# Performance of Hot-Mix-Asphalt Railway Trackbeds

JERRY G. ROSE AND M. J. HENSLEY

Current construction procedures and long-term performance of railroad trackbeds that incorporate a layer of hot-mix asphalt (HMA) as an underlayment or overlayment are highlighted. Both techniques are applicable for new construction or rehabilitation of existing trackbeds. Specifically addressed herein are the following: (*a*) optimum HMA mixture design guidelines, (*b*) long-term HMA mixture characterization in the trackbed environment, (*c*) typical construction and rehabilitation procedures, (*d*) documented performances of selected installations, (*e*) economic benefits and comparisons with conventional designs, (*f*) structural design standards, and (*g*) discussion of the inferred advantages and relative applicability of HMA trackbeds. HMA trackbeds, which currently number in the hundreds in this country, are performing extremely well under widely varying traffic, roadbed and environmental conditions. The initial economics of using HMA is attractive, and indications are that the long-term savings in maintenance and operating costs can be substantial when compared with conventional construction and rehabilitation techniques. It is anticipated that the use of HMA trackbeds will increase in this country and throughout the world during the coming years as railroads resume a greater role in the transportation system. This will require the highest quality trackbeds for efficient and economical operations of intercity freight and the expected expansion of inter- and intracity passenger systems.

During 1989, U.S. Class I railroads hauled a record revenue ton-miles of intercity freight. Intermodal loadings also set a new record, and the National Railroad Passenger Corporation (Amtrak), the nation's intercity passenger network, recorded new highs (*1*). Current proposals for high-speed passenger systems to link major cities include new dedicated lines estimated to comprise 66,000 km (41,000 mi). Design and construction of new intracity light rail, including expansion of existing systems, is under way in more than 20 major U.S. cities. Expansion of existing and new construction of yards and terminals to accommodate the increased freight and passenger traffic is expected to increase during the coming years. To accommodate this increased tonnage and patronage, the railroads and transit agencies must develop and maintain quality track systems. It is imperative that such systems have minimum interferences and temporary speed restrictions from maintenance activities.

Efforts in the United States to develop applications of hot-mix asphalt (HMA) as a premium quality integral trackbed material began sporadically during the late 1960s (*2*). Renewed interest began during the early 1980s, and since then, HMA has been applied in hundreds of marginal to poor trackbeds. This construction includes new trackbeds, yards, terminals, and loading facilities. HMA has also been installed as a solution to specific trackbed instability problems. These specific projects have included the rehabilitation of high-maintenance turnouts, crossings, bridge approaches, hump tracks, tunnel floors, highway crossings, and loading facilities where conventional procedures had failed.

Two methods are used to incorporate HMA in trackbeds (Figure 1). The method more widely accepted by the railroad industry is known as HMA underlayment. This method involves placement of an HMA mat directly on new subgrade or reconstructed old roadbed with a layer of ballast placed between the HMA and the ties. This represents little change from normal track construction practices, because the HMA layer merely serves as a subballast in place of a granular subballast. The HMA overlayment method involves placing an HMA mat in a similar manner, except no ballast is used between the HMA mat and ties. Cribbing aggregate is placed between and at the end of the ties to restrain track movement.

The locations of the primary test sites involve a wide range of traffic, roadbed, and climatic conditions across the country. Pertinent data for the projects discussed herein are presented in Table 1.

## DESIGN AND CONSTRUCTION PRACTICES

### Design Options

Structural design options include both HMA underlayment and overlayment. The underlayment serves as a subballast and does not require close grade control because the layer of ballast can be used as a leveling course for the track. The overlayment requires the ties to be placed directly on the HMA, using no ballast. The HMA for this method should be placed within 0.8 mm (0.03 in.) of the profile grade. Smoothness criteria for ties should be of the same general tolerance as the HMA mat. Small knots or humps will be flattened out by the loads because the HMA mat is soft and plastic. When the wood ties are placed directly on the fresh HMA mat and load is applied, there is usually a slight leveling effect. The ties adhere to the fresh HMA mat, therefore it is not necessary to apply a tack coat to the mat.

### Mix Design Criteria

Several types of mixes have been used since the inception of the research in 1968. Using conventional highway mixes, initial test sections were constructed with satisfactory performance. In the early 1980s a low modulus mix (plastic) was

J. G. Rose, University of Kentucky, Lexington, Ky. 40506. M. J. Hensley, Asphalt Institute, No. Little Rock, Ark. 72116.

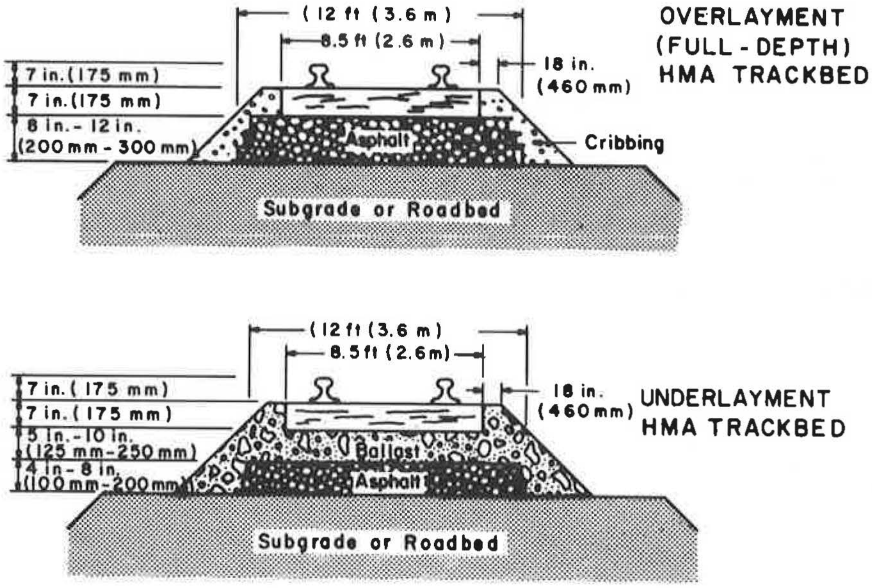


**FIGURE 1 Typical overlayment and underlayment sections.**

used. The Marshall mix properties considered ideal for both underlayment and overlayment are shown in Table 2.

HMA base course mixes have been effective in meeting the above criteria and minimizing the required asphalt content, because of the lower voids in mineral aggregate. The mixture developed specifically for trackbed applications is a slight variation of ASTM D-3515. In areas where this type mix was not available, normal HMA surface course mixes have been used, with good success, by increasing the asphalt cement to achieve the low voids range. A suggested aggregate gradation master range for both underlayment and overlayment mixes is shown in Table 3.

Normal construction practices should be followed to achieve the desired finished product in the asphalt underlayment or

TABLE 1 INSTRUMENTED HMA TEST TRACKBEDS

| Location (Railroad) | Cleveland (RTA) | New Mexico (ATSF) | Ravenna, KY (CSX) | Oklahoma City Flynn Yard (ATSF) | Conway, KY (CSX) |
|---|---|---|---|---|---|
| Type of Facility | High Speed Commuter Transit | Slow Speed Branch Line | Slow Speed Yard Main | Slow Speed Yard Lead | High Speed Mainline |
| Traffic (million gross tons per year) | Passenger (3) | Unit Coal (3) | Unit Coal (8) | Mixed Freight (10) | Unit Coal Intermodal Mixed Freight (40) |
| Year Constructed | 1968 | 1969 | 1981 | 1982 | 1983 |
| Section Length | Two 1000-ft Underlayments | Three 700-ft Underlayments | Two 500-ft Overlayments | One 532-ft Underlayment | Two 1000-ft Underlayments |
| HMA Width | 10 ft | 16 ft | 12 ft | 12 ft | 12 ft |
| HMA Thickness | 5 in. WB<br>4 in. EB | 2 1/2, 5, 7 1/2 in. | 8 & 12 in. | 8 in. | 5 & 8 in. |
| Ballast Thickness | 12 in. | 10 in. | -- | 8 in. | 5 in. |

Note: 1 in. = 25.4 mm, 1 ft = 0.305 m, 1 ton = 0.91 tonne

TABLE 2 MARSHALL MIX DESIGN CRITERIA

| Property | Range |
|---|---|
| Compaction (blows) | 50 |
| Stability, lb. (min.) | 750 |
| Flow, 1/100 in. | 15 - 25 |
| Percent Air Voids | 1 - 3 |
| Percent Voids Filled | 80 - 90 |
| In-place Density | 92 - 98%* |

* Percent of maximum theoretical density based on ASTM D-2041
1 lb = 4.5 N, 1 in. = 25.4 mm

TABLE 3 GRADATION RANGE FOR RAILWAY MIXTURES

| Sieve Size | Percent Passing |
|---|---|
| 1- 1/2 in. (37.5 mm) | 100 |
| 1- in. (25.0 mm) | 90-100 |
| 3/4 in. (19.0 mm) | --- |
| 1/2 in. (12.5 mm) | 70-90 |
| 3/8 in. ( 9.5 mm) | --- |
| No. 4 | 40-65 |
| No. 10 | 25-45 |
| No. 40 | 10-26 |
| No. 80 | 6-18 |
| No. 200 | 3-8 |
| Percent AC-10, 20 or 30* Asphalt Cement | 4-8 |

* Based upon total weight of mixture

overlayment. Resulting compaction of the finished mat should be the normal minimum of 92 percent maximum theoretical, based on the Rice method (ASTM D-2041). Most of the field densities have ranged from 93 to 99 percent in the monitored research work.

### Construction and Rehabilitation Procedures

The majority of the HMA trackbeds placed to date have utilized conventional highway paving construction techniques. For existing trackbeds, the track first must be removed and the underlying material excavated to the desired grade. The HMA mix is hauled by dump truck from a hot-mix plant and is either spread using a standard highway asphalt paver or dumped from the trucks and spread with a dozer blade (only used for short sections). The mix is normally placed in 100-mm (4-in.) lifts, although lifts 150 mm (6 in.) in thickness can be adequately compacted. Compaction is achieved with a standard roller, preferably a steel-wheel vibratory type. It is desirable to obtain a well-compacted mat with minimum air voids.

Immediately after compacting the HMA mat, the track is rebuilt or dragged back on the HMA mat using rubber-tired equipment. After the rails are joined, the ballast or cribbing aggregate is distributed using conventional on-track unloading and spreading equipment. For the underlayment procedure, the track is pulled to provide the specified ballast thickness below the ties. Either No. 24 or No. 4 ballast is generally used. The ballast or cribbing aggregate fills the crib areas between the ties and provides a 0.30- to 0.45-m- (1- to 1.5-ft-) wide shoulder.

Cranes can be used to lift crossing panels, turnouts, and crossovers. Snaking techniques are applicable for longer sections of track. Adequate space must be available to facilitate removal and replacement of the track and provide access for the HMA paving operation.

An HMA underlayment was successfully placed in 1986 under a raised track without removing the rail and ties on the Santa Fe Railway's mainline near Cassoday, Kansas (*3*). The first step involved a single-pass 350-mm (14-in.) undercutting of the trackbed. Three track slewers were used to elevate the track structure 750 mm (30 in.) above the newly cut roadbed. The HMA was delivered by dump trucks to a modified road widener positioned on the adjacent service road. A system of double augers distributed the HMA under the raised track to a strike-off blade and screed. Following was a plate compactor to densify the 150-mm- (6-in.-) thick, 260-m- (850 ft-) long HMA mat. The track was immediately lowered onto the HMA to permit uninterrupted train traffic. Subsequently 200 mm (8 in.) of ballast was added.

### Structural Designs

It is recommended that the HMA mat extend 0.5 to 0.6 m (1.5 to 2.0 ft) beyond the ends of the ties. This normally requires a 3.4- to 3.7-m- (11- to 12-ft-) wide mat on single track installations. The mat will necessarily extend proportionally wider on turnouts, crossovers and other special features of the track.

A rational and practical structural design procedure, KENTRACK, was developed for determining the required thickness of HMA for overlayments and the thicknesses of ballast and HMA for underlayments. The design is based on two failure criteria: to limit the horizontal tensile strain (fatigue) at the bottom of HMA and to limit the vertical compressive stress (permanent deformation) on the top of subgrade.

The thickness of the HMA mat depends primarily on three factors: (*a*) resilient modulus or California bearing ratio of the relative subgrade (or old roadbed) support, (*b*) the amount of train traffic, expressed as the number of million gross tons per year, and (*c*) the climatic region.

By the use of the computer program, charts were developed to determine the horizontal tensile strain and the vertical compressive stress in HMA trackbeds under various combinations of subgrade resilient modulus, HMA modulus, HMA thickness, and ballast thickness, if any. Detailed information on the development and applications of KENTRACK is provided elsewhere (*4–7*).

For the underlayment section, the recommended minimum thickness of ballast is 125 mm (5 in.) so that conventional roadbed maintenance equipment can be used when required for routine track adjustments. The required ballast thickness increases as the traffic level increases and as the subgrade support quality decreases. Typical ballast thicknesses are from 125 to 250 mm (5 to 10 in.). HMA mat thicknesses are from 100 to 200 mm (4 to 8 in).

For the overlayment section, the recommended HMA mat thickness ranges from 150 to 450 mm (6 to 18 in.). Unless the subgrade is classified as good or excellent, it is not feasible to use overlayments and maintain reasonable HMA thicknesses. It may be more economical to improve the subgrade quality before placing the HMA mat. HMA mat thicknesses for the sections under study range from 200 to 300 mm (8 to 12 in.).

## LONG-TERM HMA MIXTURE CHARACTERIZATION

Five projects that had undergone several years of weathering in the trackbed environment were chosen for characterization studies of the HMA. Pertinent data for these projects are presented in Table 1. Mat temperatures were monitored for a year, and HMA cores were periodically taken for laboratory evaluations.

### Temperature Variations

In typical highway applications, HMA undergoes relatively large temperature variations. This affects the properties of the HMA mat, primarily the stiffness. HMA in a trackbed is not exposed to ambient temperature because of the insulating effects of the cribbing and ballast, which attenuate temperature fluctuations in the HMA layer. The range between winter and summer temperatures is reduced; thus the stiffness of the HMA layer remains nearly constant throughout the year. The other factor in aging is low air voids that prevent the flow of air and moisture, which is responsible for most of the aging process. This reduces the potential for cracking in the HMA mat and increases the fatigue life. Typically, the top of an HMA underlayment system is 330 to 480 mm (13 to 19 in.) below the surface, whereas the top of the HMA overlayment lies 180 mm (7 in.) below the surface.

Temperature distributions within the track structure were measured throughout the year with thermistors embedded at various depths at two different sites. Winter measurements were taken after prolonged cold weather and at ambient temperatures near −10°C, (14°F). Summer measurements were taken during August at ambient temperatures approaching 32°C (90°F). Annual temperature measurements for those two projects are presented in Table 4. The underlayment had less temperature fluctuation, as expected, because of the thicker cover. The range in temperature extremes was considerably less than typical for HMA highway applications. Temperature gradients within the HMA layers were minimal, having a maximum value of 2.8°C (5°F ) over the section thickness. No freezing temperatures were recorded within or 100 mm (4 in.) below the HMA layer.

### HMA Core Analyses

HMA cores were extracted from trackbeds and evaluated in the laboratory to determine the aging effects of cribbing and ballast on the HMA trackbed layer. The laboratory evaluations involved extracting and recovering the asphalt cement for viscosity and penetration tests. Dimensions, density, voids, and dynamic modulus values of the compacted cores were also determined.

Extraction test results and asphalt core analyses for four HMA trackbed projects are presented in Table 5. The New Mexico and Cleveland data are of particular interest because these two trackbeds had been in service for about 15 years at the time of testing. The dynamic modulus values averaged about $1.04 \times 10^6$ kN/$^2$ ($1.5 \times 10^5$ psi), which is typical for the more recently placed Conway and Flynn Yard HMA mixes.

Absolute viscosity of the recovered asphalt from the New Mexico cores averaged 1,300 poises at 140°F (60°C), and the standard penetration averaged 72. Some loose chunks of compacted mat lying along the track were also evaluated. They represented a portion of the HMA mat removed during the installation of track scales in 1979, which had been subjected

TABLE 4 ANNUAL TRACKBED TEMPERATURE VARIATIONS

| Location And System | Range From Winter to Summer | |
|---|---|---|
| | Average Within HMA Layer | 100 mm (4 in.) Below HMA |
| Conway, KY Underlayment | 5°C - 23°C (41°F - 74°F) | 7°C - 21°C (44°F - 70°F) |
| Ravenna, KY Overlayment | 2°C - 27°C (35°F - 80°F) | 3°C - 25°C (37°F - 77°F) |

TABLE 5 MIX EXTRACTION TESTS AND CORE ANALYSES FROM HMA TRACKBEDS

| | New Mexico (1969)* | | Cleveland (1968) | Conway, Kentucky (1983) | | | Flynn Yard (1982) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Trackbed Cores After 14 Years | Chunks** | Trackbed Cores After 16 Years | Trackbed Cores After 1 Day | Trackbed Cores After 2 Years | Trackbed Cores After 7 Years | Trackbed Cores After 2 Months | Trackbed Cores After 3 Years | Trackbed Cores After 7 Years |
| Extraction Results | | | | | | | | | |
| Maximum Aggregate Size, in. | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Percent Passing No. 200 Sieve | 9.3-10.1 | 10.3 | 3.7-6.2 | 3.8-5.3 | 4.6-5.9 | 5.1-8.2 | 7.0 | 6.0-6.5 | -- |
| Asphalt, % by Weight of Total Mix | 6.9-7.3 | 6.5 | 4.1-4.2 | 4.8-4.9 | 4.5-4.8 | 4.9-5.5 | 5.7 | 5.5-5.6 | -- |
| Recovered Asphalt Viscosity, 140 F (60 C), P | 1060-1610 | 7525 | 6800-10,540 | 4400-4410 | 6250-14,060 | 5590-24,890 | 3870 | 3490 | 2495 |
| Viscosity, 275 F (135 C), cST | 270-310 | 550 | 610-710 | 530-540 | 610-840 | -- | 580 | 700-730 | 471 |
| Penetration, 77 F (25 C), 100g, 5s | 62-82 | 25 | 35-42 | 49-51 | 28-42 | 25-45 | 50 | 57-58 | 59 |
| Core Analyses | | | | | | | | | |
| Height, in. | 2 5/8-7 5/8 | -- | 4-7 | 4 1/4-8 3/8 | 4 3/4-8 1/2 | 4 1/2-8 1/4 | 6-9 1/4 | 9 1/2-10 1/2 | 8-9 |
| Air Voids, % | 3.1-4.7 | -- | 9.6-15.2 | 7.0-10.1 | 6.9-13.2 | 3.5-10.9 | 0.9-2.7 | 0.9-2.3 | -- |
| Dynamic Modulus, psi x $10^5$ @ 1 hz, 77 F (25 C) | 0.95-1.27 | -- | 1.09-1.79 | 0.84-1.71 | -- | -- | 1.45-1.63 | 1.51 | 1.25-1.75 |
| Density, lb/ft$^3$ | 136-139 | -- | 131-140 | 141-146 | 139-146 | 144-151 | 149-151 | 149-150 | -- |

*Date Constructed
**Loose chunks of discarded HMA picked up along the track, representing part of HMA removed and exposed during installation of scales four years prior.
Note: 1 in. = 25.4 mm, 1 psi = 6.9 kN/m$^2$

to atmospheric weathering for the previous 4 years. The absolute viscosity for the weathered sample was 7,500 poises, and the standard penetration was 25. An 85–100 penetration asphalt was reportedly used in the original construction. Obviously, the HMA hardened little in the trackbed environment; however, once exposed to the atmosphere, it hardened rapidly.

Higher viscosity and lower penetration values were obtained from the Cleveland cores, indicating a harder asphalt cement. This may be partly because of the higher air voids and lower asphalt content in the compacted mat, which would promote faster hardening than the New Mexico mat, which contains lower air voids and higher asphalt content. Also, a harder grade asphalt cement may have been used initially in the Cleveland mix.

Recovered asphalt and dynamic modulus tests on the more recently constructed Flynn Yard installation indicate minimal, if any, hardening or deterioration of the HMA mix after 7 years. The Conway installation was constructed with higher voids, resulting in aging similar to that of the Cleveland section. The higher viscosity on aging has not affected the dynamic modulus range, when compared with the lower viscosities at Flynn Yard. The performance has been equally good.

The ballast at the sites was clean and free of contamination, and the HMA cores were close to design thicknesses. The cores appeared to be in excellent condition, and the dynamic modulus test results confirmed the observations.

On the basis of long-term data, it appears that the insulated trackbed environment reduces weathering and hardening of an HMA mix relative to applications where the mixture is exposed. The reduced levels of oxidation and temperature fluctuations and consistent dynamic modulus values should ensure a long fatigue life for the HMA mat.

## TRACKBED PERFORMANCE TESTING

Several of the HMA trackbeds have been subjected to periodic instrumental tests and measurements. Adjacent control sections employing conventional ballasted track have been evaluated for comparison purposes. The performances of all the HMA sections have been excellent. Following is a summary of the various tests and measurements.

### Trackbed Moisture

Extensive studies have been made at the Flynn and Conway sites to evaluate the long-term waterproofing characteristics of HMA trackbeds. Samples of the roadbed material underlying the HMA mat were obtained after removal of HMA cores, and moisture tests were conducted (see Table 6).

Moisture contents of the compacted fine-grained, (CL, A-6) cohesive red clay soil underlying the HMA mat at the Flynn Yard after 7 years was 13 to 17 percent, slightly lower than the 17 percent prevailing moisture content of the soil during construction. The optimum moisture content for the soil is 18 percent.

TABLE 6 SUBGRADE/ROADBED MOISTURE CONTENTS

| In-Place Moisture Tests (%) After Coring | | | | |
|---|---|---|---|---|
| Year/Location | 1982 | 1985 | 1987 | 1989 |
| Flynn Yard Subgrade | 17.4 avg. (as constructed) | 16.8-18.5 | 15.6-17.7 | 13.1-16.9 |
| Year | 1983 | 1985 | 1990 | |
| Conway Roadbed | >20% (as constructed) | 10.7-23.4 Avg. = 18.4% | 9.8-20.9 Avg. = 13.8% | |

Similar results were obtained from subbase samples taken from the Conway test installations after 2 and 7 years of service. The underlying material is markedly different from that obtained at the Flynn Yard. It is a more granular mixture of fine soil, cinders, coal, and ballast that represents the existing 70-year-old roadbed. At the time the HMA was placed, this material was quite wet, with moisture contents in excess of 20 percent. The high moisture content also was caused by the high absorption qualities of the cinders and coal. After 7 years, the average moisture content was 14 percent, slightly lower than the as-constructed average moisture content.

Piezometers were installed at two locations just under the HMA mat at the Conway test site. Readings were taken periodically under test train and revenue train operations for a 3-year period following construction. No pore water pressures were recorded, indicating pore water pressures were not developing even under 100-car unit coal trains.

These results indicate that an HMA layer overlying either a fine-grained compacted soil or a granular mixture of old roadbed materials will maintain a moisture level in the underlying material. This waterproofing and membrane effect will provide consistent load-carrying capability from the underlying material while preventing intrusion of subgrade into the ballast and subsequent fouling and pumping. These factors are considered to be primary benefits of HMA trackbeds.

### Long-Term Track Settlement

Top-of-rail elevations were established at five test installations soon after construction. Elevation changes along the test sections at 15-m (50-ft) intervals were periodically measured using conventional leveling techniques. No significant changes in elevation occurred, even after several years of service.

In new track construction on fills and embankments, some deep-seated settlements are likely to occur regardless of whether HMA is used. However, if infiltration of surface water is a contributing cause of the settlement, then obviously an HMA layer will reduce this settlement because of its waterproofing characteristics.

### Static Track Modulus

The relative stiffness or rigidity of the track structure under static loading conditions was evaluated using the track modulus procedure. Modulus values were calculated from deflections obtained under known loads using beam on elastic foundation principles. A loaded 91-tonne (100-ton) hopper car was used for the heavy load [approximately 147-kN (33,000-lb) wheel load] and an empty 91-tonne (100-ton) car was used for the light load [approximately 35-kN (8,000-lb) wheel load]. Deflections at the base of rail and tie plate were recorded using linear scales and a transit.

Track modulus values, accumulated to date for the Conway and Flynn Yard underlayment installations, are presented in Table 7. As noted, the values tend to stabilize, after a period of time, at about 17 N/mm/mm (2,500 lb/in./in.), which corresponds to a deflection of 4.6 mm (0.18 in.) under a loaded 91-tonne (100-ton) car on heavy rail and wood ties. These values are within the desirable range for wood tie and heavy rail track to provide the optimum track stiffness and flexibility. Little variation in modulus values for different HMA thicknesses was noted. It is anticipated that HMA trackbeds will maintain an optimum stiffness level for a longer period of time and be less affected by such factors as variations in rainfall and water-table level than the typical ballast track.

### Track Geometry

Establishing and maintaining track geometry is important for safe and efficient train operations. Track geometry vehicles, which continuously record the major track geometric parameters (alignment, gage, surface, and elevation), are routinely used by the railroad industry for periodic monitoring of track conditions. Results identify defects requiring immediate corrective action and provide data for long-term maintenance planning.

Several mainline HMA trackbeds have had track geometry tests conducted at 6-month intervals. No detectable changes in geometry have occurred. This is a significant finding because the sites were specifically chosen on the basis of historically documented high maintenance costs and associated trackbed irregularities caused by poor-quality trackbed support and drainage problems.

## ECONOMIC EVALUATIONS

The widespread use of any new trackbed structure ultimately depends on a favorable comparative analysis of its long-term

TABLE 7 STATIC TRACK MODULUS VALUES

| | Track Modulus lb/in./in. |
|---|---|
| Flynn Yard built Aug. '82 | |
| Oct. '82 | 3500 - 4500 |
| Aug. '83 | 2500 - 3300 |
| June '84 | 2500 - 2900 |
| June '85 | 2200 - 3200 |
| Aug. '87 | 2600 - 3070 |
| June '89 | 2450 - 2800 |
| Conway built June '83 | |
| Nov. '83 | 2170 - 2840 |
| May '84 | 1700 - 2310 |
| Nov. '85 | 2260 - 2560 |

1 N/mm/mm = 150 lb/in./in.

cost effectiveness relative to conventional structures. Even though the new or modified structure may cost more initially, if cost savings accrue from reduced maintenance and increased operating efficiency, the new technology is justified and is a good investment.

The prices typically quoted by HMA paving contractors represent the cost and placement of all materials under the actual conditions. For example, consider an HMA mix that will compact to a density of 2240 kg/m$^3$ (140 lb/ft$^3$) and is placed 100 mm (4 in.) thick and 3.7 m (12 ft) wide. This would require 850 kg per track meter (0.28 tons per track ft). Assuming the in-place cost is $33/tonne ($30/ton), the cost would be $27.50 per track meter ($8.40 per track foot), or $7.50 per square meter ($0.70 per square foot) for the 100-mm (4-in.) lift.

The cost of obtaining and placing HMA in a trackbed varies depending on the following factors: the cost of the HMA in the local area, the length (time) of haul to the site, the size (tonnage) of the project, the availability and cooperation of local contractors, and the ease of delivery access and construction maneuverability. The $33/tonne cost ($30/ton) used in the subsequent example would represent average conditions for a fairly large tonnage project.

The cost comparisons can be viewed from three categories: initial construction, long-term maintenance, and long-term operation.

## Initial Construction Costs

New track construction represents an ideal condition for HMA trackbed installation because a prepared subgrade is available for placing the asphalt mat with conventional paving equipment before placing the ballast, ties, and rail. The cost of the HMA can be partially or totally offset by the elimination of geotextile and the replacement of subballast with a thinner HMA mat. In situations in which the traffic is not heavy and a new roadbed requires costly upgrading, stabilization, or extensive subsurface drainage improvements, it is possible that an HMA trackbed system may even represent a lower initial cost, because it can be satisfactorily placed on low-quality support without extensive roadbed preparation. However, for heavy-haul trackbeds, the subgrade may have to be marginally improved to a certain stiffness, so that the HMA will not fail by fatigue cracking.

Table 8 presents an idealized relative cost comparison of new track construction using conventional ballast-geotextile compared with an HMA underlayment installation. The two installations are considered to be equivalent initially, with regard to quality and load-carrying capability. It is assumed that all grade and drain activities are complete and the subgrade has been finished to final grade.

The new trackbed construction costs are essentially the same for the conventional and HMA sections. The inferred assumption is that a combined 300-mm- (12-in.-) thick HMA-ballast section is equivalent, or superior, to a combined 355-mm (14-in.) subballast-ballast-18-oz (0.60-kg) geotextile section.

## Long-Term Maintenance Costs

Current techniques for rehabilitation of existing trackbeds with HMA require removing the existing track, excavating the fouled ballast-subballast-soil mixture, paving with HMA, and replacing the track. The paving process involves a small percentage of the total effort. However, if rehabilitation of conventional trackbeds can be done without removing the track, the use of HMA is more difficult to justify. Further modifications of paving equipment for efficiently placing HMA under a raised track without removing the track in conjunction with an undercutting or sledding operation would greatly decrease the time and expense.

Table 9 provides an actual cost comparison developed during 1988 on a CSX Transportation mainline for the rehabilitation and renewal of a No. 10 turnout in conjunction with a bridge approach and 90 m (300 ft) of track using conventional ballast-geotextile and ballast-HMA installations. The turnout and underlying material were badly deteriorated and had to be replaced with new materials.

The two costs compare favorably. If the turnout had not required renewal and could have been rehabilitated in place,

TABLE 8 IDEALIZED NEW TRACK CONSTRUCTION COSTS PER TRACK MILE

| Materials/Labor/Equipment | Conventional | HMA Underlayment |
|---|---|---|
| New 136-lb Carbon Rail and Other Track Materials | $231,200 | $231,200 |
| New Wood Ties, 3,017 @ $31.25 | 94,300 | 94,300 |
| 8-in. Ballast (3,500 tons) @ $7.00/ton | 24,500 | 24,500 |
| Surface & Align, 2 lifts | 10,000 | 10,000 |
| 8 Field Welds @ $55 | 440 | 440 |
| 6-in. Subballast,(4,750 tons, 30 ft. wide) @ $8.00 | 38,000 | ---- |
| 18-oz Geotextile @ $2.25/yd$^2$ | 15,840 | ---- |
| 4-in. HMA (1,480 tons, 12 ft wide) @ $30/ton | ---- | 44,400 |
| Engineering/Supervision, 5% of $400,000 | 20,000 | 20,000 |
| Total Cost | $434,280 | $424,840 |

1 lb/yd = 0.5 kg/m, 1 in. = 25.4 mm, 1 oz/yd$^2$ = 34 g/m$^2$, 1 ft = 0.305 m, and 1 ton = 910 kg

TABLE 9 NO. 10 TURNOUT AND 90 m (300 ft) OF TRACK REHABILITATION AND RENEWAL COSTS, 1988

| Items | Conventional (Estimated) | HMA Underlayment (Actual) |
|---|---|---|
| New Turnout (Metal & Ties) | $16,775 | $16,775 |
| Remove Old Turnout, Track & Excavation | 11,310 | 11,310 |
| Replace New Turnout & Track | 5,220 | 5,220 |
| Welds | 570 | 570 |
| Surface & Align | 1,000 | 1,000 |
| 18-oz Geotextile | 900 | --- |
| Ballast & Unloading | (12in.) 10,000 | (8-in.) 8,700 |
| 5-in. HMA 120 tons @ $28/ton | --- | 3,360 |
| Total | $45,775 | $46,935 |

Note: 1 in. = 25.4 mm, 1 oz/sq yd = 34 g/m$^2$, 1 ton = 910 kg

the percentage increase in the combined costs for removing the turnout and using HMA would have increased. However if the service life of the turnout and ballast are substantially increased by using an HMA section, the extra costs of using HMA should be recovered within a short time.

In addition to the cost comparisons for the turnout presented here, similar cost comparisons have been made for railroad crossings, crossovers, ladder tracks, bridge and tunnel approaches, highway crossings, and short sections of regular track. All of these are typically high-maintenance areas, and the material costs are generally small compared with the removal and replacement costs.

According to recent data published by the Association of American Railroads, for Class I railroads, the annual maintenance-of-way expenditures for heavy tonnage tracks exceed $6,200/km ($10,000/mi). This includes normal ballasting, surfacing, renewing ties and rails, and other track maintenance.

As mentioned previously, more than 100 HMA trackbed installations have been built in the United States since 1981. They are being closely monitored by the various railways involved. In addition, 10 or so installations built during the 1960s and 1970s have been evaluated. To date no significant maintenance activity has been required on any of the installations and the relative serviceability of the installations remains excellent.

The advantages of a quality roadbed structure with regard to out-of-face and spot maintenance costs are grouped as follows:

- Decreased ballast applications and surfacing cycles,
- Decreased ballast cleaning and replacement,
- Decreased tie and plate wear,
- Decreased rail and other track materials wear and fatigue, and
- Decreased special trackwork replacements.

The use of HMA trackbeds has not been sufficiently widespread to conclusively produce quantitative data that would support the aforementioned items. However, the favorable test data and results and performance evaluations obtained to date indicate that HMA trackbeds should reduce track maintenance costs.

### Long-Term Operating Costs

Maintaining a quality roadbed structure will reduce operating costs by improving the operating efficiency of train movements. The advantages include:

- Increased speed and safety of operations due to good track geometry,
- Decreased train resistance and fuel consumption,
- Decreased rolling stock wear and repair,
- Increased tonnage ratings for similar motive power,
- Decreased operational interferences from maintenance activities, and
- Decreased number of slow orders and other restrictions.

The HMA trackbeds, which have been subjected to periodic track geometry tests, have not exhibited any degradation of track geometric parameters. Obviously, no slow orders or operational interferences from maintenance activities have occurred because no maintenance has been required.

Track stiffness tests and observed vertical displacements of tracks under moving loads indicate that HMA trackbeds deflect slightly less under load applications and rebound less between track loadings than conventional ballasted trackbeds. The increased stiffness and viscoelastic properties of the HMA account for these facts. The results should be decreased train resistance and fuel consumption, increased tonnage ratings for equivalent motive power, and decreased wear and repair costs for rolling stock.

## SUMMARY AND CONCLUSIONS

### Application Considerations

New line construction and passing track extensions represent ideal application conditions because the exposed subgrade is available for placing the HMA mat with conventional paving equipment before placing the ties and rails. Conventional highway construction procedures are not applicable for paving long sections of in-service single track because sufficient track time normally is not available for removing, excavating, paving, and rebuilding the track. Further modifications and optimization of equipment for placing HMA under a raised track without removing the track, in conjunction with an undercutting or sledding operation, will greatly decrease required track time.

Removing the track and paving short sections of in-service track, turnouts, crossovers, bridge and tunnel approaches, and crossings exhibiting poor soil, bad drainage, or subgrade pumping conditions can be accomplished with minor disruption to traffic. The use of an HMA base under highway crossings can provide an economical means of obtaining adequate support for the combined highway and railroad loadings, thus reducing costly repairs to crossing surfaces. HMA is proving most advantageous in these areas. Where high quality subgrade and adequate drainage conditions exist, the economic benefits of using HMA for reducing annual maintenance cost and improving levels of service are not likely to be as pronounced.

Rapid transit and high-speed passenger lines require substantial track structures to maintain accurate track geometry. Use of HMA in these track structures is appropriate, as evidenced by the Cleveland project. Where light rail lines are placed in-street (i.e., "paved track"), asphalt overlayment design, wherein ties sit directly on a smooth, stable asphalt layer, will reduce or eliminate the need for costly ballast adjustments, which require tearing up the street pavement and taking the street out of service.

The use of HMA is equally adaptable to the construction of intermodal yards. Heavy trucks and unloading equipment require substantial structural sections. A particular advantage is the waterproofing characteristics of the HMA and the positive drainage systems that can be incorporated in the design of the unloading area.

### Findings

1. The primary finding, based on the comparative performance of conventional sections and HMA sections, is that the HMA is superior to all other sections. HMA core samples indicate that the ballast keys into the low modulus mix, thus providing a stable system for tangent and curve sections.
2. The HMA sections have not required reballasting, alignment, or any other track adjustment or periodic maintenance during the 7-year study period. Most of the control sections have required or needed periodic maintenance.
3. The HMA sections have extended the life of the ballast; however, because no reballasting has been required, ultimate ballast life on the HMA system at this time cannot be assigned. It is believed that ballast life will be increased using HMA systems. Severe pumping of the subgrade and ballast wear on conventional systems were the primary causes of the fouled ballast.
4. Subgrade (roadbed) moisture contents under the HMA mat have stabilized during the 7-year study period, at or near the optima, thus providing a uniform subgrade support for the service life of the trackbed.
5. Reduced wear of the track components was noted at heavy tonnage crossings indicating the HMA system can extend the service life.
6. Reduced deflections and constant optimum track stiffness of an HMA trackbed can provide a uniform and high-speed rail system to meet increased service requirements.
7. Properties from recovered asphalt cement from the underlayment systems indicated minimal aging of the asphalt cement when covered with ballast if the recommended low-air-void content is achieved. This should provide the trackbed many years of service without replacement of the mat.
8. Cost analyses indicate that HMA systems can be installed economically at no more than 2 to 7 percent increased initial cost and in some cases less than conventional cost. In most all cases, the HMA system has more than "paid-out" in the study period.
9. Several more years will be needed to properly assess the total life-cycle performance of the HMA system because of its potential long service life.

10. The underlayment procedure appears to have general applicability for heavy-haul freight lines, whereas the overlayment procedure is limited to specific applications. Both procedures appear applicable for passenger and transit lines.

### Conclusions

The primary benefits of the HMA layer are to improve load distribution to the subgrade, waterproof and confine the subgrade, and confine the ballast, thus providing consistent load-carrying capability for a trackbed even on subgrades of marginal quality. The waterproofing effects are particularly important because the impermeable HMA mat essentially eliminates subgrade moisture fluctuations, which effectively improves and maintains the underlying support. Additionally, the resilient HMA mat provides a positive separation of ballast from the subgrade and thereby eliminates subgrade pumping without substantially increasing the stiffness of the trackbed. The resultant stable trackbed has the potential to provide increased operating efficiency and decreased maintenance costs, which should result in long-term economic benefits for the railroad and rail transit industries.

All of the HMA test tracks and specific problem-solving installations are performing extremely well. The increased cost of using HMA is most often minimal, and indications are that at many sites the long-term savings may be substantial when compared with conventional construction, maintenance, and rehabilitation techniques. Additional improvement and optimization of the field construction procedures represent activities of continuing interest.

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