Test Measurements and Performance Evaluations of In-Service Railway Asphalt Trackbeds

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During the past twenty-five years the use of Hot Mix Asphalt (HMA) as a subballast layer, or underlayment, within the track structure has steadily increased until it is becoming standard practice in many areas of the United States. This asphalt-bound impermeable layer, typically 5 to 8 in. (125 to 200 mm) thick, provides a “hardpan” to protect the underlying roadbed and to support the overlying ballast and track. Long-term performance studies on numerous HMA installations attest to the improved attributes and economic benefits of the asphalt layer, particularly on heavy tonnage lines traversing areas of marginal geotechnical engineering characteristics.

Recent studies involve instrumenting HMA trackbeds with earth pressure cells and displacement transducers to measure pressure levels and distributions within the track structure and rail deflections under moving trains. These tests, conducted in real time domain train operations, confirm the positive attributes of the asphalt layer. Results are presented in detail for test installations on a CSX Transportation heavy tonnage mainline and at the Transportation Technology Center (Pueblo) low track modulus heavy tonnage test track.

KENTRACK, a finite element, layer-elastic trackbed structural design computer program, is utilized for determining the effects of varying trackbed materials, component thicknesses, and designs on pressure distributions in the track structure. Predictive values from the KENTRACK model are compared with in-track measurements. The predictive values, obtained from KENTRACK, compare well with in-track measurements for similar conditions providing a measure of credibility for the model.

TEST MEASUREMENTS AND PERFORMANCE EVALUATIONS OF IN-SERVICE RAILWAY ASPHALT TRACKBEDS

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INTRODUCTION

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. 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 141,000-mile (227,000 km) railroad network. The average freight car weight has increased to 129 tons (117 metric tons) with most new cars having gross weights of 143 tons (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 difficulty maintaining track geometric features necessary for efficient and safe train operations. Maintenance costs and track outages increase due to frequent maintenance and renewal cycles.

TYPICAL TRACKBED FAILURE MODES

The inability of the track structure to adequately carry the imposed loadings can be categorized into two primary failure types. The first one is failure of the **subgrade** when the pressure transmitted to the subgrade is higher than the inherent bearing capacity of the particular subgrade. The subgrade soil's ability to accommodate loading pressures is a function of its shear strength, cohesion, plasticity, density, and moisture content. A well-compacted subgrade soil that is confined and maintained reasonably dry will normally perform adequately for an indefinite period of time. A possible exception is a highly compressible soil such as peat. Subgrade failures adversely affect track geometry and are normally difficult and expensive to correct.

The second type of trackbed failure occurs when one or more of the **trackbed structural components** fail to perform satisfactorily for a reasonable period of time. This is commonly manifested by the subballast, and particularly the ballast, becoming clogged (fouled) with excessive quantities of fine size material. This lowers the shear strength of the ballast and bearing capacity of the subballast. Fouling is normally due to degradation of the ballast, infiltration of subgrade soil particles, extraneous droppings from hopper cars, or wind-blown fine particles. Track geometry is adversely affected to varying degrees. The geometry is difficult to rectify since it is difficult to manipulate and adjust the fouled ballast with typical trackbed maintenance surfacing equipment.

Periodic replacement of the track components (rails, ties, fasteners, and special trackworks) cannot be avoided (Lopresti, Davis and Kalay, 2002). It is desirable to increase the service life of the components. The adequacy of the trackbed structural components supporting the track can have a significant effect on the life of the track components by reducing impact stresses and minimizing deflections of the track.

The solution for minimizing **subgrade** failures involves a combination of reducing the pressure on the top of the subgrade, improving drainage (effectively improving the properties of the subgrade), adding thickness to the trackbed structural components, or utilizing higher quality/load bearing trackbed components. The solution for minimizing **structural component** failure is designing and selecting reasonable fasteners and track components so that an optimum track structural support stiffness will be achieved. In order to design optimum track structural support stiffness, it is necessary to determine the pressures at different levels in the track support structure such as at the rail base/tie plate, tie plate/tie, tie/ballast, ballast/subballast, and subballast/subgrade interfaces.

HOT MIXED ASPHALT TRACKBEDS

The most common trackbed is composed of all-granular materials consisting of layers of ballast and subballast over a prepared subgrade, as noted in Figure 1a. Trackbeds containing a layer of hot mixed asphalt (HMA) are becoming more prevalent in recent years. 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, Brown, and Osborne, 2000). The most common HMA trackbed, termed asphalt underlayment as depicted 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. Also, the ballast permits adjustment of track geometry with typical maintenance equipment and procedures. Figure 2a shows a layer of HMA being laid over the subgrade during the construction of an HMA trackbed and Figure 2b illustrates the structural components of an underlayment trackbed.

IN-SITU TEST SITES

Two test sites have been utilized to obtain trackbed pressure and deflection measurements. The **Revenue** line is the CSXT 40 MGT (36 MGt) heavy tonnage **Mainline** between Cincinnati, OH and Atlanta, GA at Conway, KY. Two 1,000-ft (305 m) long asphalt underlayment sections, consisting of 5-in. (125 mm) and 8-in. (200 mm) thick layers of asphalt, were placed during 1983. This section of track has remained virtually maintenance free for nearly 25 years and has been subjected to numerous tests and evaluations.

The **Non-Revenue** line is on the **High Tonnage Loop** at the Transportation Technology Test Center (TTCI) near Pueblo, CO. Two 350-ft (107 m) long asphalt underlayment sections, consisting of 4-in. (100 mm) and 8-in. (200 mm) thick layers of asphalt, were placed during 1999 over the soft clayey subgrade portion of the test track. Test trains with 40-ton (36 metric ton) axle load continuously circle the loop to provide accelerated loading (Li, Lopresti and Davis, 2002).

PRESSURE AND DEFELCTION MEASUREMENT TECHINQUES

Pressures exerted by the wheel loads on the trackbed support materials were obtained with Geokon Model 3500 Earth Pressure Cells. These were imbedded in the track structure above and below the HMA mat. Figure 3a is schematic view of the pressure cell configuration for in-track tests. Figure 3b is a view of an in-track test.

The portion of the cell that receives the load consists of two slightly convex stainless steel circular plates that are 9 in. (230 mm) in diameter welded together at their edges. The void between the two plates is filled with a de-aired hydraulic fluid. When a load is applied to the plates, the load compresses the fluid and forces it down a short length of high-pressure stainless steel tubing. This tubing connects to a pressure transducer, which converts the pressure of the compressed fluid into an electrical signal. From the pressure transducer, the electrical signal is transmitted through a signal cable to the readout location (Rose, Li and Walker, 2002). The Geokon Pressure Cells used in the field to determine pressures in the trackbed have a 100-psi (690 kPa) limit.

In addition to the pressure cell, a computer, power source, and junction box are required. A 12-volt battery provides power for the electrical signal. The junction box acts as a hub through which all components are connected. It also provides multiple ports for additional pressure cells, thereby allowing for multiple pressure readings to be recorded simultaneously. Snap-Master is the data acquisition system used for obtaining the pressure measurements for in-track measurements. The program allows the user to record the electrical signal from the pressure cell in real time.

Each Geokon Pressure Cell is calibrated prior to in-track tests. This provides a calibration factor, which converts voltage readings to actual pressure values. The procedure involves developing a plot of recorded voltages for known vertical pressures. From this plot, the inverse of the slope is determined, which is the calibration factor. The calibration factor is then multiplied by the voltage reading to determine pressure.

Defections under the dynamic loadings of the railcars were recorded in conjunction with the pressure measurements using Linear Variable Displacement Transducers (LVDT). An obstacle to using LVDTs to measure track deflections is establishing a fixed point of reference (datum). The fixed datum is achieved by driving a 1-in. diameter steel road through the track structure and into solid sub-strata. Therefore, the rod is unaffected by the passing of the trains and remains at a fixed elevation. Figure 4a is a schematic view of the LVDT configuration for in-track tests. Figure 4b is a view of an in-track test arrangement. The LVDT consists of a nonmagnetic shell and a magnetic core. The relationship between input and output voltage is related to displacement.

The LVDT is attached to a removable clamp that can be secured to the base of the rail. Two pieces of angle steel are securely clamped to the stationary rod. The LVDT is rotated so that the movable indicator (core) is positioned over a piece of the angle steel and zeroed. Snap-Master is used as the data acquisition system for obtaining the deflection measurements in the real-time domain. A 6-volt battery supplies the power for the LVDT.

Track deflection is considered to be a primary indicator for predicting track strength, life, and quality. Excessive deflection causes accelerated movement and wear of ballast and ties through inter-partical powdering and abrasion. The ideal track structure provides a balance of stiffness and flexibility – not too stiff, not too resilient.

CONWAY, KY (CSXT) TEST RESULTS

Trackbed Pressure Measurements

Figure 5 is a typical plot of the pressures exerted on top of the HMA mat for an empty coal train in the time domain (Rose, Li and Walker, 2002). Vertical pressures imposed by typical 286,000-lb (130-metric ton) locomotives and loaded coal cars range from 13 to 17 psi (90 to 120 kPa) on top of the HMA mat. The average locomotive wheel load is 35,000 lb (16 metric tons). Pressures are reduced to 2 to 4 psi (15 to 30 kPa) under the 63,000 lb (29 metric ton) empty cars, which have an average wheel load of 8,000 lb (3.5 metric tons).

The beam action of the track, which distributes the concentrated wheel loadings over several ties and the confined, high modulus ballast layer, serve to effectively reduce the heavy wheel loadings. By comparison, a 180-lb (82 kg) person will exert about 6 psi (40 kPa) pressure while standing on a level surface. Furthermore, typical tire pressures imposed on highway asphalt surfaces under loaded trucks range from 100 psi (700 kPa) to over 150 psi (1,050 kPa) depending on the magnitude of loading and tire configurations.

Trackbed vertical stress levels on top of the HMA mat under heavy tonnage railroad loadings are very low and only a fraction of those imposed by high-pressure truck tires on highway pavements. The HMA mat should have an extremely long fatigue life at the load-induced pressure levels existing in the trackbed environment.

Trackbed Deflection Measurements

Dynamic track deflections were recorded in conjunction with the pressure measurements using LVDTs referenced to a fixed datum. Figure 6 is a typical plot of rail deflections under 286,000-lb (130-metric ton) locomotives and loaded cars. The deflections average 0.25 in. (6.4 mm) for wood tie track and around 0.05 in. (1.3 mm) for concrete tie track. These are considered optimum for both track types.

Based on the wheel loadings and measured track deflections, the calculated dynamic track modulus (stiffness) values are in the 2,500 lb/in/in (17 MPa) range for wood tie track and around 7,500 lb/in/in (52 MPa) for concrete tie track. These are also considered optimum. The concrete tie track deflects much less than the wood tie track and is thus much stiffer. This increases pressure within the ballast. The ballast must be properly supported from below so it can develop high shear strength to reduce the higher than normal imposed loading pressures. The high modulus HMA mat provides increased support and confinement for the ballast in concrete tie track.

TTCI (PUEBLO) TEST TRACK RESULTS

Trackbed Pressure Measurements

HMA underlayment sections were placed over a soft subgrade (low track modulus) and subjected to 40-ton (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. Since its installation, the performance of this test track has been evaluated in terms of track geometry degradation with traffic as well as the amounts of track modulus increase and subgrade stress reduction compared to conventional granular layer construction (Li, Lopresti and Davis, 2002).

Figure 7 gives the track modulus test results obtained at 92 MGT (83 MGt) and the subgrade stress results under a static wheel load of 20 tons (18 metric tons). As shown, the average modulus values for the two HMA segments are 2,800 lb/in/in (20 MPa) and 3,300 lb/in/in (23 MPa) for the fully consolidated ballast (increased from 2,600 and 2,800 lb/in/in (18 and 19 MPa)), respectively, at 0 MGT (0 MGt). The track modulus for the 18-in. (450-mm) granular track averaged 2,000 lb/in/in (14 MPa). As a result, the measured subgrade stresses were lower for the asphalt trackbeds than for the 18-in. (450-mm) granular track. Under 20-ton (18-metric ton) static wheel load, only 7 to 8 psi (50 to 55 kPa) of subgrade stress was generated under the HMA underlayments, compared to 12 psi (83 kPa) under the 18-in. (450-mm) granular track structure.

To indicate how stresses induced by wheel loads are reduced from the HMA to the subgrade, Figure 8 shows the dynamic stress results under an actual train operation at 40 mph (64 km/hr) measured on the 8-in. (200-mm) HMA surface as well as on the subgrade surface. As illustrated, use of a 8-in. (200-mm) HMA underlayment reduced the subgrade stress by approximately one-half.

In addition, the data in Figure 8 indicates that the dynamic pressures measured on the top of the HMA surface for the 16- to 20-ton (15- to 18-metric ton) wheel loads range from 11 to 19 psi (75 to 130 kPa). These values compare favorably with the 13- to 17-psi (90- to 120-kPa) dynamic pressures measured on top of the HMA mat at the CSXT Conway test site for the 18-ton (16-metric ton) wheel loads, as indicated in Figure 5.

Trackbed Temperature Measurements

An additional benefit of using a HMA layer beneath the ballast is the insulation of asphalt from the sunlight and extreme weather, thus keeping asphalt less susceptible (compared to highway applications) to oxidation and temperature effects, which should lead to longer asphalt life with less weathering and cracking due to environment factors. Temperature recordings were made over a span of close to one year for both the HMA layer and the air. As shown in Figure 9, HMA temperature experienced much less variation than the air temperature at the Pueblo test facility.

Previous temperature data was obtained in a similar manner in the Kentucky climate (Rose, Li and Walker, 2002). The maximum temperature recorded in the summer was 75°F (24°C) and the minimum in the winter was 36°F (2°C). Asphalt highway pavements exposed to the atmosphere and direct sunlight will typically experience temperature extremes of 120°F (50°C) to 0°F (-17°C) from summer to winter.

PREDICTIVE PROGRAM

A structural design computer program, KENTRACK, was developed for analyzing railroad trackbeds by the Department of Civil Engineering, University of Kentucky in early 1980s (Huang, Lin, Deng and Rose, 1984). The program was modified (Rose, Su and Long, 2003) from the initial Disk Operating System (DOS) system. The modification permits the user to change various properties of the track structure much easier than previously when values were entered by DOS. A user-friendly Window's based Graphical User's Interface, containing four descriptive forms (or screens), allows the user the option of entering varying values for the track structure components. Only a brief description of this computer program is contained herein. More details about the latest version of KENTRACK and its applications can be found in a related reference (Rose and Konduri, 2006).

The railroad track structure typically consists of rail, fastener, tie, and a multi-layered support system from top to bottom, as shown in Figure 10. The multi-layered support system consists of trackbed, subgrade, and bedrock. The trackbed normally consists of two layers – ballast overlying an all-granular subballast or bound material such as HMA mix. When several loads are applied to the rail, the stress, strain, and deflection of rail and tie can be obtained by superimposing the effect of each load. Computations of the stress and strain in rail and tie are based on the finite element method in KENTRACK. The rail and tie are classified as beam elements. The spring element is used to simulate the tie plate and the fastener between rail and ties. For KENTRACK, only four layers are used – ballast, subballast or HMA, subgrade soil, and bedrock – from top to bottom. The details of multi-layered system solution method can be found in a related reference (Huang, 1993).

An HMA railroad trackbed is composed of three different materials – ballast, HMA, and subgrade soil. Although all of them are considered as elastic materials, different numerical equations are used to describe them due to their different inherent properties. Ballast can be considered as either a non-linear or linear material. When a railroad trackbed is recently constructed and has not been compacted, ballast will behave non-linearly. Whereas, if the trackbed has been used for an extended time and the ballast has become compacted, it is more reasonable to use the linear model rather than the non-linear model for calculating the modulus.

HMA is a temperature dependent material. Its dynamic modulus can be calculated by using the method developed by the Asphalt Institute (Hwang and Witczak, 1979). Different temperatures should be used for different months or seasons.

Subgrade soils are always considered as linear elastic materials regardless of the type. However, the program permits using different subgrade soil parameters having different Poisson ratios and elastic modulus values. The program considers the bottom layer to be an ideal material – bedrock – that has an infinite elastic modulus (incompressible) and 0.5 for Poisson's ratio.

Damage analysis, a function provided by KENTRACK, can predict the service life of the railroad trackbed because a prediction function has been integrated into the program based on the Minor linear damage analysis criteria. Two failure criteria are utilized in the KENTRACK program due to the different properties of materials. For HMA, it is the tensile strain on the bottom of asphalt that controls asphalt life to prevent tensile cracking. For subgrade soil, it is the vertical compressive stress that controls subgrade life to prevent excessive settlement and deformation, which is determined to adversely affect track geometry. The service life of the track structure is governed by the lesser one, either tensile failure of the HMA layer or vertical permanent deformation of the subgrade.

COMPARISONS OF MEASURED AND PREDICTIVE VALUES

The vertical compressive stresses over the HMA layers, obtained from earth pressure cells, were checked with the predictive values from KENTRACK. Tables 1a and 1b contain all the KENTRACK Predictive Values (KPV) and In-Track measured Data (ITD) for the Conway and TTCI tests. For the CSXT track at Conway, KY, measured vertical compressive stresses were 16 psi (110 kPa) in the 5 in. (125 mm) thick HMA trackbed and 15 psi (100 kPa) in the 8 in. (200 mm) thick HMA trackbed as shown in Figure 5. Predictive values from KENTRACK for these two cases were 21 psi and 22 psi (145 kPa and 150 kPa). Also, for the track at TTCI, measured values were 15 psi (100 kPa) in both sections, as shown in Figure 8. KENTRACK predictive values were 12 psi (80 kPa) for the 4-in. (100 mm) HMA section and 22 psi (150 kPa) for the 8-in. (200 mm) HMA section.

Subgrade vertical compressive stress is an important issue since it is closely related to the performance of the track. In-track measurements were conducted on the 8-in. (200-mm) HMA section at the TTCI test track for a dynamic case. The test results shown in Figure 8, indicate that the vertical compressive stress over subgrade is about 8.0 psi (55 kPa). Meanwhile, vertical compressive stress at subgrade in the 4-in. (200-mm) HMA section was also recorded and it is 7.7 psi (53 kPa). The KENTRACK predictive values for these two cases are 8.3 and 8.2 psi (57 and 56 kPa), very close to the actual measurement. For comparison, a traditional ballast trackbed was selected at TTCI for comparison. It has an 18-in. (450-mm) thick ballast layer. The vertical compressive stress measured for this track is around 11.6 psi (80 kPa) whereas KENTRACK predicted a value of 11 psi (75 kPa).

FINDINGS

- Peak dynamic pressures range from 13 to 17 psi (90 to 120 kPa) on top of the HMA mat under 286,000 lb (130 metric ton) locomotives and heavily loaded cars – only two to three times greater in magnitude than the pressure exerted by an average-size person standing on an asphalt pavement.
- Peak dynamic vertical pressures under similar loading are further reduced to 7 to 8 psi (50 to 55 kPa) under the HMA layer at the subgrade interface.
- Dynamic track deflections for HMA trackbeds under 286,000 lb (130 metric ton) locomotives average 0.25 in. (6.4 mm) for wood tie track and 0.05 in. (1.3 mm) for concrete tie track. These are considered optimum.
- Dynamic track modulus (stiffness) values consistently average 2,900 lb/in/in (20 MPa) for wood tie track and 7,200 lb/in/in (50 MPa) for concrete tie track. These are considered optimum.
- In-track test measurements on HMA underlayment trackbeds obtained on CSXT's heavy-haul revenue line and obtained at TTCI's heavy-haul research test facility are consistent.
- Based on findings from previous studies, moisture contents of old roadbeds/subballasts/subgrades under the HMA mat remain at or near optimum after many years assuring optimum support for the HMA mat. This attests to the waterproofing attributes provided by the HMA mat. An equally important attribute of the HMA mat is the confinement it provides for the ballast so that the ballast can develop maximum shear strength and compactness.
- The HMA mat in the insulated trackbed environment undergoes minimum variation in temperature extremes throughout the year and it is not exposed to direct sunlight. The modulus (stiffness) is reasonably uniform throughout the year and weathering (oxidation) of the HMA has been shown to be minimal compared to highway applications.
- The combination of low inducted stress levels, minimal temperature changes, and minimal weathering in the trackbed environment assures a very long fatigue life for the HMA mat as compared to highway HMA applications.

CONCLUSIONS

Stresses at critical interfaces in the railroad trackbeds have been predicted and measured. The results compare favorably. Geokon earth pressure cells provide a method for direct measurements of trackbed pressures.

The KENTRACK computer program, based on finite element method and multi-layered theory, has been utilized to predict stresses in trackbeds. The program is capable of analyzing both traditional ballast trackbeds and HMA trackbeds. In-track measurements confirm the predictive values from KENTRACK thus providing this program a measure of credibility.

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Lindsay Walker, Frank Twehues, and Karthik Konduri. The comments, findings, and conclusions contained herein represent the views of the author.

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TABLE 1a. Comparison of the KENTRACK Predictive Values (KPV) versus In-Track Data (ITD) for the CSXT mainline at Conway, Kentucky – 1 in. = 25 mm, 10 psi = 69 kPa.

Thickness Ballast/HMA in	Vertical Compressive Stress on **Ballast** KPV/ITD, psi	Vertical Compressive Stress on **HMA** KPV/ITD, psi	Vertical Compressive Stress on **Subgrade** KPV/ITD, psi
10.0 / 5.0	47.9 / -	21.0 / 16.0	13.6 / -
10.0 / 8.0	48.7 / -	22.0 / 15.0	11.7 / -

TABLE 1b. Comparison of the KENTRACK Predictive Values (KPV) versus In-Track Data (ITD) at TTCI in Pueblo, Colorado – 1 in. = 25 mm, 10 psi = 69 kPa.

Thickness Ballast/HMA, in.	Vertical Compressive Stress on **Ballast** KPV/ITD, psi	Vertical Compressive Stress on **HMA** KPV/ITD, psi	Vertical Compressive Stress on **Subgrade** KPV/ITD, psi
12.0 / 4.0	43.5 / -	11.7 / 14.9	8.3 / 8.0
8.0 / 8.0	47.0 / -	21.9 / 14.9	8.2 / 7.7

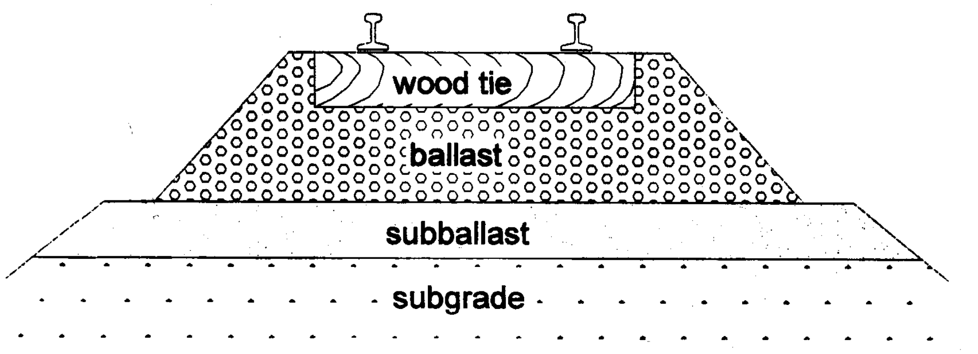


FIGURE 1a. Typical All-Granular Ballast Trackbed.

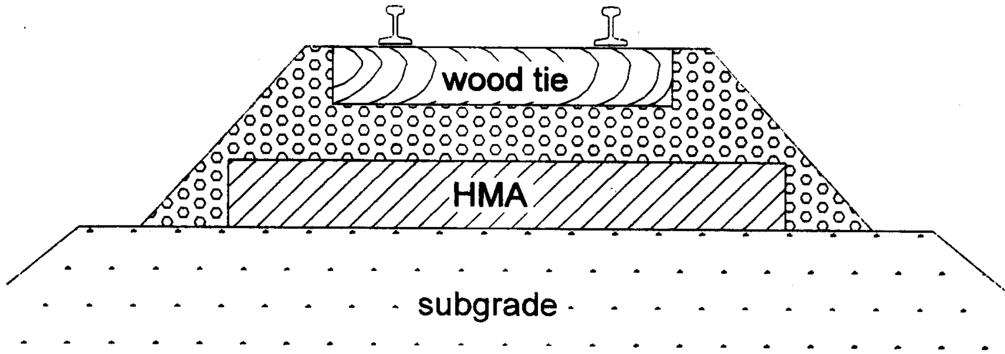


FIGURE 1b. Typical Hot Mixed Asphalt (Underlayment) Trackbed.

FIGURE 2a. Placing an HMA Underlayment on Subgrade during the Construction of a Second Track Next to an Existing Ballast Track.

FIGURE 2b. Exposed HMA Underlayment in Trackbed with Ballast and Wood Tie Track.

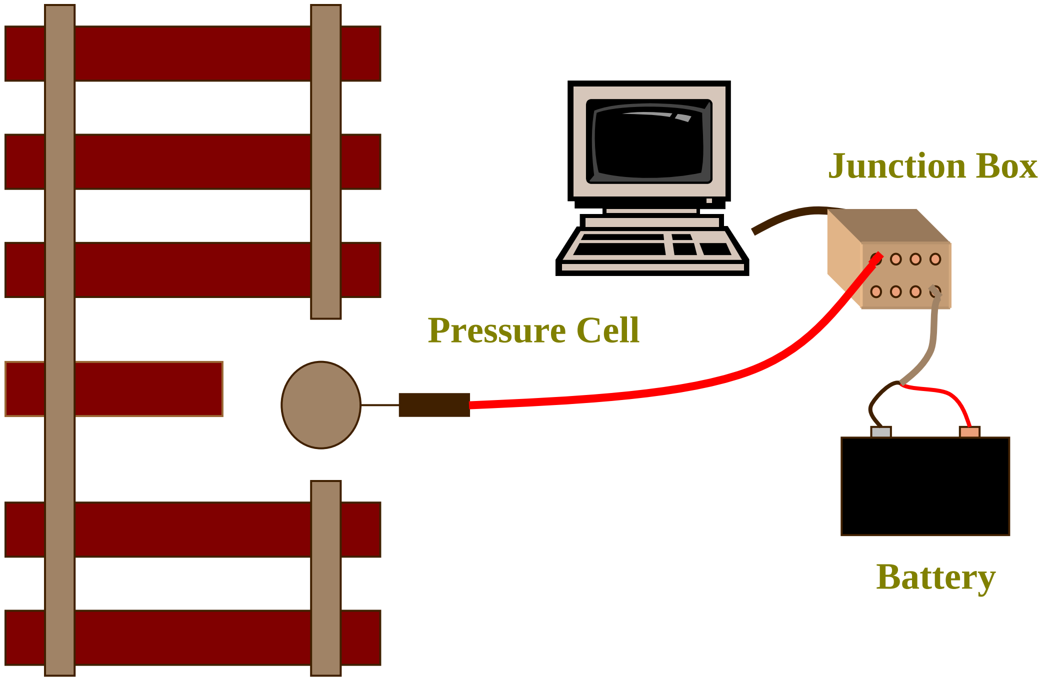


FIGURE 3a. Pressure Cell Measurement Configuration.

FIGURE 3b. In-track View of Pressure Cell Testing.

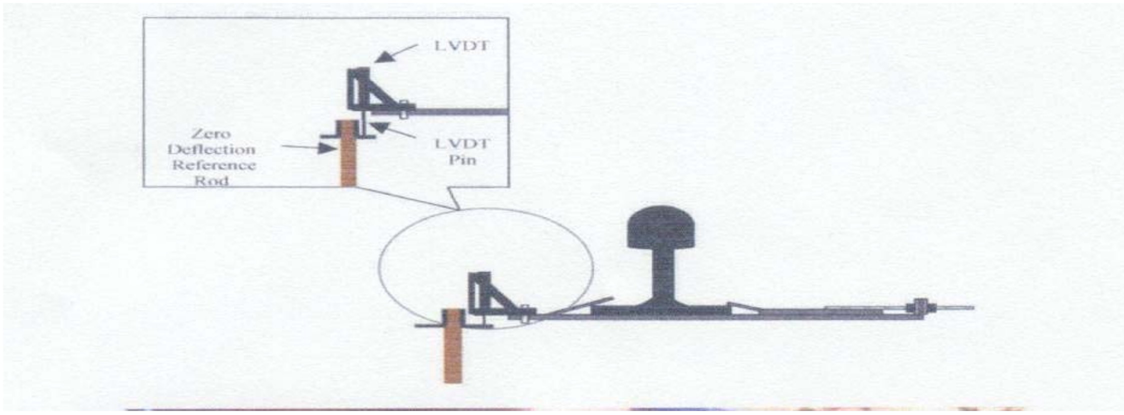


FIGURE 4a. LVDT Measurement Configuration.

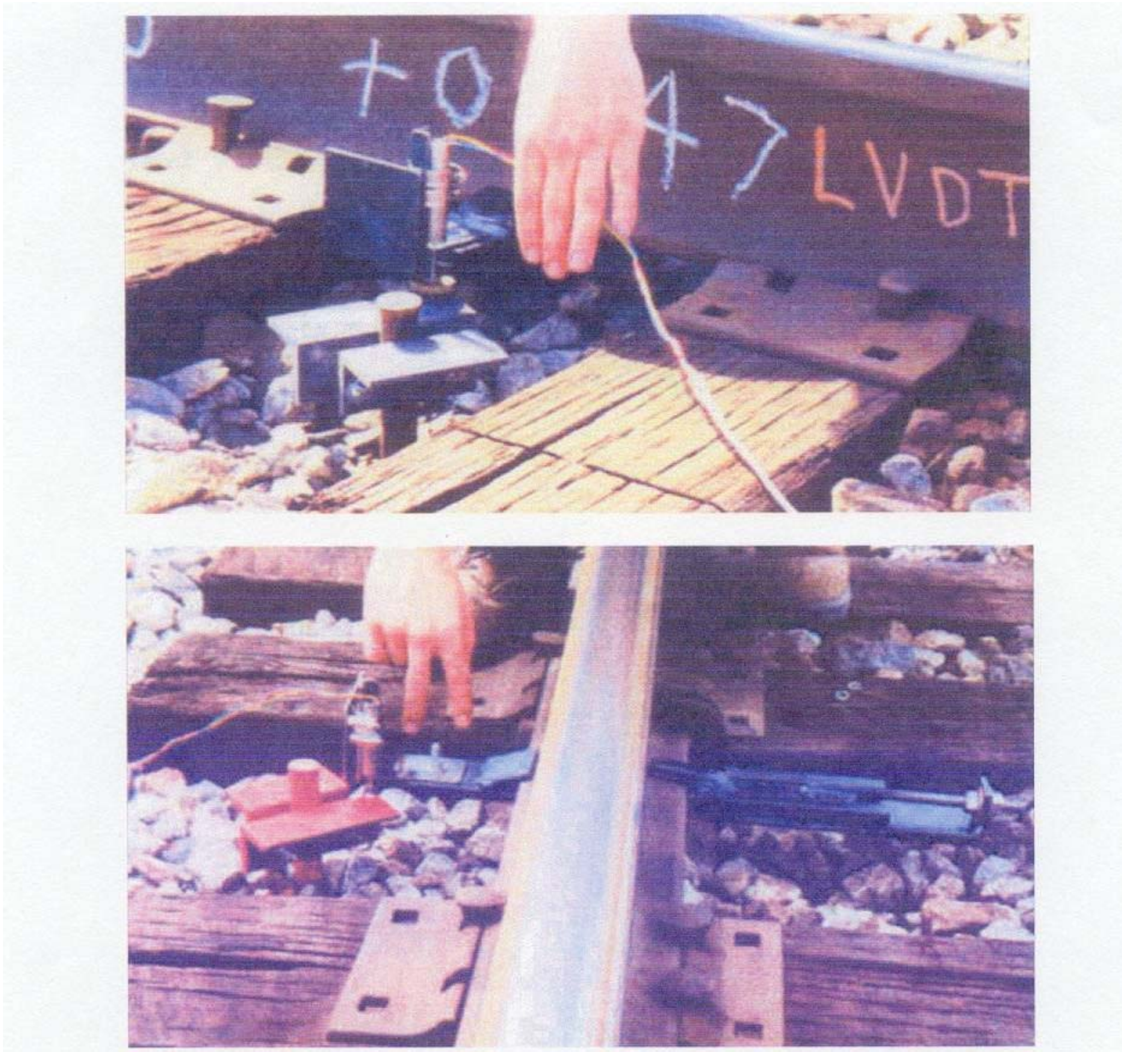
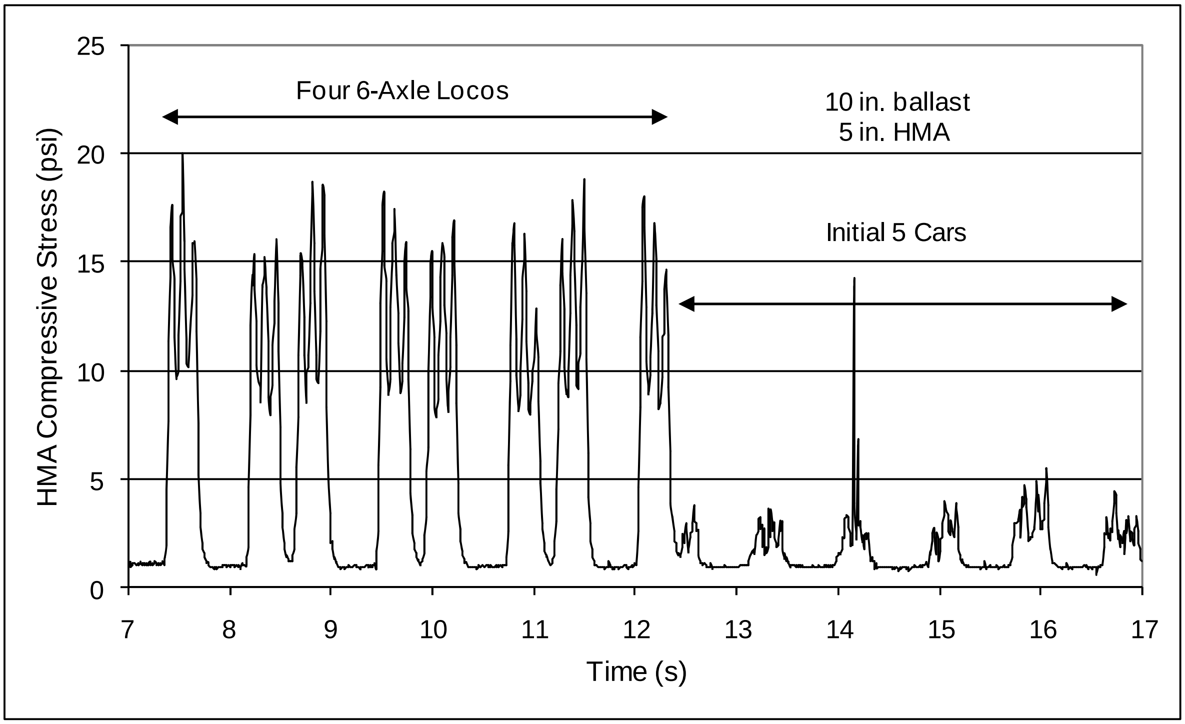


FIGURE 4b. In-track View of LVDT Deflection Testing.



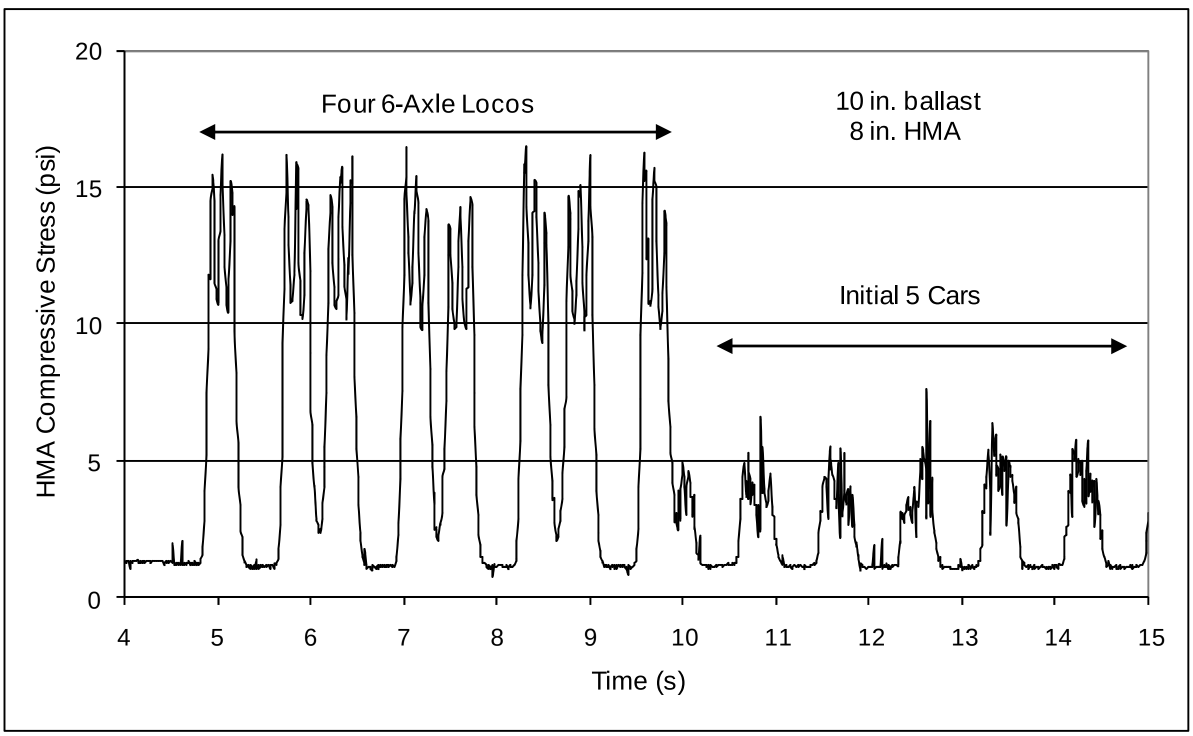


Figure 5. Representative Dynamic Compressive Stress on HMA Layer Measured for Empty Coal Train on CSXT Mainline at Conway, KY. (10 psi = 69 kPa and 1 in. = 25.4 mm)

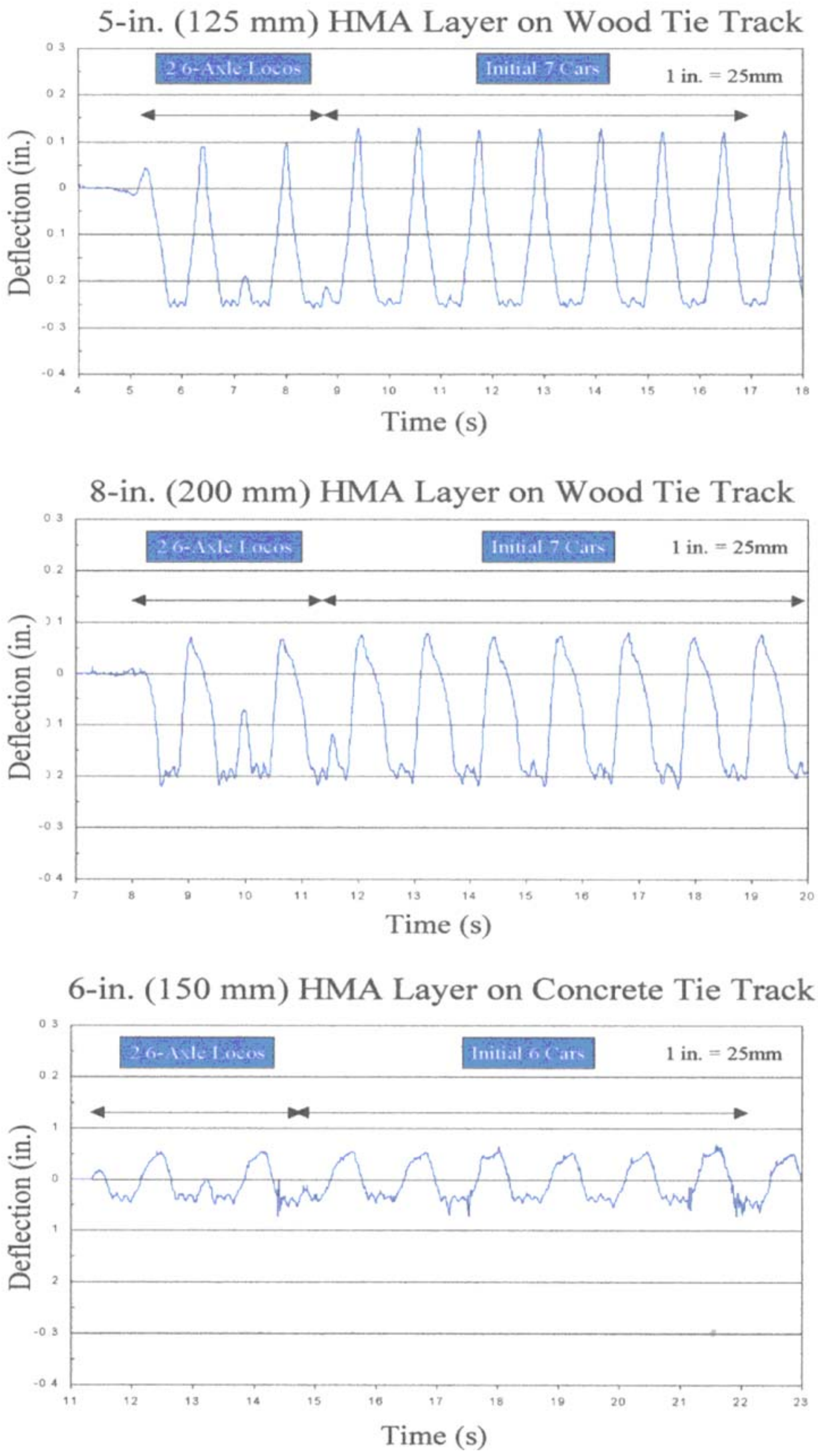
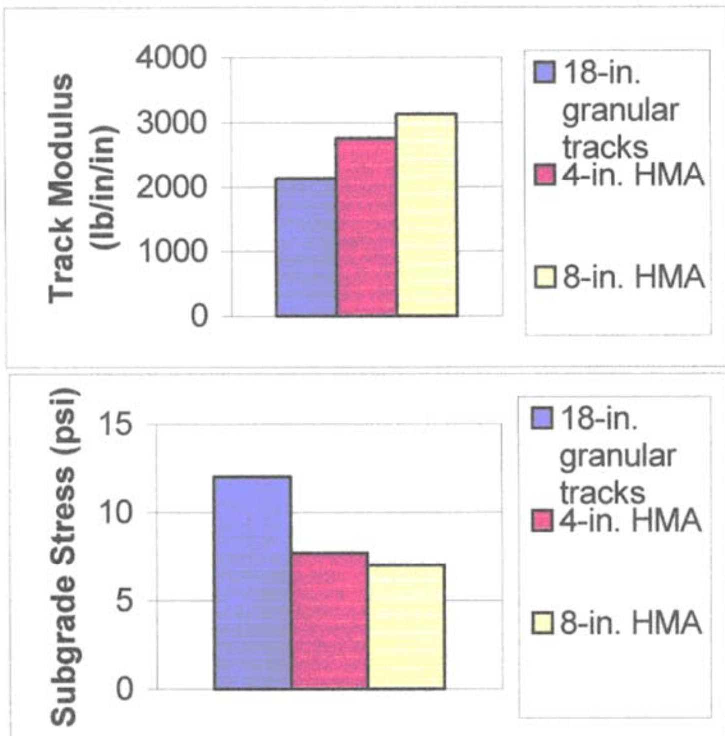


FIGURE 6. Representative Deflections Under Loaded Coal Train.



1 in = 25 mm
1000 lb/in/in = 6.89 MPa

1 in = 25 mm
10 psi = 69 kPa

FIGURE 7. Test Results for Track Modulus (Consolidated Ballast) and Subgrade Stress Under 20 ton (18 metric ton) Static Wheel Load.

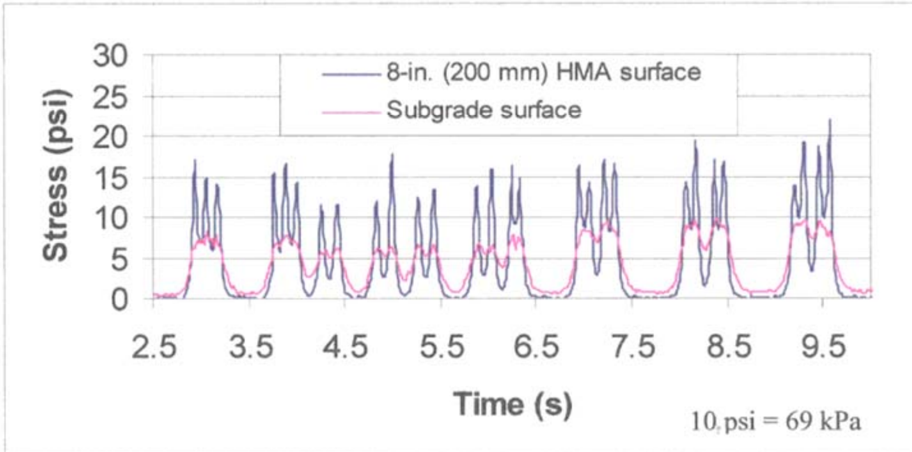


FIGURE 8. Reduction of Dynamic Stresses from 8-in. (200 mm) HMA Surface to Subgrade Surface Under 39 ton (35 metric ton) Axle Cars.

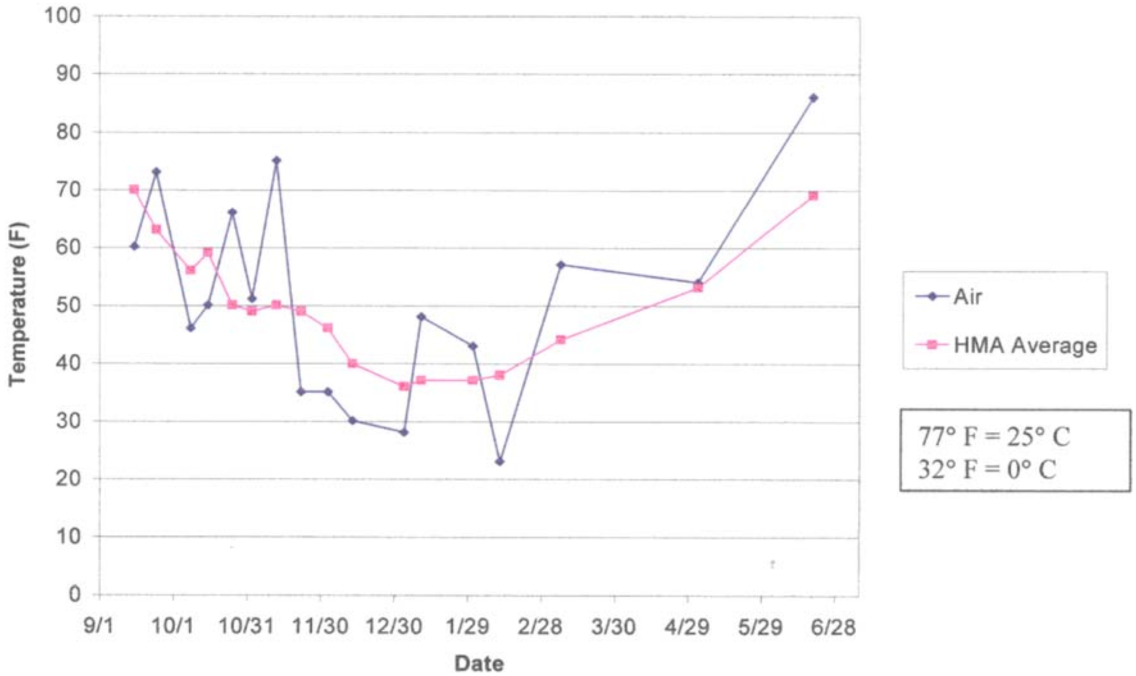


FIGURE 9. HMA Temperature Versus Air Temperature.

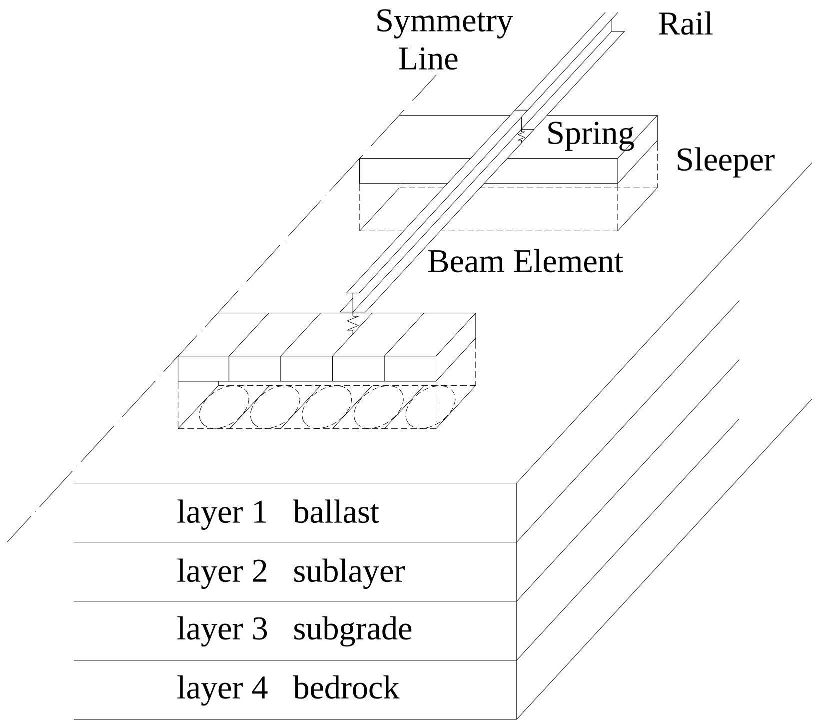


FIGURE 10. Railroad Track Model.