Performance Evaluation of a 100% Recycled Asphalt Pavement Mixture using a Polymer Binder: A Pilot Study

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ABSTRACT: Recently, a significant increase in the use of recycled asphalt pavement (RAP) in the United States (US) has been observed. In 2014, more than 70 million tons of RAP material was used in new pavements making RAP one of, if not the largest, recycled materials in the US. Old and aged RAP material is known to have an asphalt binder that is stiffer and more brittle than virgin asphalt binders typically used in asphalt mixtures. While the use of RAP in an asphalt mixture is expected to improve the mixture's resistance to rutting, it has a great tendency to reduce the mixture's resistance to cracking especially at the significantly high amount of RAP (more than 30%). In this pilot study, a new polymer binder called TechniSoil G5® was evaluated for use with a 100% RAP material. An extensive laboratory evaluation of the mechanical and mechanistic performance of the stabilized 100% RAP mixture was conducted. The designed mixture was evaluated in terms of its dynamic modulus property, resistance to rutting, and resistance to fatigue and thermal cracking. A mechanistic analysis was also conducted to determine the fatigue life of the stabilized 100% RAP mixture when used in a typical pavement structure at two different vehicle speeds using the 3D-Move Analysis software. The data showed that the stabilized 100% RAP with TechniSoil G5® has excellent resistance to the evaluated and critical asphalt pavement distresses. A significant increase in the fatigue life was also observed when compared to a typical dense-graded asphalt mixture. Based on the promising laboratory results, a field demonstration project was constructed in 2016 at the Al Wakar water station in Doha, Qatar. Initial field inspection six months after construction showed that the pavement with G5®-stabilized RAP mixture is performing very well under the hot desert environment.

INTRODUCTION

Reclaimed asphalt pavement (RAP) is the mixture of aggregate and asphalt generated when asphalt pavements are removed for reconstruction, resurfacing, and/or to obtain access to buried utilities. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt binder that is stiffer and more brittle than virgin asphalt binders typically used (FHWA, 2008). The asphalt industry has been using the RAP mainly in two different ways: (a) by incorporating it in hot and warm asphalt mixtures at different percentages, or (a) as 100 percent recycling, either hot or cold, by mixing it with a binding agent. The 100 percent cold in-place recycling (CIR) is becoming more and more popular due to its environmental and economic benefits (Sanjeevan et al. 2014 & Kim et al. 2010). Asphalt emulsions are typically used with CIR as a binding agent to generate a stabilized base course or a low volume road granular surface course. Polymeric binders can be used as a viable alternative for the asphalt emulsion. 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.

The TechniSoil G5® binder is a patent pending, new class of super polymers. It is an engineered polymer binder that reacts with RAP/soil/base components, forming a water insoluble polymer network. In this study, the properties and characteristics of 100 percent RAP stabilized with TechniSoil G5® material that are critical to its resistance to various distresses were evaluated. The dynamic modulus test was used to evaluate the stiffness of the mixture at multiple loading rates and temperatures. Furthermore, the G5®-stabilized RAP mixture was evaluated for the following modes of pavement failure using the most widely accepted laboratory tests:

- Permanent deformation,
- Fatigue cracking, and
- Thermal cracking.

The results for a typical dense-graded hot mix asphalt (DG-HMA) were used in this study for reference purposes to demonstrate the behavior of the evaluated G5®-stabilized RAP mixture in comparison to that of a typical asphalt mixture. It should be recognized that the properties of asphalt 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 test results for the G5®-stabilized RAP mixture was also compared to well-established criteria for asphalt mixtures.

Additionally, a simple mechanistic-empirical analysis was conducted to estimate the fatigue life of the G5®-stabilized RAP mixture, which is one of the critical distresses for stiffer material like RAP. Two typical thin pavement sections; one with the G5®-stabilized RAP mixture and the other one with typical DG-HMA, at two different vehicle speeds were considered for the analysis using the 3D-Move Analysis software.

SAMPLE PREPARATION

The RAP material obtained from millings was crushed to have 100 percent passing 9.5 mm sieve. The extracted and recovered RAP binder was graded as PG100-4 in accordance with AASHTO M320 (AASHTO, 2015). The RAP binder was extracted using a centrifuge in accordance with AASHTO T164 (AASHTO, 2015) and recovered using a rotary evaporator in accordance with ASTM D5404 (ASTM, 2015) with a solution of 85% Toluene and 15% Ethanol by volume. The TechniSoil G5® was added to the crushed RAP material (100 percent) at a rate of 9.5% by weight of RAP. The mixture was placed and compacted using a small roller compactor in a large slab in a controlled environment. The whole process took place at the room temperature. Core samples were taken from the compacted slab and evaluated for dynamic Modulus, rutting resistance (permanent deformation), and thermal cracking resistance. Beam specimens were also cut out of a compacted slab for the mixture evaluation to fatigue cracking resistance. Figure 1(a) shows the compaction of the G5®-stabilized RAP mixture in a slab and figure 1(b) shows the coring of cylindrical samples.

(a) (b) (c)

Figure 1. G5®-stabilized RAP mixture (a) Compaction, (b) Coring of cylindrical samples, and (c) Cored sample.

MECHANICAL PROPERTY OF G5®-STABILIZED RAP MIXTURE

The dynamic modulus (E*) is a fundamental engineering property which provides an indication of the overall quality of a mixture. It is calculated by dividing the peak-to-peak stress by peak-to-peak strain when the sample is subjected to a sinusoidal loading. Phase angle is the angle in degrees between a sinusoidal applied stress and the resulting strain, which is an indicator of the viscoelastic behavior of the material. For a pure elastic and pure viscous material, the phase angle will be zero and 90 degrees, respectively. The E* values and the phase angles of G5®-stabilized RAP mixture was measured in accordance with AASHTO TP79 standard. The dynamic modulus test was conducted on 100 mm diameter by 150 mm height cylindrical samples cored from the compacted slab, at three different temperatures (4, 20, and 45°C), and multiple frequencies (0.01, 0.1, 1, and 10Hz). The target air voids of test samples was 12±1 percent which is typical for CIR applications (Piratheepan, 2011 & Kim at al. 2010). The master curve, which is a single curve developed using the time-temperature superposition principle, is used to identify the material stiffness behavior with frequency at a reference temperature. Figure 2 shows a picture of the AMPT equipment used for dynamic modulus test along with a typical E* master curve for a DG-HMA.

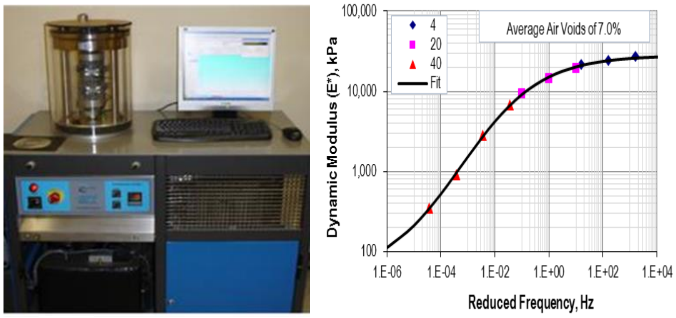


Figure 2. Asphalt mixture performance tester (AMPT) and a typical master curve for asphalt mixture.

Figure 3 shows the measured dynamic modulus values (average) of the G5®-stabilized RAP mixture at multiple temperatures and frequencies (average of three test replicates) while Figure 4 shows the average dynamic modulus values calculated at reduced frequencies along with the master curve developed at 20 °C in accordance with the test method AASHTO PP61 (AASHTO, 2015). Figure 4 shows the average phase angles calculated at reduced frequencies. The changes in dynamic modulus and phase angle with frequencies shown in figures 4 and 5 indicate that the G5®-stabilized RAP mixture behaves like a viscoelastic material similar to asphalt mixtures.

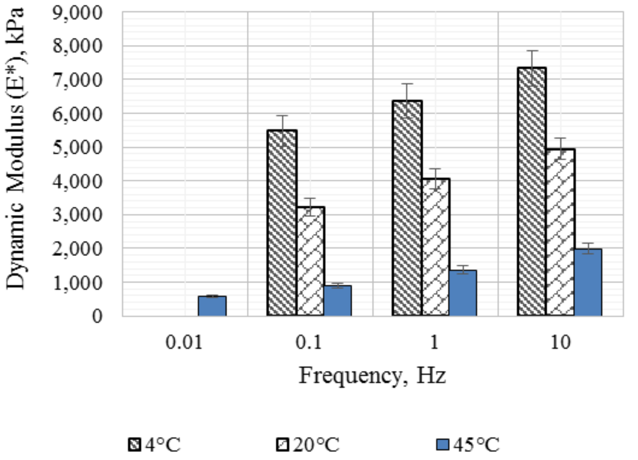


Figure 3. Measured dynamic modulus values of the G5®-stabilized RAP mixture. (Error bars represent the mean value plus or minus 95% confidence interval).

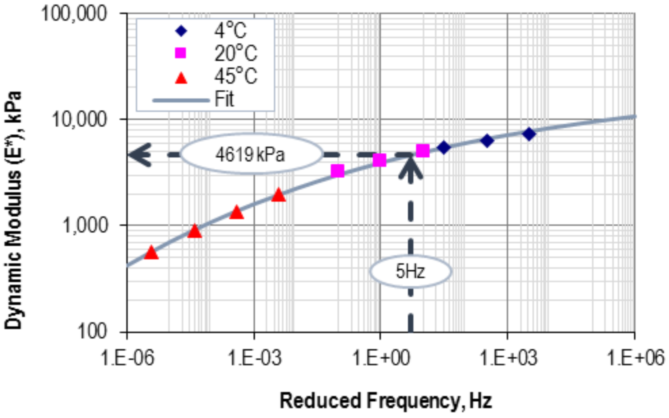


Figure 4. Dynamic modulus master curve for the G5®-stabilized RAP mixture.

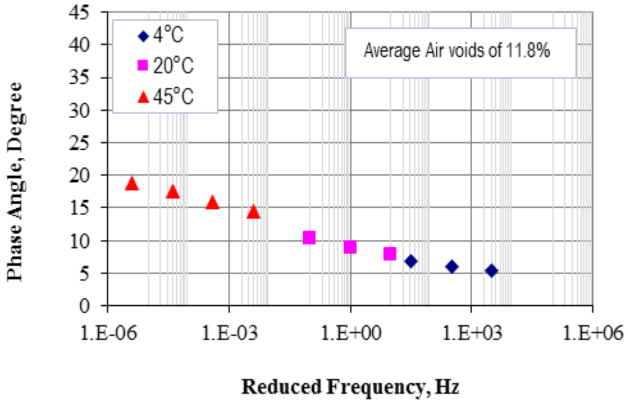


Figure 5. Average phase angle measured during the dynamic modulus test for the G5®-stabilized RAP mixture.

The dynamic modulus values of the G5®-stabilized RAP mixture are comparable to those observed with typically used dense-graded asphalt mixtures. The observed phase angle values for the G5®-stabilized RAP mixture were between 5 and 20 degrees indicating a good elastic property for the mixture at both low and high temperatures.

LABORATORY PERFORMANCE OF G5®-STABILIZED RAP MIXTURE

The laboratory performance of the G5®-stabilized RAP mixture was evaluated for permanent deformation, Fatigue cracking, and thermal cracking.

Resistant to permanent deformation

The permanent deformation, also known as rutting in paving materials develops gradually with higher load applications, usually appearing as longitudinal depressions in the wheel paths accompanied by small upheavals to the sides (Sousa et al. 1991). It occurs at the early ages of the asphalt pavement and becomes more susceptible during the summer because of the elevated temperature of the pavement. It is caused by a combination of densification (decrease in volume and, hence, increase in density) and shear deformation. The rut pavement can hold water and cause hydroplaning and steering difficulties that will become a safety concern to the drivers.

The resistance of the G5®-stabilized RAP mixture to permanent deformation was evaluated in accordance with test method AASHTO TP79 (AASHTO, 2015). The AMPT machine shown in figure 2 was used to perform the flow number (FN) test. A 100 mm diameter by 150 mm high cylindrical specimen cored from the compacted slab was subjected to a repeated haversine axial compressive pulse load of 0.1 s and rest period of 0.9 s. The deviatory stress of 600 kpa with zero confinement was applied to the test samples. The resulting axial permanent deformation was measured as a function of the load cycles. The cumulative permanent strain can be defined by the primary, secondary, and tertiary zones as shown in figure 6. In the primary zone, the permanent strain increases rapidly with a decreasing rate predominantly associated with increase in volume. In the secondary zone, the permanent strain rate maintains a constant value until it starts increasing in the tertiary creep zone. In the tertiary zone, the permanent deformation increases exponentially predominantly associated with plastic deformations under no volume change conditions. The point at which the tertiary flow starts is called the flow number (FN). The higher the flow number (FN) value the better the resistance of the mixture to permanent deformation. The permanent strain of the tested G5®-stabilized RAP samples with number of cycles was fit to the Franken model and the flow number (FN) was computed. The test temperature of 60°C was selected based on 7-day maximum pavement temperature 20 mm below the pavement surface, at 50% reliability, using the LTPPbind software (Pave Sys, 2014). The selected FN test temperature is typical and applicable to multiple locations in the United States. The percent air voids of the tested samples were between 11 and 13 percent. Figure 7 depicts the average axial permanent strain of three samples as a function of number of cycles. The figure shows that the samples did not experience any flow and the permanent deformation was less than 1 percent even after 20,000 cycles, indicating an excellent resistance to permanent deformation. Hence, super-exceeding the minimum FN requirements for asphalt mixtures shown in table 1 (AASHTO TP79).

In Summary, the evaluated G5®-stabilized RAP 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.

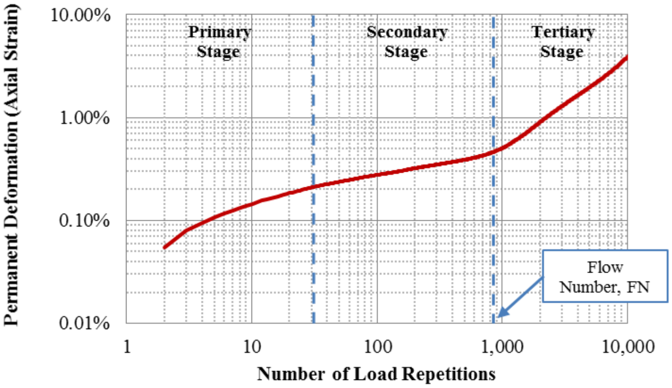


Figure 6. Typical permanent deformation curve for a DG-HMA mixture.

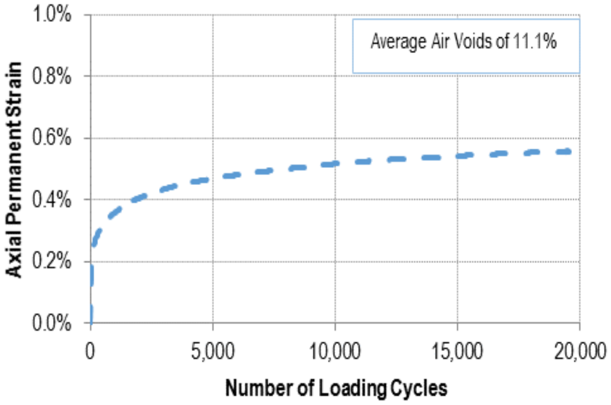


Figure 7. FN test results for the G5®-stabilized RAP mixture.

Table 1. FN criteria according to AASHTO TP79 (AASHTO, 2015)

AASHTO TP79 – FN Requirements				
Traffic Level (Million ESALs)	< 3	3 to < 10	10 to < 30	≥ 30
Minimum Flow Number (Cycles)[1]	Test not needed	53	190	740
[1] *FN test conditions: (1) unconfined; (2) 600 kPa (87 psi) deviator stress; (3) and at 7-day maximum pavement temperature 20 mm below the pavement surface, at 50% reliability.*				

Resistance to fatigue cracking

The resistance to fatigue cracking of an asphalt mixture is its ability to withstand repeated loading without any cracking. Fatigue in asphalt concrete pavements appears as cracking at the surface of the pavement and it is one of the most common distresses found in major highways and local roads (Souliman et al. 2012). When the asphalt mixture ages, it loses its elastic behavior and becomes more prone to fatigue cracking. Therefore, the fatigue cracking is not critical at the early ages of asphalt pavement. The resistance to fatigue cracking of an asphalt mixture depends on multiple factors such as aggregate gradation, asphalt binder grade, asphalt content, and asphalt mixture volumetrics. The Flexural beam fatigue test (AASHTO T321 or ASTM D7460) (AASHTO, 2015 & ASTM, 2015) is typically used to determine the laboratory fatigue life of an asphalt mixture under repeated loading. Although the field performance of an asphalt mixture is impacted by many factors (traffic variation, speed, and wander; climate variation; rest periods between loads; aging; etc.), it has been more accurately predicted when laboratory properties are known along with an estimate of the strain level induced at the layer depth by the traffic wheel load traveling over the pavement (ASTM, 2015).

The fatigue resistance of the G5®-stabilized RAP mixture was determined in accordance with test method AASHTO T321 (AASHTO, 2015). A rectangular beam (50x63x380 mm) was cut from the compacted slab and subjected to a 4-point bending, with free rotation and horizontal translation at all load and reaction points, until failure. This produces a constant bending moment over the center portion of the specimen. The deflection of the beam at mid-span is measured and recorded at each load cycle using a linear variable differential transformer (LVDT). In this study, constant strain tests were conducted at different strain levels using a repeated haversine load at a frequency of 10 Hz and temperature of 21.1 °C. The failure at a given strain level is defined as the point of 50% reduction in initial stiffness. The test Specimens with air voids between 11 and 13 percent were long-term aged for 5 days at 85 °C in a forced-draft oven in accordance with AASHTO R30 (AASHTO, 2015) to simulate the critical condition for fatigue cracking. The fatigue cracking prediction model shown in equation 1 was derived for the evaluated G5®-stabilized RAP mixture using the multi-regression analysis of the fatigue curves at multiple strain levels and one temperature.

$$N_f = k_1 (1/\varepsilon_t)^{k_2} \quad (1)$$

Where, N_f is the fatigue life (number of load repetitions to fatigue damage), ε_t is the applied tensile strain, k_1 and k_2 are experimentally determined coefficients. The comprehensive fatigue model which includes the effect of temperature was not derived in this study due to limited test specimens. Figures 8 and 9 show pictures of the flexural beam fatigue testing equipment and the fatigue relationship for the G5®-stabilized RAP mixture along with a typical DG-HMA, respectively. Table 2 compares the fatigue relationship parameters (k_1 and k_2) between the G5®-stabilized RAP mixture and a typical DG-HMA.

Figure 9 shows that if the beam fatigue test samples are subjected to 750µstrain of tensile strain, they will fail after 652,922 cycles for the G5®-stabilized RAP mixtures while it is only 28,706 for typical a DG-HMA. It is also reminded that the fatigue performance of a DG-HMA changes drastically with aggregate gradation, asphalt binder grade, and mixture volumetrics. As it is mentioned earlier, the beam fatigue test was conducted only at 21.1 °C because of limited material.

In summary, the evaluated G5®-stabilized RAP mixture is expected to have an excellent resistance to fatigue cracking.

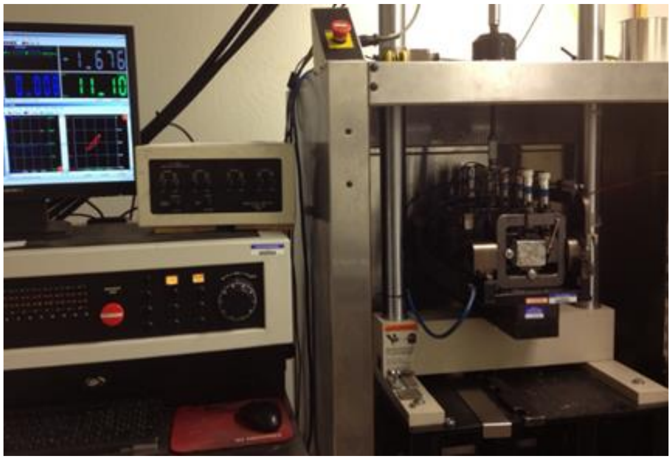


Figure 8. Flexural beam fatigue testing equipment

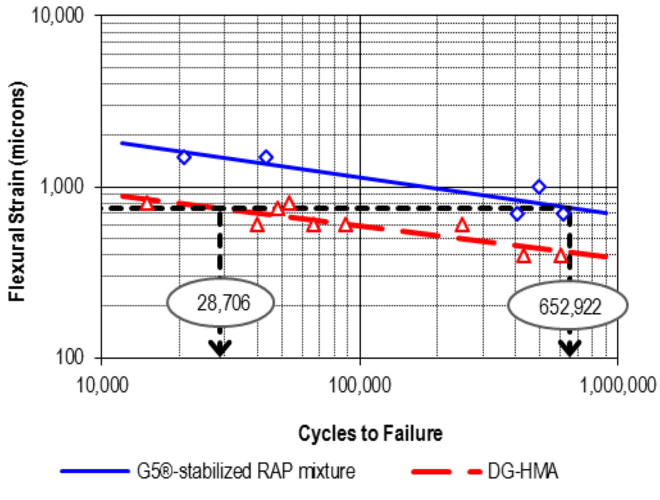


Figure 9. Fatigue relationships for the G5®-stabilized RAP mixture and a typical DG-HMA.

Table 2. Fatigue relationship parameters (k_1 and k_2) for G5®-stabilized RAP mixture and a typical dense graded HMA.

Property	G5®-stabilized RAP	DG-HMA
Average air voids	11.2%	6.7%
Average flexural stiffness	5,812 MPa	1,186 MPa
K_1	4.524E-09	8.293E-13
K_2	4.531	5.293

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 Test (UTSST) (Alavi *et al.*, 2013; Hajj *et al.*, 2013; Morian, 2014a; Morian *et al.*, 2014b) was used to determine the thermal cracking resistance of the G5®-stabilized RAP mixture. The test measures the thermal stress build-up in a restrained cylindrical specimen (57x140 mm) and thermal strain in an unrestrained cylindrical specimen (57x270 mm) when subjected to a cooling rate of 10 °C/hour. While the UTSST specimen is being cooled down, tensile stresses are generated due to the ends being restrained and it will crack when the internally generated stress exceeds its tensile strength. The temperature at which the specimen cracks is referred to as the fracture temperature and the stress at which the fracture occurs is referred to as fracture stress. The fracture temperature and fracture stress represent the anticipated field condition under which the pavement will most likely experience thermal cracking. These two properties were measured from the restrained specimen and the linear coefficient of thermal contraction was obtained from the un-restrained specimen. The test specimens were long-term aged for 5 days at 85 °C in a forced-draft oven in accordance with AASHTO R30 (AASHTO, 2015) to simulate the long-term aging properties of the mixture in the field when thermal cracking becomes critical. Figure 10 shows a picture of UTSST experimental setup and a schematic diagram of the setup. Figure

11 shows the average test results for the G5®-stabilized RAP mixture. The UTSST test results show that the G5®-stabilized RAP mixture exhibited a low fracture temperature (-34.1 °C) while maintaining a high fracture stress (4,227 kPa) indicating a good resistance to thermal cracking. It should be noted that the air voids of the G5®-stabilized RAP specimens were between 11 and 13 percent. Thus, suggesting that the evaluated mixture can successfully withstand thermal cracking in cold climates when used as a surface layer

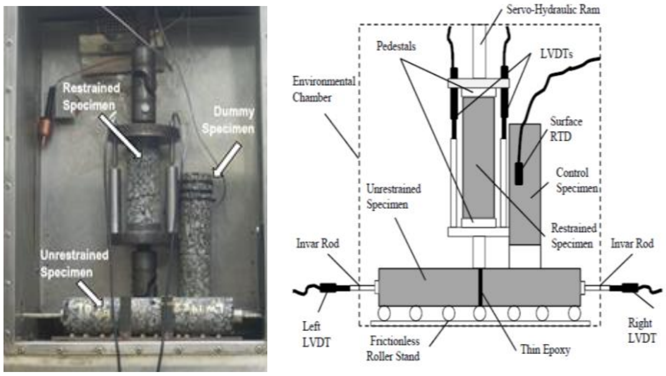
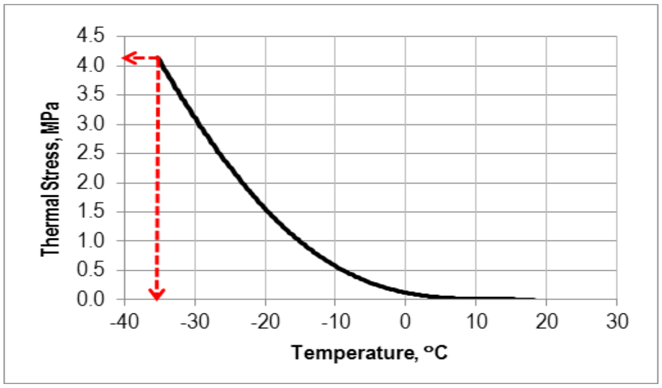


Figure 10. UTSST experimental set-up for asphalt mixtures.



Property	Value
Fracture	
Fracture Temperature	-34.1 °C
Fracture Stress	4,227 kPa
Linear Coefficient of Thermal Contraction (CTC)	
CTC_{liquid}	2.42×10^{-5} /°C

Figure 11. UTSST test result for G5®-stabilized RAP mixture.

SIMPLE MECHANISTIC-EMPIRICAL (M-E) ANALYSIS

Mechanistic analysis covers the determination of the responses of the flexible pavement structure to the loads imparted by heavy vehicles and their impact on pavement life. In this study, a simple mechanistic analysis was conducted to investigate the influence of the G5®-stabilized RAP material on pavement fatigue life. The mechanistic analysis incorporates the combined impact of the measured dynamic modulus (E*) and the developed fatigue relationship.

Pavement layers deflect under moving wheel truck loading resulting in repeated tensile strains and stresses at the bottom of the surface layer. Figure 12 shows the state of strains for the fatigue cracking analysis of the pavement. With continued bending due to moving truck loading, the tensile strains cause cracks to initiate at the bottom of the surface layer before propagating to the surface. This bottom-up fatigue cracking phenomenon was evaluated in this study for the G5®-stabilized mixture and a typical DG-HMA. Two thin pavement sections were considered for the analysis as shown in the figure 13 below. The layer moduli values on the figure for both G5®-stabilized mixture and DG-HMA were measured in the laboratory.

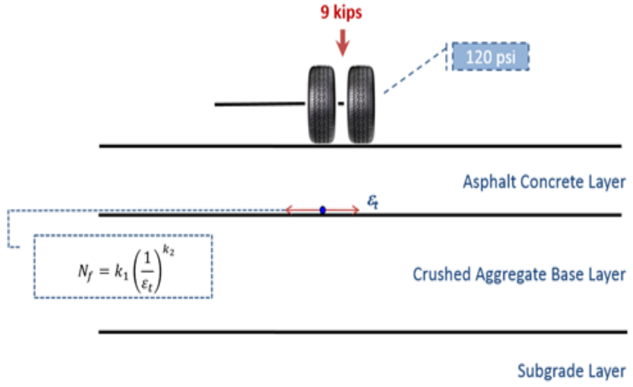


Figure 12. Schematic diagram of state of strains for a bottom-up fatigue cracking analysis.

The maximum tensile strain at the bottom of the surface layer underneath the tire was computed using the 3D-Move Analysis software (UNR, 2013) which considers the viscoelastic properties of the surface layer. The number of repetitions to fatigue failure of the pavement at two different vehicle speeds (72 and 16 km/h) was computed using the laboratory derived fatigue performance models and the tensile strains obtained from the 3D-move analysis. The laboratory fatigue model coefficients are given in table 2. The fatigue life ratio was obtained by dividing the number of repetitions to failure of the pavement with the G5®-stabilized RAP mixture to that of a typical DG-HMA.

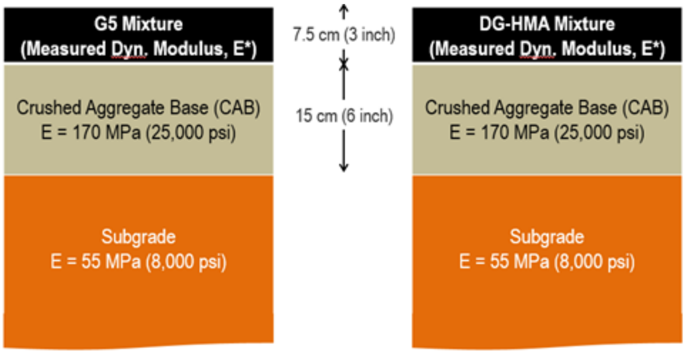


Figure 13. Pavement sections considered for the mechanistic analysis.

Table 3 shows the results of the simple mechanistic-empirical analysis. The tensile strain induced at the bottom of the surface layer with G5®-stabilized RAP mixture was less than that of DG-HMA. Furthermore, the fatigue number of repetitions to fatigue failure was significantly higher for the G5®-stabilized RAP mixture when compared to a typical DG-HMA. The fatigue life ratio was 8.0 and 147 for the 72 km/h and 16 km/h vehicle speeds, respectively.

In summary, the mechanistic analysis indicates a good resistance to fatigue cracking for the G5®-stabilized RAP mixture when used as a surface layer.

Table 3. Summary of the Mechanistic Analysis.

Vehicle Speed	Surface Mixture	Fatigue Analysis at 21°C Tensile strain, ε_t, (microns)	Number of repetitions to failure, N_f (millions)	Fatigue life ratio
72 km/h	**G5®-stabilized RAP mixture**	341	23.2	**8.0**
	DG-HMA	313	2.9	
16 km/h	**G5®-stabilized RAP mixture**	363	17.6	**14.7**
	DG-HMA	373	1.2	

DEMONSTRATION PROJECT

The promising performance of the G5®-stabilized RAP mixture observed during the extensive laboratory evaluation led to a demonstration field project in Doha, Qatar. The project was located at the entrance/exit to the Al Wakar water station in Doha with approximately 60 m long and 3 m wide. The pavement carries approximately 1,000 water trucks per day, 7 days per week, each loaded with 4,000 to 5,000 gallons of water. Doha has an average high air temperature of over 38 °C with daily high air temperature often exceeds 43 °C during the summer. It has a very dry climate with the annual rainfall of approximately 75 mm.

The existing pavement had badly deteriorated consisting of 75-100 mm of dense graded HMA on top of a subbase and a subgrade. The scope of the work consisted of removing the existing HMA and subbase and replacing it with a Type C subbase, meeting Doha standards followed by 70-75 mm of 100 percent RAP combined with G5® binder. The mix design of G5®-stabilized RAP mixture was conducted by Arab Center for Engineering Studies (ACES) and resulted in a 5 percent G5® binder in the mixture.

After removing the HMA and subbase, the subgrade and newly placed subbase were compacted with roller compactors. The G5®-stabilized RAP mixture was placed on top of the compacted subbase and was compacted with a 5-ton rollers with minimum three vibratory passes. The in-place density of the G5®-stabilized RAP mixture layer was measured using cores taken right after construction. The bulk specific gravity measurements of the cores showed that the G5®-stabilized RAP mixture layer had an average air voids of 10 percent at the top lift and 14.5 percent at the bottom lift of the layer. Figure 14 shows the mixing process, placement, and compaction of the G5®-stabilized RAP mixture at Al Wakar water station in Doha. Initial inspection 6 months after construction showed that the pavement with the G5®-stabilized RAP mixture is still performing well with no visual distresses associated with traffic loading or climate conditions. The field performance will continue to be monitored over the next few years and distress survey data will be collected.

Figure 14. Mixing, placement, and compaction of the G5®-stabilized RAP mixture at Al Wakar water station in Doha.

CONCLUSIONS

In this study, an extensive laboratory evaluation of the mechanical and mechanistic performance of TechniSoil G5® polymer binder with 100 percent RAP material was conducted. The designed mixture was evaluated in terms of its dynamic modulus property, resistance to permanent deformation, and resistance to fatigue and thermal cracking. A mechanistic analysis was conducted to determine the fatigue life of the G5®-stabilized 100 percent RAP mixture when used in a typical thin pavement structure at two different vehicle speeds using the 3D-Move Analysis software. The test data showed that the evaluated G5®-stabilized 100 percent RAP mixture had excellent resistance to the evaluated critical asphalt pavement distresses. In general, the G5®-stabilized RAP mixture showed a superior performance indicating a good field performance when used as a surface layer. A significant increase in the fatigue life was also observed when compared to a typical dense-graded asphalt mixture.

A demonstration project was constructed in Al Wakar water station in Doha, Qatar where a G5®-stabilized RAP mixture was used as a surface layer. No construction-related issues were observed due to the use of the G5®-stabilized RAP mixture. A recently completed visual distress survey revealed no distresses in the pavement thus far 6 months after construction.

In summary, this pilot study showed that the Technisoil G5® polymer binder, which is an environmental friendly product, combined with 100 percent RAP is a viable potential alternative to cold in-place recycling with traditional asphalt emulsions.

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