THICKNESS EQUIVALENCIES FOR ASPHALT-TREATED AND UNTREATED AGGREGATE BASE COURSE LAYERS

MICHIGAN
RESEARCH LABORATORY SECTION

MICHIGAN DEPARTMENT OF
STATE HIGHWAYS AND TRANSPORTATION

THICKNESS EQUIVALENCIES FOR ASPHALT-TREATED AND UNTREATED AGGREGATE BASE COURSE LAYERS

F. T. Hsia

Research Laboratory Section
Testing and Research Division
Research Project 68 E-42
Research Report No. R-1025

Lansing, November 1976

Base course material for flexible pavements can be divided into the following three major categories: untreated aggregate, asphalt-treated material, and portland cement-treated material. Asphalt-treated base courses, commonly referred to as "black base," are reported to increase the strength of the pavement as a whole, and act as a waterproofer, maintaining base strength under all moisture conditions. The general superiority of black bases was demonstrated in the AASHTO Road Test where it was observed that test sections constructed of untreated aggregate bases were inferior to those of a black base or cement-treated base, as measured by rut depth increases (1).

Although black bases may outperform aggregate bases, they have the disadvantage of higher cost and, to be successful, must contain only high quality aggregate (2). For example, an extremely dirty gravel with a high fines content and some plasticity may be worsened by the addition of bituminous material. In view of these facts, the design engineer must decide whether black base offers an advantage over aggregate bases and if so, he must determine an economical thickness to use while obtaining a structural strength equivalent to conventional methods.

In this study, pavements are considered to have the same structural strength when their subgrade compressive strains are equal. To determine these strains, a multi-layer elastic analysis computer program was used. Thickness equivalency was estimated by comparing the thickness of black base required to produce the same strength as obtained by a standard thickness of 22A aggregate base.

Criterion Used to Determine Equivalency

Figure 1 shows the typical structures of aggregate base and black base pavement as used in Michigan. In this figure h_i, E_i, and ν_i (where i = 1, 2, 3, . . .) are thickness, resilient modulus, and Poisson's ratio for each layer, respectively. Three criteria can be used, under a certain loading condition, to evaluate structural strength of pavements: surface deflection; tensile strain at the bottom of the asphalt concrete, or; vertical compressive strain on the subgrade (3). Surface deflection criteria are used because AASHTO Road Test results have shown that this factor correlates well with observed performance. Tensile strain in the asphalt concrete is used because several investigators have shown the significance of the magnitude on the fatigue life of asphalt concrete pavements. Vertical compressive strain on the subgrade has been found to have a direct correlation with performance, particularly in terms of riding quality and rut depth. On the basis of a computer study performed by the Research Laboratory it was

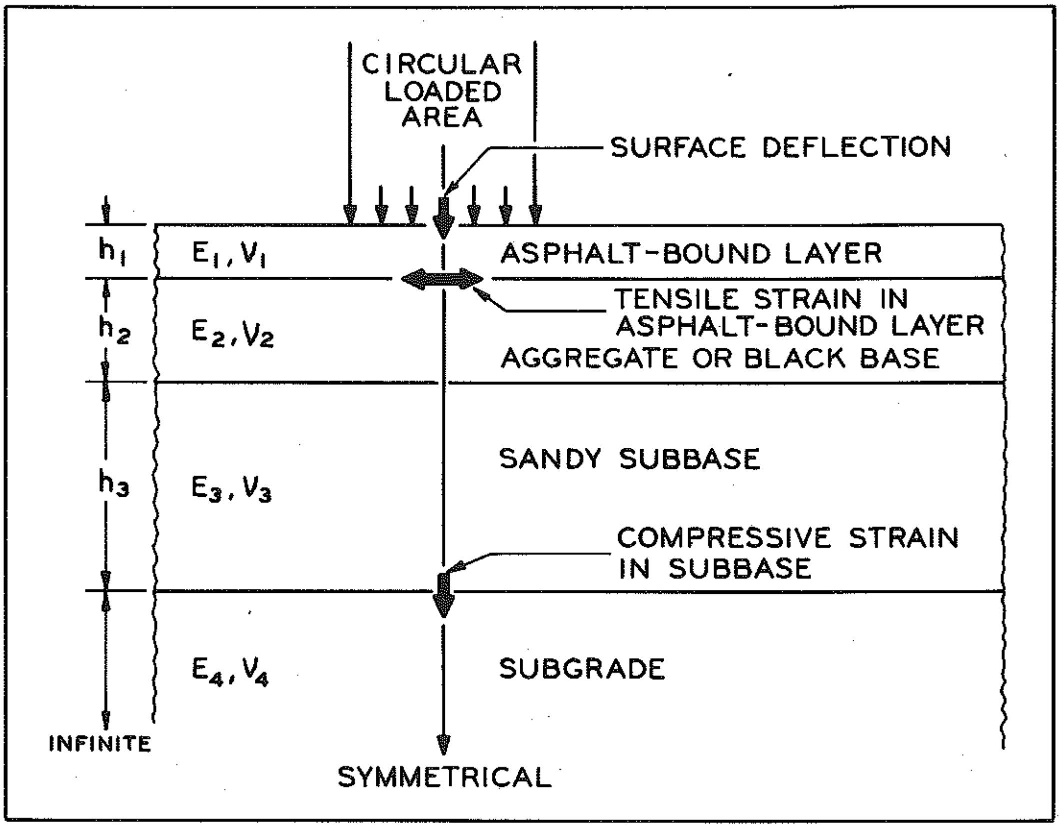

Figure 1. Typical structure of pavement layered system as used in Michigan.

decided that tensile strain and surface deflection are not satisfactory criteria for evaluating structural strength because both are dependent upon accurate measurement of Poisson's ratio which, as indicated in Ref. (4), can hardly be achieved using present laboratory methods. In addition, the pavement surface consists of layers of bituminous concrete which are viscoelastic in nature and very difficult to analyze under traffic loading conditions. Reference (5) points out some of these difficulties. For example, it was found that surface deflections increased when softer subgrades were used, but this condition did not lead to higher tensile stresses and strains at the bottom of the asphalt-bound layers.

Reference (5) also indicates that the most promising design parameter for flexible pavements is the compressive strain developed at the top of the supporting subgrade. This statement agrees with previous research findings (6).

As a result of the above discussion, compressive strain at the top of the subgrade, shown in Figure 1, was used in this study as the criterion for determining equivalent thicknesses of black bases. The basic assumption for determining thickness equivalency is that for any given pavement cross-section, where the only variables are base thickness and material (resilient modulus), alternative bases will be considered to yield equivalent pavement performance when any given pavement loading results in the same subgrade compressive strain.

Compressive Strain Computations

Compressive strains for pavement sections of various thicknesses and resilient moduli combinations can be computed by the CHEV5LM computer program developed by the Chevron Research Company. This program is capable of analyzing a five-layered elastic system when a single vertical uniform circular load is applied at the surface of the system (Fig. 1). Basic assumptions used in this program are:

1) The subgrade (bottom layer) of the system is semi-infinite, all other layers are of uniform thickness,

2) All layers extend infinitely in the horizontal direction,

3) The top surface of the system is free of shear,

4) All interfaces between layers have full continuity of stress and displacements,

5) Homogeneity and isotropy of the material is assumed in each layer.

A shortcoming of CHEV5LM, in its original form, is that it does not calculate compressive strains on the subgrade. A modification of the program was made by the Research Laboratory to build this characteristic into the system. According to the basic theory of continuous mechanics (7), strain tensor, ϵ_{ij}, is expressed in terms of stress tensor, σ_{ij} or σ_{kk}, and engineering constants, E and ν, as:

$$\epsilon_{ij} = \frac{1}{E}\left[(1+\nu)\sigma_{ij} - \nu\sigma_{kk}\delta_{ij}\right] \qquad (1)$$

where δ_{ij} is the Kronecker delta function, that is:

$$\delta_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}$$

TABLE 1
TYPICAL RESILIENT MODULUS VALUES FOR FLEXIBLE PAVEMENT MATERIALS BASED ON LITERATURE SURVEY

	Material	Environmental Condition	Range of Resilient Modulus, psi	Recommended Design Modulus, psi
Subgrade	clays, silts, loams, etc. (poor subgrade)	winter (frozen)	> 10,000	10,000
		winter-spring (unfrozen)	1,000 to 3,000	2,000
		summer	2,000 to 5,000	3,000
	loamy sands, gravels, etc. (fair subgrade)	winter (frozen)	> 10,000	10,000
		winter-spring (unfrozen)	3,000 to 10,000	5,000
		summer	5,000 to 15,000	10,000
	sand-gravels of low fines cont. (good subgrade)	winter (frozen)	> 15,000	15,000
		winter-spring (unfrozen)	10,000 to 20,000	12,000
		summer	12,000 to 25,000	15,000
Subbase	sands	winter (frozen)	> 15,000	15,000
		winter-spring (unfrozen)	8,000 to 15,000	10,000
		summer	12,000 to 20,000	15,000
Base	hot mix-asphalt treated gravel (good aggregate)[1]	winter < 40°F	300,000 to 1,000,000	500,000
		winter-spring 40 to 80°F	150,000 to 500,000	300,000
		summer > 80°F	15,000 to 150,000	100,000
	hot mix-asphalt treated gravel (poor aggregate)[2]	winter < 40°F	100,000 to 300,000	200,000
		winter-spring 40 to 80°F	50,000 to 150,000	100,000
		summer > 80°F	25,000 to 75,000	50,000
	aggregate base	winter (frozen)	> 20,000	20,000
		spring-fall (unfrozen)	10,000 to 20,000	15,000
		summer	15,000 to 30,000	20,000
Surface	bituminous concrete aggregate	winter < 40°F	> 600,000	900,000
		spring-fall 40 to 80°F	300,000 to 1,000,000	600,000
		summer > 80°F	< 300,000	150,000

[1] Assuming use of good quality aggregates such as 20A or 21A.
[2] Assuming use of poor quality aggregates such as 23A or 24A.

CHEV5LM uses the cylindrical coordinate system, therefore, vertical compressive strain on the top of the subgrade, ϵ_c, is deduced from Eq. (1) as:

$$\epsilon_c = \epsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - \nu \ (\sigma_{rr} + \sigma_{\theta\theta})\right] \tag{2}$$

where σ_{zz} = vertical stress in the subgrade

σ_{rr} = radial stress in the subgrade

$\sigma_{\theta\theta}$ = tangential stress in the subgrade

ν = Poisson's ratio of the subgrade

E = resilient modulus of the subgrade

ϵ_{zz} = vertical strain in the subgrade

Equation (2) was programmed into CHEV5LM to allow computation of the vertical compressive strain on top of the subgrade in the principal direction, the symmetrical line of the circular load as shown in Figure 1.

Properties of Michigan Flexible Pavement Components

An important input item for the CHEV5LM program is the resilient modulus for each material in the layered system. At present, these values have not been established by the Department. However, the resilient modulus values summarized in Table 1, based on data found in the literature, may be used as a guide for design purposes until more accurate data are available.

Although other states generally do not use a subbase layer for flexible pavements, Michigan includes this layer in order to provide satisfactory drainage and reduce subgrade stress. Typical Michigan flexible pavement systems for aggregate base and black base are illustrated in Figure 2.

On the basis of published resilient modulus values and typical Michigan cross-section plans, the layer properties such as E, ν , and h were generalized as shown in Figure 3. Values in this figure were programmed into the CHEV5LM program to compute compressive strains at the top of the subgrade.

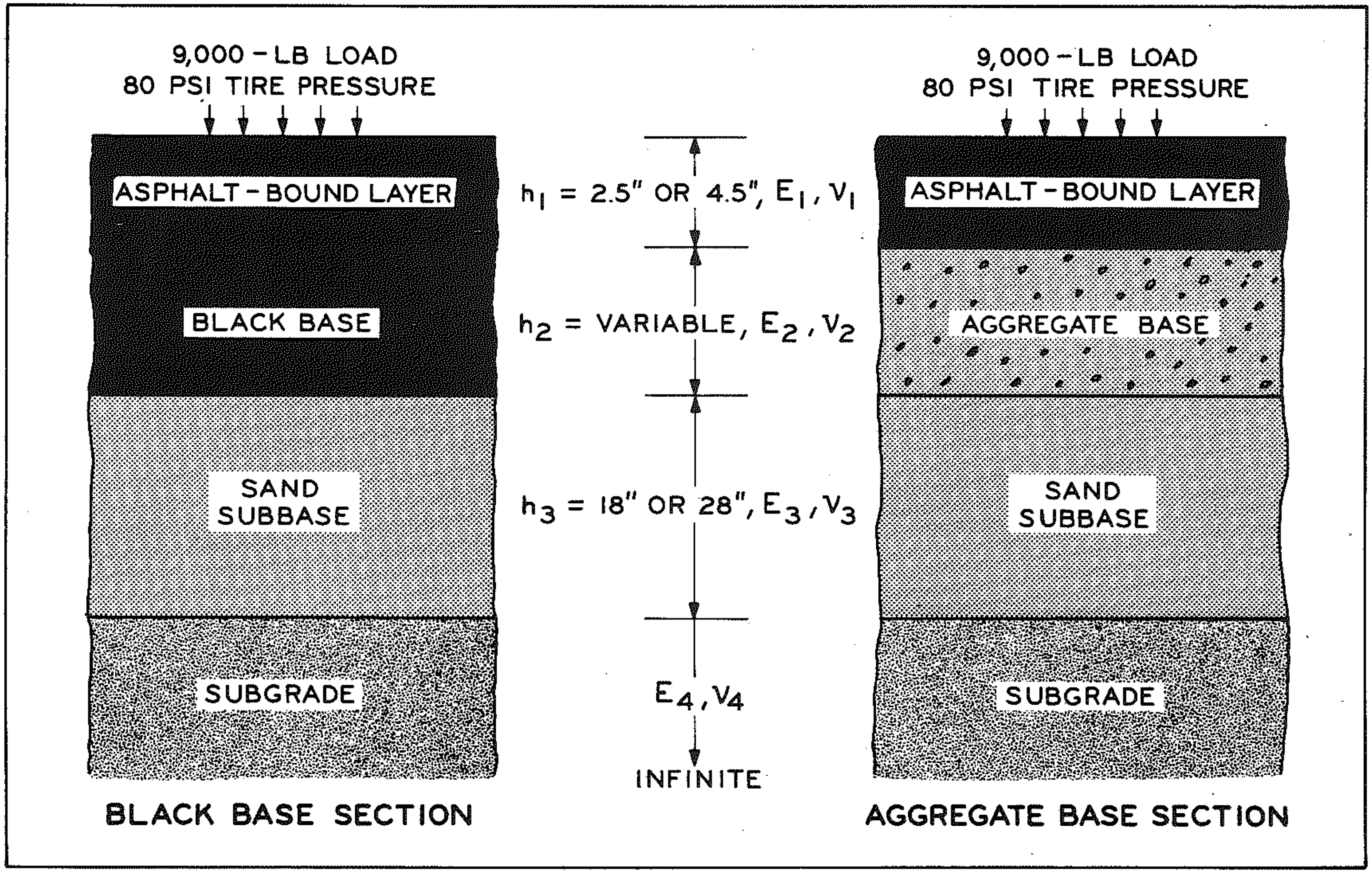

Figure 2. Flexible pavement systems used in Michigan.

	PROPERTIES	BLACK BASE SYSTEM*	AGGREGATE BASE SYSTEM
SURFACE	E_1 (PSI)	150,000 (SUMMER), 600,000 (SPRING AND FALL)	
	V_1	0.35	
	h_1 (IN.)	2.5 (GENERAL USE), 4.5 (INTERSTATE TRUNKLINE ONLY)	
BASE	E_2 (PSI)	50,000, 150,000, 300,000	15,000, 25,000
	V_2	0.40	0.35
	h_2 (IN.)	2, 4, 6, 8	2, 4, 6, 8, 11
SUBBASE	E_3 (PSI)	10,000 (WEAK), 20,000 (STRONG)	
	V_3	0.40	
	h_3 (IN.)	18, 28	
SUBGRADE	E_4 (PSI)	3,000 (POOR) 7,500 (FAIR) 15,000 (GOOD)	
	V_4	0.50	

* CAN ALSO BE ADAPTED TO OTHER BASE COURSE MATERIAL SUCH AS CEMENT TREATED BASE.

Figure 3. Generalized section properties for Michigan pavement systems.

Development of Strain-Thickness Curves

Computer solutions of the compressive strain for the various pavement combinations included in Figure 3 are given in Table 2. From these subgrade compressive strain data, 48 different sets of strain-thickness curves were plotted to show the relationship between subgrade compressive strain and base thickness for various levels of base modulus. Figure 4 is typical of one set of these curves plotted from data of column 4 of Table 2a with all other properties of the section being constant as shown in the small box of the figure. Strain-thickness curves provide the information required to construct the base thickness-equivalency curves which are used to estimate the equivalent thickness of black base or any other kind of base when used as a substitute for standard aggregate base.

Construction of Base Thickness Equivalency Curves

From the strain-thickness curves in Figure 4, it is possible to replot, for constant levels of subgrade compressive strain, base thickness as a function of base resilient modulus. These base thickness equivalency curves are shown in Figure 5 on a log-log scale. Three constant strain values in Figure 4 (6.0×10^{-4}, 4.95×10^{-4}, and 3.85×10^{-4}) representing the maximum, intermediate, and minimum strain values which intercept all five modulus curves, were used to plot these curves.

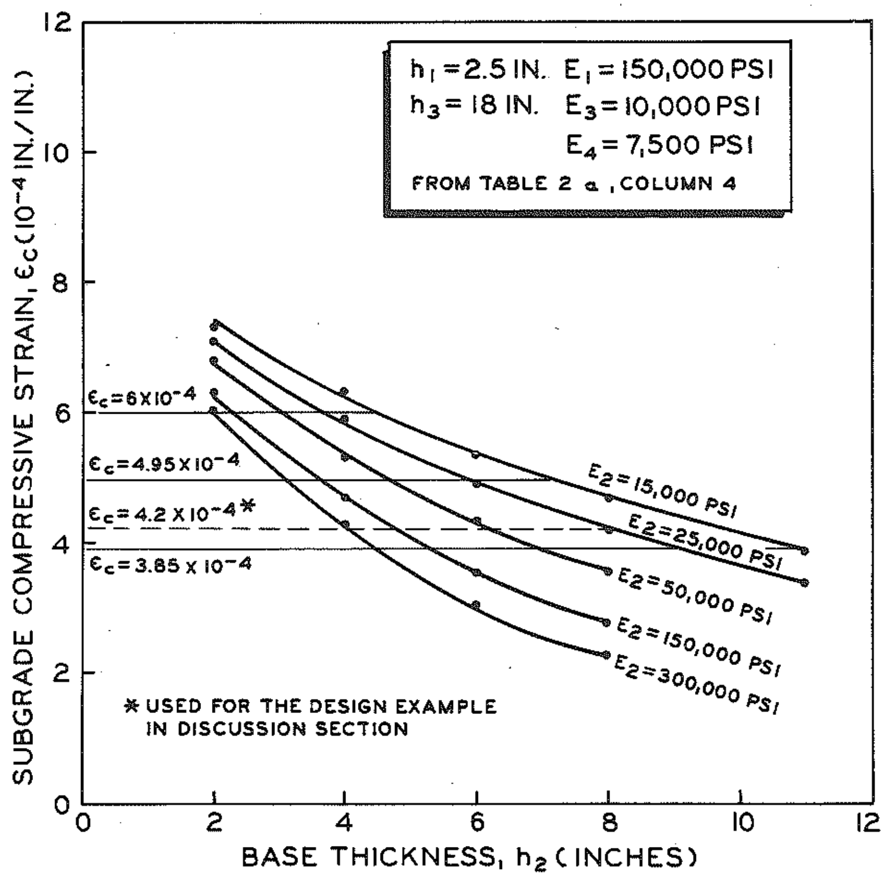

Figure 4. Compressive strain on the subgrade as a function of base thickness and base modulus.

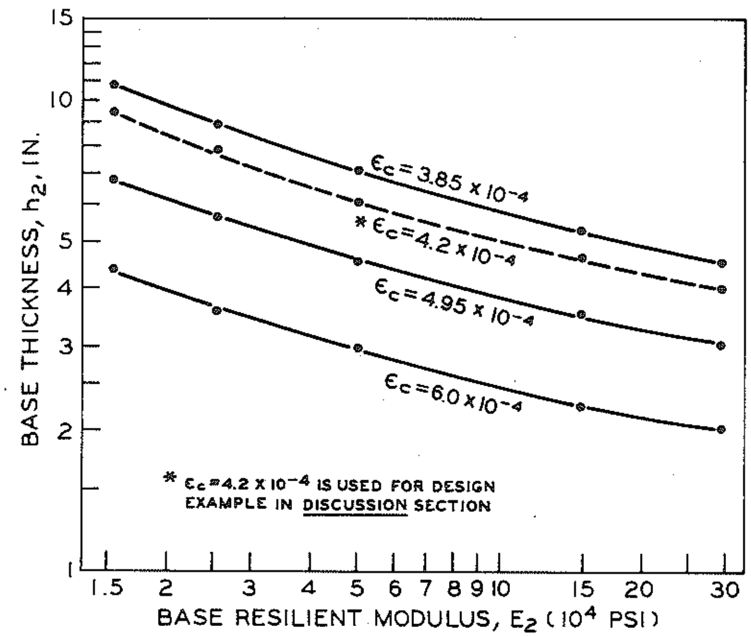

Figure 5. Base thickness equivalency curves - illustration of the parallelism of curves for different strain values.

TABLE 2a

COMPRESSIVE STRAIN VALUES IN (10^{-4} in.) ON THE SUBGRADE WITH ASPHALTIC CONCRETE THICKNESS, h_1 = 2.5 in. AND ASPHALTIC CONCRETE MODULUS, E_1 = 150,000 psi

Base Modulus, E_2, psi	Base Thickness, h_2, in.	Subbase Thickness, h_3											
		18 in.						28 in.					
		Subbase Modulus, E_3, psi						Subbase Modulus, E_3, psi					
		10,000			20,000			10,000			20,000		
		Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi		
		3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000
15,000	2	11.882	7.365	4.552	8.504	5.974	4.078	6.162	3.884	2.426	4.234	3.004	2.078
	4	10.020	6.249	3.875	7.378	5.199	3.555	5.404	3.413	2.139	3.823	2.707	1.873
	6	8.561	5.375	3.345	6.439	4.545	3.113	4.785	3.026	1.902	3.467	2.447	1.694
	8	7.397	4.670	2.917	5.658	3.997	2.742	4.271	2.702	1.702	3.157	2.220	1.537
	11	6.047	3.842	2.414	4.723	3.333	2.291	3.649	2.305	1.456	2.767	1.933	1.336
25,000	2	11.466	7.107	4.394	8.168	5.744	3.924	6.024	3.796	2.374	4.120	2.924	2.024
	4	9.366	5.850	3.630	6.903	4.880	3.346	5.162	3.262	2.046	3.646	2.583	1.791
	6	7.806	4.915	3.064	5.910	4.194	2.886	4.478	2.835	1.785	3.253	2.298	1.596
	8	6.609	4.194	2.629	5.115	3.639	2.513	3.928	2.489	1.573	2.925	2.059	1.431
	11	5.273	3.377	2.135	4.195	2.987	2.073	3.284	2.077	1.318	2.526	1.764	1.227
50,000	2	10.962	6.784	4.188	7.806	5.487	3.747	5.875	3.701	2.311	4.017	2.848	1.971
	4	8.551	5.328	3.300	6.342	4.482	3.073	4.884	3.081	1.932	3.460	2.447	1.698
	6	6.852	4.310	2.684	5.255	3.732	2.572	4.115	2.601	1.638	3.015	2.124	1.477
	8	5.612	3.566	2.238	4.428	3.155	2.186	3.513	2.222	1.406	2.655	1.861	1.296
	11	*	*	*	*	*	*	*	*	*	*	*	*
150,000	2	10.291	6.334	3.897	7.488	5.248	3.576	5.708	3.582	2.233	3.942	2.792	1.931
	4	7.497	4.643	2.862	5.751	4.045	2.764	4.542	2.851	1.783	3.289	2.316	1.604
	6	5.620	3.526	2.191	4.506	3.183	2.189	3.644	2.291	1.441	2.762	1.930	1.340
	8	4.326	2.754	1.733	3.606	2.557	1.774	2.961	1.859	1.177	2.343	1.623	1.129
	11	*	*	*	*	*	*	*	*	*	*	*	*
300,000	2	9.874	6.053	3.714	7.328	5.124	3.484	5.602	3.508	2.182	3.916	2.768	1.914
	4	6.830	4.219	2.594	5.391	3.777	2.574	4.304	2.693	1.681	3.186	2.233	1.545
	6	4.841	3.043	1.894	4.026	2.834	1.947	3.307	2.071	1.303	2.589	1.797	1.245
	8	3.534	2.259	1.432	3.080	2.176	1.512	2.164	1.605	1.017	2.125	1.457	1.011
	11	*	*	*	*	*	*	*	*	*	*	*	*

* Not required in this project.

TABLE 2b
COMPRESSIVE STRAIN VALUES IN (10^{-4} in.) ON THE SUBGRADE WITH ASPHALTIC CONCRETE THICKNESS, h_1 = 2.5 in. AND ASPHALTIC CONCRETE MODULUS, E_1 = 600,000 psi

Base Modulus, E_2, psi	Base Thick-ness, h_2, in.	Subbase Thickness, h_3											
		18 in.						28 in.					
		Subbase Modulus, E_3, psi						Subbase Modulus, E_3, psi					
		10,000			20,000			10,000			20,000		
		Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi		
		3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000
	2	10.122	6.260	3.856	7.512	5.286	3.608	5.608	3.526	2.202	3.954	2.798	1.938
	4	8.709	5.431	3.362	6.600	4.653	3.183	4.966	3.130	1.962	3.603	2.540	1.759
15,000	6	7.565	4.753	2.957	5.828	4.112	2.817	4.434	2.797	1.758	3.292	2.312	1.600
	8	6.626	4.188	2.618	5.177	3.651	2.505	3.987	2.514	1.584	3.018	2.110	1.458
	11	5.507	3.501	2.203	4.384	3.084	2.119	3.439	2.162	1.365	2.667	1.850	1.277
	2	9.806	6.074	3.746	7.216	5.092	3.484	5.474	3.446	2.154	3.832	2.714	1.883
	4	8.170	5.115	3.175	6.173	4.380	3.012	4.720	2.981	1.872	3.412	2.409	1.674
25,000	6	6.903	4.366	2.729	5.342	3.803	2.627	4.114	2.603	1.642	3.062	2.154	1.498
	8	5.906	3.768	2.372	4.670	3.328	2.308	3.624	2.292	1.452	2.769	1.939	1.349
	11	4.774	3.071	1.952	3.880	2.762	1.924	3.050	1.921	1.220	2.408	1.672	1.162
	2	9.350	5.792	3.572	6.840	4.830	3.310	5.298	3.336	2.086	3.692	2.614	1.815
	4	7.364	4.616	2.867	5.574	3.963	2.733	4.380	2.766	1.739	3.168	2.234	1.555
50,000	6	5.922	3.761	2.358	4.638	3.313	2.301	3.670	2.321	1.468	2.757	1.933	1.349
	8	4.865	3.123	1.978	3.929	2.812	1.966	3.124	1.972	1.253	2.430	1.692	1.181
	11	*	*	*	*	*	*	*	*	*	*	*	*
	2	8.498	5.250	3.230	6.354	4.476	3.062	4.996	3.138	1.959	3.538	2.496	1.732
	4	6.055	3.795	2.356	4.782	3.388	2.334	3.851	2.423	1.523	2.880	2.018	1.403
150,000	6	4.483	2.861	1.804	3.720	2.649	1.844	3.028	1.904	1.207	2.388	1.657	1.155
	8	3.446	2.224	1.425	2.984	2.126	1.495	2.440	1.523	0.970	2.019	1.384	0.965
	11	*	*	*	*	*	*	*	*	*	*	*	*
	2	7.824	4.820	2.962	6.018	4.224	2.882	4.754	2.976	1.857	3.438	2.420	1.675
	4	5.239	3.289	2.045	4.304	3.038	2.089	3.504	2.198	1.382	2.711	1.888	1.310
300,000	6	3.688	2.362	1.498	3.203	2.271	1.582	2.647	1.655	1.050	2.180	1.499	1.042
	8	2.726	1.759	1.136	2.476	1.752	1.235	2.066	1.274	0.809	1.792	1.211	0.841
	11	*	*	*	*	*	*	*	*	*	*	*	*

* Not required in this project.

TABLE 2c

COMPRESSIVE STRAIN VALUES IN (10^{-4} in.) ON THE SUBGRADE WITH ASPHALTIC CONCRETE THICKNESS, h_1 = 4.5 in. AND ASPHALTIC CONCRETE MODULUS, E_1 = 150,000 psi

Base Modulus, E_2, psi	Base Thickness, h_2, in.	Subbase Thickness, h_3											
		18 in.						28 in.					
		Subbase Modulus, E_3, psi						Subbase Modulus, E_3, psi					
		10,000			20,000			10,000			20,000		
		Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi		
		3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000
15,000	2	8.796	5.456	3.368	6.640	4.672	3.190	5.034	3.168	1.982	3.610	2.550	1.766
	4	7.629	4.768	2.957	5.873	4.138	2.832	4.485	2.828	1.775	3.303	2.325	1.610
	6	6.683	4.206	2.621	5.216	3.677	2.520	4.030	2.542	1.601	3.029	2.123	1.469
	8	5.900	3.734	2.338	4.658	3.281	2.252	3.646	2.298	1.450	2.787	1.944	1.344
	11	4.958	3.154	1.988	3.974	2.792	1.919	3.171	1.991	1.259	2.475	1.713	1.182
25,000	2	8.504	5.280	3.264	6.370	4.492	3.074	4.906	3.090	1.935	3.498	2.470	1.713
	4	7.164	4.493	2.793	5.500	3.895	2.678	4.269	2.696	1.696	3.133	2.207	1.532
	6	6.127	3.879	2.427	4.800	3.409	2.354	3.757	2.375	1.500	2.828	1.984	1.379
	8	5.302	3.383	2.132	4.228	3.006	2.083	3.339	2.109	1.337	2.571	1.795	1.248
	11	4.347	2.793	1.777	3.548	2.519	1.753	2.841	1.787	1.135	2.252	1.559	1.082
50,000	2	8.124	5.044	3.116	6.066	4.278	2.928	4.758	2.996	1.876	3.382	2.388	1.656
	4	6.535	4.101	2.550	5.031	3.567	2.456	4.001	2.525	1.589	2.941	2.067	1.437
	6	5.367	3.407	2.137	4.249	3.025	2.096	3.412	2.154	1.363	2.589	1.810	1.261
	8	4.485	2.874	1.820	3.643	2.598	1.811	2.947	1.857	1.180	2.303	1.600	1.115
	11	*	*	*	*	*	*	*	*	*	*	*	*
150,000	2	7.496	4.642	2.862	5.752	4.044	2.764	4.542	2.852	1.783	3.290	2.316	1.604
	4	5.620	3.526	2.191	4.506	3.183	2.189	3.644	2.291	1.441	2.762	1.930	1.340
	6	4.326	2.754	1.733	3.606	2.557	1.774	2.961	1.859	1.177	2.343	1.623	1.129
	8	3.414	2.195	1.400	2.946	2.091	1.463	2.443	1.524	0.969	2.013	1.378	0.959
	11	*	*	*	*	*	*	*	*	*	*	*	*
300,000	2	7.072	4.374	2.692	5.576	3.912	2.668	4.398	2.754	1.720	3.250	2.282	1.578
	4	5.080	3.189	1.983	4.210	2.965	2.035	3.427	2.147	1.349	2.670	1.857	1.286
	6	3.735	2.383	1.505	3.234	2.286	1.585	2.688	1.679	1.063	2.203	1.515	1.051
	8	2.824	1.817	1.166	2.542	1.794	1.367	2.143	1.324	0.840	1.839	1.245	0.863
	11	*	*	*	*	*	*	*	*	*	*	*	*

* Not required in this project.

TABLE 2d

COMPRESSIVE STRAIN VALUES IN (10^{-4} in.) ON THE SUBGRADE WITH ASPHALTIC CONCRETE THICKNESS, h1 = 4.5 in. AND ASPHALTIC CONCRETE MODULUS, E_1 = 600,000 psi

Base Modulus, E_2, psi	Base Thick-ness, h_2, in.	Subbase Thickness, h_3											
		18 in.						28 in.					
		Subbase Modulus, E_3, psi						Subbase Modulus, E_3, psi					
		10,000			20,000			10,000			20,000		
		Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi			Subgrade Modulus, E_4, psi		
		3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000	3,000	7,500	15,000
	2	6.355	3.941	2.429	5.126	3.590	2.447	4.063	2.543	1.590	3.097	2.162	1.493
	4	5.703	3.563	2.209	4.631	3.242	2.213	3.700	2.317	1.454	2.872	1.996	1.376
15,000	6	5.142	3.233	2.016	4.197	2.934	2.006	3.388	2.120	1.333	2.667	1.844	1.270
	8	4.655	2.939	1.843	3.821	2.665	1.823	3.116	1.945	1.225	2.482	1.707	1.174
	11	4.041	2.559	1.614	3.346	2.323	1.590	2.768	1.718	1.082	2.238	1.527	1.047
	2	6.219	3.866	2.387	4.970	3.494	2.390	3.983	2.496	1.564	3.009	2.103	1.456
	4	5.457	3.430	2.135	4.404	3.106	2.136	3.550	2.229	1.404	2.738	1.906	1.321
25,000	6	4.817	3.055	1.918	3.932	2.777	1.919	3.186	2.000	1.264	2.506	1.736	1.203
	8	4.277	2.730	1.728	3.535	2.495	1.730	2.878	1.802	1.142	2.306	1.589	1.101
	11	3.620	2.320	1.481	3.047	2.143	1.491	2.500	1.554	0.985	2.052	1.402	0.968
	2	6.011	3.744	2.314	4.762	3.354	2.299	3.872	2.429	1.523	2.906	2.030	1.407
	4	5.049	3.188	1.991	4.057	2.873	1.986	3.329	2.092	1.321	2.557	1.777	1.235
50,000	6	4.268	2.725	1.723	3.503	2.486	1.732	2.879	1.807	1.146	2.275	1.571	1.093
	8	3.645	2.343	1.497	3.060	2.171	1.521	2.516	1.570	0.998	2.043	1.400	0.973
	11	*	*	*	*	*	*	*	*	*	*	*	*
	2	5.516	3.447	2.135	4.441	3.129	2.148	3.644	2.285	1.435	2.772	1.932	1.340
	4	4.202	2.673	1.683	3.507	2.485	1.725	2.911	1.825	1.156	2.311	1.596	1.110
150,000	6	3.262	2.100	1.344	2.832	2.009	1.410	2.355	1.464	0.931	1.956	1.334	0.928
	8	2.608	1.681	1.089	2.344	1.654	1.171	1.950	1.194	0.758	1.685	1.131	0.785
	11	*	*	*	*	*	*	*	*	*	*	*	*
	2	5.048	3.165	1.966	4.171	2.937	2.016	3.429	2.148	1.350	2.668	1.854	1.285
	4	3.584	2.293	1.454	3.115	2.204	1.534	2.599	1.622	1.028	2.114	1.470	1.021
300,000	6	2.646	1.706	1.101	2.407	1.699	1.197	2.022	1.243	0.790	1.758	1.184	0.822
	8	2.049	1.311	0.854	1.928	1.346	0.955	1.633	0.980	0.619	1.476	0.973	0.670
	11	*	*	*	*	*	*	*	*	*	*	*	*

* Not required in this project.

Examination of Figure 5 raises the question, at what strain level should thickness equivalency be established, and is it different at different strain levels? Two findings from Figure 5, as well as from other base thickness equivalency curves developed during this study, lead to the answer of this question:

1) all curves are parallel to each other,

2) no matter which curve is used for comparison, the maximum difference in thickness ratio is within the range of $\pm$ 5 percent of the average ratio.

The first statement is obvious from observation whereas the second statement can be explained by using curves in Figure 5 as an example. For modulus values of 15, 000 psi, 50,000 psi, and 300,000 psi and compressive strain levels of 6.0×10^{-4}, 4.95×10^{-4}, and 3.85×10^{-4} the thickness equivalencies in inches are:

Strain Level	Base Modulus, psi		Thickness Ratio, aggregate/black	Base Modulus, psi		Thickness Ratio, aggregate/black
	Aggregate 15,000	Black 50,000		Aggregate 15,000	Black 300,000	
6.0×10^{-4}	4.4	3	1.47	4.4	2	2.2
4.95×10^{-4}	7	4.7	1.49	7	3.2	2.2
3.85×10^{-4}	11	7	1.57	11	4.6	2.4

The above data indicate that thickness ratio is relatively independent of strain level, hence any convenient strain value could be used to construct the base thickness equivalency curve.

Based on the above discussion, strain-thickness curves derived from Table 2 were replotted into 48 sets of base thickness equivalency curves, summarized in Figures 6 through 13. These curves represent the relationship between base thickness and modulus for a condition of equal subgrade compressive strain, presented as a family of parallel curves spaced for approximately 1-in. base thickness increments at E_2 = 15,000 psi.

As long as the resilient modulus of the base can be reasonably estimated, Figures 6 through 13 may be used to determine the thickness equivalency of any base material as compared to that of standard typical aggregate base material.

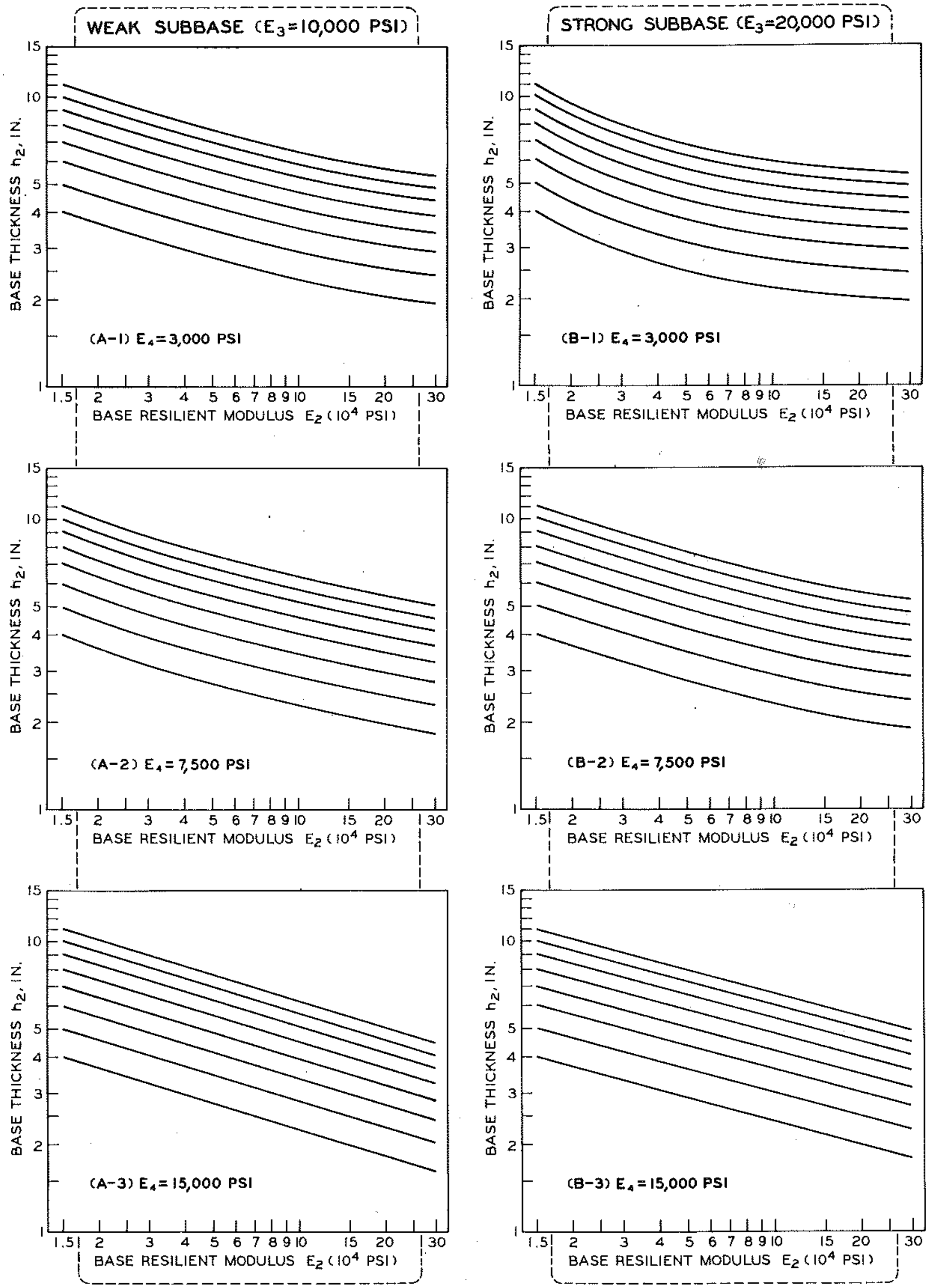

Figure 6. Thickness equivalency curves for 2.5 in. thick A.C. layer (h_1 = 2.5 in., h_3 = 18 in., E_1 = 150,000 psi - summer).

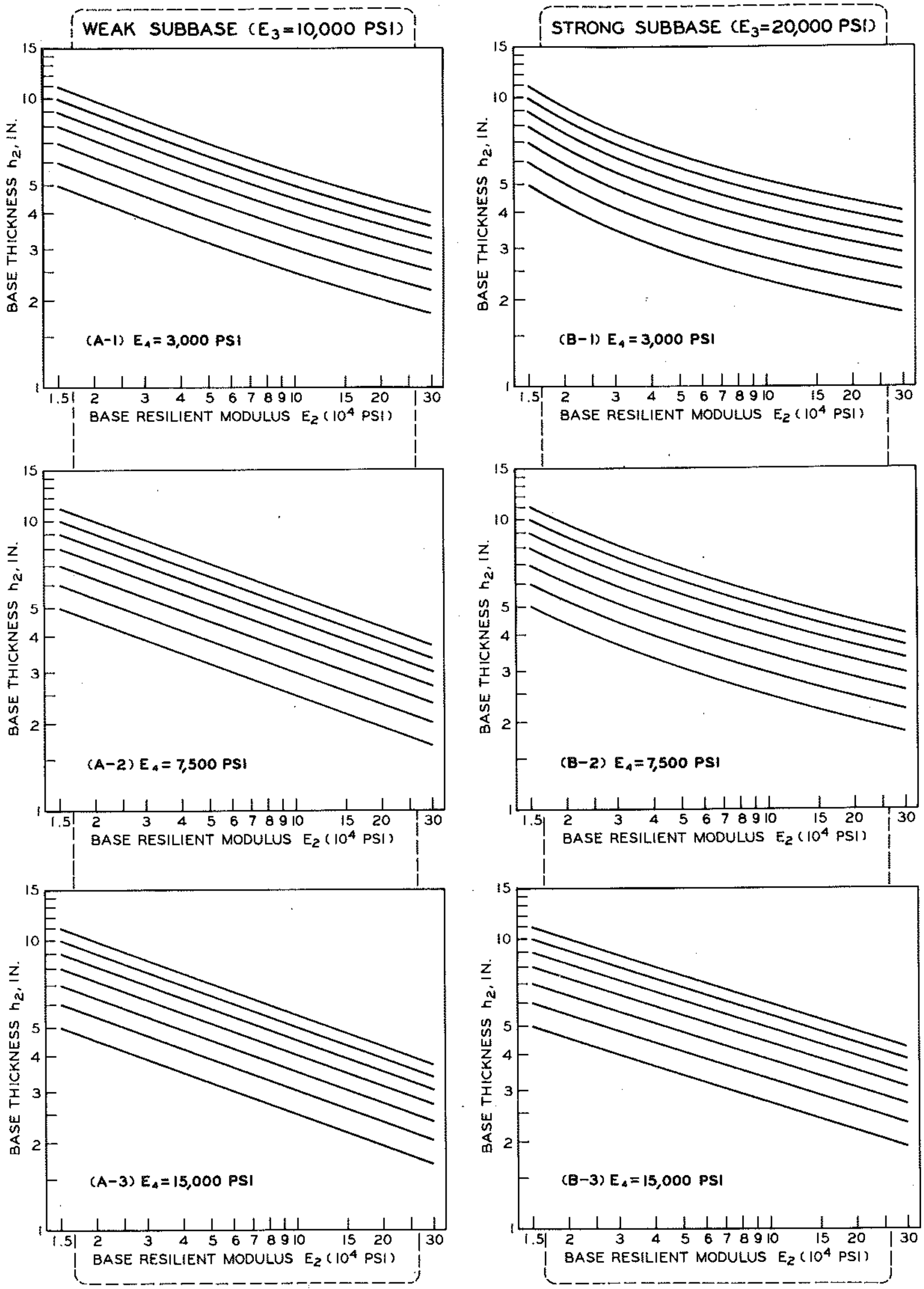

Figure 7. Thickness equivalency curves for 2.5 in. thick A.C. layer (h_1 = 2.5 in., h_3 = 18 in., E_1 = 600,000 psi - spring).

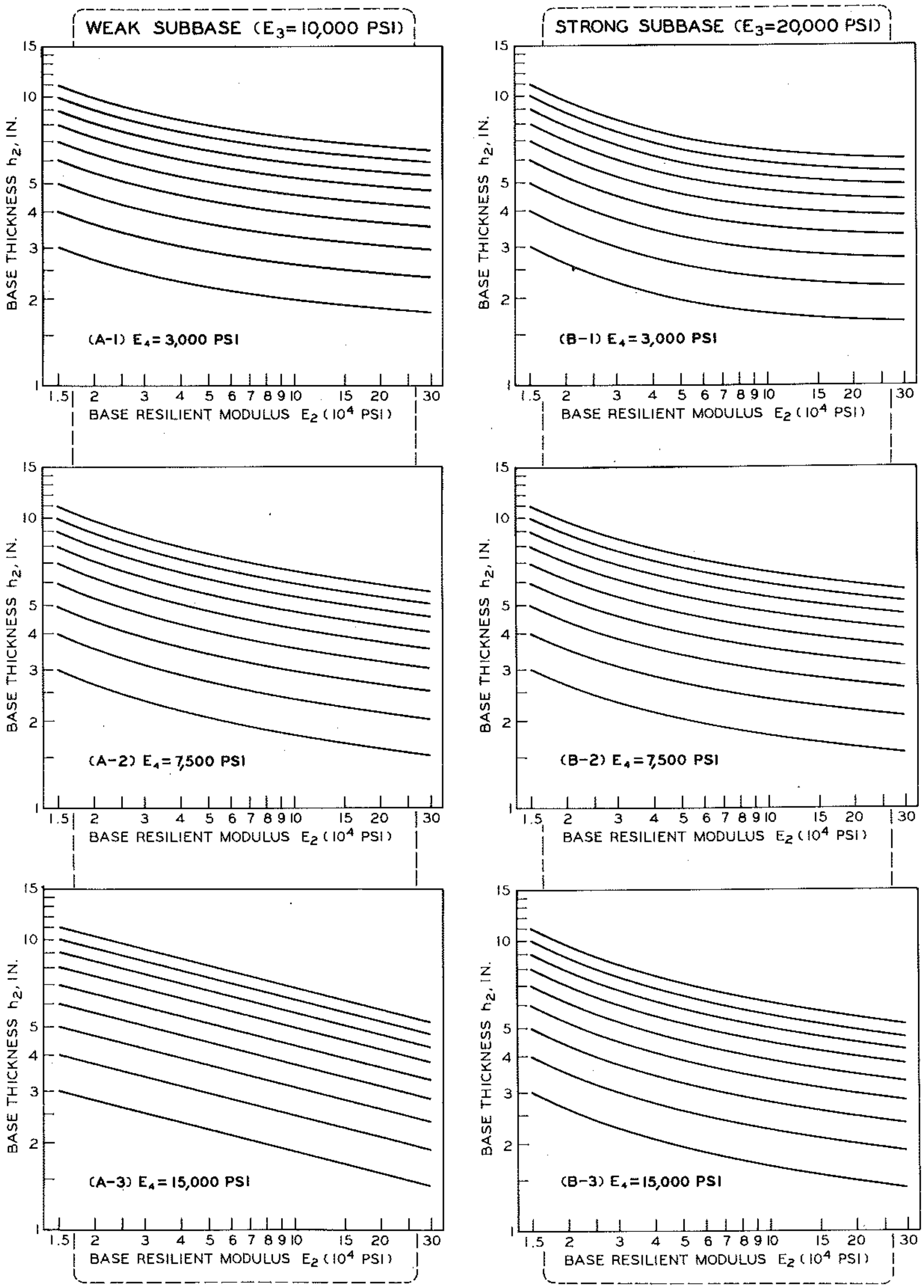

Figure 8. Thickness equivalency curves for 2.5 in. thick A.C. layer (h_1 = 2.5 in., h_3 = 28 in., E_1 = 150,000 psi - summer).

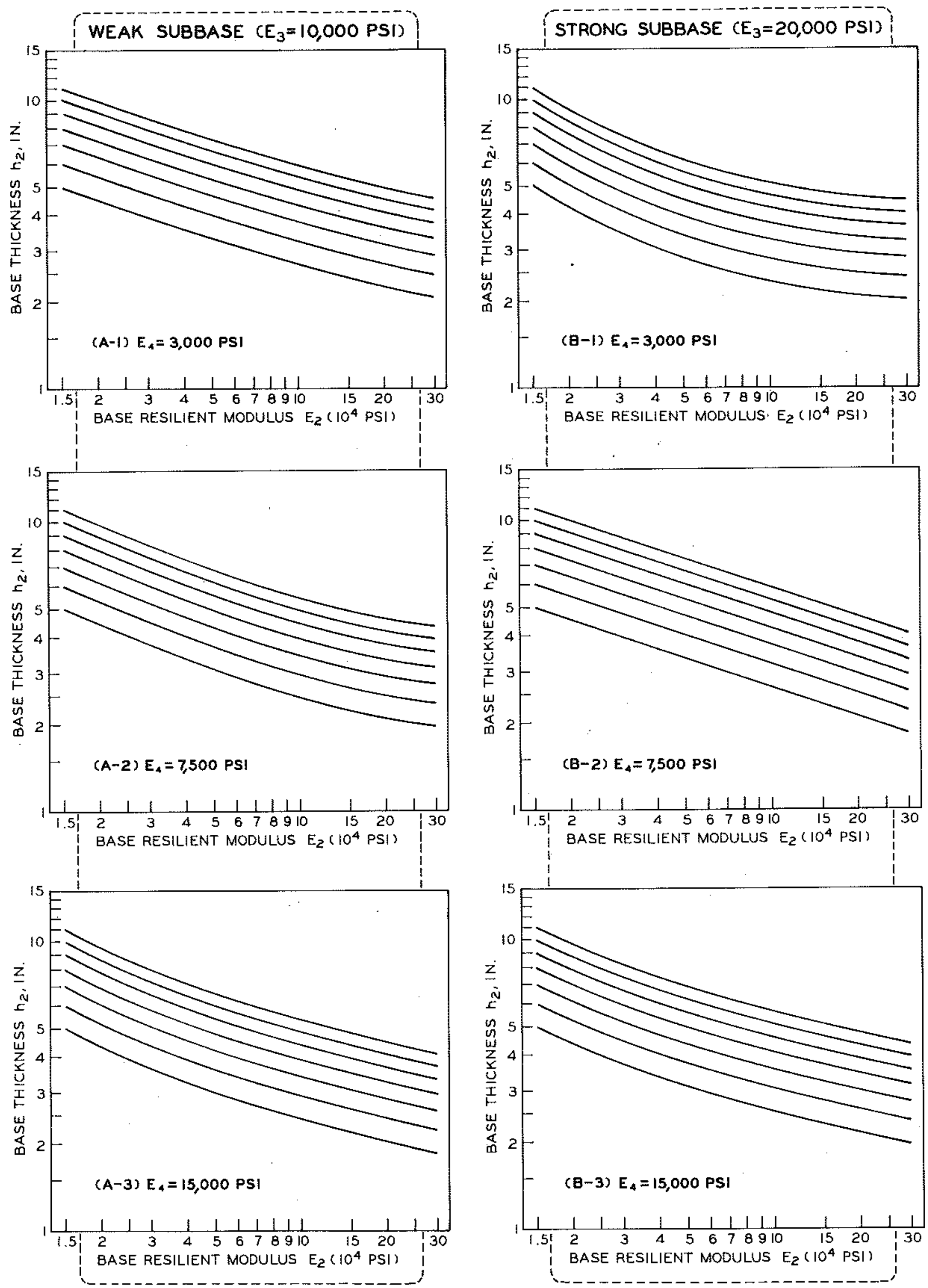

Figure 9. Thickness equivalency curves for 2.5 in. thick A.C. layer (h_1 = 2.5 in., h_3 = 28 in., E_1 = 600,000 psi – spring).

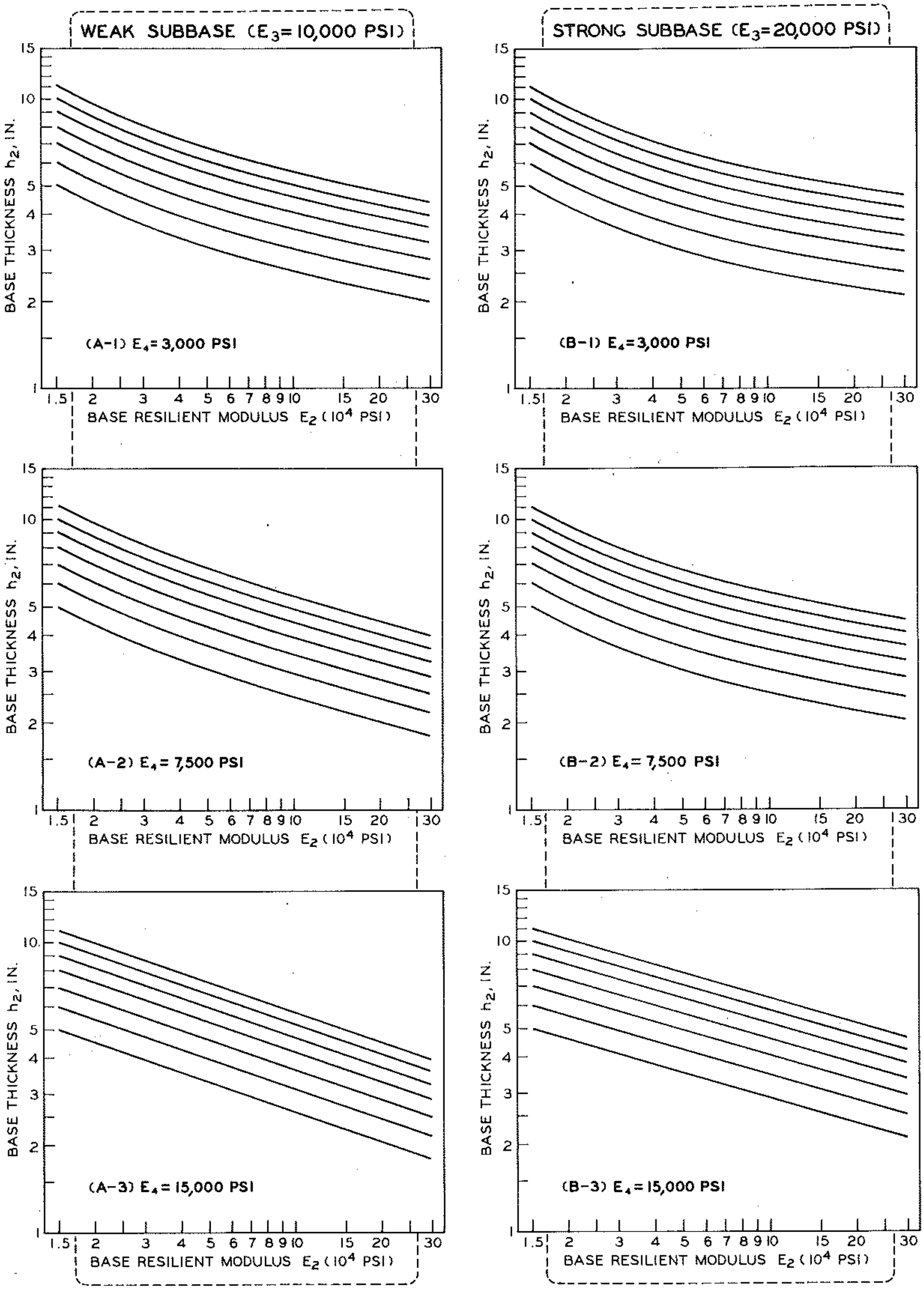

Figure 10. Thickness equivalency curves for 4.5 in. thick A.C. layer - Interstate only (h_1 = 4.5 in., h_3 = 18 in., E_1 = 150,000 psi - summer).

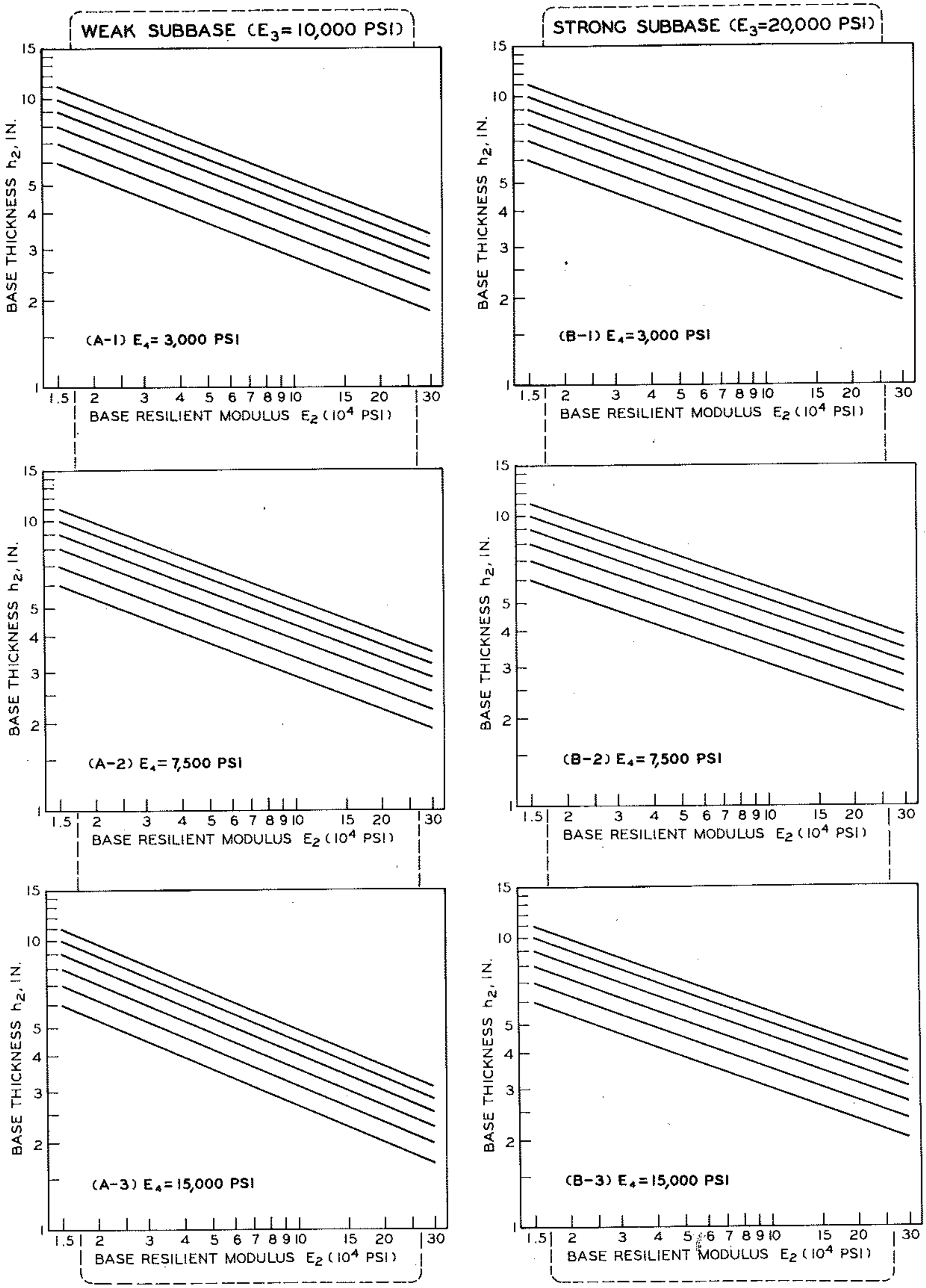

Figure 11. Thickness equivalency curves for 4.5 in. thick A.C. layer - Interstate only (h_1 = 4.5 in., h_3 = 18 in., E_1 = 600,000 psi - spring).

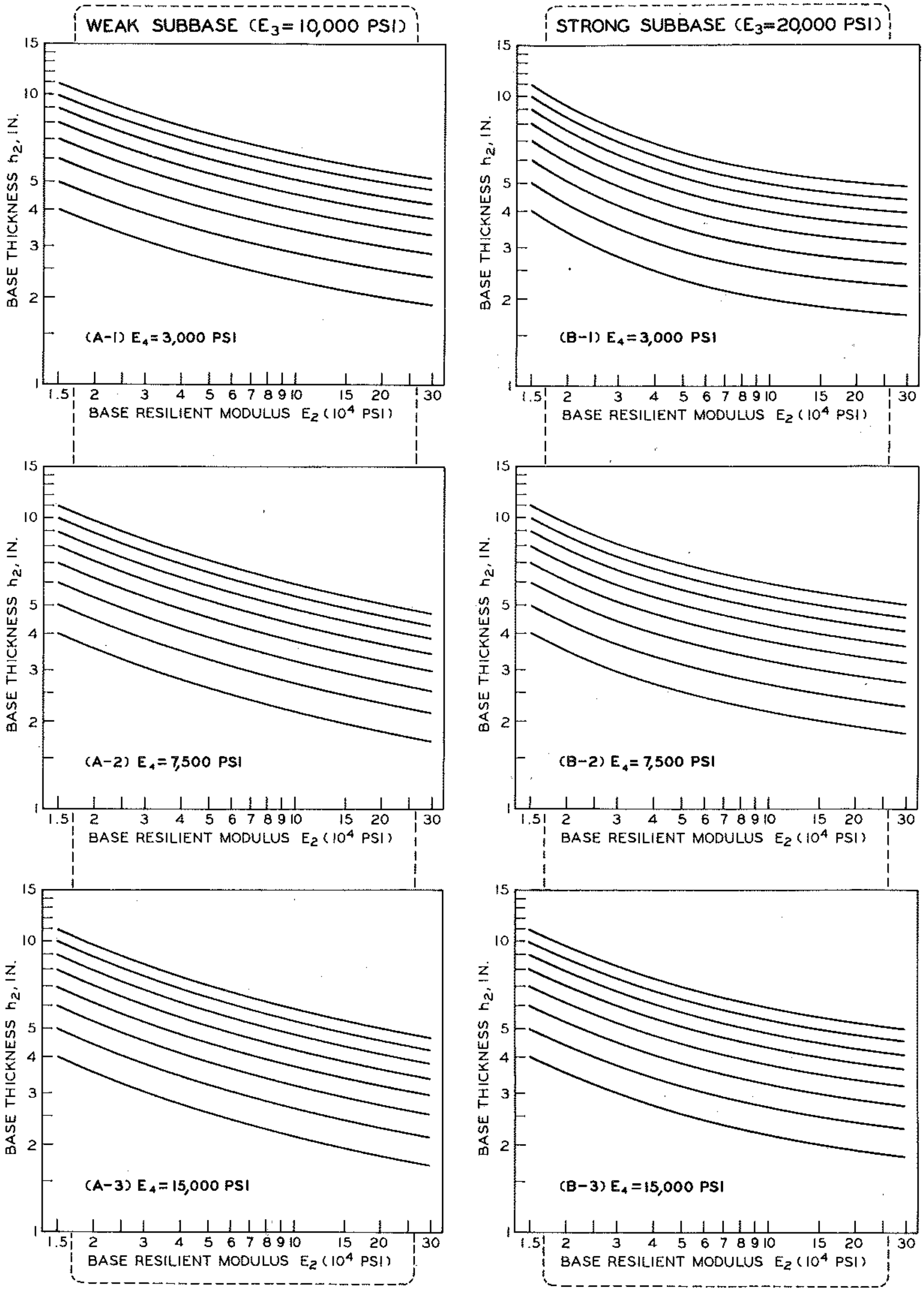

Figure 12. Thickness equivalency curves for 4.5 in. thick A.C. layer - Interstate only (h_1 = 4.5 in., h_3 = 28 in., E_1 = 150,000 psi - summer).

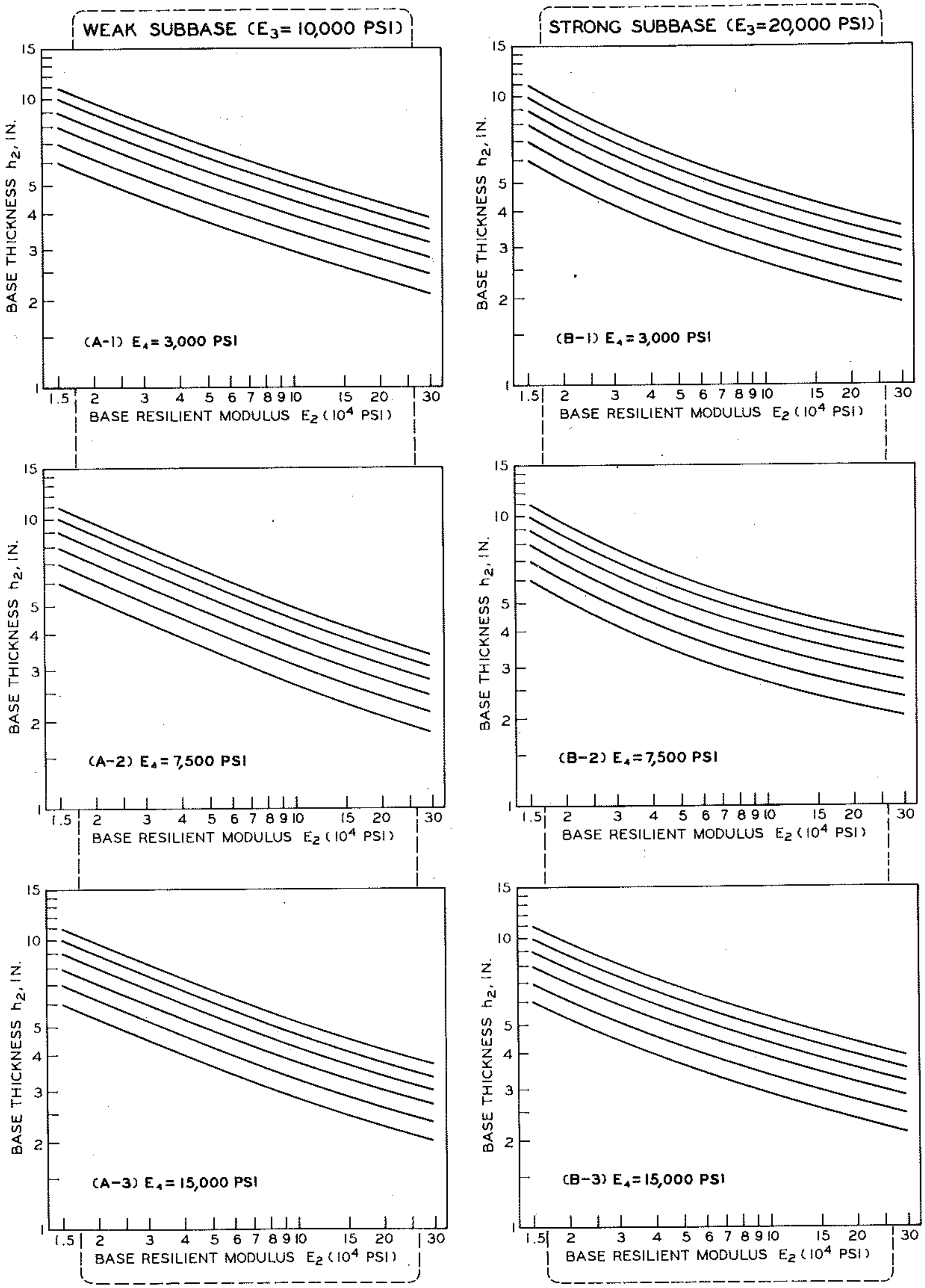

Figure 13. Thickness equivalency curves for 4.5 in. thick A.C. layer - Interstate only (h_1 = 4.5 in., h_3 = 28 in., E_1 = 600,000 psi - spring).

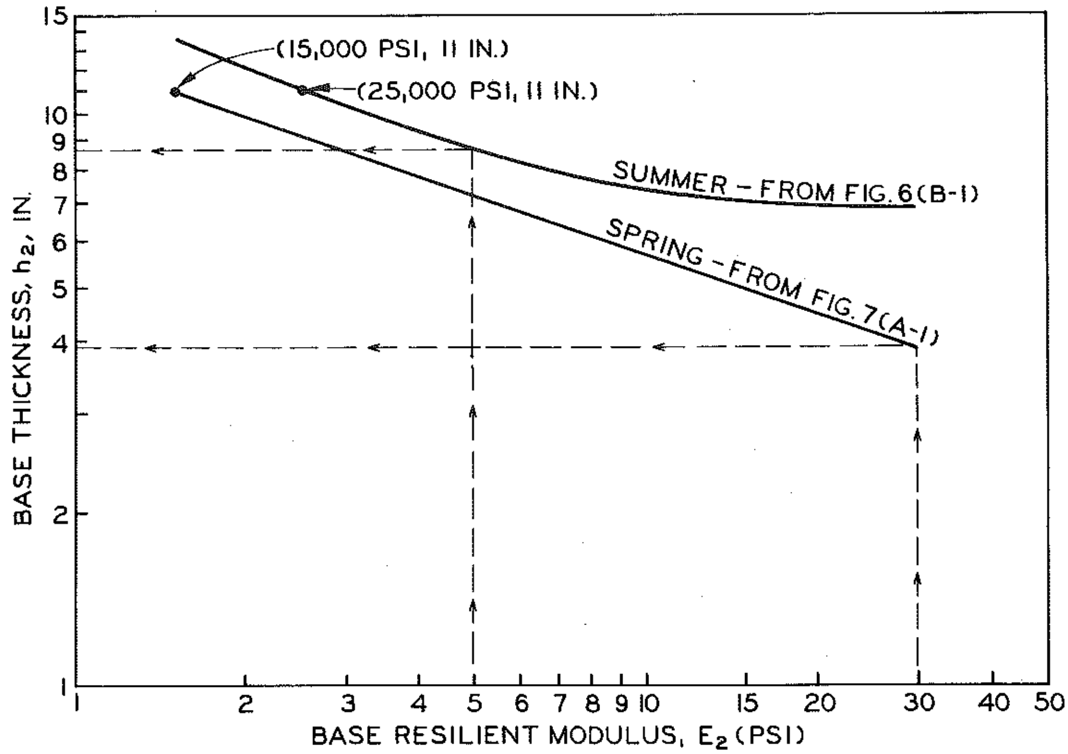

Figure 14. Thickness equivalency curves as applied to the illustrative example.

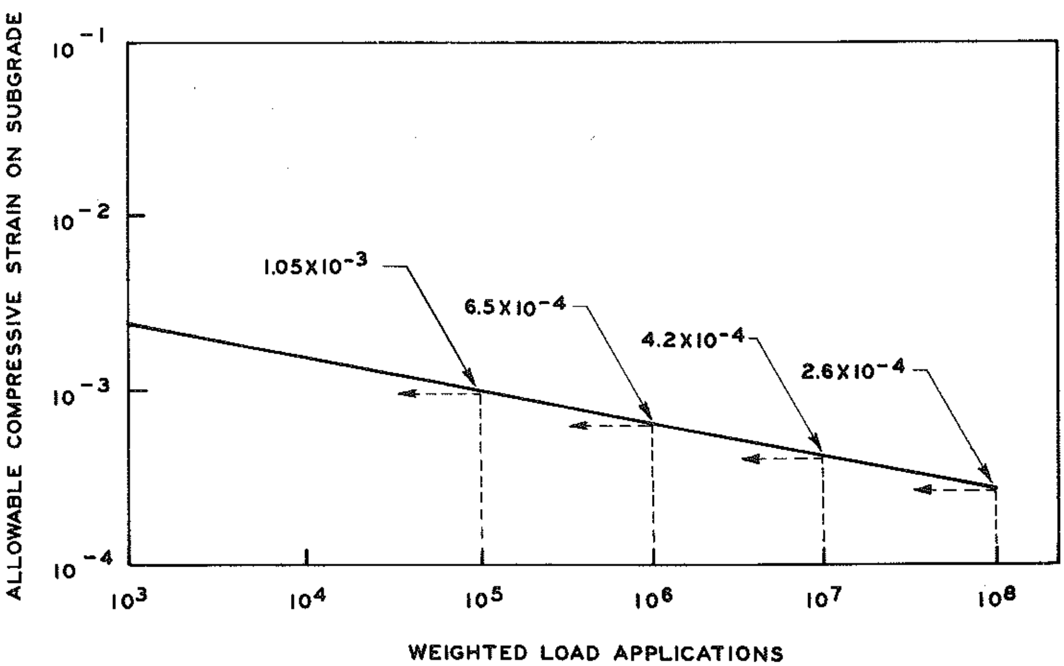

Figure 15. Relationship between allowable compressive strain on the subgrade and 18,000 lb axle load applications based on AASHTO road test results.

Illustrative Example of Applying Base Thickness Equivalency Curves

A standard 2.5-in. bituminous concrete pavement is to be constructed on 11 in. of aggregate base and 18 in. of subbase. The subgrade is assumed to be a loam. The alternative pavement is to have 2.5 in. of bituminous concrete constructed on black base and 18 in. of subbase. Since both pavements would have the same environmental, traffic volume, and subgrade conditions, it is possible, with the aid of Table 1 and Figures 7(A-1) and 6(B-1), to estimate the equivalent black base thickness which would give the same performance as that of the 11-in. aggregate base.

Table 1 shows that during the spring season the pavement is cold so the bituminous concrete is estimated to have a resilient modulus of 600,000 psi. The aggregate and black bases have estimated moduli of 15,000 and 300,000 psi, respectively. Both subbases and subgrade are considered to be saturated most of the time during the spring; therefore, subbase and subgrade modulus are assumed to be 10,000 and 3,000 psi, respectively. With the above section properties, Figure 7(A-1) is used to determine the equivalent black base thickness.

The equivalent base thickness during the spring is determined from Figure 7(A-1). Using the curve passing through $E_2 = 15,000$ psi and $h_2 = 11$ in. for the aggregate base, the equivalent thickness of the black base with $E_2 = 300,000$ psi is read from the curve as 3.95 in. Figure 14 labels this particular curve for explanatory purposes.

During the summer the bituminous concrete and black base soften and have resilient modulus values estimated to be 150,000 and 50,000 psi, respectively. At the same time, the aggregate base and subbase should dry and increase in strength to 25,000 and 20,000 psi, respectively. However, for the loam subgrade, drainage time is assumed to be too long to cause an increase in stiffness; therefore, its modulus remains at 3,000 psi. Using Figure 6(B-1) and the same procedure as was used for the spring condition, the equivalent base thickness is found to be 8.7 in. In this case, the summer conditions control and the equivalent black base thickness is 9 in., approximately.

Discussion

This study illustrates a method for determining the equivalent thickness of a black base as compared to that of an aggregate base. Actually, it can be applied to all kinds of pavement bases as long as their resilient moduli are known, or can be reasonably estimated.

Quasi-elastic moduli have been evaluated for some Michigan highway materials (8, 9) using conventional triaxial equipment with repetitive loading cycles, in an effort to simulate field loading conditions. However, the rate of loading is very slow compared to that of even slow moving traffic. Since asphalt materials are viscoelastic their strength properties are dependent on strain rate; the greater the strain rate the larger the E value. E values obtained using the quasi-elastic modulus described in Ref. (8) varied for black base material at 77 F between 30,000 to 45,000 psi, while the resilient modulus dynamically determined at load rates duplicating traffic speeds of around 30 mph are reported to be between 350,000 psi to 1,000,000 psi, or even greater (3, 10). In the light of this difference, a laboratory repetitive loading device capable of varying frequency and duration of stress application should provide more accurate duplication of field loading conditions and result in more realistic E values for Michigan paving materials. Table 1 and Figure 3 could then be modified accordingly. Until such time as more accurate values can be developed, the assumed E values of Table 1 may be used for thickness equivalency. Should any significant differences in modulus be determined in the future, they can be incorporated by an extension of the thickness equivalency curve to the desired modulus.

Although this report is primarily directed to base thickness equivalency studies, it could also be used as a base thickness design criterion. The design curve is based on the use of a limiting strain value representing one condition of heavy traffic loading. By empirical correlation with AASHTO Road Test results, the relation between allowable compressive strain and number of load applications was established by Dorman (11) as shown in Figure 15.

In the case of Figure 4, for example, if 10^7 load applications are decided for design purposes, the allowable compressive strain, from Figure 15, would be 4.2×10^{-4}. This strain value is used with Figure 4 to develop a base thickness design curve in Figure 5 (dashed line). The minimum required base thickness corresponding to different base resilient moduli can, therefore, be obtained from this curve. For example, a black base with 300,000 psi modulus, will require a minimum thickness of 4.0 in. and an aggregate base with 20,000 psi modulus will require an 8.4 in. thickness. It is imperative to note that this design curve is based on compressive strain only. Other factors, such as thermal and fatigue cracking, drainability, etc., should also be considered. With a minimum effort, strain-thickness curves, as derived from Table 2 could be transferred into thickness design curves.

It should also be realized that some of the specified section properties listed in Figure 3 may vary. However, following the procedure described in this report, any variation can be worked out with little difficulty.

Conclusions

1) Base thickness equivalency can be established based on the subgrade compressive strain and the resilient modulus of the base material.

2) It is desirable to evaluate the resilient modulus of each component in the pavement system by a dynamic testing device.

3) Base thickness design curves can be developed on the basis of limiting subgrade compressive strains.

4) Figures 6 through 13 of this report can be used to determine the equivalent thickness of various base course materials for equal pavement performance characteristics.

REFERENCES

1. Benkelman, A. C., Kingham, R. I., and Schmitt, H. M., "Performance of Treated and Untreated Aggregate Bases," 1st International Conference on the Structural Design of Asphalt Pavement, 1962.

2. Yoder, E. J., "Principle of Pavement Design," John Wiley and Sons, New York, 1959.

3. Van Til, C. J., McCullough, B. F., Vallarga, B. A., and Hicks, R. G., "Evaluation of AASHO Interim Guides for Design of Pavement Structures," NCHRP Report 128, 1972.

4. Barksdale, R. D., and Hicks, R. G., "Material Characterization and Layered Theory for Use in Fatigue Analysis," Highway Research Board, Special Report 140, 1973.

5. Jung, F. W., and Phang, W. A., "Elastic Layer Analysis Related to Performance in Flexible Pavement Design," Transportation Research Board, Record No. 521, 1974.

6. Dorman, G. M., and Edwards, J. M., "Shell 1963 Design Charts for Flexible Pavements, An Outline of Their Development," Shell International Petroleum Co., Ltd., London, O.P.D., Report 232/64M.

7. Malvern, L. E., "Introduction to the Mechanics of a Continuous Medium," Prentice-Hall, Englewood Cliffs, N. J., 1969.

8. AlNouri, I., "Evaluation of a Quasi-Elastic Modulus of Granular Base Material," Michigan Department of State Highways and Transportation, Research Report No. R-749, September 1970.

9. AlNouri, I., "Effect of Temperature on the Elastic Response of Asphalt Treated Base Material," Michigan Department of State Highways and Transportation, Research Report No. R-816, June 1972.

10. Finn, F. N., Hicks, R. G., Kari, W. J., Coyne, L. D., "Design of Emulsified Asphalt Treated Bases," Highway Research Board, Record No. 239, 1968.

11. Dorman, G. M., Metcalf, C. T., "Design Curves for Flexible Pavements Based on Layered System Theory," Highway Research Board, Record No. 71, 1965.