the following conclusions can be made:

- The G5-stabilized aggregate mixture had high moduli values and was stable at low loading frequencies and/or high temperatures. This indicates a stable mixture in hot climates and at intersections on urban streets and on off-ramps.
- The G5-stabilized aggregate mixture resisted the tertiary flow at 60°C (140°F) after 20,000 loading cycles while maintaining the permanent axial strain below 0.20%. This indicates that the mixture will offer an excellent resistance to rutting at elevated temperatures and at intersections on urban streets and on off-ramps.
- The G5-stabilized aggregate mixture exhibited an excellent resistance to reflective cracking. The mixture did not reach failure in the Overlay Tester even after 9,000 loading cycles.
- The G5-stabilized aggregate mixture exhibited an excellent resistance to thermal cracking after long-term aging. The mixture was able to resist a low temperature of -42°C (-43.6°F) without fracturing or developing any micro cracks in the specimen while maintaining a high tensile strength.
- The G5-stabilized aggregate mixture exhibited an excellent resistance to fatigue cracking at 21.1°C (70°F) after long-term aging. Given both, the state of strains under typical traffic loads and the extremely higher number of cycles to failure, the G5®-stabilized aggregate mixture is expected to perform extremely well in fatigue resistance as well.

In summary, the G5-stabilized aggregate mixture exhibited unique characteristics with superior performance at high, intermediate, and low temperatures suggesting a very good performance in the field when used as a surface course layer. The mixture may offer excellent alternatives when used as a surface layer in hot climate areas with heavy traffic and/or braking actions such as at traffic lights on urban streets and off-ramps. The mixture is also anticipated to perform very well when used in cold climates and/or on top of a cracked asphalt pavement due to its high resistance to reflective cracking and thermal cracking.

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