Pressure Measurements and Structural Performance of Hot Mixed Asphalt Railway Trackbeds

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ABSTRACT: In order to assess pressure distributions within the track and support structure, earth pressure cells have been installed in selected hot mix asphalt (HMA) trackbeds on a CSX Transportation heavy tonnage revenue freight line and at the TTCI heavy tonnage test track at Pueblo. The measured values of pressure distribution within each layer were used to establish a pressure index. This pressure index is the ratio of pressure at the interface of a layer, to the predicted bearing capacity of the layer. A pressure index value of one implies failure of the layer. The pressure index and other measures of structural performance such as track modulus and subgrade stiffness were assessed. From these assessments, relationships were established whereby the pressure distribution and deflection characteristics of the trackbed were quantified in terms of material type and layer thickness. Thus, allowing for a rational performance assessment of the overall trackbed system.

1 INTRODUCTION

The United States freight railroad industry is currently experiencing unprecedented growth in traffic volumes, revenue ton-miles, and wheel loadings. Railways have been a significant mode of transport for 175 years in the United States. During the late 1800s and early 1900s it was the dominant mode. In recent years train speeds, gross ton-miles, and axle loads have increased significantly on the freight railroads. This marked turn around began in the early 1980s as the industry was relieved by many of the regulations that had stemmed innovations and growth for approximately 50 years.

The latest Association of American Railroads statistics (AAR, 2006) indicate that in 2005 an all-time record 1.7 trillion ton-miles of freight was carried over the nation’s nearly 227,000 km railroad network. The average freight car weight has increased to 117 metric tons with most new cars having gross weights of 130 metric tons.

The importance of developing and specifying premium track structures and components to adequately carry the increased tonnage is a current reality of the industry. Failure of the track structure and components results in an inability to maintain track geometric features necessary for efficient and safe train operations. Maintenance costs and track outages increase due to frequent maintenance and renewal cycles. Advanced technologies are necessary to provide stronger and longer-lasting track and support structures to accommodate the record volumes.

Conventional trackbeds are typically composed of all-granular materials consisting of layers of ballast and subballast over a prepared subgrade, as noted in Figure 1a. However, in recent years trackbeds containing a layer of hot mixed asphalt (HMA) are becoming more prevalent. Development of HMA trackbeds began in the early 1980s. Various tests and performance evaluations have shown numerous advantages over traditional all-granular (ballast) trackbeds (Rose and Lees, 2008; Anderson and Rose, 2008). The most common HMA trackbed, termed asphalt underlayment as shown in Figure 1b, incorporates a layer of HMA in lieu of the subballast. Ballast is used above the HMA layer in a similar manner as the conventional all-granular trackbed. The ballast provides a protective cover for the HMA by blocking the sunlight, protecting the surface from air and water, and maintaining a relatively constant temperature and environment.

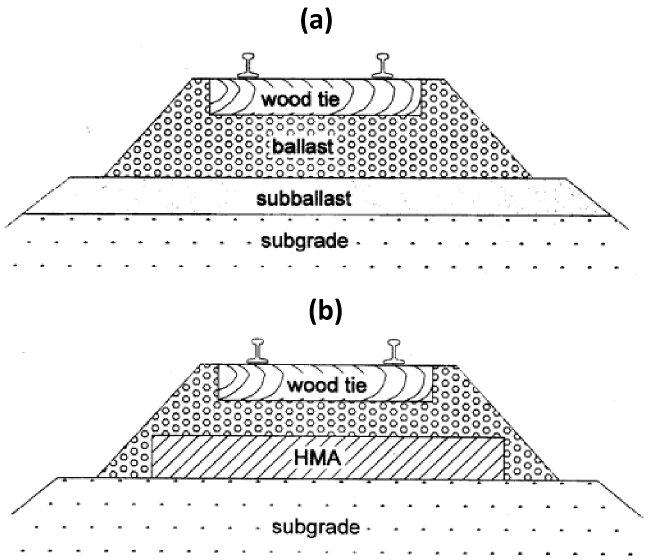

Figure 1. Typical trackbed cross sections: (a) all-granular ballast section; (b) hot mixed asphalt section.

HMA is used for new track construction and for rehabilitation/maintenance of existing lines. It has a wide range of applications including open track, special trackwork (switches or turnouts, crossing diamonds, etc.) bridge approaches, tunnel floors and approaches, and highway/rail crossings.

2 PREVAILING DESIGN PRACTICES

2.1 *Design Specifications*

Asphalt underlayment design and construction standards for railways typically follow recommendations set forth by the Asphalt Institute (Asphalt Institute, 1998; Asphalt Institute, 2007). The typical HMA layer is approximately 3.7 m wide and is approximately 125 to 150 mm thick. For poor trackbed support conditions and high impact areas, a 200-mm thickness is used. Thickness of the overlying ballast normally ranges from 200 to 300 mm.

The typical HMA mixture specification is the prevailing dense-graded highway base mix in the area having a maximum aggregate size of 25 to 37.5 mm. This slight modification to the typical highway mix imparts ideal properties to the track structure. Normally the asphalt binder content is increased by 0.5% above that considered optimum for highway applications resulting in a low to medium modulus (plastic) mix, having a design air voids of 1 to 3%. This mix is easier to densify to less than 5% in-place air voids and therefore facilitates adequate strength and an impermeable mat. Rutting of the plastic mix is not a concern in the trackbed since the pressures are applied through the ballast over a wide area. Bleeding and flushing are also of little concern since the wheels do not come in direct contact with the HMA layer and the temperature extremes are minimized in the insulated trackbed environment.

2.2 *Installation Equipment and Costs*

The equipment required for installing the HMA layer varies depending on the size of the installation. For short maintenance/rehabilitation projects, the HMA is normally back-dumped on grade and spread with a trackhoe, small dozier, bobcat, etc. already on site, prior to compacting with a conventional vibratory roller. This process requires that the old track panel be removed. Thus the cost to place the HMA is minimal, basically no more than placing conventional granular subballast. The cost of the HMA material delivered to the job site adds a small percentage to the total track removal and replacement costs but is basically insignificant, since it replaces the granular subballast. The majority of the costs involve equipment, labor and track materials. The added time to the track outage to place HMA is insignificant, provided the track is to be removed and the underlying ballast/subballast replaced with new ballast.

For larger out-of-face projects, mainly new construction with a prepared subgrade, the HMA is placed with conventional asphalt laydown (paving) equipment and compacted with large vibratory rollers. The procedure is similar to highway construction. The cost of the HMA may be less that the cost of granular subballast if quality granular subballast has to be transported long distances due to insufficient quality or quantity in the immediate area. Normally HMA is compatible with a wide variety of subballast aggregates. The thickness and width of the HMA is less than that of granular subballast, thus about one-half or less material is required, which is also a cost advantage for HMA. The HMA can be placed with highway paving equipment as rapidly as highway paving with much less hand-work and concerns of smoothness.

3 OBSERVED PERFORMANCE OF ASPHALT UNDERLAYMENTS

Rose and Lees (2008) reported on recent investigations that involved asphalt core drilling and, sampling and characterization of trackbed materials. These investigations were conducted on numerous in-service HMA trackbeds on CSXT and BNSF revenue lines in several states. These HMA trackbeds ranged from 12 to 26 years of service and were selected to include varying geographical and geological conditions. The investigations involved a wide variety of subgrades that ranged from low-strength, high plasticity (fat) clays to moisture-sensitive silts to higher quality granular materials.

The HMA cores and extracted/recovered asphalt binders were extensively evaluated at the National Center for Asphalt Technology at Auburn University. The primary purpose was to determine if any significant weathering or deterioration of the HMA was occurring in the trackbed environment, which could adversely affect long-term performance. A variety of HMA mixture compositions and mat thicknesses were evaluated.

3.1 *Asphalt Underlayment Durability*

It was concluded that the various asphalt binders and HMA mixes did not exhibit any indication of excessive hardening (brittleness), weathering, or deterioration even after many years in the trackbed environment. This is primarily due to the insulative effects of the overlying ballast. This protects the HMA from sunlight and excessive temperature extremes, which significantly reduces oxidation and hardening of the asphalt binder. The mat remains slightly flexible, which contributes to a long fatigue life for the HMA layer. There is no indication that the HMA mats are experiencing any loss of fatigue life. These findings substantiated earlier findings (Rose et al., 2000).

3.2 *Effects on Structural Performance*

It has been observed that mixes specifically designed to be more viscous (plastic) are conducive to the angular ballast particles slightly penetrating or imbedding into the top surface of the asphalt mat. This increases the interfacial shear strength and improves overall structural value of the track structure. Furthermore, the uniformly high level of support provided by the HMA mat maintains a high degree of ballast compaction which results in increased modulus, reduced wear, and increased life of the ballast. This is a primary contributor to the extended excellent track geometry indicators provided by the HMA mat and confined ballast layer. The combined supports provided by the HMA mat and the confined ballasts layer are believed to be primary contributors to the excellent track geometry indicators routinely measured over long periods of time.

3.3 *Trackbed Pressure Measurements*

Two sites were selected for the trackbed pressure tests. One was on a heavy-tonnage CSXT revenue mainline in east-central Kentucky, near Conway, KY. The other was on the high-tonnage test trackbed at TTCI in Pueblo, Colorado. Trackbed pressure measurements were obtained at prevailing speeds under heavy tonnage railroad loadings. Pressure measurements were recorded using (Geokon) hydraulic type earth pressure cells. These were imbedded in the track structure above and below the HMA mat (Rose et al., 2002; Anderson and Rose, 2008).

3.3.1 *CSXT Revenue Line Tests*

Figure 2 is a typical plot of the pressures exerted on top of the HMA mat for a CSXT empty coal train in the time domain (Rose et al., 2002). Vertical pressures imposed by typical 130-metric ton locomotives and loaded coal cars range from 90 to 120 kPa on top of the HMA mat. The average locomotive wheel load is 16 metric tons. Pressures are reduced to 15 to 30 kPa under the 29 metric ton empty cars, which have an average wheel load of 3.5 metric tons. Two cross sections were investigated. One cross section consisted of 130 mm of HMA overlain by 200 mm of ballast (Figure 2a) and the other section consisted of 200 mm of HMA overlain by 200 mm of ballast (Figure 2b).

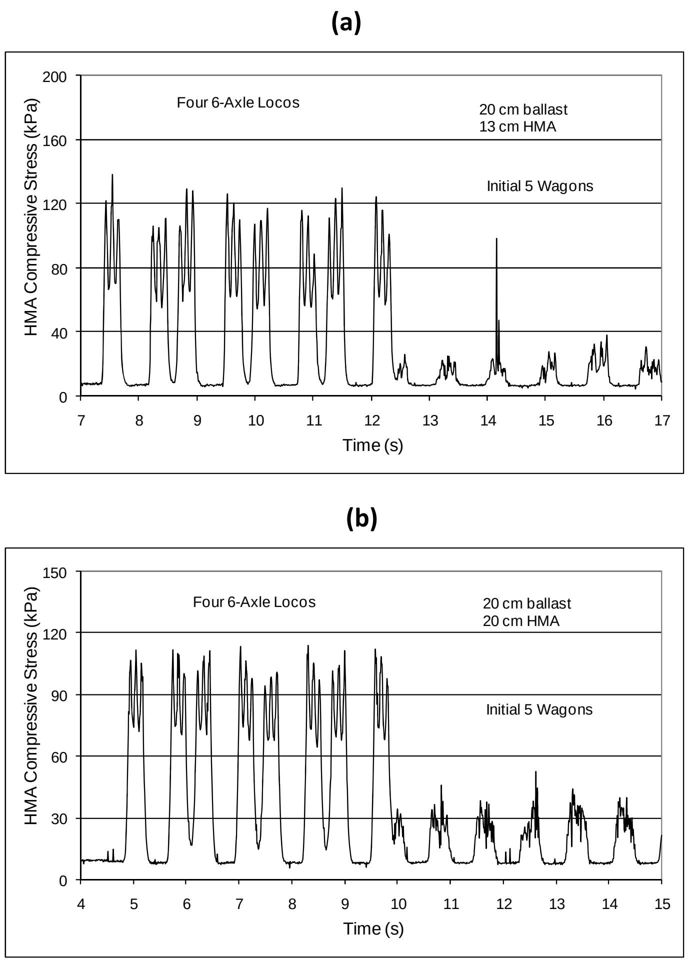

Figure 2. Representative Dynamic Compressive Stress on HMA Layer Measured for Empty Coal Train on CSXT Mainline at Conway, KY: (a) 13 cm HMA Layer; (b) 20 cm HMA layer.

The figure shows the beam action of the track, which distributes the concentrated wheel loadings over several ties and the confined, high modulus ballast layer, serves to effectively reduce the heavy wheel loadings. In general, trackbed vertical stress levels on top of the HMA mat are very low under heavy tonnage railroad loadings and are only a fraction of those imposed by high-pressure truck tires on highway pavements. By comparison, typical tire pressures imposed on highway asphalt surfaces under loaded trucks range from 700 kPa to over 1,050 kPa depending on the magnitude of loading and tire configurations. Thus, it is assumed the HMA mat will have an extremely long fatigue life at the load-induced pressure levels existing in the trackbed environment.

3.3.2 *TTCI High Tonnage Trackbed*

Li et al. (2002) presented the results of testing performed at the TTCI High Tonnage trackbed. HMA underlayment sections were placed over a soft subgrade (low track modulus) and subjected to 36-metric ton axle loads. The use of HMA underlayment was intended to reduce load-induced stresses to the subgrade and to provide a waterproof layer over the underlying soil. In these tests, three different track structures were evaluated; (i) a conventional granular track structure; (ii) a 102 mm-thick HMA trackbed; and (iii) a 203 mm-thick HMA trackbed. The conventional track structure was representative of typical of mainline railroad tracks and was used as a point of reference. This track consisted of 305 mm of ballast and approximately 150 mm of subballast. The 102 mm-thick HMA trackbed consisted of 305 mm of ballast, 102 mm of asphalt, and 102 mm of subballast. The 203 mm-thick HMA trackbed consisted of 203 mm of ballast, 203 mm of asphalt, and 102 mm of subballast. All track structures were placed over a soft subgrade comprised of Vicksburg (Buckshot) clay. This clay is a high moisture content clay with an average liquid limit of 64 percent, an average plasticity index of 38 percent and an average natural moisture content of 34.6 percent. The average undrained shear strength was reported as approximately 90 kPa.

Figure 3 gives the subgrade stresses obtained at 83 MGt under a static wheel load of 18 metric tons. As shown, the measured subgrade stresses were lower for the asphalt trackbeds than for the 450-mm granular track. Under the 18-metric ton static wheel load, only 49 to 55 kPa of subgrade stress was generated under the HMA underlayments, compared to approximately 83 kPa under the 450-mm granular track structure.

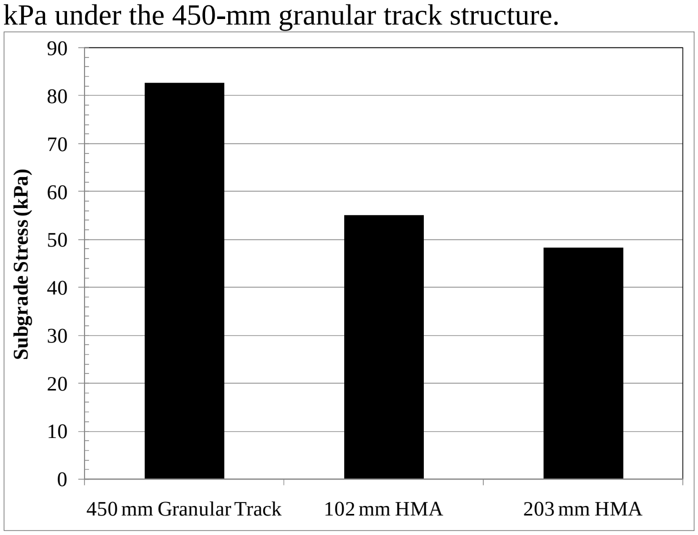

Figure 3. Test Results for Subgrade Stress under 18 metric ton Static Wheel Load.

Figure 4 shows the dynamic stress results under an actual train operating at 64 km/hr measured on the 203-mm HMA surface as well as on the subgrade surface. The data indicates that the dynamic peak pressures measured on the top of the HMA surface for the 15- to 18-metric ton wheel loads (39 metric ton axle load) range from 75 to 150 kPa. These measured stresses compare favorably with the 90- to 120-kPa dynamic pressures measured on top of the HMA mat at the CSXT Conway test site for the 16-metric ton wheel loads (cf. Figure 2). As illustrated in Figure 4, use of a 203-mm HMA underlayment reduced the subgrade stress by approximately one-half. At the subgrade surface, the measured peak stresses ranged between 39 to 66 kPa. This reduction is similar to that shown for the static wheel load (cf. Figure 3).

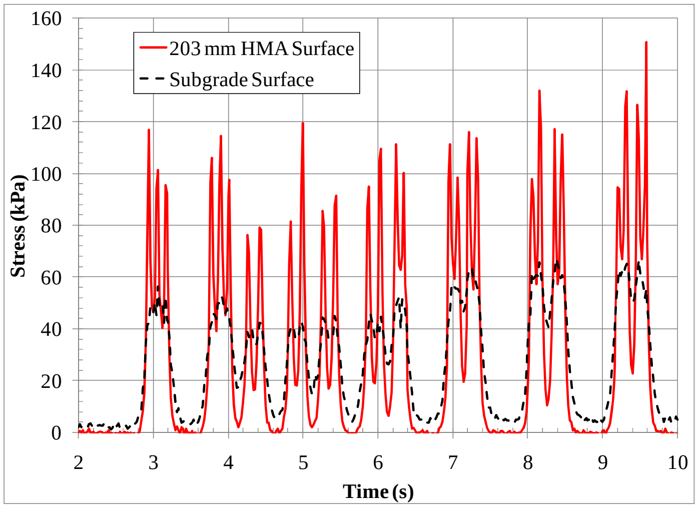

Figure 4. Reduction of Dynamic Stresses from 203 mm HMA Surface to Subgrade Surface under 36 metric ton Axle Cars.

The stress reduction behavior is most likely due to the HMA layer acting as an arching mechanism to the stress distribution. This seems logical given the HMA layer is much more rigid, relative to the ballast materials. With the reduction in the stress levels being transmitted to the subgrade, it can be concluded that HMA layers will reduce the cyclic load-induced strength loss to the subgrade soils.

3.4 *Trackbed Structural Performance*

In addition to the subgrade stress (σ_{meas}), the data presented by Li et al. (2001) also included track modulus (K_r) data. Figure 5 shows the track modulus as a function of asphalt thickness (t). The figure shows that the modulus increases linearly with increasing thickness of the HMA layer. The expression that represents this linear increase is given as

$$K_r = 0.44(t) + 14.16 \tag{1}$$

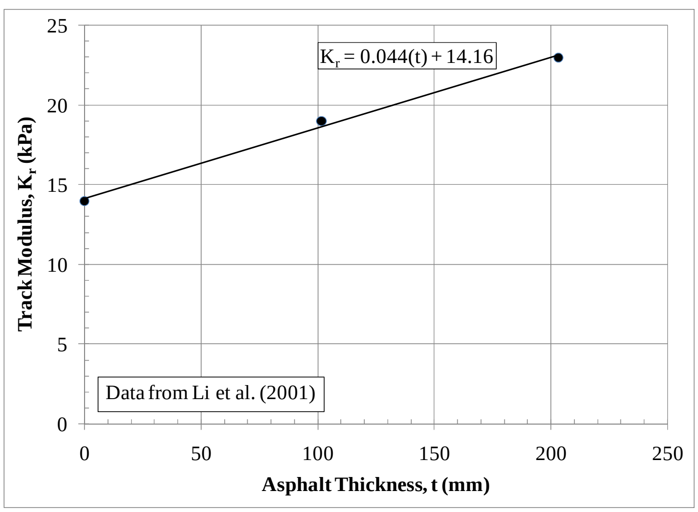

Figure 5. Track modulus as a function of thickness of the asphalt layer.

The increase in track modulus implies a decrease in track settlement, which translates into more durable tracks. Thus, asphalt underlayment will tend to produce a general reduction of required maintenance cycles.

Improvement of the structural performance of the track structure offered by HMA underlayment can also be assed from the pressure index. The pressure index is the ratio of pressure at the interface of a layer, to the predicted bearing capacity (q_{ult}) of the layer. A pressure index value of unity implies failure of the layer. Figure 6 presents the pressure index at the top of the subgrade as a function of asphalt thickness. The bearing capacity used for the figure was obtained from a modified form of the Meyerhof and Hanna (1978) general bearing capacity equation for a stronger soil underlain by a weaker soil (*the reader is referred to Selig and Waters, 1994 for further details on bearing capacity for track structures*). The form of the equation used in this study is given as

$$q_{ult} = c'N_c\left(1+0.2\frac{B}{L}\right)+\gamma H^2\left(1+\frac{B}{L}\right)\left(1+\frac{2D}{H}\right)\left(\frac{K_p \tan\delta}{B}\right)-\gamma H \qquad (2)$$

where c' = the effective cohesion intercept of the bearing soil; N_c = the bearing capacity factor = 5.12; B = the width of the tie = 229 mm; and L = the $1/3$ length of the tie = 864 mm; γ = the unit weight of the bearing soil = 18.85 kN/m^3; D = the depth of embedment of the tie; H = the thickness of the granular layer; K_p = the passive earth pressure coefficient; δ = the inclination of the passive earth force = $2\phi'/3$; ϕ' = the effective phi angle of the soil. The shear strength parameters of the subgrade soil were taken from Miller et al. (2000). They performed isotropically consolidated undrained (CU) triaxial test on undisturbed samples of subgrade soil and reported that the effective stress Mohr-Coulomb failure envelope gave $\phi' = 22.7^\circ$ and $c' = 15.9\ kPa$.

It is noted the Meyerhof and Hanna (1978) bearing capacity equation assumes a homogeneous bottom layer overlain by a homogeneous top layer. For the two case of asphalt underlayment, the thickness of the asphalt layers were added to the depth of embedment and it was assumed that the thickness of the granular layer was approximately 406 mm. Although this is a greatly simplified treatment of the HMA underlayment system, this provides a qualitative means by which the improvements to the structural performance can be evaluated. As seen in the figure, the asphalt underlayment significantly improves the pressure index. The factor of safety against punching shear failure increases by roughly 35 percent with 102 mm of HMA underlayment and by approximately 46 percent for 203 mm of HMA underlayment. Although Figure 6 shows the improved structural performance due to the HMA layers, it also highlights the need for additional studies to understand bearing capacity for these types of systems.

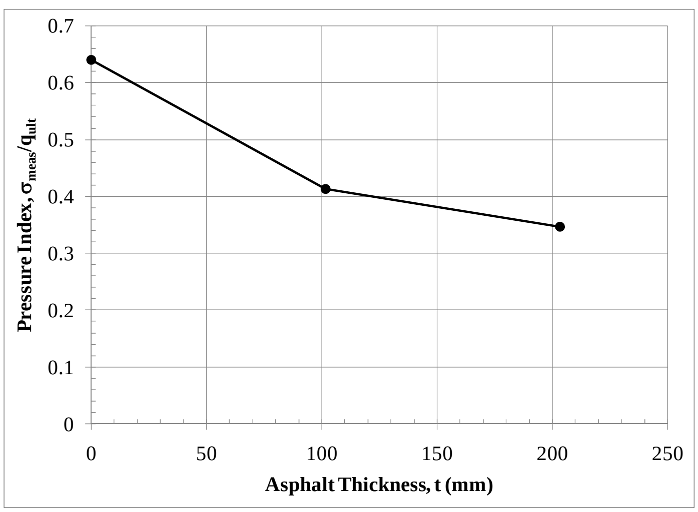

Figure 6. Pressure index as a function of thickness of the asphalt layer.

3.5 *Benefit to the Subgrade*

An additional benefit of asphalt underlayment is that subgrades tend to maintain their insitu moisture contents at or near the optimum moisture content. Rose and Lees (2008) investigated several HMA track systems and found this to be the case. This is of interest in that shear strength of compacted soils tends to decrease with increasing moisture content, greater that optimum moisture (Lambe and Whitman, 1969). This behavior was also observed at the TTCI test track. The Rose and Lees (2008) study found that the in-situ moisture contents were within one percent of the laboratory determined optimum values for maximum density of the respective materials. Figure 7 shows the undrained shear strength versus the insitu water content. The undrained shear strength was obtained from unconfined compression tests reported by Li (2000).

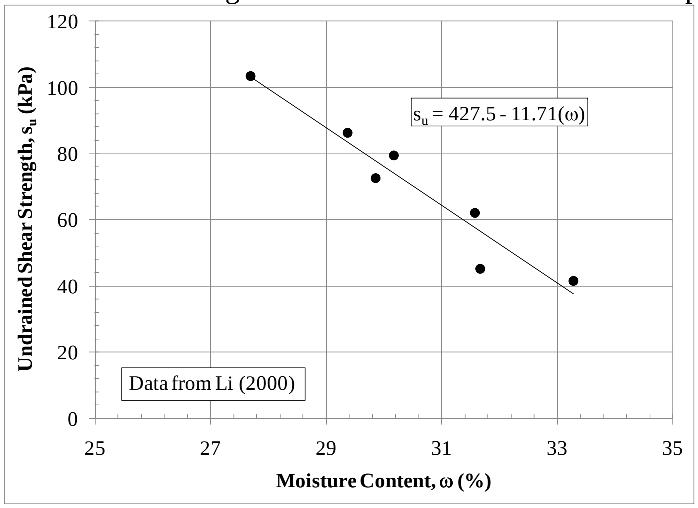

Figure 7. Undrained shear strength as a function of moisture content.

The data shows a consistent linear relation between undrained shear strength and moisture content. For the clay subgrade, the relation is given by the following expression

$$s_u = 427.5 - 11.71(\omega) \tag{3}$$

The observation of a decrease in strength with increasing moisture content was also found for the case of cyclic loading. Miller et al. (2001) presented cyclic triaxial data for the Vicksburg clay. Figure 8 presents the cyclic shear strength (τ_f) as a function of water content. A trend line is shown in the figure to emphasize that the general relation observed with the monotonic loading condition is the same with the cyclic loading condition. The undrained cyclic shear data is included for completeness. However, as is fundamental in the nature of the test, the moisture content does not change during shear.

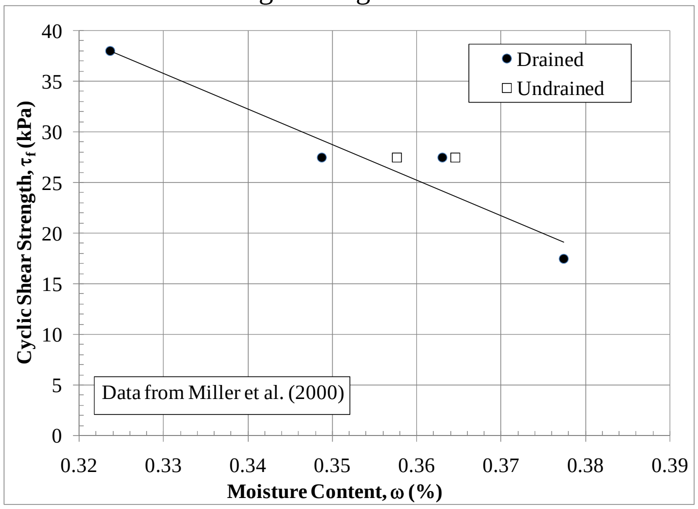

Figure 8. Influence of moisture content on the cyclic shear.

The data presented by Miller et al. (2001) was also used to evaluate the influence of the moisture content on the maximum shear modulus (G_{max}) and moisture content. These data are shown in Figure 9. The shear modulus is typically used to reflect the stiffness of a material. As stiffness increases, the overall deflection of the material will decrease. Thus, the figure gives an indication of the influence of moisture content on the deflection response of subgrade soil. The maximum shear modulus values were obtained from the Hardin and Drnevich (1972) equation and is given by the following expression

$$G_{max} = \frac{3230(2.97-e)^2}{1+e}(OCR)^K(\bar{\sigma}_o)^{0.5} \quad (4)$$

where e = the void ratio; OCR = the over consolidation ratio; K = a constant = $f(plasticity\ index, OCR)$; and $\bar{\sigma}_o$ = mean normal stress = $(\sigma_1' + 2\sigma_3')/3$; σ_1' = maximum effective principal stress; and σ_3' = minimum effective principal stress.

As with Figure 8, a trend line has been included to qualitatively show the influence on increasing moisture content. Although a unique expression cannot be obtained from the presented data, the figure clearly shows that increased deflection of the subgrade soil is associated with increased moisture content.

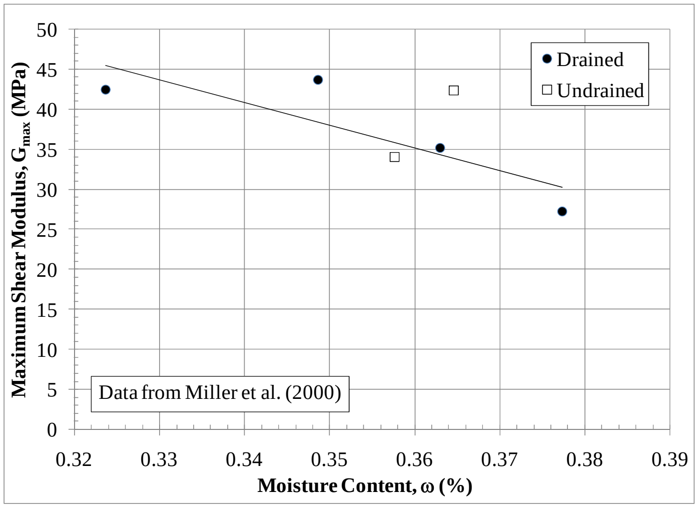

Figure 9. Influence of moisture content of the maximum shear modulus.

It can be thus concluded that the use of HMA underlayment will yield stronger, more durable track structures and will resist excessive deflections. These factors imply safer and more economical tracks structures.

4 CONCLUSIONS

The primary purpose of this investigation was to assess the improvements to structural performance of trackbed structures provided by asphalt underlayment. For this study, two sites were selected for the trackbed pressure tests and structural performance assessments. The significant findings of this investigation include:

– The overlying ballast acts as an insulator to the asphalt layer, protecting the HMA from sunlight and excessive temperature extremes. This significantly reduces oxidation and hardening of the asphalt binder and thus greatly increases the fatigue life of the HMA layer.
– The combined supports provided by the HMA mat and the confined ballasts layer are believed to be primary contributors to the excellent track geometry indicators routinely measured over long periods of time.
– The arching effects of HMA layer significantly reduces the level of stress transmitted to the subgrade soils. In particular, use of a 203-mm HMA underlayment reduced the subgrade stress by approximately one-half. Thus, it can be concluded that HMA layers will reduce the cyclic load-induced strength loss to the subgrade soils.
– The track modulus tends to increase linaeraly with increasing asphalt thickness. The increase in track modulus implies a decrease in track settlement, which translates into more durable tracks. Thus, asphalt underlayment will tend to produce a general reduction of required maintenance cycles.
– The asphalt underlayment significantly improves the pressure index. The factor of safety against punching shear failure increases by roughly 35 percent with 102 mm of HMA underlayment and by approximately 46 percent for 203 mm of HMA underlayment.

– The in-situ moisture contents at the various asphalt underlayment sites were within one percent of the laboratory determined optimum values for maximum density of the respective materials. This implies that the strengths and load carrying capacities of the underlying materials remained uniformly high.

All of these conclusions indicated that HMA underlayment will yield stronger, more durable track structures and will resist excessive deflections. These factors imply safer and more economical tracks structures.

5 ACKNOWLEDGEMENTS

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