Hot-Mix Asphalt Railroad Trackbeds

YANG H. HUANG, JERRY G. ROSE, AND CHARLES J. KHOURY

Since 1981 about 30 experimental sections of hot-mix asphalt trackbeds have been built and evaluated. The hot-mix asphalt can be used either as an overlay placed directly under the tie or as an underlay placed under the ballast. Because of the similarity between highway pavements and railroad trackbeds, the concept developed for the design of highway pavements is investigated and extended to the design of hot-mix asphalt trackbeds. The design is based on two criteria: limiting the horizontal tensile strain at the bottom of the hot-mix asphalt to prevent fatigue cracking and limiting the vertical compressive stress on the top of the subgrade to reduce permanent deformation. The use of vertical compressive stress, instead of vertical compressive strain, is a deviation from highway practice that is found to be more applicable to railroad trackbeds. A computer program based on the finite element method and Burmister's layered theory was developed for the design and analysis of asphalt trackbeds. The results of analysis show that underlays are far superior to overlays from a structural viewpoint. Because of the difference in load distribution, an increase in the thickness of hot-mix asphalt is not as effective in reducing the stresses and strains in railroad trackbeds as it is in highway pavements. In designing underlays, the use of a thin layer of hot-mix asphalt and a thick layer of ballast is recommended. The main function of hot-mix asphalt underlays is to waterproof the subgrade, thus providing consistent load-carrying capability for the trackbed even on subgrades of marginal quality. The hot-mix asphalt mat will separate the ballast from the subgrade, confine the ballast, and eliminate pumping without substantially increasing the stiffness of the trackbed.

Although hot-mix asphalt (HMA) has been used for the construction of highway pavements for more than a century, its use in railroad trackbeds is relatively new and is still in the experimental stage. The first recorded use of hot-mix asphalt for railroad trackbeds in the United States was in 1968 when the Cleveland Transit Authority placed two 1,000-ft (305-m) asphalt test sections on a line extension near the airport *(1)*. The westbound section had 5 in. (127 mm) of hot-mix asphalt, the eastbound 4 in. (102 mm), and the asphalt mats were placed directly on the subgrade and topped with 8 in. (203 mm) of ballast. In 1969 the Santa Fe Railway placed three 700-ft (215-mm) asphalt test sections on a new line to service a coal-mining region in northeastern New Mexico *(2)*. The asphalt mats were 2.5 in. (63 mm), 5 in. (127 mm), and 7.5 in. (190 mm) thick, respectively, and were placed under a 10-in. (254-mm) ballast. In spite of the excellent performance of these experimental sections, little work was done on hot-mix asphalt trackbeds until 1981 when a research project was initiated at the University of Kentucky under the joint financial support of the National Asphalt Pavement Association and the Asphalt Institute. The overall objective of this research is to evaluate and document the technical and economic benefits of railroad trackbeds containing a layer of dense-graded hot-mix asphalt. With the cooperation of several railway companies, approximately 30 different installations of asphalt trackbeds under a variety of traffic, soil, and environmental conditions have been built. A further objective is to use the responses and performances of these test trackbeds to develop a rational method for the design of hot-mix asphalt trackbeds. It is the purpose of this paper to describe the design, construction, and performance of hot-mix asphalt trackbeds with particular emphasis on the design differences between highway pavements and railroad trackbeds.

CONSTRUCTION AND PERFORMANCE

Two methods have been used to incorporate hot-mix asphalt in railroad trackbeds. One method, which is similar to the construction of highway pavements, is to place the hot-mix asphalt on top of the subgrade or above a layer of base course. The ties are then placed directly on the asphalt mat. This type of construction is called full depth if the asphalt mat is built directly on the subgrade or overlay if a layer of granular base is used. The geometry of full depth and overlay is similar to that of highway pavements except that wheel loads are transmitted through rails and ties over a large area on the asphalt mat instead of through tires over small areas. Another method is to place the asphalt mat under the ballast. The asphalt mat actually serves as a subballast. For heavy-tonnage main lines on a poor subgrade, a granular base course or other stabilized materials may be placed between the hot-mix asphalt and the subgrade. This type of construction is called underlay and is preferred by railroad engineers because conventional railroad maintenance procedures can still be applied. Figure 1 shows typical cross sections for hot-mix asphalt trackbeds.

When the asphalt mat is placed on existing trackbeds, the track must be removed and the underlying material excavated to the desired grade. The asphalt mat may be built directly on the subgrade or a new granular base course may be constructed. The upper portion of old trackbeds can also be used as a base course. The asphalt mat is then placed by a standard highway asphalt paver and compacted by a standard roller. The track is then rebuilt or dragged back on the asphalt mat. For the full-depth and overlay sections, cribbing aggregate is spread to fill the space between the ties and to form the shoulders so the ties will not slip on the asphalt mat. For the underlay sections, ballast is spread from railroad cars and the track is raised to accommodate a specified thickness of ballast under the ties. The ballast also fills the crib areas between the ties and provides the shoulders.

The recommended asphalt mix is a slightly modified dense-graded highway mix composed of 1- to 1.5-in. (25- to 38-mm) maximum sized aggregated and AC–10 or AC–20 viscosity-graded asphalt cement. The proportions are slightly different

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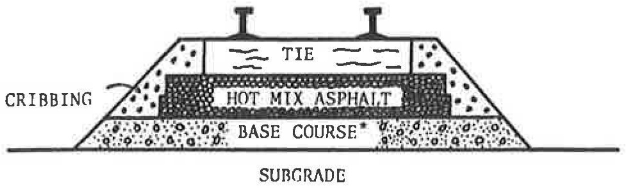
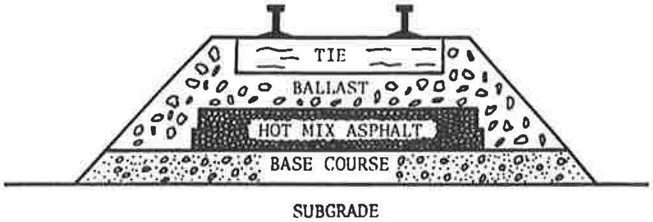
Department of Civil Engineering, University of Kentucky, Lexington, Ky. 40506–0046.



*If no base course is used, the overlay is called full depth

(a) OVERLAYMENT



(b) UNDERLAYMENT

FIGURE 1 Typical cross sections of hot-mix asphalt trackbeds.

from those of typical highway dense-graded base mixes; the mix contains slightly more asphalt cement, more mineral aggregate fines, and lower air voids, which enhance compactibility and impermeability of the mat.

Approximately 30 installations, including numerous highway and railroad crossings, were constructed in Kentucky, Oklahoma, West Virginia, Massachusetts, Indiana, Louisiana, and Missouri. Several significant test tracks have been constructed since 1981 (1 ft = 0.305 m; 1 in. = 25.4 mm):

- Seaboard System Railroad, Ravenna, Kentucky, yard, 1981: two 500-ft-long, 12-ft-wide full-depth sections, one 8 in. thick, the other 12 in. thick, constructed on a curved portion of the main line.
- Santa Fe Railway, Oklahoma City, Flynn yard, 1982: one 532-ft-long, 12-ft-wide, 8-in.-thick underlay section constructed on a curved portion of the trim lead track.
- Santa Fe Railway, Oklahoma City, automobile-unloading yard, 1982: approximately 5 acres of 4-in.-thick underlay section with asphalt-paved driving areas between tracks.
- Seaboard System Railroad, Conway, Kentucky, 1983: two 1,000-ft-long, 12-ft-wide underlay sections, one 5 in. thick, the other 8 in. thick, constructed on the Cincinnati to Knoxville main line.
- Chessie System Railroads, Deepwater, West Virginia, bridge approaches, 1984: two 200-ft-long, 12-ft-wide underlay sections, 4 in. and 8 in. thick, constructed on the Huntington to Hinton main line.

The test installations have been subjected to periodic instrumented tests and measurements to monitor the performances and responses of the track system. Among the periodic measurements are the moisture contents of the subgrade and the old roadbed under the asphalt mat, the temperature distribution within the trackbed, the elevations along the top of the rail, the stiffness or track modulus under static loading conditions, and the determination of geometric parameters by track geometry vehicles.

All installations have exhibited excellent performance. Compared with that of conventional ballasted trackbeds, the moisture content of the subgrade or old roadbed directly under the asphalt mat was lower. Moisture contents directly under the asphalt mats were near optimum for maximum density and varied only slightly from as-constructed conditions. This waterproofing effect will provide consistent load-carrying capability of the subgrade, even on subgrades of marginal quality, and prevent the intrusion of subgrade soils into the ballast with subsequent fouling and pumping. The temperature fluctuations in the asphalt mat were minimal because of the insulative and temperature attenuative characteristics of the overlying ballast and cribbing aggregate. For the overlay at Ravenna yard, the maximum temperature of the asphalt mat was 35°F (1.7°C) in the winter and 80°F (26.7°C) in the summer; for the underlay at Conway, the temperature ranged from 36°F (2°C) to 79°F (26°C). The absence of extreme temperatures, such as are experienced in highway pavements, will increase fatigue life during the winter and decrease permanent deformation during the summer. It was found that no significant changes in elevation occurred, even after several years of heavy traffic on old roadbeds, which had previously exhibited frequent settlements due to soft roadbeds and pumping. The deflections and track moduli of underlays were near optimum (i.e., slightly resilient and not overly stiff) and could be maintained for a longer period of time and be less affected by variations in rainfall and other environmental conditions than are typical ballasted tracks. Track geometry tests indicated that no detectable changes in geometric parameters had ever occurred.

Asphalt cores were obtained from the Cleveland and New Mexico installations constructed during the late 1960s. Viscosity and penetration tests on the recovered asphalt indicated no hardening of the asphalt cement and no deterioration of the mixtures under the insulated environment. Because asphalt retains its resilient characteristics for a long period of time, there is a significantly reduced tendency for the asphalt mat to become brittle and cracked. This will greatly prolong the structural life of an asphalt mat in a track structure compared with that revealed by data obtained on highways.

COMPUTER MODELING

A computer program named KENTRACK *(3)* was developed for the structural analysis and design of railroad tracks. Figure 2 shows the various components of the track system to be analyzed. From top to bottom, the track is composed of rails, tie plates, ties, and the layered system. The finite element method was used in the analysis; the rails and ties were considered beam elements and the tie plates spring elements. The load is transmitted from the ties to the layered system through circular areas of equal diameter, thus Burmister's layered theory, so well known in the analysis of highway pavements, can be applied. By simply changing the properties of the layers, the program can be used for conventional ballasted tracks as well as hot-mix asphalt trackbeds. Major responses computed by the program include the deflections of rail, the bending and shear stresses in rail and tie, the contact pressure between tie and layered system, the horizontal tensile stress and strain at the bottom of hot-mix asphalt, and the vertical compressive stress

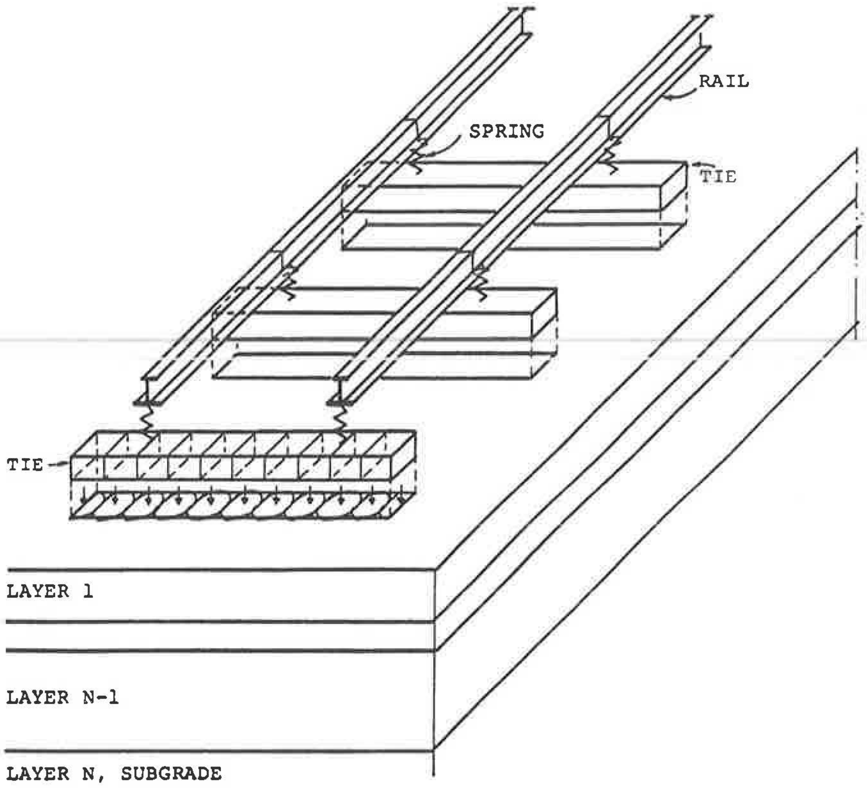


FIGURE 2 Modeling of railroad trackbeds.

and strain on the top of the subgrade. The rails, tie plates, ties, hot-mix asphalt, and subgrade are assumed to be linear elastic and the ballast and other granular layers as nonlinear elastic with an elastic modulus determined by

$$E_g = K_1\theta^{K_2} \tag{1}$$

where

E_g = elastic modulus of ballast or other granular materials,
θ = sum of the three principal stresses due to loading and overburden, and
K_1, K_2 = nonlinear coefficients.

By using the critical stress or strain in the trackbed, damage analysis can be performed by Miner's hypothesis *(4)*. Because the elastic moduli of a layered system, particularly the hot-mix asphalt, vary with the time of the year, each year can be divided into 12 months or a number of seasons for damage analysis. Damage, computed on a monthly or seasonal basis for given traffic and material properties, is accumulated up to a damage ratio of 1.0 using the concept of linear summation of cycle ratios. Two criteria, similar to those used for highway pavements, are proposed for damage analysis: limiting the horizontal tensile strain at the bottom of hot-mix asphalt to prevent fatigue cracking and limiting the vertical compressive stress on the top of the subgrade to reduce permanent deformation. The reason for using the vertical compressive stress, instead of compressive strain, as is done in standard highway practice, will be discussed later.

The purpose of damage analysis is to determine design life. In highway pavements there is only one design life because the hot-mix asphalt must be replaced or overlaid whenever the design life for fatigue cracking or pavement deformation is reached. In railroad trackbeds there are two design lives, one involving the fatigue cracking of hot-mix asphalt and the other involving the permanent deformation of the track. The required design life for fatigue cracking should be much greater than that for permanent deformation because the latter can be corrected by adjusting the ballast or shimming the rails or ties. When permanent deformation has been corrected, the track is considered new and requires further correction only when the new design life for permanent deformation is reached.

To compute the stresses and strains in highway pavements, a program called KENLAYER was also developed. KENLAYER has the same capability as KENTRACK except that wheel loads are applied directly on the layered system through single, dual, or dual-tandem circular areas.

DESIGN CRITERIA

Fatigue cracking and permanent deformation are the two criteria used most frequently for the design of highway pavements. In the Asphalt Institute's design method *(5)*, the allowable number of load repetitions for fatigue cracking (N_c) is related to the horizontal tensile strain at the bottom of hot-mix asphalt (ε_t) by

$$N_c = 0.0795\,\varepsilon_t^{-3.291}\,E_a^{-0.854} \tag{2}$$

where E_a is the elastic modulus of hot-mix asphalt in psi. In the Shell design method *(6)*, the allowable number of load repetitions for permanent deformation (N_d) is related to the vertical compressive strain on the top of subgrade (ε_c) by

$$N_d = 6.15 \times 10^{-7}\ \varepsilon_c^{-4.0} \qquad (3)$$

Equations 2 and 3 are based on long years of experience and the analysis of AASHO Road Test data. The design system is based on the asphalt surface being exposed to the atmosphere, which accelerates oxidation and hardening of the asphalt and shortens fatigue life. Because of the difference in loading conditions, environmental effects, and performance requirements, these equations may not be applicable to the design of railroad trackbeds. However, in the absence of experience in railroad applications, these equations can be used as a guide. They should be modified as more experience is gained. The reason that the Shell criterion for permanent deformation is used, instead of the Asphalt Institute's criterion, is because it allows a greater number of load repetitions and is more compatible with the larger compressive strain under railroad loadings. It is believed that the use of highway failure criteria for the design of railroad trackbeds is quite conservative because the hot-mix asphalt and subgrade are better confined and insulated and should offer greater resistance to fatigue cracking and permanent deformation.

The use of compressive strain, instead of compressive stress, in Equation 3 is a convenient way to eliminate the effect of the stiffness or modulus of the subgrade. However, it has been found that the vertical compressive stress is a much better and more sensitive indicator of structural adequacy, particularly for railroad trackbeds *(7)*. This can also be seen from Table 1 in which the stresses and strains in a 4-in. (102-mm) full depth are compared with those in an overlay composed of a 4-in. (102-mm) hot-mix asphalt on a 4-in. (102-mm) granular base. In the analysis, it is assumed that the hot-mix asphalt has an elastic modulus of 500,000 psi (3.5 GPa) and a Poisson's ratio of 0.45 and that the subgrade has an elastic modulus of 7,500 psi (51.7 MPa) and a Poisson's ratio of 0.40. The granular base is assumed to be nonlinear with K_1 of 7,500 psi and K_2 of 0.5. The highway loading is a standard 18,000-lb (80-kN) single axle load with dual tires that have a contact pressure of 70 psi (482 kPa) and a spacing of 13.5 in. (343 mm) on centers. The railroad loading consists of two 66,000-lb (294-kN) axle loads spaced 70 in. (1.78 m) apart and is applied to RE132 rails on wood ties spaced 20 in. (508 mm) on centers. These are the two axles at the end of one car. Actually, there are two more axles at the end of the adjacent car and these four axles should be grouped as a unit and considered as one load repetition. Because the stresses and strains under the two axles in one car are greater than those under the four axles in two adjoining cars, only two axles were used in the analysis. The consideration of two axles at the end of one car, or four axles on two adjoining cars, as one load repetition is also quite conservative. When a train travels at a high speed, the stress and strain under one group of axle loads is not completely released before the application of the next loads, which results in less destructive effect. The elastic modulus of wood ties is assumed to be 1.5×10^6 psi (10.3 GPa) and the tie plate stiffness is assumed to be 7×10^6 lb/in. (791 N-m/mm). Unless noted otherwise, these parameters and assumptions were used for all the analysis presented in this paper.

Table 1 gives the effect of 4-in. (102-mm) granular base on the stresses and strains in highway pavements and railroad trackbeds. Assuming the stress or strain in a 4-in. (102-mm) full depth with no base as unity, the stress and strain in a 4-in. (102-mm) hot-mix asphalt on a 4-in. (102-mm) base is expressed as a fraction, as indicated by the values in parentheses. It can be seen that the effect of granular base in reducing the horizontal tensile strain is nearly the same as that in reducing the horizontal tensile stress. Therefore it does not make any significant difference whether the horizontal tensile stress or strain is used as a design criterion. However, this is not the case for the vertical compressive stress or strain. For highway pavement, the addition of a 4-in. (102-mm) base reduces the vertical stress to 76 percent but the vertical strain to 92 percent. For railroad trackbed, the vertical stress is reduced to 88 percent but the vertical strain is increased to 106 percent. This clearly indicates that the vertical compressive strain is not a good indicator of structural adequacy because the addition of a 4-in. (102-mm) granular base does not decrease, but actually increases, the compressive strain. The reason for the increase in vertical compressive strain is the decrease in average lateral compressive stress (Table 1).

Based on the AASHTO equation, Equation 3 in terms of

TABLE 1 STRESSES AND STRAINS FOR 4-IN. HOT-MIX ASPHALT WITH AND WITHOUT GRANULAR BASE

Loading	Granular Base	Horizontal Tensile Strain ($\times 10^{-3}$)	Horizontal Tensile Stress (psi)	Vertical Compressive Strain ($\times 10^{-3}$)	Vertical Compressive Stress (psi)	Average Lateral Compressive Stress (psi)
Highway	No base	0.368(1)[a]	285(1)	1.11(1)	11.40(1)	3.78(1)
	4-in. base	0.316(0.86)	244(0.86)	1.02(0.92)	8.72(0.76)	1.30(0.34)
Railroad	No base	0.248(1)	207(1)	1.23(1)	14.77(1)	6.88(1)
	4-in. base	0.224(0.90)	183(0.88)	1.30(1.06)	12.95(0.88)	4.04(0.59)

Note: 1 in. = 25.4 mm, 1 psi = 6.89 kPa.

[a] Values in parentheses are stress and strain in a 4-in. (102-mm) hot-mix asphalt on a 4-in. (102-mm) base if the stress or strain in a 4-in. (102-mm) full depth with no base is assumed to be unity.

TABLE 2 COMPARISON OF HIGHWAY PAVEMENTS AND RAILROAD TRACKBEDS

Type	Loading	Thickness[a] (in.)	Horizontal Tensile Strain ($\times 10^{-3}$)	Horizontal Tensile Stress (psi)	Vertical Compressive Strain ($\times 10^{-3}$)	Vertical Compressive Stress (psi)	Allowable Repetitions: Tensile Strain ($\times 10^6$)	Allowable Repetitions: Compressive Strain ($\times 10^6$)	Allowable Repetitions: Compressive Stress ($\times 10^6$)	Contact Pressure (psi)
Full depth	Highway	4	3.68(1)[b]	285(1)	1.111(1)	11.40(1)	0.22	0.40	0.42	70(1)
		6	2.31(0.628)	179(0.628)	0.653(0.588)	6.43(0.564)	1.00	3.38	3.56	70(1)
		8	1.58(0.429)	122(0.428)	0.430(0.387)	4.18(0.367)	3.50	17.99	17.76	70(1)
		10	1.14(0.310)	90(0.315)	0.308(0.277)	10.24	2.93	68.34	66.93	70(1)
		12	0.87(0.236)	70(0.246)	0.233(0.210)	2.18(0.191)	24.92	208.67	201.89	70(1)
	Railroad	4	2.48(1)	207(1)	1.230(1)	14.77(1)	0.79	0.27	0.16	47.44(1)
		6	2.70(1.089)	224(1.082)	1.130(1.919)	12.84(0.869)	0.56	0.38	0.27	72.57(1.530)
		8	2.62(1.056)	216(1.043)	1.010(0.821)	11.07(0.749)	0.66	0.59	0.47	97.20(2.049)
		10	2.40(0.968)	197(0.951)	0.881(0.716)	9.53(0.645)	0.88	1.02	0.82	118.22(2.492)
		12	2.11(0.851)	173(0.835)	0.762(0.620)	8.19(0.555)	1.35	1.82	1.44	129.05(2.720)
Underlay	Highway	2	1.65(1)	124(1)	0.546(1)	6.05(1)	3.03	6.92	4.47	70(1)
		4	1.55(0.939)	119(0.960)	0.480(0.879)	5.07(0.838)	3.72	11.59	8.64	70(1)
		8	1.19(0.721)	94(0.758)	0.340(0.623)	3.34(0.552)	8.89	46.02	41.04	70(1)
		12	0.87(0.527)	70(0.565)	0.233(0.427)	2.18(0.360)	24.92	208.67	201.89	70(1)
	Railroad	2	1.47(1)	119(1)	0.883(1)	11.25(1)	4.43	1.01	0.44	48.44(1)
		4	1.66(1.129)	134(1.126)	0.870(0.985)	10.72(0.953)	2.97	1.07	0.53	54.24(1.120)
		8	1.93(1.313)	156(1.311)	0.813(0.921)	9.37(0.833)	1.81	1.41	0.87	73.56(1.519)
		12	3.11(1.435)	173(1.454)	0.762(0.863)	8.19(0.728)	1.35	1.82	1.44	129.05(2.664)
Overlay	Highway	0	1.58(1)	122(1)	0.430(1)	4.18(1)	3.50	17.99	17.76	70(1)
		4	1.50(0.949)	116(0.951)	0.415(0.965)	3.54(0.847)	4.15	20.73	33.03	70(1)
		8	1.44(0.911)	110(0.909)	0.365(0.849)	02.96(0.708)	4.75	34.65	64.43	70(1)
		12	1.39(0.880)	106(0.869)	0.313(0.728)	2.46(0.589)	5.33	64.08	128.58	70(1)
	Railroad	0	2.62(1)	216(1)	1.010(1)	11.07(1)	0.66	0.59	0.47	97.20(1)
		4	2.46(0.939)	200(0.926)	1.010(1)	9.89(0.893)	0.81	0.59	0.71	100.77(1.037)
		8	2.34(0.893)	190(0.880)	0.933(0.924)	8.80(0.795)	0.96	0.81	1.10	102.77(1.057)
		12	2.25(0.859)	182(0.843)	0.859(0.850)	7.89(0.713)	1.09	1.13	1.66	104.20(1.072)

Note: 1 in. = 25.4 mm, 1 psi = 6.89 kPa.

[a] Thickness of hot-mix asphalt for full depth and underlay and thickness of granular base for overlay.

[b] Values in parentheses are ratios with respect to the smallest thickness.

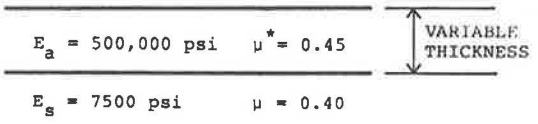
vertical compressive strain (ε_c) was converted to Equation 4 in terms of vertical compressive stress (σ_c) *(3)*:

$$Nd = 4.837 \times 10^{-5} \sigma_c^{-3.734} E_s^{3.583} \quad (4)$$

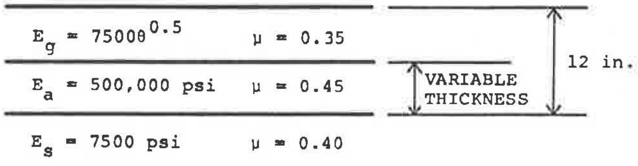
where E_s is the elastic modulus of the subgrade. It should be noted that the conversion was based on full-depth highway pavements. Significant discrepancies between Equations 3 and 4 should be expected when they are applied to railroad trackbeds or highway pavements with granular bases, as will be discussed later.

HIGHWAY PAVEMENTS VERSUS RAILROAD TRACKBEDS

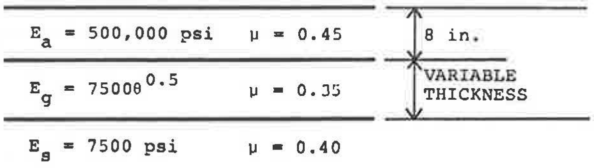
Table 2 gives the critical stresses and strains, the allowable number of load repetitions, and the tire or tie contact pressure for highway pavements and railroad trackbeds. Three types of construction, viz full depth, underlay, and overlay with parameters shown in Figure 3, were investigated. In the full depth, the thickness of hot-mix asphalt varies from 4 to 12 in. (102 to 305 mm). In the underlay, the combined thickness of ballast and hot-mix asphalt is fixed at 12 in. (305 mm) but the thickness of hot-mix asphalt varies. In the overlay, the thickness of hot-mix asphalt is 8 in. (203 mm) but the thickness of granular base varies. Although underlays are not used for highway pavements, they are included in Table 2 to show their behavior under highway loadings versus that under railroad loadings. The loadings used for Table 2 are the same as those for Table 1



(a) FULL DEPTH



(b) UNDERLAY



(c) OVERLAY

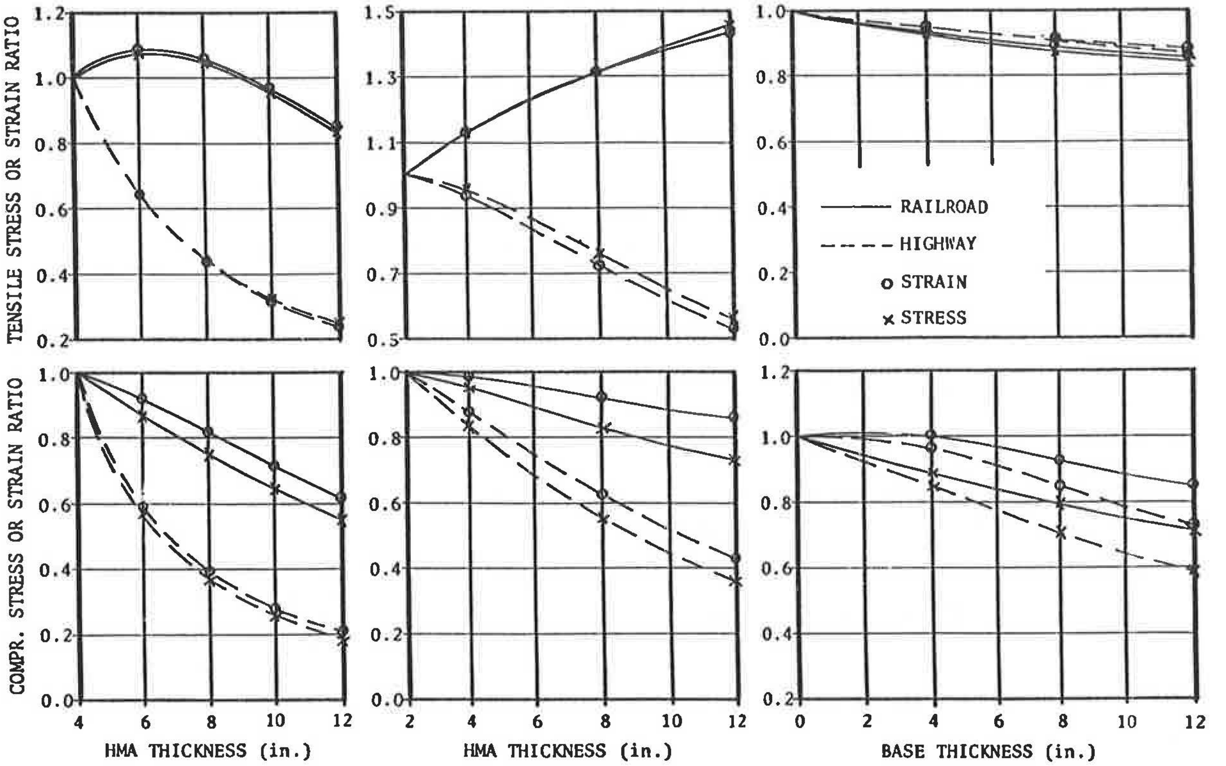
* Poisson's Ratio

FIGURE 3 Parameters of layered system for analysis (1 in. = 25.4 mm, 1 psi = 6.9 kPa).

as described in the previous section. The values shown in parentheses are the ratios with respect to the smallest thickness. These stress or strain ratios are plotted in Figure 4. The allowable number of load repetitions was computed from Equation 2 for horizontal tensile strains, from Equation 3 for vertical compressive strains, and from Equation 4 for vertical compressive stresses. The contact pressure for highway pavements is the tire contact pressure on the layered system, and that for railroad trackbeds is the maximum contact pressure between the tie and the layered system.

Figure 4 shows the effect of hot-mix asphalt or base thickness on the stress or strain ratios. A review of Figure 4 and Table 2 reveals the following:

1. The effect of thickness on the horizontal tensile strain at the bottom of hot-mix asphalt is nearly the same as that on the horizontal tensile stress, as indicated by the close proximity of the two curves. Therefore either tensile strain or tensile stress can be used as a design criterion for fatigue cracking. Following highway practice, the use of tensile strain is recommended for railroad trackbeds.
2. An increase in the thickness of hot-mix asphalt decreases the tensile strain in highway pavements but not necessarily in railroad trackbeds. For railroad underlays with a given combined thickness of ballast and hot-mix asphalt, the tensile strain increases as the thickness of hot-mix asphalt increases, which indicates that the use of ballast is more effective than the use of hot-mix asphalt in reducing tensile strains. That the replacement of ballast by hot-mix asphalt increases the tensile strain is due to the load concentration as indicated by the tremendous increase in contact pressure near the wheel load caused by the stiffer trackbed.
3. The use of full-depth construction is effective in reducing the tensile strain in highway pavements but not in railroad trackbeds. However, the use of a thicker base course is slightly more effective in reducing the tensile strain in railroad trackbeds than in highway pavements, which indicates the importance of foundation support in railroad trackbeds to reduce tensile strains. Therefore the use of full depth is not recommended for railroad trackbeds unless a good foundation exists.
4. The effect of thickness on the vertical compressive strain at the top of the subgrade is different from that on the vertical compressive stress, particularly for railroad trackbeds, as indicated by the large spacing between the two curves. Therefore designs based on compressive strain are expected to be different from those based on compressive stress. Because compressive stress is more sensitive to changes in thickness, it is recommended for use in the design of railroad trackbeds.
5. An increase in the thickness of hot-mix asphalt or granular base decreases the vertical compressive stress on the top of the subgrade. However, the decrease is much greater in highway pavements than in railroad trackbeds. This is as expected because highway loadings are distributed through tires over small areas, whereas railroad loadings are distributed through rails and ties over a large area.
6. Except for full-depth highway pavements, the allowable number of load repetitions for permanent deformation based on compressive stress is quite different from that based on compressive strain. The close agreement in the full-depth highway pavements is as expected because the conversion from Equa-



(a) FULL DEPTH (b) UNDERLAYM (c) OVERLAY

FIGURE 4 Effect of layer thickness on stress or strain ratios (1 in. = 25.4 mm).

tion 3 to Equation 4 was based on full-depth highway pavements *(3)*. This clearly indicates the inadequacy of applying highway criteria to railroad design. The highway criteria should only be used as a guide and should be revised later to meet railroad requirements. It is worthy of note that, for cases of full depth and underlay, the use of compressive stress results in a small number of allowable repetitions and is therefore on the safe side.

7. For railroad underlays with a given combined thickness of ballast and hot-mix asphalt, the vertical compressive stress decreases with an increase in the thickness of hot-mix asphalt, which indicates that the use of hot-mix asphalt is more effective than the use of ballast in reducing compressive stress. This is in contrast to horizontal tensile strain that increases with an increase in the thickness of hot-mix asphalt. The increase in tensile strain is due to the combined effect of larger contact pressures near the wheel loads, which result in greater positive moments, and smaller contact pressures away from the loads, which result in smaller negative moments. The net effect is a tremendous increase in bending moments, which overshadows the effect of increase in the thickness of hot-mix asphalt.

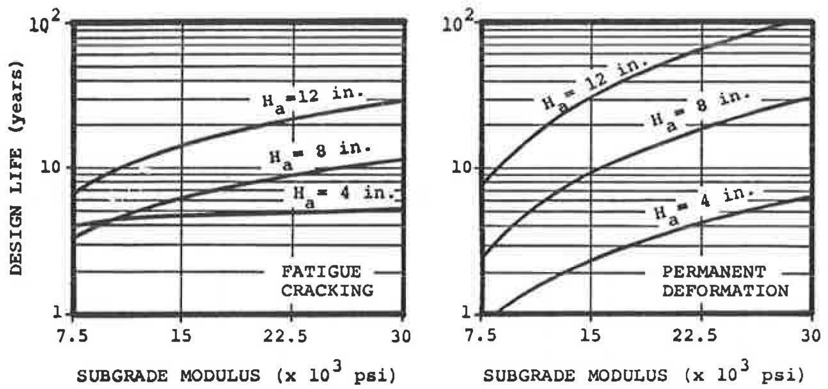
The allowable number of load repetitions shown in Table 2 is based on highway criteria. The application of Equations 2 and 4 to Cleveland and New Mexico test sections constructed during the late 1960s indicates that the former has a design life of 384 years for fatigue cracking and 172 years for permanent deformation and that the latter has design lives of 116 and 62 years, respectively *(8)*. The long design life at Cleveland is due to small wheel loads and light traffic, whereas that at New Mexico is due to an excellent subgrade and light traffic. Because neither installation has reached its design life, there is no way to check the validity of the criteria.

A heavy-tonnage main line may carry more than 26 million gross tons of equivalent fully loaded cars per year. Considering the passage of one car as one repetition and that each car weighs 132 gross tons, the number of load repetitions is 200,000 per year. Comparing this number with those shown in Table 2 indicates that most of the hot-mix asphalt trackbeds could last no more than a few years. Therefore the applicability of the highway criteria and the ability of hot-mix asphalt trackbeds to carry heavy-duty railroad traffic need further investigation.

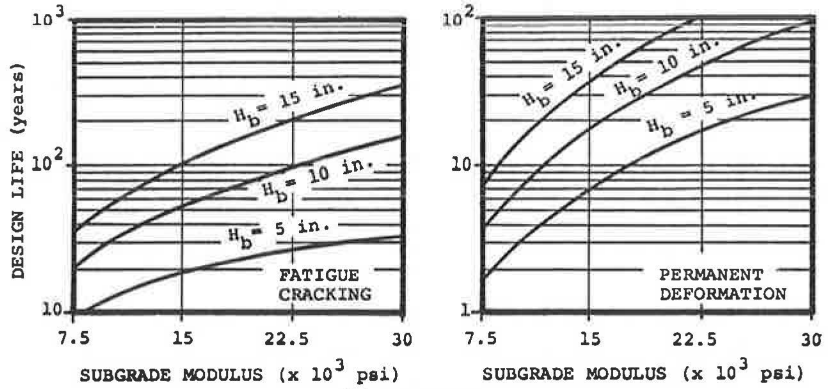
DESIGN FOR HEAVY TRAFFIC

Using the loadings, material properties, and highway failure criteria described before and assuming load repetitions of 200,000 per year, the design lives, or allowable number of load repetitions, for fatigue cracking and permanent deformation of both full depth and underlay with subgrade moduli ranging from 7,500 to 30,000 psi (51.7 to 207 MPa) were determined by KENTRACK and plotted in Figure 5. For underlays, the thickness of hot-mix asphalt is 4 in. (102 mm) but the thickness of ballast varies from 5 to 15 in. (127 to 381 mm).

It can be seen from Figure 5*a* that unless a hot-mix asphalt mat more than 12 in. (305 mm) thick is built on an excellent



(a) FULL DEPTH



(b) UNDERLAY

FIGURE 5 Design life of hot-mix asphalt trackbeds (1 in. = 25.4 mm, 1 psi = 6.9 kPa).

TABLE 3 COMPARISON OF UNDERLAYS AND CONVENTIONAL TRACKBEDS

Modulus of Subgrade, psi			3,000	7,500	15,000	30,000
Conventional		σ_c, psi	8.2	11.1	14.1	16.7
		N_d	5.38×10^4	4.63×10^5	2.27×10^6	1.45×10^7
Modulus of Hot-Mix Asphalt 10^3 psi	200	σ_c, psi	8.2	11.4	14.7	18.9
		N_d	5.38×10^4	4.19×10^5	1.94×10^6	9.12×10^6
	500	σ_c, psi	7.8	10.6	13.7	17.5
		N_d	6.49×10^4	5.50×10^5	2.53×10^6	1.22×10^7
	1000	σ_c, psi	7.4	10.1	12.7	16.1
		N_d	7.90×10^4	6.59×10^5	3.36×10^6	1.66×10^7

Note: 1 psi = 6.89 kPa, σ_c = vertical compressive stress on the top of subgrade, N_d = allowable number of repetitions for permanent deformation

subgrade with a modulus of 30,000 psi (207 MPa), there is no way for the full-depth trackbed to achieve a fatigue life of 30 years as recommended for fatigue cracking. The same is true for overlays unless the subgrade is greatly improved by soil stabilization or by incorporating a thick layer of granular base. The shorter fatigue life for the 8-in. (203-mm) full depth on a weak subgrade, compared with the 4-in. (102-mm) full depth, is due to the load concentration caused by the stiffer trackbed. If the track can be shimmed to adjust elevations, there should be no difficulty in achieving a design life of 5 years as recommended for permanent deformations. If the track cannot be shimmed and the design life for permanent deformation should also be 30 years, the required design life will be more difficult to obtain. Because of the high tensile strain at the bottom of hot-mix asphalt and the inapplicability of existing railroad maintenance procedures, the use of full depth and overlay for heavy-haul trackbeds is not recommended.

Figure 5*b* shows that even underlays with a 4-in. (102-mm) hot-mix asphalt can still be made to achieve a fatigue life of 30 years by simply increasing the thickness of ballast. Also there is no difficulty in achieving a design life of 5 years for permanent deformation. The use of 5 years for design life is reasonable because any permanent deformations can be easily corrected by adjusting the ballast during routine maintenance.

It can be seen that, from both the design and maintenance viewpoints, an underlay is far superior to an overlay because the required hot-mix asphalt is much thinner and the existing railroad maintenance method can still be applied.

UNDERLAYS VERSUS CONVENTIONAL TRACKBEDS

Because of the better load-carrying characteristics of hot-mix asphalt, the combined thickness of ballast and hot-mix asphalt in an underlay should be smaller than that of ballast and subballast in a conventional trackbed. It was found that a conventional trackbed with 8-in. (203-mm) ballast and 6-in. (152-mm) subballast is initially equivalent to an underlay with 8-in. (203-mm) ballast and 4-in. (102-mm) hot-mix asphalt. This equivalency is based on the vertical compressive stress on the top of the subgrade as given in Table 3. It is assumed that the ballast, subballast, and subgrade in the conventional trackbed remain separated without pumping, a condition difficult to achieve in reality. The compressive stresses were determined by KENTRACK using the geometry and material parameters described previously. The allowable number of load repetitions was computed by Equation 4. Four different moduli of subgrade were used. In the conventional trackbeds, the subballast was considered nonlinear with K_1 = 3,750 psi, K_2 = 0.5, and a Poisson's ratio of 0.35. In the underlays, three different moduli were assumed for the hot-mix asphalt.

It can be seen from Table 3 that the conventional trackbed and the hot-mix asphalt underlay are equivalent because the compressive stress in the conventional trackbed lies between the extreme values shown for the underlay. The comparison is based on the assumption that both systems have the same modulus of subgrade. Because of the waterproofing effect of hot-mix asphalt, the modulus of subgrade in the underlay will be kept intact, while that in the conventional trackbed will be lowered as the moisture content increases. If the modulus of subgrade is reduced from 7,500 psi (5.17 MPa) to 3,000 psi (20.7 MPa), the compressive stress in the conventional trackbed will be reduced from 11.1 to 8.2 psi (77 to 57 kPa) but the allowable number of load repetitions will be reduced from 463,000 to 53,800. In this case the design life of an underlay with 8-in. (203-mm) ballast and 4-in. (102-mm) hot-mix asphalt is more than eight times greater than that of a conventional trackbed with 8-in. (203-mm) ballast and 6-in. (152-mm) subballast.

CONCLUSIONS

The design, construction, and performance of hot-mix asphalt railroad trackbeds are presented. The excellent performance of some 30 experimental sections constructed so far has offered the railroad industry a timely and viable option for reducing trackbed maintenance costs and improving train operating efficiency. On the basis of the critical stresses and strains in highway pavements and railroad trackbeds and the application of highway failure criteria, the following general conclusions can be drawn:

1. Similar to highway pavements, the design of hot-mix asphalt trackbeds should consider both fatigue cracking and permanent deformation. The fatigue cracking can be based on the horizontal tensile strain at the bottom of hot-mix asphalt, but the permanent deformation should be based on the vertical compressive stress on the top of the subgrade.

2. In the design of railroad trackbeds, there are two separate design lives: one that requires the replacement or rehabilitation of hot-mix asphalt that has suffered fatigue cracking and another that requires the adjustment of track that has experienced permanent deformation. In the design of highway pavements, there is only one design life because both fatigue cracking and permanent deformation occur in the hot-mix asphalt and whichever has a lesser life controls the design.

3. Because of the differences in loading conditions, environmental effects, and performance requirements, the failure criteria for highway pavements may not be applicable to railroad trackbeds. Given the lack of railroad data, highway criteria can only be used as a guide and should be revised as more experience is gained. The analysis by KENTRACK shows that underlays can be designed economically to satisfy the highway failure criteria. It is believed that the use of highway failure criteria is quite conservative because the hot-mix asphalt and subgrade in a railroad trackbed are better confined and insulated and the railroad loadings are repeated at shorter intervals.

4. Increasing the thickness of hot-mix asphalt is not as effective in reducing the critical stress and strain in railroad trackbeds as in highway pavements. The requirement of a very thick hot-mix asphalt to reduce the horizontal tensile strain makes it uneconomical to use full depth or overlays for heavy-haul trackbeds.

5. A direct comparison of predicted design life for conventional trackbeds and asphalt trackbeds must consider the effect of lowering, over time, of the subgrade modulus of the conventional trackbed, which is caused by the increased moisture content of the subgrade. Also, as the subgrade mixes with the ballast, the ballast modulus is decreased substantially. These effects decrease the number of allowable load repetitions for conventional trackbeds. Because the asphalt layer separates the ballast from the subgrade and provides a drier subgrade, optimum subgrade and ballast qualities will be maintained.

6. From both design and maintenance viewpoints, underlays are far superior to overlays. Both failure criteria can be easily satisfied by increasing the thickness of ballast.

7. In designing underlays, the use of a thick layer of hot-mix asphalt is not warranted. For a given combined thickness of ballast and hot-mix asphalt, the thicker the hot-mix asphalt, the shorter the fatigue life and the greater the contact pressure between tie and ballast. Therefore the use of a thin layer of hot-mix asphalt, say 3 to 4 in. (76 to 102 mm), with a thick layer of ballast, say 8 in. (203 mm) or more, is recommended.

8. The main function of hot-mix asphalt underlays is to waterproof the subgrade and thus provide consistent load-carrying capability for the trackbed even on marginal subgrades. The asphalt mat will confine the ballast and eliminate pumping without substantially increasing the stiffness of the trackbed.

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