

PERFORMANCE-BASED TRACKBED STRUCTURAL DESIGN AND ANALYSIS UTILIZING KENTRACK

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ABSTRACT

The design and construction of the trackbed support structure is extremely important for controlling track settlement, dynamic deflection, and the overall quality of the trackbed. These factors largely influence the long-term performance of the track relative to maintaining adequate geometric features for efficient and safe train operations. Performance-based design methods provide design criteria to assess the relative effects of various factors affecting long-term performance of different trackbed designs. These designs involve, in large part, selecting layer thicknesses and constituent materials possessing various properties inherent to influencing long-term track performance.

By using a performance-based design method, it is possible for designers to select trackbed support layer thicknesses and constituent materials to satisfy roadbed performance requirements. Specifically, by considering each layer's fatigue life related to the number of trains and tonnages, a method is available for designing thicknesses of the various layers and selecting materials according to the importance of a particular section of track. Thus, the predicted design life for various design criteria can be determined.

Layer-elastic, finite-element computer programs are available for performance-based structural design and analysis of railway trackbeds. This paper utilizes the KENTRACK design program to illustrate the effects of varying axle loads, subgrade resilient modulus, and layer thicknesses on the fatigue lives of the various layers. The service lives of the subgrade and asphalt layer are predicted by damage analysis.

KENTRACK allows users to select individual trackbed layers and associated thicknesses to satisfy roadbed performance requirements. In addition, users may performance-rank different track sectional designs based on the relative importance of the particular track section and the track type.

1. INTRODUCTION

The properties and thicknesses of the various layers comprising the track structural support largely determine the quality of the trackbed substructure and its ability to adequately withstand the various loading intensities. Minimizing track deflections and subsequent permanent track settlements are desired goals for a track design and construction. A primary influencing factor is the level of substructural support. Specifying specific design parameters and construction techniques for track on earthen structures are extremely important for controlling dynamic deflections and track settlement, both of which greatly influence the ultimate track performance and quality. Performance based design methods provide design criteria to assess the expected long-term performance of different track designs. These designs involve selecting layer thicknesses and constituent materials possessing various properties inherent to influencing long-term track performance.

2. TRADITIONAL APPROACH TO SUBSTRUCTURE DESIGN AND ANALYSIS

The American Railway Engineering and Maintenance-of-Way Association (AREMA) publishes track design guidelines. Included are recommended methods for determining ballast thickness (AREMA, 2010). One is the widely-used method derived empirically from experiments conducted by A.N. Talbot at the University of Illinois in the 1920s (Talbot, 1920). Known as the Talbot Equation,

$$h = (16.8p_a/p_c)^{4/5} \quad (1)$$

where h is the ballast thickness (inches), including subballast; p_a is the pressure (psi) on the top of the ballast layer (tie pressure); and p_c is the allowable vertical compressive subgrade stress (psi) (herein simply called subgrade stress). AREMA also recognizes the Japanese National Railways Equation, the Boussinesq Equation, and Love's Formula for determining ballast layer thickness (AREMA, 2010). Each incorporates p_c and p_a in different ways.

These accepted methods all have serious shortcomings. One is the determination of the allowable subgrade stress. If the subgrade stress is excessive, unacceptable permanent deformations will occur leading to rough track, possible slow orders, and resurfacing. However, although subgrade strength can be determined through testing, subgrade strength can be quite variable and the application of an appropriate factor of safety is left to the designer's discretion. The most glaring shortcoming is that subgrade and ballast material properties (other than subgrade strength) are not considered. Finally, these methods are only applicable for all-granular trackbed designs. There is no way to incorporate an asphalt layer into the design or perform an analysis of a design with an asphalt layer using these methods.

Track dynamic deflection is another factor to consider in track design. Talbot found that keeping deflections relatively low under repeated loadings resulted in acceptable track performance. AREMA recommends that deflections fall within a range of $\frac{1}{8}$ to $\frac{1}{4}$ inch (3 to 6 mm) for mainline freight traffic (AREMA, 2010). Traditional design approaches translate this into the Modulus of Track Elasticity (a.k.a. Track Modulus, u or k) which is then used to compute, among other things, a rail seat load that must be carried by the ballast and subgrade. This rail seat load is converted into p_a used above to determine ballast thickness. Unfortunately, the Track Modulus represents the combined stiffness of all track components below the rail. Thus, a serious shortcoming is knowing what the stiffness contributions are from each component and how much the stiffness might be affected if component variables are changed (e.g. changing ballast thickness). Commonly, one or more Track Modulus values are assumed for design, but the resulting in-track values are largely not certain, often to the detriment of long-term track performance.

3. KENTRACK

KENTRACK is a computer program based on layer elastic finite element. It was specifically developed to design and analyze railway trackbeds. KENTRACK was initially developed (Huang, et al., 1984) to analyze traditional all-granular layered trackbeds and asphalt layered trackbeds. It was subsequently expanded to analyze trackbeds containing a combination of granular and asphalt layers (Rose, et al., 2010). The principle factor in the analysis is to limit the subgrade stress. In addition, it is possible to consider the fatigue lives of the various layers relative to the effects of wheel loads, tonnages, environmental conditions and other factors using appropriate failure criteria. The service lives of the individual trackbed layers are predicted by damage analysis for various combinations of traffic, tonnages, subgrade support, component layer properties and thicknesses.

The latest Microsoft Windows® version, KENTRACK 3.0, is coded in C#.NET a popular computer language. A graphical user interface is provided to aid in the design and analysis of trackbeds. The development of KENTRACK Version 3.0 is described in an application tutorial (Rose, et al., 2010).

4. THEORY

The basic theory, on which KENTRACK is based, is described elsewhere (Rose, et al., 2010). The primary single failure criterion for the all-granular trackbed is the cumulative effects of the subgrade stress leading to excessive permanent deformation. However, since an asphalt-bound layer

can resist deformation as a function of its tensile strength, an additional failure criterion – tensile strain at the bottom of the asphalt layer – is included in the analysis of asphalt trackbeds to limit asphalt cracking. The subgrade stress failure criterion is also applicable for asphalt trackbeds.

The loading configuration in KENTRACK uses the principles of superposition and track symmetry for distributing the wheel loads over several ties (Huang, et al., 1984). The damage factors are calculated based on highway failure criteria used in the DAMA program (Asphalt Institute, 1982; Hwang & Witczak, 1979). This program is widely applied for the structural design and analysis of highway pavements.

The asphalt damage factors, incorporated into the KENTRACK program from the highway developed DAMA program, are believed to be more severe for highway applications than railroad environments. Previous analyses have indicated that the asphalt layer in the insulated trackbed environment weathers at an extremely slow rate (Rose and Lees, 2008). Ultraviolet and oxygen-induced effects are minimized by the ballast cover. Also, temperature extremes in the asphalt layer are minimized due to ballast cover (Rose, 2008). Thus, the predicted design lives for the asphalt trackbeds reported herein are likely very conservative. Furthermore, moisture tests on subgrade/subballast samples, taken directly under the asphalt layers at several trackbed sites, indicated that the subgrade/subballast moisture contents remain constant, at or near optimum, even after many years in asphalt trackbeds (Rose and Lees, 2008).

5. APPLICABILITY

KENTRACK is applicable for analyzing three types of trackbed structures as depicted in Figure 1. The traditional all-granular trackbed consists of four layers: Ballast, subballast, subgrade, and bedrock. The primary failure criterion is the vertical compressive stress on the subgrade (herein simply called subgrade stress). The asphalt underlayment trackbed contains a layer of asphalt in place of the granular subballast. It also has four layers – ballast, asphalt, subgrade, and bedrock. These asphalt trackbeds are widely accepted and commonly considered as an alternative to the traditional all-granular trackbed. The asphalt layer is similar in composition to the asphalt mix used for highway pavements. Documented benefits are that the asphalt layer 1) strengthens trackbed support by reducing subgrade stress, 2) waterproofs the roadbed to reduce subgrade moisture contents and fluctuations, and 3) provides a consistently high level of confinement for the ballast enhancing the shear strength of the ballast (Anderson and Rose, 2008), (Rose and Lees, 2008) (Rose and Bryson, 2009). The combination trackbed contains five layers – ballast, asphalt, subballast, subgrade, and bedrock. The subballast layer can be considered as an improved subgrade. This design is an alternate to the asphalt underlayment trackbed and contains subballast between the asphalt layer and subgrade. This is typical for most asphalt trackbeds placed on existing trackbed substructures during a rehabilitation process. Basically a granular layer is present, consisting of degraded ballast/sand/soil, somewhat similar to granular subballast, upon which the asphalt layer is placed.

The predicted design lives reported herein are believed to be conservative for the trackbed environment. The asphalt and subgrade layers in highway environments, on which the predictions are based, undergo larger temperature and moisture variations. Furthermore, subgrades are likely to absorb more moisture, and asphalt layers weather at a faster rate exposed to the atmosphere. These factors serve to accelerate the rate of deterioration of the layers. The trackbed environment provides encapsulation and insulation for the layers. In addition, a small crack in the asphalt is considered “failure” for highway applications. This would not necessarily constitute failure within a trackbed; nor would a slight settlement of the subgrade constitute failure since it can be easily corrected by adjusting the ballast during routine track surfacing activities.

6. DATA PORTRAYAL

KENTRACK is applicable for calculating stresses and strains in the trackbed and associated design lives for a specific set of design parameters. In addition, selected parameters can be varied in magnitude and the relative influences evaluated. Data derived from the program are provided in Table 1 for the default thicknesses of the trackbed layers and loading conditions (U.S. customary units) indicated in Figures 2 and 3 respectively. Traffic density is assigned 200,000 repetitions per year of a 286,000-lb car, or 28.6 MGT/year. This is utilized for the subgrade and asphalt life predictions. Each car is considered equivalent to one load application. Subgrade resilient modulus was varied from a weak 3000 psi (20.7 MPa) to a strong 30,000 psi (207 MPa). Also, an average subgrade resilient modulus of 12,000 psi (83 MPa) and a moderately strong 21,000 psi (145 MPa) subgrade resilient modulus were included. Standard design axle loads of 33 and 36 tons and the anticipated 39-ton axle load were selected for evaluations. Additional specific input parameters are described elsewhere (Rose, et al., 2010).

7. EFFECTS OF SUBGRADE AND LOADING VARIABLES

Data contained in Table 1 assess the effects of two primary variables – subgrade resilient modulus and axle loads – on the calculated subgrade stresses and asphalt tensile strains, along with associated predicted design lives, for the all-granular, asphalt and combination trackbeds. For this analysis a combined trackbed thickness of 14 inches (35.6 cm) for the ballast and subballast/asphalt layers was selected for the all-granular and asphalt designs. The combination design utilizes the 14-inch (35.6 cm) thick asphalt design plus a 4-inch (10.2 cm) thick subballast layer for a total trackbed thickness of 18 inches (45.7 cm).

7.1 Effect of Varying Subgrade Resilient Modulus and Axle Loading on Subgrade Stresses and Asphalt Strains

Subgrade stresses, depicted in Figure 4a for the 36-ton axle load, are relatively low, even for the all-granular trackbed, ranging from 8 to 20 psi (55 kPa to 138 kPa). Subgrade stresses are even lower for the asphalt trackbed. This illustrates the positive influence of the asphalt layer. The addition of the subballast layer in the combination trackbed results in even lower subgrade stresses for a given subgrade resilient modulus.

In-track vertical compressive stress measurements utilizing in-bedded pressure cells compare favorably with the KENTRACK calculated stresses (Rose, et al., 2004). Based on the output from the KENTRACK design, stress levels within the track structure are quite low and only marginally affected by variable axle loads. Therefore, differential trackbed performance is likely a function of the quality of the support as defined by the resilient modulus of the subgrade.

Figure 4b indicates that the tensile strains at the bottom of the asphalt layer decrease as the subgrade stiffens. This is expected since the asphalt layer deflects less over stiffer subgrades. The additional subballast layer in the combination trackbed further reduces tensile strains. The asphalt tensile strain levels are very low in magnitude relative to highway pavement applications. This is likely due to the fact that the imposed loading stresses in the trackbed are very low as well. Also, previous studies have revealed that the asphalt layer in the insulated trackbed weathers, or hardens, at a very slow rate compared to highway pavement applications (Rose and Lees, 2008). Furthermore, the temperature extremes in the insulated trackbed environment are less when compared to exposed asphalt highway pavements.

Figure 5a shows the effects of varying subgrade resilient modulus on the predicted subgrade design life for the three trackbed types. This analysis is based on rail traffic of 28.6 MGT/year and a 36-ton axle load. As the subgrade stiffness increases the predicted subgrade design life increases significantly for all three trackbed designs. This occurs even though the subgrade stress increases as

subgrade stiffness increases. The advantage of stiffer subgrades is readily apparent. The addition of the asphalt layer results in an increase in subgrade design life relative to the all-granular trackbed.

Figure 5b shows the effects of varying the subgrade resilient modulus on the predicted asphalt design life for the three types of trackbeds. As the subgrade resilient modulus stiffens, the predicted asphalt design life increases significantly for both types of asphalt trackbed designs. The stiffer subgrades minimize the deflection of the asphalt layer and the resulting tensile strains, thus the design life expectancy prior to a crack in the asphalt layer increases. The positive effect of stiff subgrades on extending the design life of the asphalt layer is apparent.

As indicated previously in Figure 4a for a 36-ton axle load, subgrade stress increases as subgrade modulus increases for all three trackbed types. This is also the case for 33 and 39-ton axle loads. Increasing axle loads from 33 to 39 tons slightly increase subgrade stresses, typically about 1 to 2 psi (6.9 to 13.8 kPa) for a specific subgrade resilient modulus. Therefore, the effect of increasing axle loads results in minimal increases in subgrade stresses for a given subgrade resilient modulus and trackbed design.

Table 1 also shows the effects of varying axle loads and subgrade resilient modulus on asphalt tensile strain for the two types of asphalt trackbed designs. As indicated previously in Figure 4b, asphalt tensile strain decreases as subgrade modulus increases for both types of asphalt trackbeds. This is the case for the 33 and 39-ton axle loads in addition to the previously detailed 36-ton axle load. Typically the decrease in asphalt tensile strain is 0.0001. Increasing axle loads from 33 to 39 tons slightly increase asphalt tensile strains for a specified subgrade resilient modulus. Typically the increase in strain is only 0.00002, therefore the effect of increasing axle loads results in minimal increases in asphalt tensile strains for a given subgrade resilient modulus and trackbed design.

7.2 Effect of Varying Subgrade Resilient Modulus and Axle Loading on Design Life

Table 1 shows the effects of varying subgrade resilient modulus and axle loads on subgrade design lives for the three types of trackbed designs. The all-granular trackbed subgrade design life predictions indicate the significant effect of subgrade resilient modulus on predicted design lives. Predicted subgrade design life substantially increases as subgrade resilient modulus also increases. These trends are similar for the asphalt and combination trackbeds. Also, increasing axle loads indicate reductions in subgrade life.

In addition, the predicted subgrade design lives for a given subgrade modulus and axle load increase significantly for the asphalt trackbed and increase even more for the combination trackbed.

The additional data in Table 1 show the effects of varying axle loads and subgrade resilient modulus on asphalt design lives for the two types of asphalt trackbed designs. As for subgrade design life, the asphalt trackbed design life is substantially increased as subgrade modulus increases. In addition, increasing axle loads indicate reductions in asphalt design life. These trends are similar for the asphalt and combination trackbeds.

In addition, the predicted asphalt design lives for a given axle load and subgrade resilient modulus increase significantly for the combination trackbed relative to the asphalt trackbed. This illustrates the structural advantage of the subballast layer in the combination trackbed design. The effects of axle loadings is presented in more detail in elsewhere (Rose, et al., 2011).

The importance of maintaining stiff, high-modulus track support is readily apparent. Soft subgrades require frequent surfacing to correct track settlement and deformation, as indicated by the low predicted design lives.

8. EFFECTS OF LAYER THICKNESS ON STRESSES, STRAINS, AND DESIGN LIVES

KENTRACK analyses were conducted to examine how ballast and asphalt layer thicknesses effect calculated stresses/strains and predicted design lives. The data are presented in Tables 2, 3 and 4.

8.1 Effect of Varying Ballast Thickness for All-Granular Trackbeds

Figure 6a shows the effect of varying ballast thickness and subgrade resilient modulus on subgrade stresses for all-granular trackbeds. The axle loadings and subballast thicknesses are held constant. Increasing ballast thickness from 4 to 12 inches (10.2 to 30.5 cm) decreases subgrade stress by about 20% for the least stiff subgrade. The effect is even more significant for the stiffer subgrades. For the 30,000 psi (207 MPa) resilient modulus subgrade, the reduction in subgrade stress is nearly 50% for the same ballast thickness increase. The stiffer subgrades provide the level of support necessary for the ballast to develop sufficiently high shear strength for proper dissipation of stresses. Thus, the potential benefit of the additional ballast can be achieved.

Figure 6b shows the effects of ballast thickness and subgrade resilient modulus on the predicted design life of the subgrade. For the 3000 psi (20.7 MPa) subgrade resilient modulus case, predicted subgrade design lives are substantially less than one year, regardless of the ballast thickness, even though the imposed stresses are reasonably low in magnitude (Figure 6a). This situation is experienced in existing trackbeds when track sections overlying weak subgrades must be raised and surfaced by maintenance forces multiple times during the year. However, for the stiffer subgrades, the predicted subgrade design life is increased substantially.

8.2 Effect of Varying Asphalt Thickness for Asphalt Trackbeds

The effect of varying asphalt thickness and subgrade resilient modulus on subgrade stress for asphalt trackbeds is shown in Figure 7a. The axle loadings and ballast thicknesses are held constant. As the asphalt layer thickness increases, the subgrade stress decreases. Also, comparing subgrade stress values with the 8-inch (20.3 cm) thick ballast section for the all-granular trackbed, shows that subgrade stresses are further reduced. This illustrates the added advantage of the incorporation of an asphalt layer within the track structure.

Figure 7b shows the comparable effects of varying asphalt thickness and subgrade resilient modulus on the predicted design life of the subgrade. Increasing asphalt thickness from 3 to 9 inches (7.6 to 22.9 cm) typically increases subgrade predicted design life by 5 to 6 times. This is due to the reduction in subgrade stresses as asphalt thickness increases.

The effect of varying asphalt thickness and subgrade resilient modulus on asphalt tensile strain is shown in Figure 7c. As can be seen, as the asphalt layer thickness increases, the tensile strain decreases.

Figure 7d shows that as the asphalt layer increases in thickness, the predicted design life for the asphalt layer also increases. For weak subgrades and thin asphalt layers, the predicted asphalt design life is greater than that of the subgrade. However, as the subgrade resilient modulus increases and the asphalt layer thickness increases, the predicted subgrade design life is greater than that of the asphalt. This is indicative of the ability of stiff subgrades to accommodate substantially more axle loads while sustaining less damage.

8.3 Effect of Varying Ballast Thickness for Asphalt Trackbeds

Figure 8a shows the effects of varying ballast thickness and subgrade resilient modulus on subgrade stress for asphalt trackbeds. The axle loadings and asphalt thicknesses are held constant. As the ballast thickness increases, the subgrade stress decreases. The values and trends are very similar to those shown in Figure 7a for asphalt trackbeds – as the asphalt thickness increases, for a constant ballast thickness, the subgrade stress decreases. Therefore, both ballast and asphalt serve to decrease imposed subgrade stresses for asphalt trackbeds.

The effects of varying ballast thickness and subgrade modulus on the predicted design life of the subgrade are illustrated in Figure 8b. Increasing ballast thickness from 4 to 12 inches (10.2 to

30.5 cm) typically increases predicted design life of the subgrade by 5 to 7 times. This is due to the reduced subgrade stresses as ballast thickness increases.

Likewise, the effects of varying ballast thickness and subgrade resilient modulus on asphalt tensile strain is presented in Figure 8c. As the ballast thickness increases, the tensile strain decreases.

Figure 8d shows that thicker ballast sections increase predicted design lives for the asphalt layer. For the weaker subgrades and thinner ballast sections, the predicted asphalt design life is greater than that of the subgrade.

The effect of increasing ballast thickness from 4 to 12 inches (10.2 to 30.5 cm) for a constant asphalt layer thickness of 6 inches (15.2 cm) (see Figure 7) is similar to the effect of increasing asphalt thickness from 3 to 9 inches (7.6 to 22.9 cm) for a constant ballast thickness of 8 inches (20.3 cm) (see Figure 8). Typical asphalt trackbed designs, specify asphalt layer thickness of about 6 inches (15.2 cm) and ballast thickness of 8 to 12 inches (20.3 to 30.5 cm).

8.4 Effects of Varying Asphalt and Ballast Thicknesses for Combination Trackbeds

The effects of varying asphalt and ballast thicknesses for combination trackbeds are not specifically presented herein. However, it is obvious from Figures 4 and 5 that the addition of a 4-inch (10.2 cm) thick subballast layer below the asphalt layer – the combination trackbed – provides additional subgrade stress and asphalt tensile strain reductions. Concurrently, predicted subgrade and asphalt design lives are increased.

Most existing trackbeds which have been rehabilitated by replacing a portion of the granular support with asphalt have an effective subballast layer composed of degraded ballast, sand, cinders, or other granular material. Thus, the rehabilitated trackbeds classify essentially as combination trackbeds. Most asphalt trackbed designs on new alignments/embankments specify that the upper portion of the subgrade consist of “select” material. The select material designation implies the layer is similar to a subballast layer.

9. CONCLUSIONS

In the not-to-distant past, ballast thicknesses were determined using Talbot or other empirically derived formulae. These traditional approaches have major shortcomings, including the inability to account for material properties of the ballast and subgrade layers. Also, the ability to design and analyze trackbeds with asphalt layers was not possible.

The KENTRACK program was developed, in part, to overcome these shortcomings. KENTRACK was utilized in this illustrative study to determine the effects of varying axle loadings, subgrade resilient modulus, and layer thicknesses on stress/strain indices and predicted design lives of the subgrade and asphalt layers. Three types of trackbed designs were evaluated; all-granular, asphalt, and combination asphalt/granular. Highway failure criteria, considered to be conservative for railroad environments, were utilized for predicting the design lives for the subgrade and asphalt layers.

For a given type of trackbed, the effect of subgrade stiffness (resilient modulus) is the most significant factor influencing the design. For a given loading configuration, stiffer subgrades produce slightly higher subgrade stresses, but the predicted design lives for the stiffer subgrades are increased by several orders of magnitude. Asphalt tensile stresses are lower for the stiffer subgrades and the design lives are increased proportionally. This indicates that selecting and maintaining a stiff, high resilient modulus subgrade is extremely important.

Increasing axle loadings result in increased subgrade stresses and reduced predicted subgrade life for all three types of trackbeds. Asphalt tensile strains are marginally increased and the predicted asphalt lives are marginally reduced with increased loadings. The effects of the higher axle loads can be offset by increasing the effective stiffness of the subgrade.

An asphalt trackbed results in lower subgrade stress than a similar thickness of all-granular trackbed. This is more pronounced when subballast is added to the asphalt trackbed forming a combination trackbed. For a given level of subgrade stiffness and axle loading, predicted subgrade design lives are higher for both the asphalt and combination trackbeds as compared to an all-granular design

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11. REFERENCES

Anderson, J.S. and J.G. Rose. (2008). "In-Situ Test Measurement Techniques Within Railway Track Structures," 2008 ASME/IEEE/ASCE Joint Rail Conference Proceedings, Wilmington, DE, 21 pages.

AREMA. (2010). Manual for Railway Engineering, American Railway Engineering and Maintenance-of-Way Association, 4 volumes.

Asphalt Institute (1982). Research and Development of The Asphalt Institute's Thickness Design Manual (MS-1) Ninth Edition, Research Report 82-2, 150 pages.

Hwang, D. and Witczak, M. (1978). Program DAMA (Chevron) User's Manual, Department of Civil Engineering, University of Maryland, September, pp. 9-11.

Huang, Y.H., Lin, C., Deng, X. and Rose, J. (1984). KENTRACK, A Computer Program for Hot-Mix Asphalt and Conventional Ballast Railway Trackbeds, Asphalt Institute (Publication RR-84-1) and National Asphalt Pavement Association (Publication QIP-105), 164 pages.

Rose, J. (2008). Test Measurements and Performance Evaluations of In-Service Railway Asphalt Trackbeds, Proceedings of the Transportation Systems 2008 Workshop, Phoenix, 17 pages.

Rose, J., Agarwal, N., Brown, J., and N. Ilavaia, (2010). "Kentrack, A Performance-Based Layered Elastic Railway Trackbed Structural Design and Analysis Procedure – A Tutorial," ASME, IEEE, ASCE, AREMA, & TRB 2010 Joint Rail Conference. Paper JRC 2010-36067, Urbana, IL, 38 pages.

Rose, J.G. and L.S. Bryson. (2009). "Optimally Designed Hot Mix Asphalt Railway Trackbeds – Test Measurements, Trackbed Materials, Performance Evaluations, and Significant Implications," 2009 International Conference on Perpetual Pavements, Ohio Research Institute for Trans. and Envir., Columbus, 19 pages.

Rose, J. and Lees, H. (2008). Long-Term Assessment of Asphalt Trackbed Component Materials' Properties and Performance, Proceedings of the 2008 AREMA Conference, 28 pages.

Rose, J., Su, Bei, and Twehues, F. (2004). Comparisons of Railroad Track and Substructure Computer Model Predictive Stress Values and In-situ Stress Measurements, Proceedings of the 2004 AREMA Annual Conference, 17 pages.

Rose, J., Trella, M., and N. Agarwal. (2011). "Structural Design of Railway Trackbeds – Relative Effects of Various Variables," ASME/ASCE/IEEE 2011 Joint Rail Conference. Paper JRC 2011-56016, Pueblo, CO, 20 pages.

Talbot, A.N. (1920). "Second Progress Report of the Special Committee on Stresses in Railroad Track," Proceedings of the AREA, Vol. 21, 1920, pp. 645-814.

Table 1. Effect of Varying Axle Load and Subgrade Modulus on Trackbed Stresses, Strains, and Predicted Design Lives

Trackbeds		All-Granular Trackbed		Asphalt Trackbed				Combination Trackbed			
Axle Load (ton)	Subgrade Modulus (psi)	Layer 3 Subgrade Compressive Stress (psi)	Layer 3 Predicted Subgrade Life (years)	Layer 2 Asphalt Tensile Strain	Layer 3 Subgrade Compressive Stress (psi)	Layer 2 Predicted Asphalt Life (years)	Layer 3 Predicted Subgrade Life (years)	Layer 2 Asphalt Tensile Strain	Layer 4 Subgrade Compressive Stress (psi)	Layer 2 Predicted Asphalt Life (years)	Layer 4 Predicted Subgrade Life (years)
33	3000	8.09	0.28	0.000207	5.68	4.62	1.03	0.000191	5.51	6.05	1.16
	12000	12.18	8.83	0.000122	9.43	26.25	21.72	0.000106	8.58	42.36	31.71
	21000	14.98	30.23	0.000098	11.59	55.10	74.21	0.000083	10.25	92.88	120.92
	30000	17.07	66.60	0.000084	13.24	88.69	161.06	0.000072	11.48	145.42	283.03
36	3000	8.80	0.21	0.000226	6.14	3.48	0.77	0.000209	5.96	4.53	0.86
	12000	13.23	6.48	0.000133	10.23	19.92	16.07	0.000115	9.31	31.53	23.27
	21000	16.28	22.15	0.000107	12.60	40.84	54.16	0.000090	11.15	69.28	88.35
	30000	18.58	48.63	0.000092	14.43	65.33	116.82	0.000081	12.58	99.15	199.77
39	3000	9.49	0.16	0.000245	6.60	2.67	0.58	0.000226	6.41	3.47	0.66
	12000	14.28	4.87	0.000144	11.04	15.19	12.09	0.000124	10.04	24.68	17.64
	21000	17.58	16.64	0.000116	13.62	31.02	40.57	0.000098	12.04	52.93	66.24
	30000	20.07	36.45	0.000101	15.61	49.46	87.18	0.000089	13.61	75.92	149.30

Note: Compressive Stresses and Tensile Strains are Calculated.
 Subgrade and Asphalt Lives are Predicted based on Highway Design Failure Criteria.
 Subgrade and Asphalt Life Predictions based on 28.6 MGT/year.
 Subballast thickness for All-Granular and Combination Trackbeds is 4 in. (10.2 cm)
 1000 psi = 6.9 MPa, 10 psi = 69 kPa

Table 2. Effect of Varying Ballast Thickness and Subgrade Modulus on Subgrade Compressive Stress and Predicted Design Life for All-Granular Trackbeds.

Ballast Thickness (in.)	Subgrade Modulus (psi)	Layer 3 Subgrade Compressive Stress (psi)	Layer 3 Predicted Subgrade Life (years)
4	3000	10.16	0.12
8		8.56	0.22
12		8.08	0.28
4	12000	18.34	1.91
8		14.69	4.73
12		11.91	9.58
4	21000	24.36	4.93
8		18.47	13.84
12		14.56	33.63
4	30000	29.12	9.08
8		21.34	28.96
12		16.44	76.79

Note: Compressive Stresses are Calculated.
 Subgrade Lives are Predicted based on Highway Design Failure Criteria.
 Subgrade Life Predictions are based on 28.6 MGT/year.
 Subballast Thickness is 4 in. (10.2 cm)
 Axle Load is 36 tons.
 1 inch = 2.54 cm, 1000 psi = 6.9 MPa, 10 psi = 69 kPa

Table 3. Effect of Varying Asphalt Thickness and Subgrade Modulus on Subgrade Compressive Stress and Asphalt Tensile Strain and Predicted Subgrade and Asphalt Design Lives for Asphalt Trackbeds

Asphalt Thickness (in.)	Subgrade Modulus (psi)	Layer 3 Subgrade Compressive Stress (psi)	Layer 3 Predicted Subgrade Life (years)	Layer 2 Asphalt Tensile Strain	Layer 2 Predicted Asphalt Life (years)
3	3000	7.59	0.35	0.000251	2.47
6		6.14	0.77	0.000226	3.48
9		5.02	1.56	0.000198	5.28
3	12000	13.30	6.26	0.000149	13.79
6		10.23	16.07	0.000133	19.92
9		8.07	34.90	0.000108	31.57
3	21000	16.99	18.49	0.000124	25.19
6		12.60	54.16	0.000107	40.84
9		9.97	123.99	0.000091	67.62
3	30000	19.84	37.19	0.000109	39.02
6		14.43	116.82	0.000092	65.33
9		11.29	276.37	0.000078	111.38

Note: Compressive Stresses and Tensile Strains are Calculated.
 Subgrade and Asphalt Lives are Predicted based on Highway Design Failure Criteria.
 Subgrade and Asphalt Life Predictions based on 28.6 MGT/year.
 Ballast Thickness is 8 in. (20.3 cm)
 Axle Load is 36 tons.
 1 inch = 2.54 cm, 1000 psi = 6.9 MPa, 10 psi = 69 kPa

Table 4. Effect of Varying Ballast Thickness and Subgrade Modulus on Subgrade Compressive Stress and Asphalt Tensile Strain and Predicted Subgrade and Asphalt Design Lives for Asphalt Trackbeds

Ballast Thickness (in.)	Subgrade Modulus (psi)	Layer 3 Subgrade Compressive Stress (psi)	Layer 3 Predicted Subgrade Life (years)	Layer 2 Asphalt Tensile Strain	Layer 2 Predicted Asphalt Life (years)
4	3000	7.41	0.37	0.000275	1.82
8		6.14	0.77	0.000226	3.48
12		5.13	1.49	0.000189	6.17
4	12000	12.49	7.42	0.000171	8.71
8		10.23	16.07	0.000133	19.92
12		8.64	30.54	0.000110	37.38
4	21000	15.75	22.84	0.000142	15.78
8		12.60	54.16	0.000107	40.84
12		10.58	106.03	0.000087	80.86
4	30000	18.54	43.29	0.000130	21.75
8		14.43	116.82	0.000092	65.33
12		12.04	233.94	0.000075	131.11

Note: Compressive Stresses and Tensile Strains are Calculated.
 Subgrade and Asphalt Lives are Predicted based on Highway Design Failure Criteria.
 Subgrade and Asphalt Life Predictions based on 28.6 MGT/year.
 Asphalt Thickness is 6 in. (15.2 cm)
 Axle Load is 36 tons.
 1 inch = 2.54 cm, 1000 psi = 6.9 MPa, 10 psi = 69 kPa

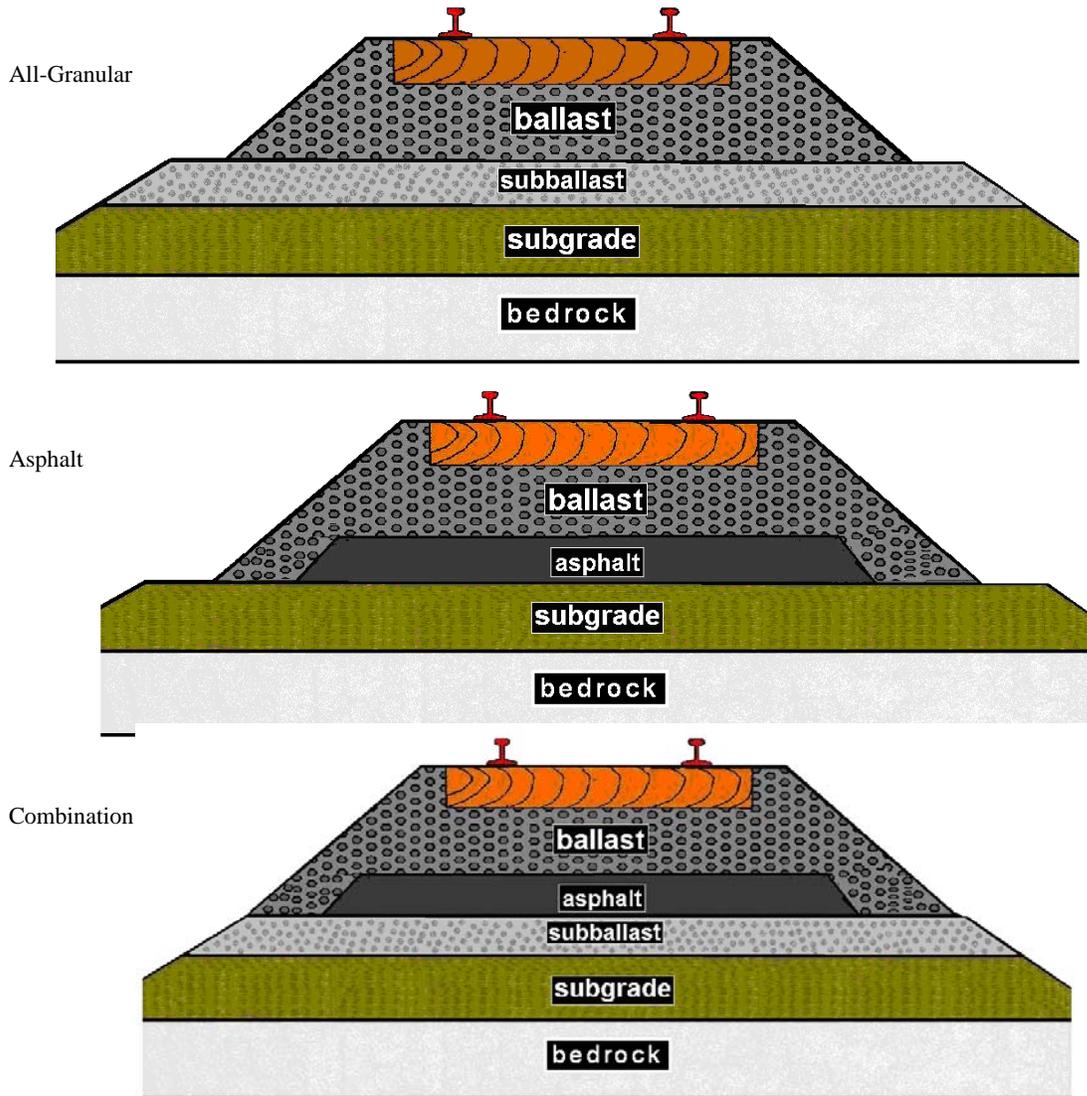


Figure 1. Three Types of Ballasted Tracked Structures Applicable for KENTRACK.

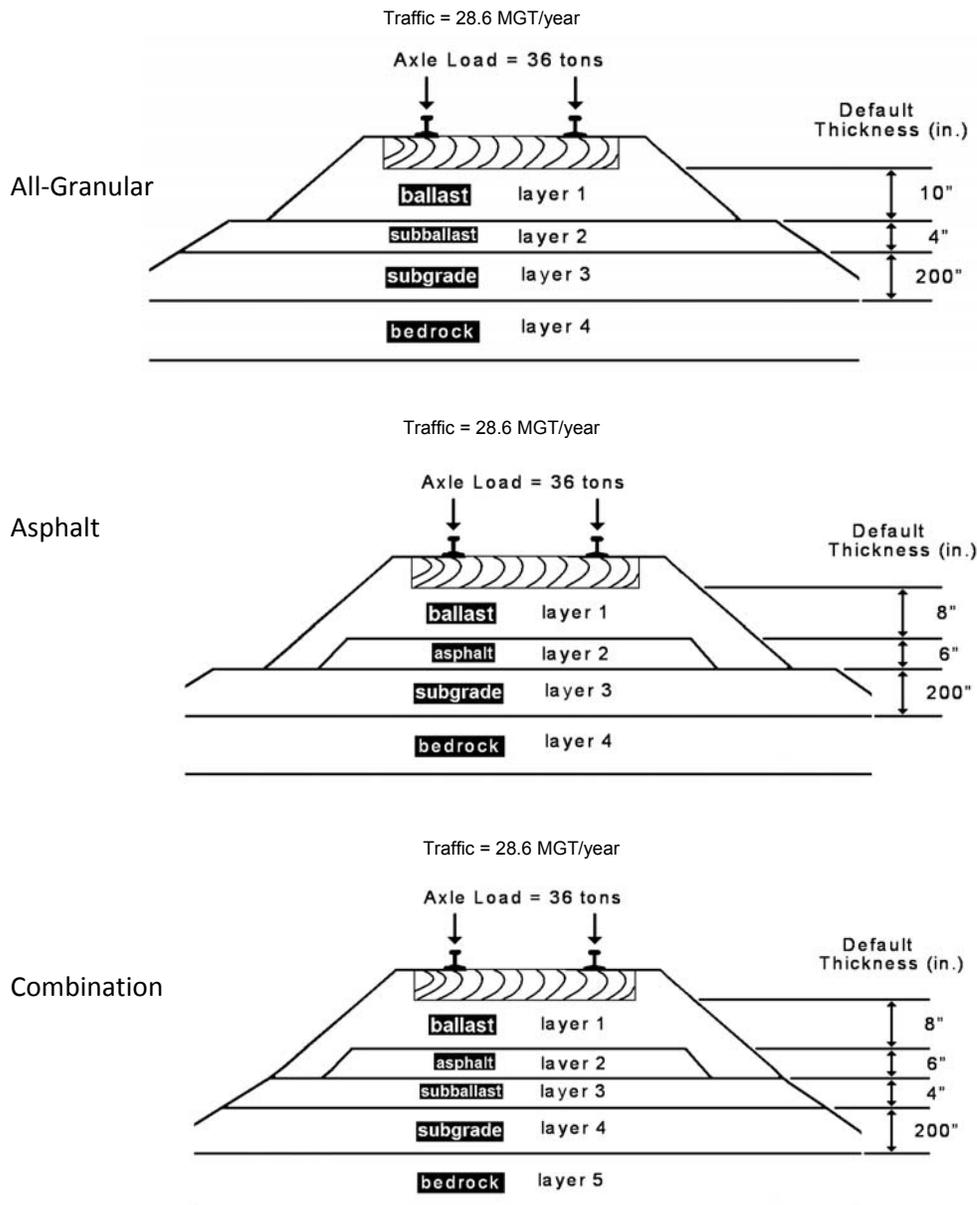
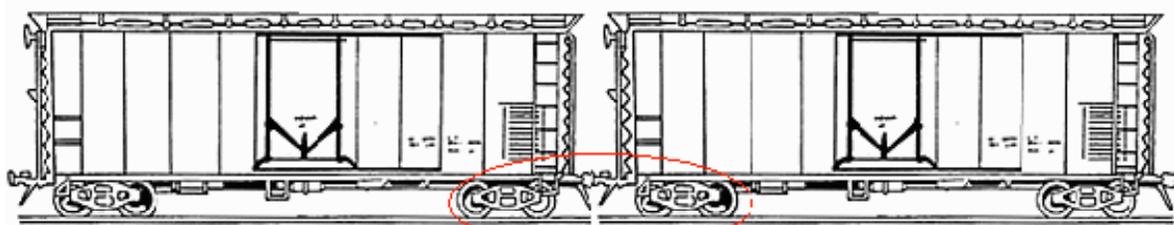


Figure 2. Default Thicknesses for the Trackbed Layers and Loading Conditions (1 inch = 2.54 cm).



Wheel load	= 36,000 lb/wheel
For one car the total weight	= 36,000 lb/wheel x 8 = 286,000 lb/rep
	= 143 ton/rep
The number of repetitions assumed per year	= 200,000 rep/yr
The traffic per year	= 200,000 rep/yr x 143 ton/rep
	= 28,600,000 GT/yr
	= 28.6 MGT/yr

Figure 3. Million Gross Tons Per Year Calculation, U.S. Customary Units.

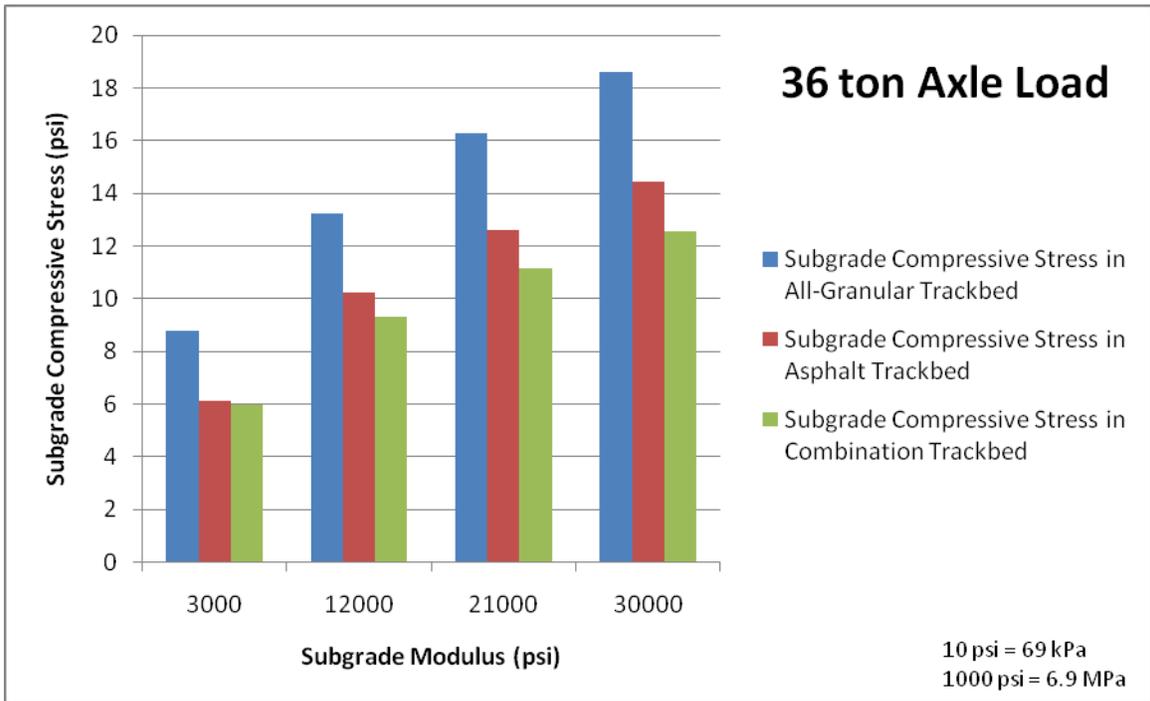


Figure 4a. Effect of Subgrade Modulus on Subgrade Compressive Stress.

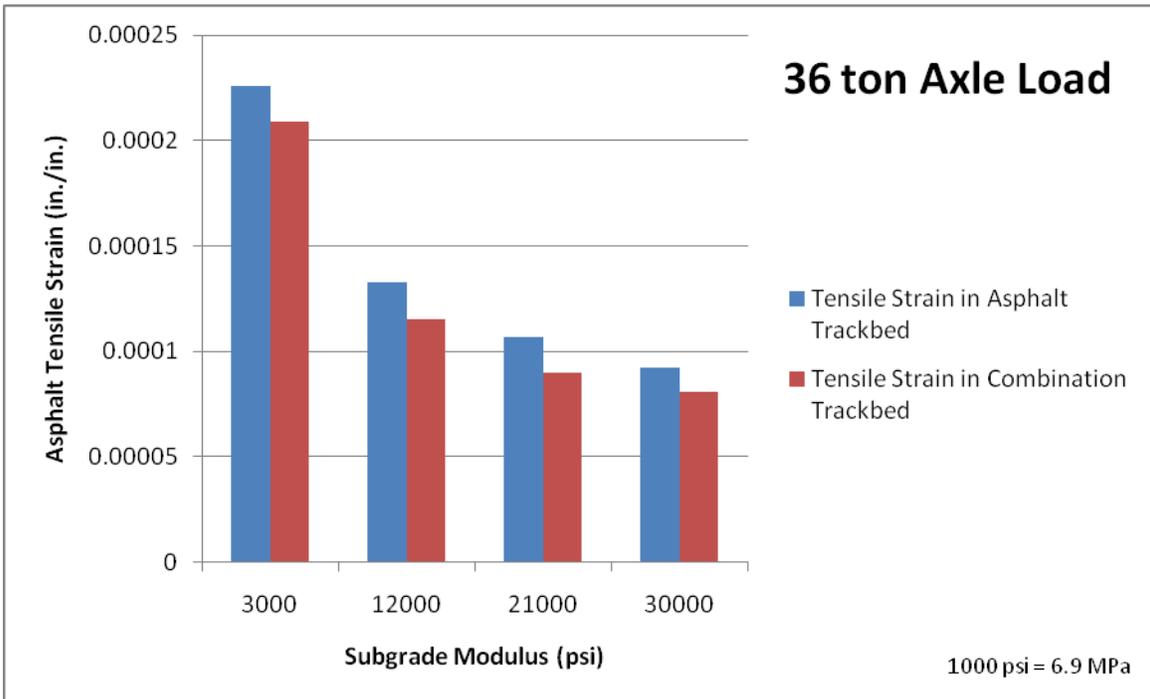


Figure 4b. Effect of Subgrade Modulus on Asphalt Tensile Strain.

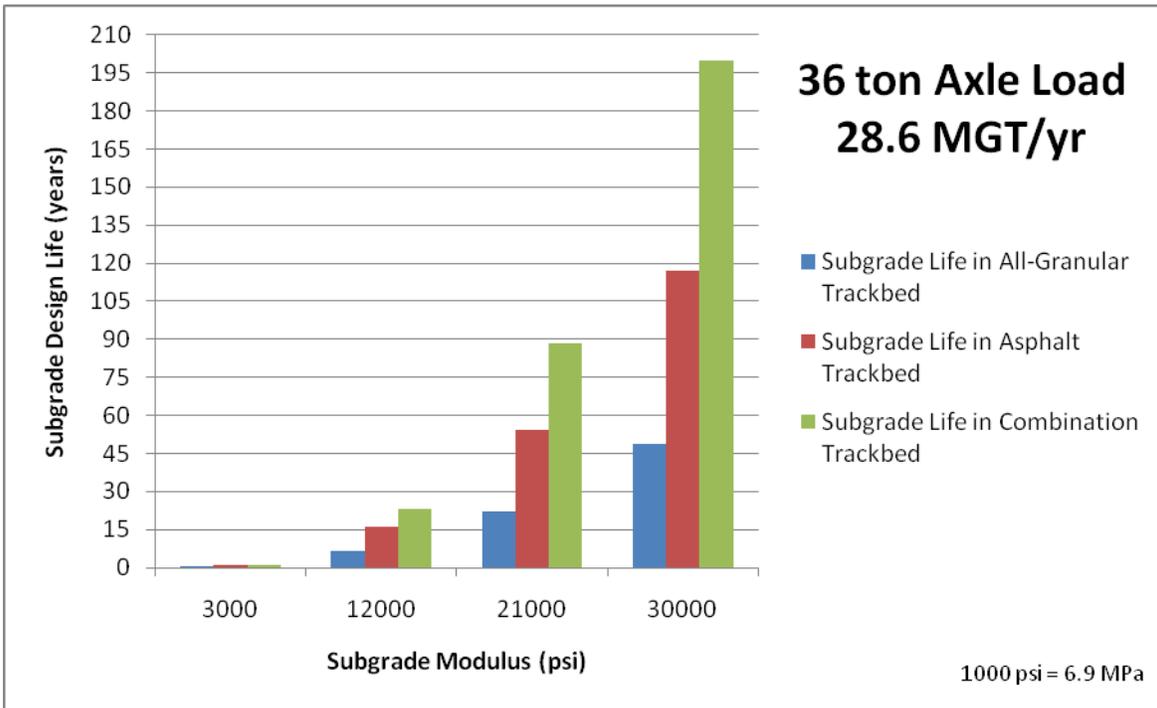


Figure 5a. Effect of Subgrade Modulus on Subgrade Design Life.

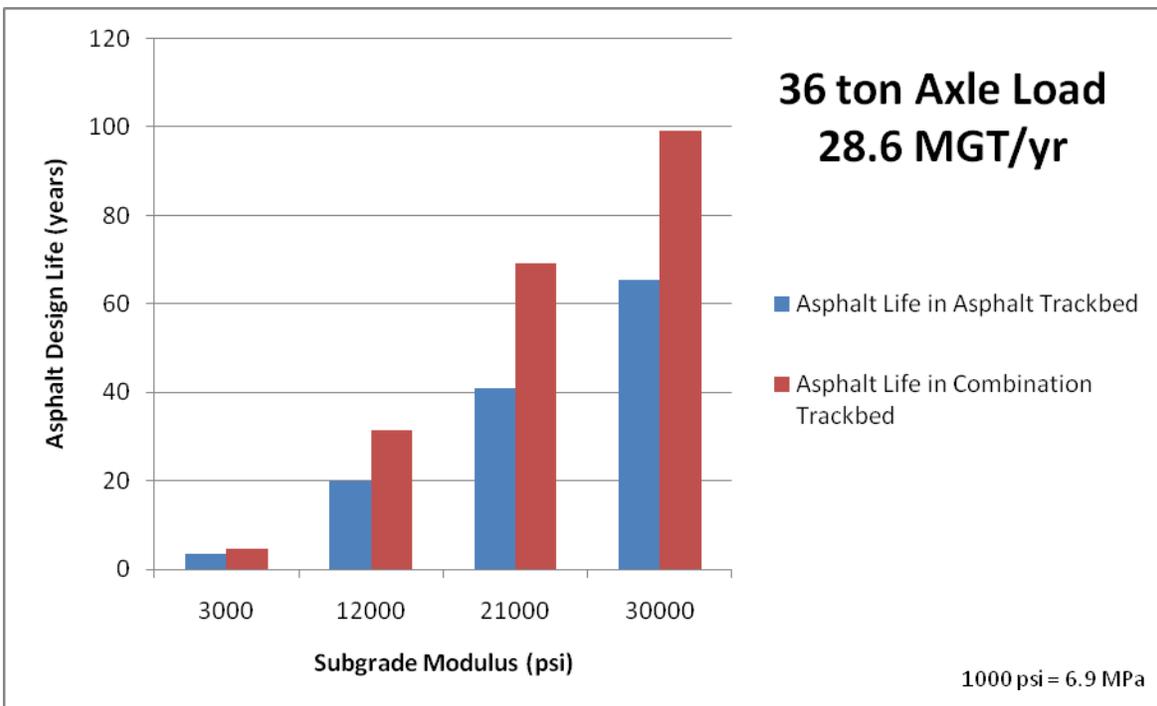


Figure 5b Effect of Subgrade Modulus on Asphalt Design Life.

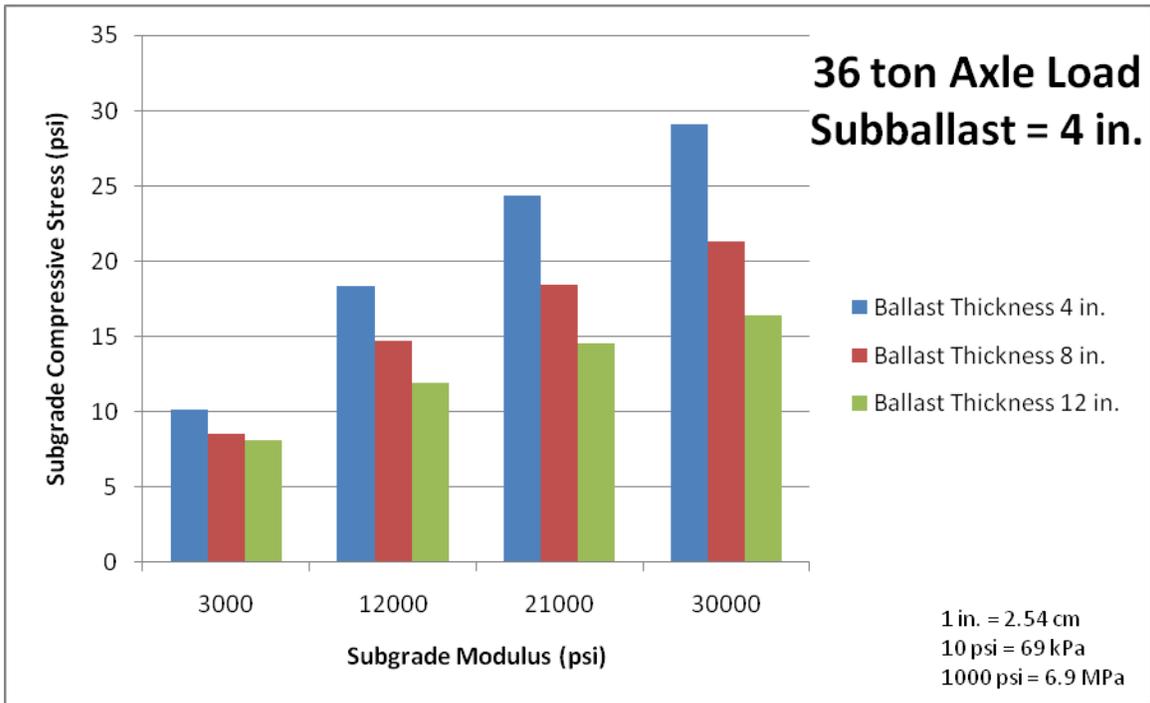


Figure 6a. Effect of Ballast Thickness and Subgrade Modulus on Subgrade Compressive Stress for All-Granular Trackbed.

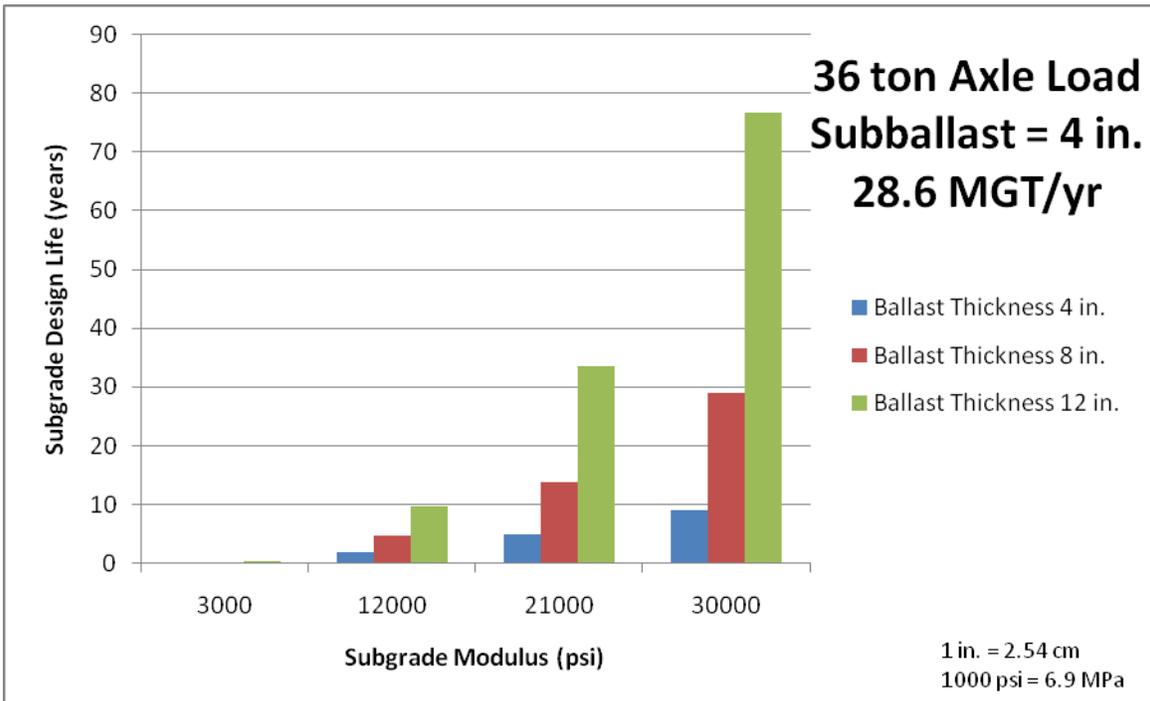


Figure 6b. Effect of Ballast Thickness and Subgrade Modulus on Subgrade Design Life for All-Granular Trackbed.

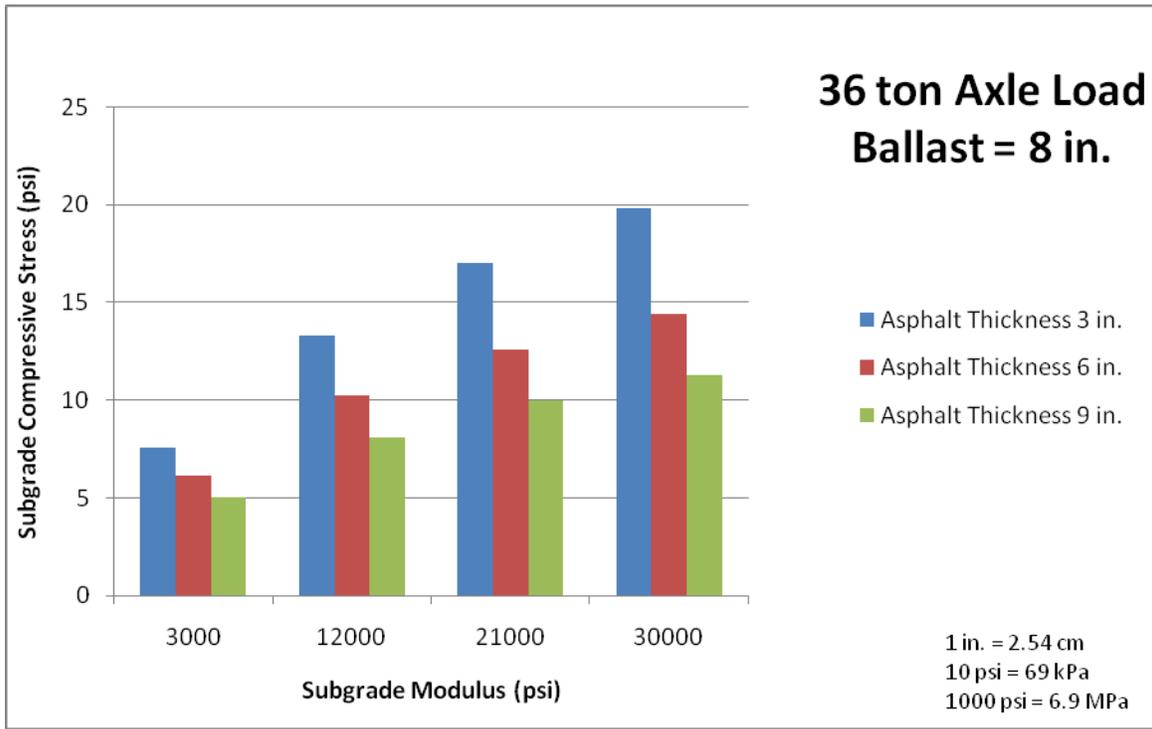


Figure 7a. Effect of Asphalt Thickness and Subgrade Modulus on Subgrade Compressive Stress for Asphalt Trackbed.

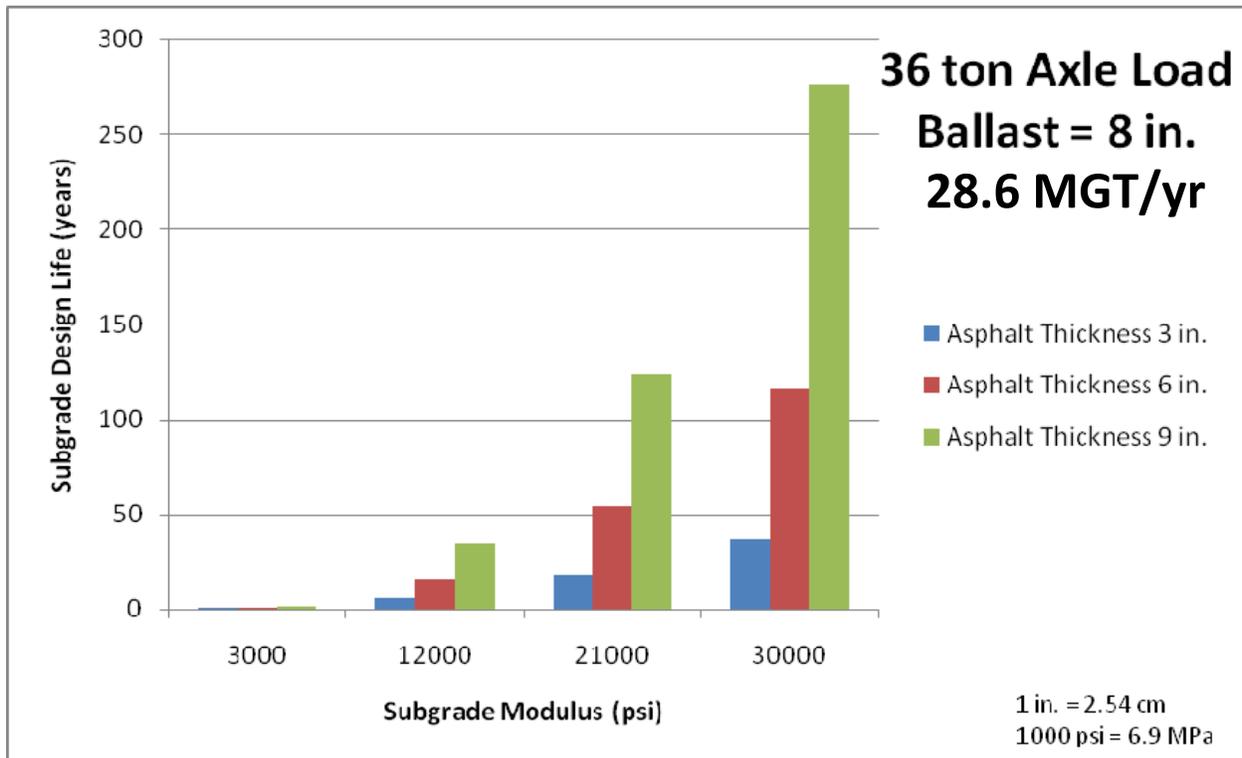


Figure 7b. Effect of Asphalt Thickness and Subgrade Modulus on Subgrade Design Life for Asphalt Trackbed.

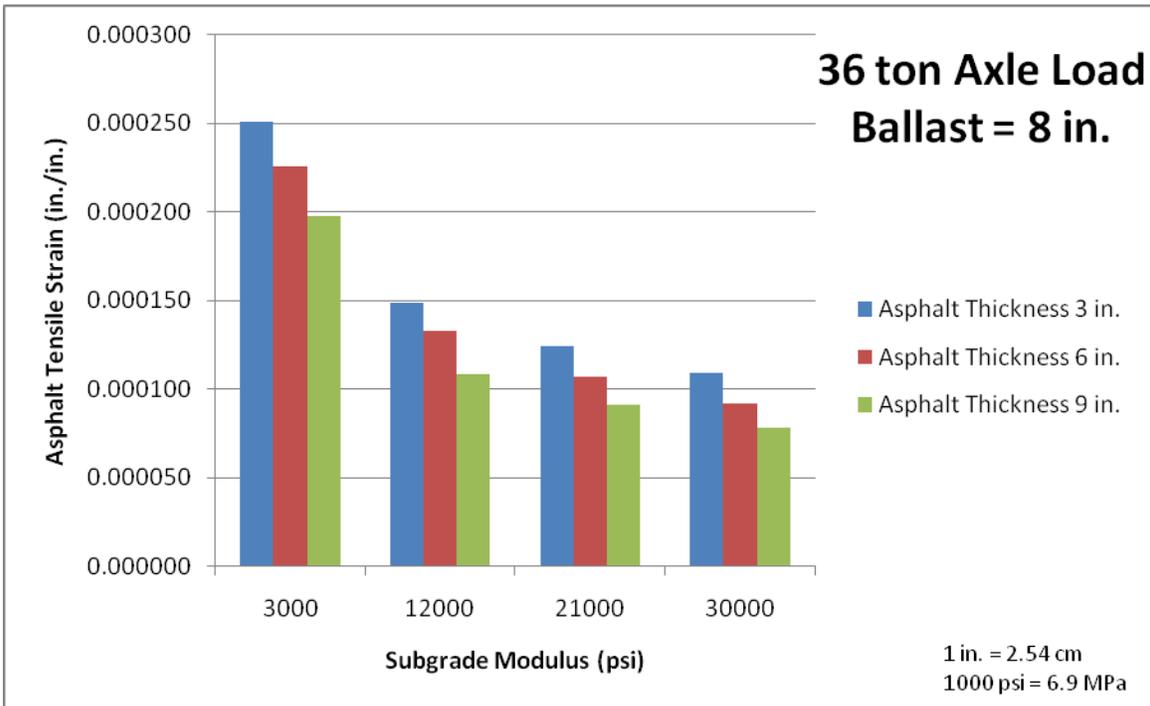


Figure 7c. Effect of Asphalt Thickness and Subgrade Modulus on Asphalt Tensile Strain for Asphalt Trackbed.

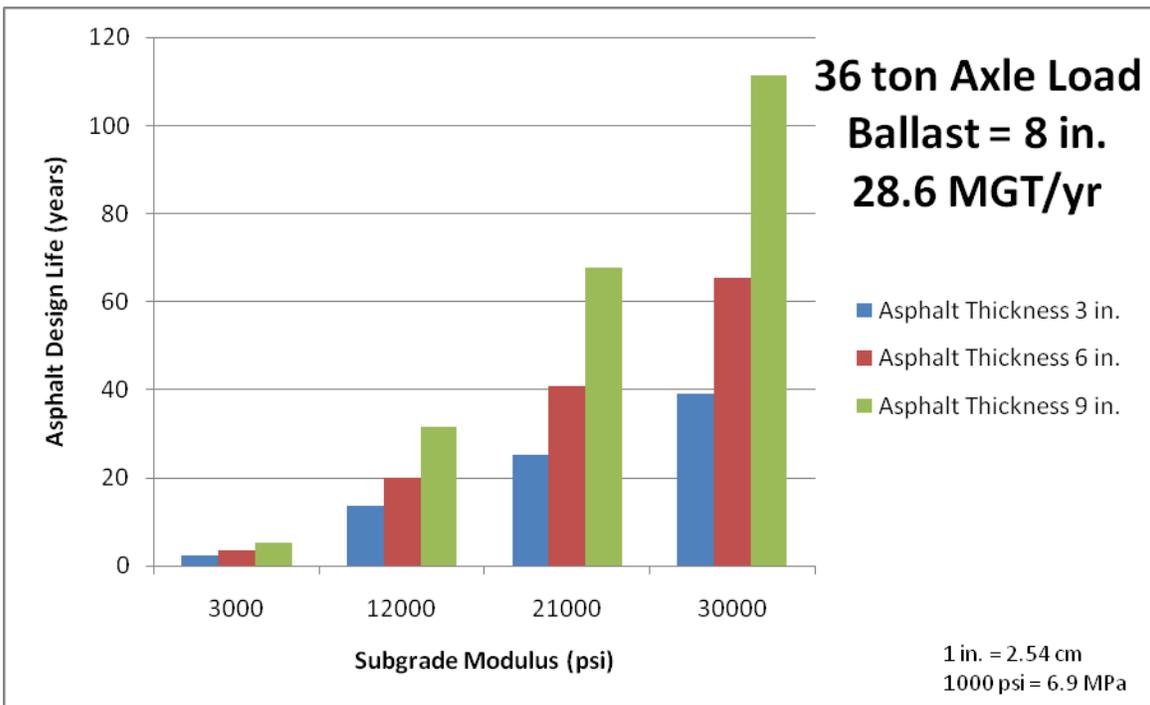


Figure 7d. Effect of Asphalt Thickness and Subgrade Modulus on Asphalt Design Life for Asphalt Trackbed.

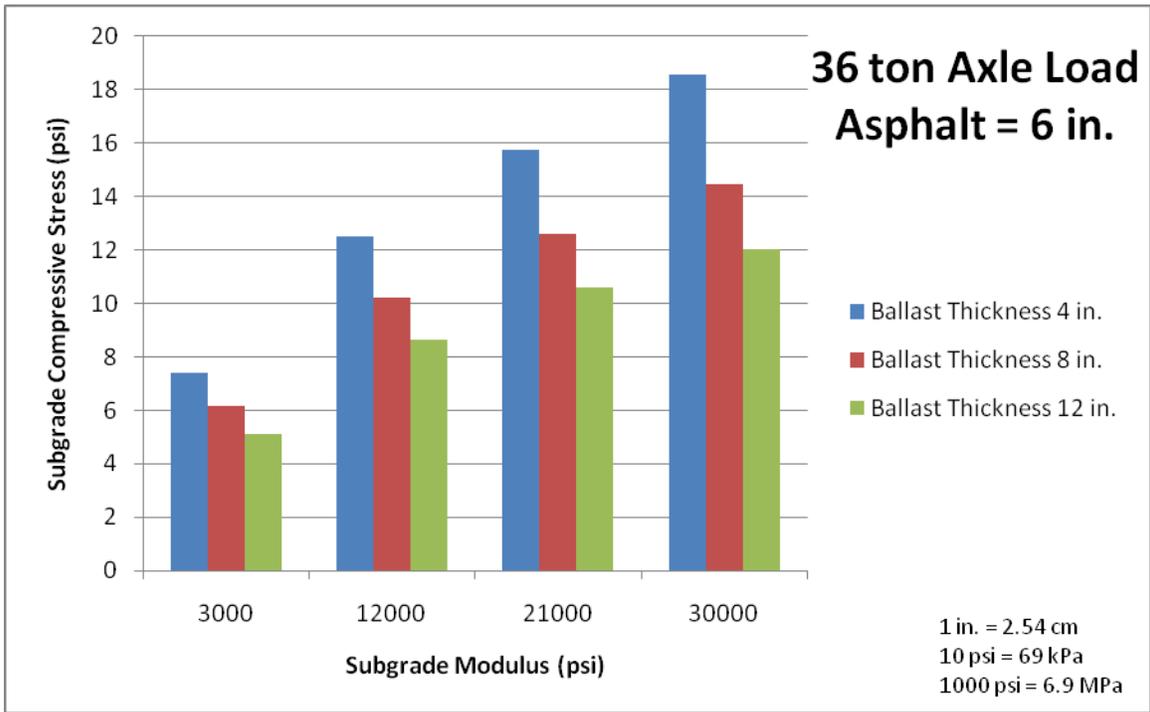


Figure 8a. Effect of Ballast Thickness and Subgrade Modulus on Subgrade Compressive Stress for Asphalt Trackbed.

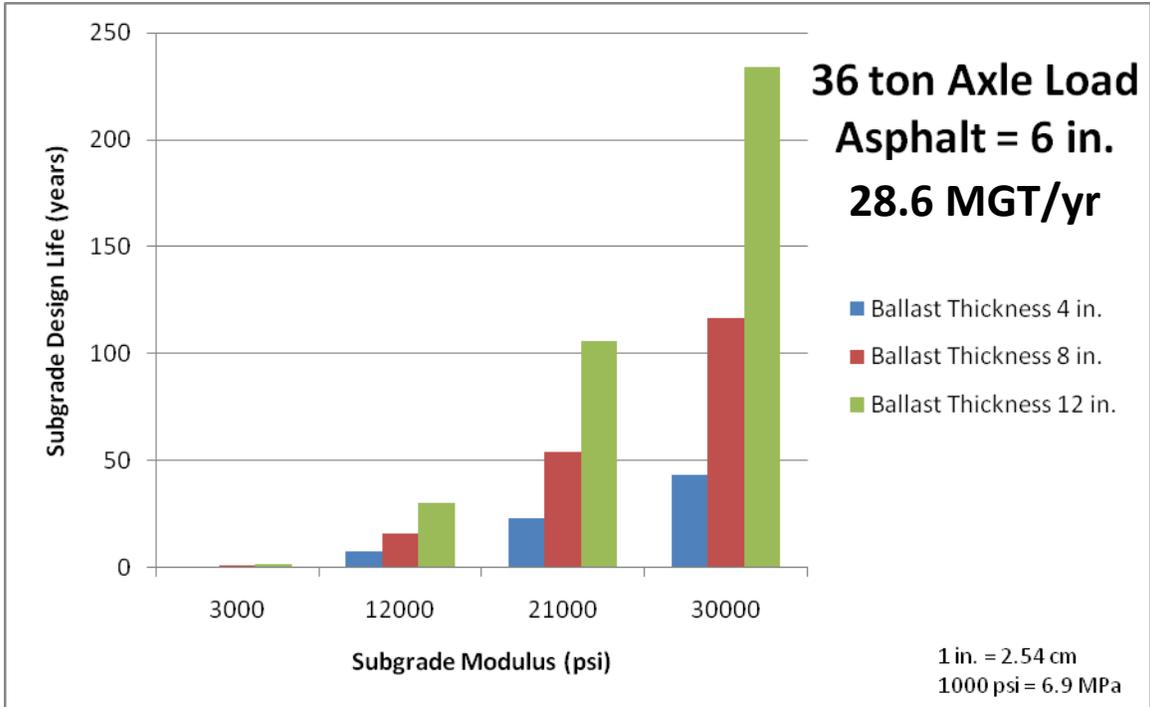


Figure 8b. Effect of Ballast Thickness and Subgrade Modulus on Subgrade Design Life for Asphalt Trackbed.

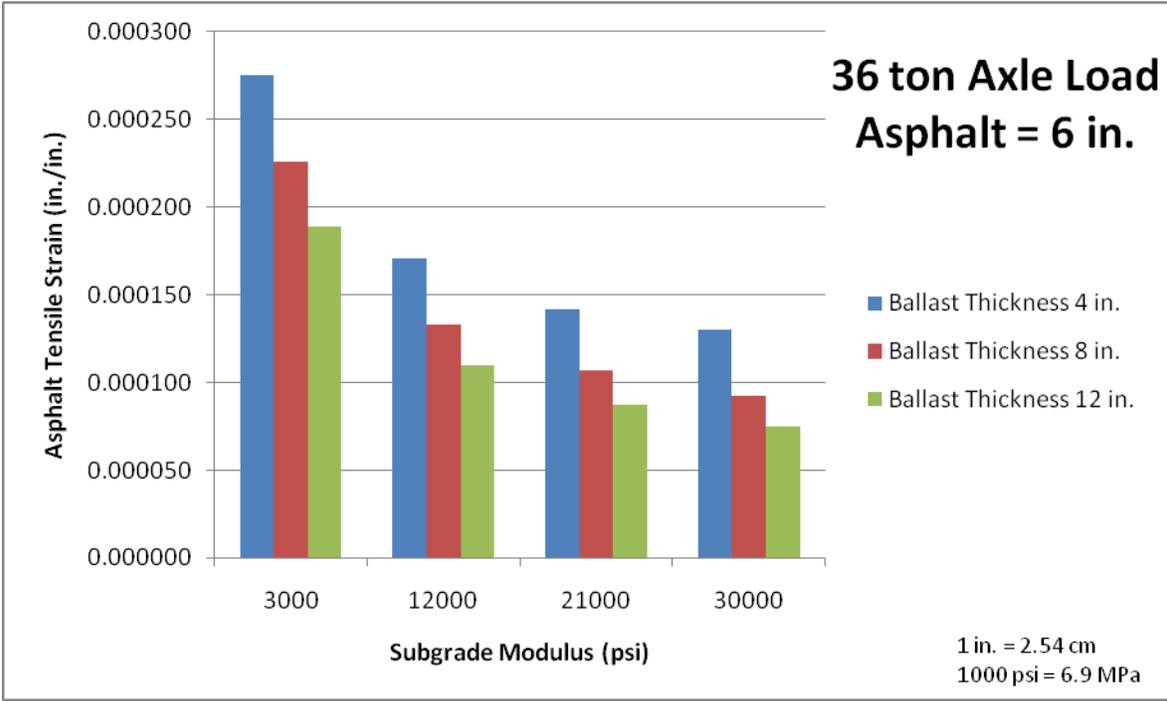


Figure 8c. Effect of Ballast Thickness and Subgrade Modulus on Asphalt Tensile Strain for Asphalt Trackbed.

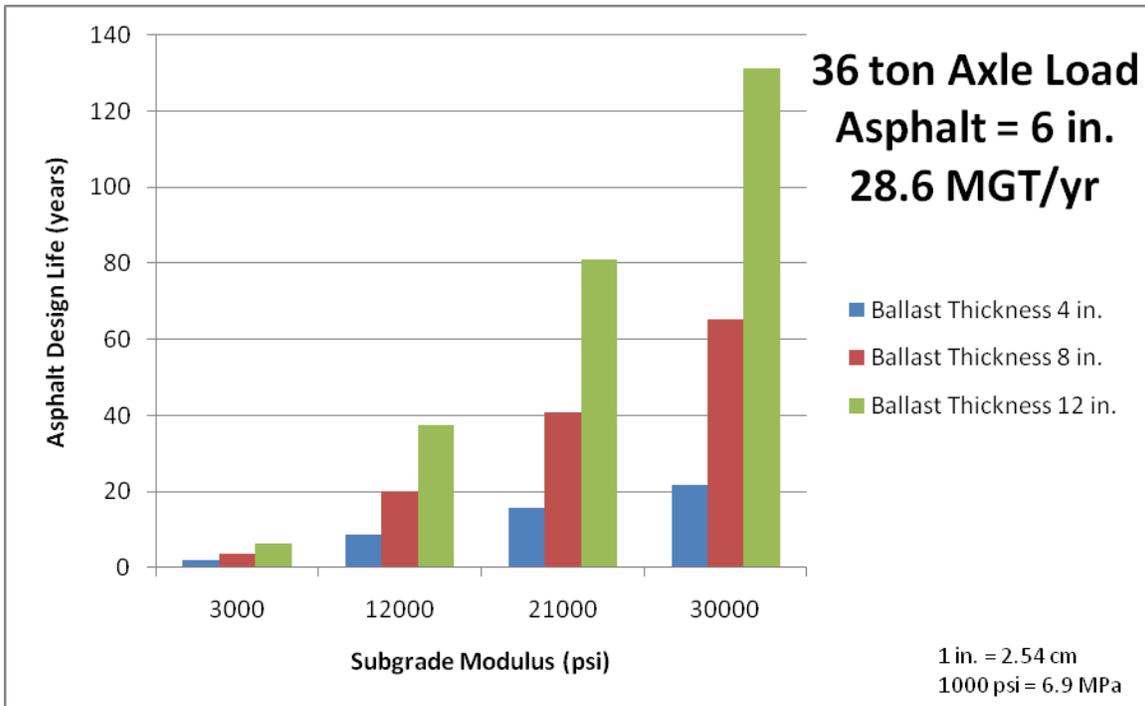


Figure 8d. Effect of Ballast Thickness and Subgrade Modulus on Asphalt Design Life for Asphalt Trackbed.