tionship between TQIs and ride quality can be used to determine the timetable speeds for safe shipment of goods. TQIs offer an additional potential use in the quality assurance of discretionary maintenance.

FRA plans to continue this research to develop analytical techniques for maintenance planning. The major emphasis of the future research will be to develop an analytical technique for planning expenditures for basic maintenance.

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Use of Stabilized Layers in Track Structure

MARSHALL R. THOMPSON

Stabilization of soils and granular materials by using various admixtures (lime, cement, lime and fly ash, and bituminous materials) significantly improves pertinent engineering properties. Typical effects are increased strength, increased stiffness, improved durability under adverse conditions such as excess moisture and freezing and thawing, reduced plasticity and swell potential, and improved workability. Stabilized subgrade and subballast layers have been successfully used in track structure for various purposes. The effects of stabilized layers on ballast properties, track structure behavior, and performance are considered. Specific topics considered are (a) alleviation of subgrade intrusion, (b) shear-strength conditions at interface between ballast and subgrade, (c) comparative behavior of track sections with and without stabilized layers, and (d) thickness design concepts (based on analyses that use models such as ILLI-TRACK).

Stabilization of soils and granular materials by using various admixtures (lime, cement, lime and fly ash, and bituminous materials) significantly improves pertinent engineering properties. Typical effects are increased strength, increased stiffness, improved durability, reduced plasticity and swell potential, and improved workability. Current stabilization technology and practices have been well summarized in recent publications (1-11).

Stabilized materials, particularly lime and cement, have been successfully used in track structure for various purposes. Stabilization of in situ soils or imported materials is becoming more common in track construction. In a recent article (12), Newby indicated the potential of admixture stabilization for subgrade stabilization.

In this paper, emphasis is placed on the effect of stabilized layers on track structure behavior and performance. Specific topics considered are (a) alleviation of subgrade intrusion, (b) shear-strength conditions at the interface between ballast and subgrade, (c) comparative behavior of track sections that have stabilized layers and those that do not, and (d) thickness design concepts (based on analyses that use models such as ILLI-TRACK).

SUBGRADE INTRUSION

Many engineering properties of granular materials are adversely affected by an increase in the amount of fines. Shear strength, permeability, resilient moduli, plastic deformation, repeated-loading response, frost-action potential, and ballast-pumping potential are generally detrimentally influenced if fines accumulate in excess of those in the granular material originally placed (13).

Since most in situ subgrade stabilization procedures cement the soil particles together, the probability of subgrade intrusion is greatly reduced, if not eliminated. Even if some intrusion does occur, the fact that most stabilized soils, particularly those that are lime-treated, have substantially reduced plasticity (compared with the plasticity index of the natural soil) minimizes the detrimental effects of any possible intrusion.

A layer of imported stabilized material will also obviously act as effective separation between the subgrade and the layer of granular material.

It is apparent that the positive aggregate-soil separation provided by a stabilized layer will have a significant beneficial effect on track support system behavior and performance.

CONDITIONS AT INTERFACE BETWEEN BALLAST AND SUBGRADE

A stabilized layer in the track structure provides an interface between the ballast and the stabilized material. In a conventional track structure, the interface is between ballast and subgrade soil.

Waters (14), in a study of the behavior of granular ballast on fine-grained subgrades, found that lateral movement of the ballast layer was due to rotation on a thin layer of failing clay at the interface between ballast and subgrade. Coombes (15) also suggested that the condition at the interface between ballast and subgrade is critical and indicated that control of the interface condition helped solve the design problem. Extensive lateral movement of layers of granular material over the subgrade was noted in the flexible pavements at the American Association of State Highway Officials (AASHO) road test (16).

Barenberg's shear-layer theory (17) demonstrates the importance of maintaining a high shear strength in the soil at the interface between the granular material and the subgrade. The theory shows that the loss of shear strength at this interface effects a substantial decrease in load-distribution capability and increases the deflection of the granular layer.

Thompson and Raad (13) used the BISAR elastic-layer computer program to analyze the effect of slippage between a layer of crushed stone and the subgrade layer. Larger surface deflections were obtained when slippage occurred.

This information strongly supports the contention that the maintenance of high shear strength at the interface between the granular material and the support layer is required to ensure good performance of the layers of granular material. The stabilized layer ensures good interface conditions at the bottom of the granular layer. The stabilized layer is moisture resistant and durable, and thus adequate interface shear strength can be maintained even though such adverse climatic conditions as excess moisture or freezing and thawing may prevail.

TRACK STRUCTURE BEHAVIOR

In conventional track structure, ballast and subballast layers are placed over the subgrade. The presence of a stabilized layer of high strength and modulus significantly alters the basic behavior of the track structure.

ILLI-TRACK (18) analyses were conducted of a conventional track section and of the same section with a stabilized layer. Track section input data are summarized below:

1. Rail: 68 kg/m (136 lb/yd); I, 3954 cm^4 (94.9 in^4); E, 207 GPa (30 x 10^6 psi).
2. Ties: timber; width, 20.3 cm (8 in); thickness, 17.8 cm (7 in); length, 2.44 m (8 ft); spacing, 50.8 cm (20 in); compressive modulus, 8.6 MPa (1250 ksi); effective bearing length under each rail, 30 cm (12 in).
3. Ballast: crushed stone, American Railway Engineering Association (AREA) no. 4 gradation; resilient response model, $E_R = 6000\ (\theta)^{0.50}$ (E_R and θ in kPa); $\mu = 0.35$; thickness, 30 cm.
4. Subgrade: $\mu = 0.45$; resilient response curve data (average subgrade) (1 kPa = 0.145 psi; 1 MPa = 145.1 psi):

σ_D (kPa)	E_R (MPa)
0.7	102.1
42.8	55.1
249.6	20.1

5. Wheel loading: magnitude, 133.5 kN (30 000 lb); axle spacing, 178 cm (70 in).

Comparative response data are summarized in Table 1.

The stabilized layer effects (a) a decrease in track deflection, (b) decreases in subgrade stress and subgrade strain, (c) an increase in maximum tie reaction, (d) a substantial increase in the confinement of the granular layer, and (e) a slight reduction in rail bending stress.

Hay (19) has emphasized the importance of track deflection on performance. Lundgren, Martin, and Hay (20) have developed the deflection criteria shown in Figure 1. AREA (21) has proposed a maximum rail deflection of 0.25 in.

Significant reductions in subgrade deviator stress and vertical strain are other beneficial effects of the stabilized layer. As illustrated in Figure 2, lower stress typically relates to a reduction in the accumulation of permanent subgrade deformation. Reduced subgrade strain contributes to lower rates of accumulation of permanent subgrade soil deformation. Both subgrade stress and strain criteria are used in design procedures for flexible pavement.

The implications of increased confinement of the granular layers are significant:

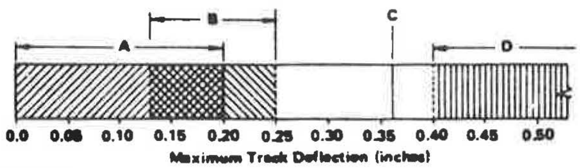
1. The shear strength of granular materials is improved by an increase in confinement.
2. Knutson and Thompson (22) have demonstrated that the resilient modulus (repeated deviator stress divided by recoverable axial strain) of ballast material is stress dependent. This process is shown in Figure 3 [from Knutson and Thompson (22)]. Thus, the equation $E_R = k\theta^n$, where E_R is the resilient modulus, θ is the first stress invariant ($\theta = \sigma_1 + 2\sigma_3$) for triaxial testing, and k, n are experimental parameters derived from triaxial testing data, becomes applicable to both ballast and subballast granular materials. The increased confinement induced by the presence of the stabilized layer contributes to a large increase in resilient modulus. Comparative data for θ and the resilient moduli for the conventional and the stabilized track sections were shown in Table 1.
3. Permanent deformation behavior of ballast under repeated loading is primarily related to the repeated stress state. Knutson and Thompson (23) indicated the importance of increased confinement for minimizing permanent deformation accumulation in the ballast layer. The increased accumulation of permanent deformation at very low levels of confin-

Table 1. Track and ballast response summaries.

	Track Response Summary								Ballast Response Summary	
	Stabilized Layer									
Case	Thickness (cm)	Modulus (GPa)	Maximum Tie Reaction (kN)	Tie Deflection (mm)	Rail Bending Stress (GPa)	Stabilized Material Tensile Stress (kPa)	Subgrade Deviator Stress (kPa)	Subgrade Strain	Avg Resilient Modulus (MPa)	Avg θ (kPa)
A	20	10.3	64.5	2.3	62.4	1054	37.2	8.3×10^{-4}	495	989
B	0	-	46.7	3.0	75.2	-	67.5	14.9×10^{-4}	397	635
C	20	1.7	58.7	2.4	66.6	384	44.8	9.8×10^{-4}	469	885
D	15	10.3	61.4	2.4	64.3	1268	39.3	8.8×10^{-4}	484	943
E	25	10.3	67.2	2.3	60.8	916	35.1	7.3×10^{-4}	502	1017

Notes: 1 cm = 0.39 in; 1 GPa = 145.1 ksi; 1 kN = 225 lbf; 1 mm = 0.039 in; 1 kPa = 0.145 psi; 1 MPa = 145.1 psi.
Thickness of crushed-stone ballast, 30 cm (12 in) for all cases.

Figure 1. Track-deflection criteria.

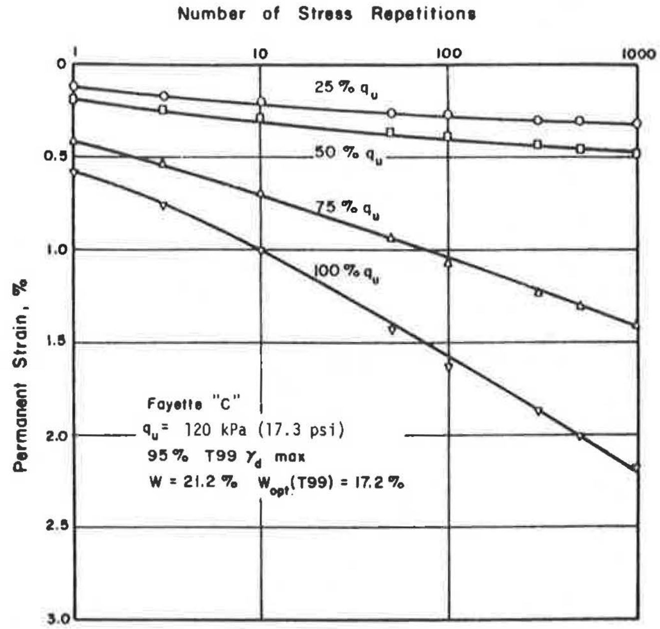


Range	Track Behavior
A	Deflection range for track which will last indefinitely.
B	Normal maximum desirable deflection for heavy track to give requisite combination of flexibility and stiffness.
C	Limit of desirable deflection for track of light construction (< 100lb).
D	Weak or poorly maintained track which will deteriorate quickly.

Values of deflection are exclusive of any looseness or play between rail and plate or plate and tie and represent deflections under load

Note: 1 in = 25.4 mm.

Figure 2. Relation between stress level and permanent strain for Fayette C [AASHTO class A-4(9), unified class ML].



ing pressure (such as those at the bottom of a conventional ballast track section) was noted by Thompson, Hay, and Tayabji (24).

Decreased rail bending stress is indicative of increased fatigue life.

It is apparent that the stabilized layer improves the structural responses (and thus the performance) of the track structure. Although it is not possible to assess the economic benefits of the improved response and performance accurately, in many conditions stabilized layers offer an attractive cost/benefit ratio.

DESIGN FACTORS FOR STABILIZED STRUCTURAL LAYERS

Stabilized materials for use in structural layers must possess adequate strength and durability and be of proper thickness. For layers of stabilized material that have strength and modulus, design thickness is generally controlled by tensile stress considerations at the bottom of the stabilized layer.

Concepts of fatigue and slab-crack propagation should be used to establish an allowable tensile stress for stabilized material. Terrel and others (1) document the fatigue behavior of the more-popular stabilized materials. Repeated excessive tensile stresses will cause premature cracking and breaking of the stabilized layer, thus reducing its effectiveness as a structural layer.

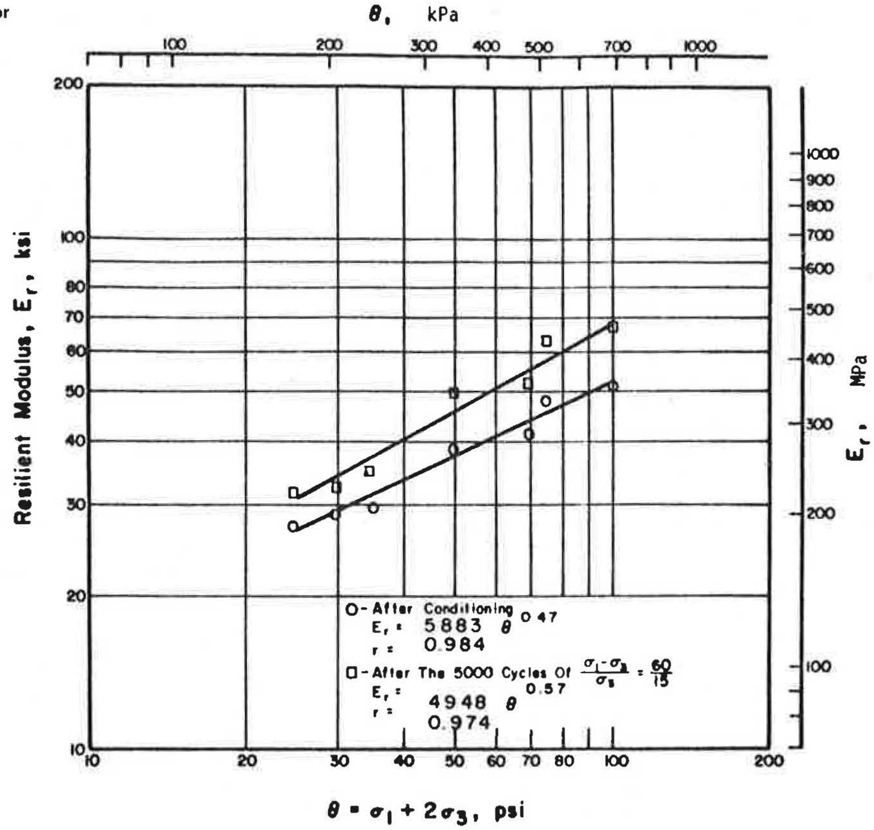
Crack initiation at the bottom of the stabilized layer is not a failure condition. The propagation of the crack to the surface of the stabilized layer requires a significantly larger stress. The large ultimate load-carrying capacity of stabilized layers has been documented (3,25). Recent analytical work by Raad, Monismith, and Mitchell (26) contributes to the mechanistic interpretation of the high load-carrying capacity of stiff stabilized layers.

Ballast thickness, loading conditions, and subgrade support are obvious factors that will influence the required thickness for a given stabilized material of designated quality. Thus a standard-section approach (use the same thickness for all conditions) may be inadequate for certain situations.

Stabilized layers that have high strength and modulus may develop transverse cracks due to shrinkage or repeated loading. It has been noted that in cases of heavy loading, high water content, and low-strength fine-grained subgrade soils, pumping (ejection of subgrade material through transverse cracks) may occur. Pumping is a common distress mode for construction of such stiff sections as concrete pavements. Pumping-type failures have been noted in track sections that contain ballast over stabilized layers. Details of the occurrences are not available. Proper subgrade evalution, selection of materials, and structural design of the track support system should preclude pumping-type activity.

For given loading conditions, subgrade support, rail size, and tie spacing, thickness of the ballast

Figure 3. Relation between E_R and θ for AREA no. 4 limestone ballast material.



and of the stabilized layer is the major design factor. The ballast layer over the stabilized layer should be of sufficient thickness [probably greater than 200-250 mm (8-10 in)] to accommodate normal surfacing and tamping operations. For a particular stabilized material that has certain modulus and strength characteristics, layer thickness can be determined to achieve acceptable track support system responses (deflections, stabilized-layer stresses and strains, subgrade stresses and strains, etc.).

Currently, ILLI-TRACK (18) is the structural model best suited for analysis of track support systems that contain a stabilized layer. The effect of the thickness of the stabilized layer on the structural behavior of a typical track structure [stabilized material modulus of elasticity of 10.3 GPa (1.5×10^6 psi)] is demonstrated in Table 1. The major effects of increased thickness of the stabilized layer are reduced stabilized material bending stress, reduced subgrade deviator stress, and decreased subgrade strains. Note that the thicker stabilized layers result in increased maximum tie reactions due to a stiffer track section.

The influence of reducing the modulus of the stabilized layer from 10.3 GPa to 1.7 GPa (250 000 psi) is demonstrated by comparing cases A and C in the track response summary, Table 1. The reduced modulus results in decreased maximum tie reaction, reduced tensile stress of the stabilized material, and increased values of subgrade deviator stress and strain.

Thompson and Figueroa (27) have demonstrated that structural analysis concepts similar to those of ILLI-TRACK can be used to develop design algorithms. The algorithms can be presented as simple design nomographs. Such algorithms and nomographs can be easily developed for typical track systems. Stabilized-layer thickness, stabilized-material properties (modulus of elasticity and strength), subgrade strength, and ballast thickness are the major design parameters that would be included. Once a matrix of design parameter levels had been analyzed by using ILLI-TRACK, the design algorithms and nomographs could be established for general design use and applications.

SUMMARY

Admixture-stabilized soils and granular materials can be effectively used in conventional track support system construction. A stabilized layer will prevent and/or minimize subgrade intrusion and improve shear strength at the ballast interface.

Track system behavior is beneficially modified by the stabilized layer. Track deflection, subgrade stress, subgrade strain, and rail bending stress are reduced. A substantial increase in ballast-layer confinement is achieved. All the behavior improvements noted will contribute to enhanced track system performance.

The stabilized layer should possess adequate strength and durability and be of an appropriate thickness. Tensile stress generally controls the thickness design of the stabilized layer. Important thickness design factors for a given stabilized material are ballast depth, wheel loading, and subgrade support. The use of a standard-section concept is not advocated.

ILLI-TRACK is an appropriate mechanistic structural model for analyzing track sections that contain a stabilized layer. The development of simple design algorithms and nomographs is proposed.

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Better Track at Lower Cost: Advantages, Benefits, and Limitations of Track Renewal

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A discussion of the track-renewal method of railroad track maintenance is presented that emphasizes the operational advantages, economic benefits, and limitations of the method in comparison with the selective-maintenance method. Track renewal is the predominant maintenance method in Europe and is currently spreading to other parts of the world. The method consists of using a highly mechanized on-track system to completely rebuild the track in one continuous pass. Therefore, the track needs little work until the next rebuilding. In contrast, under selective maintenance (still the predominant method in North America), track structure components are replaced individually as they fail or wear out. There is growing interest in track renewal in North America, and this paper is based on research studies of track renewal sponsored by the Federal Railroad Administration and performed by Unified Industries Incorporated (UII). Those studies resulted in the development of a detailed framework for conducting a comparative economic analysis of track renewal versus selective maintenance within a North American context. The framework was subsequently used by UII in a sample analysis of 14 specific track-maintenance scenarios designed to reflect a range of track conditions. From the results of the sample analysis (reported in this paper), UII concluded that track renewal offers the potential of significant operational advantages, which include a completely rebuilt track structure, a major reduction in the track occupancy time needed for track maintenance, and a smaller workforce. In addition, it offers the prospect of major cost savings. On a long-term (life-cycle) basis, track renewal can generate a savings of $15 000-$30 000-plus/track mile under certain conditions. Furthermore, in a limited number of cases, there may also be a first-year track-renewal savings, despite the heavy investment needed in new ties. The limitations of track renewal include the need for major financial, planning, and management commitments and the inevitable risks associated with the introduction of a new method of maintenance in North America. A discussion of research areas for further study and a short summary that emphasizes the potential of track renewal to produce better track at lower cost are given in conclusion.