High-Strength Stabilized Base Thickness Design Procedure

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The basic concepts and the development of a high-strength stabilized-base (HSSB) thickness design procedure are presented. Cement-aggregate mixtures and pozzolanic-stabilized substances are typical HSSB materials. The proposed procedure is based on resilient soil and material testing procedures, the ILLI-PAVE stress-dependent modulus structural model, and design algorithms developed from an extensive ILLI-PAVE HSSB pavement response (stress, strain, deflection) data base. Required inputs are subgrade resilient modulus (E_{Ri}, ksi), HSSB modulus (E, ksi), asphalt concrete (AC) thickness (T_{AC}, in.) and modulus (E_{AC}, ksi), HSSB Design Compressive Strength (psi), and HSSB thickness (T, in.). The AC modulus and the HSSB modulus are used to convert the AC thickness (T_{AC}) to an equivalent HSSB thickness. The thickness design criterion is FATIGUE of the HSSB pavement layer. The HSSB FATIGUE relation is based on the HSSB stress ratio, which is equal to HSSB design flexural stress/HSSB flexural strength. Traffic is considered in terms of 18-k equivalent single-axle loads (SAL). Simplified design charts are presented for routine HSSB design.

High-strength stabilized base materials are "cementitiously stabilized" coarse-grained materials characterized by high-strength and modulus properties. Typical HSSB materials are pozzolanic stabilized mixture (PSM), cement aggregate mixture, and similar types of high-quality cementitiously stabilized materials. Most HSSB materials are capable of developing cured compressive strengths in excess of 5 MPa (750 psi).

HSSB materials are generally used as base layers in pavement sections with minimum AC surface thicknesses. In some low traffic volume situations, surface treatments or lower quality asphalt-type surface courses are used. Cementitious stabilizers typically increase compressive strength, shear strength (large increase in cohesion), tensile strength (flexural and split tensile), and modulus of elasticity. Freeze-thaw and moisture resistance are significantly enhanced by stabilization. HSSB material durability is an important property and should be carefully considered in the HSSB mixture design process (in fact, durability requirements may control the mixture design proportions).

A summary of the strength, modulus, and fatigue properties for cementitiously stabilized materials has been presented in a previous University of Illinois project report (*1*). That report emphasized those areas of HSSB technology particularly relevant to thickness design considerations. Other recent references (*2–5*) are more comprehensive in scope.

HSSB DESIGN: PERFORMANCE CONSIDERATIONS

Costigan and Thompson (*6*) summarized and analyzed the response and performance of nine cement-stabilized structural sections subjected to channelized traffic. Longitudinal cracking (starting at a transverse crack) indicated the initiation of structural failure. Wang and Kilareski (*7*) noted similar cracking patterns in cement-stabilized sections trafficked in the Pennsylvania State University Test Track. American Association of State Highway Officials' Road Test cracking progression studies for thin and structurally inadequate nonreinforced jointed portland cement concrete sections also indicated that structural failure initiated with longitudinal cracking in the wheel path.

A recent Transport and Road Research Laboratory (TRRL) study (*8*) based on extensive field survey data for "lean concrete roads" also indicated that structural failure begins with "longitudinal cracks in the wheel path." TRRL suggests, "it is preferable for heavily trafficked roads to use a design that is sufficiently strong to resist longitudinal cracking." The TRRL study substantiated the validity of using flexural stress and flexural strength as indicators of the potential for developing "cracking"-type distress.

It is apparent that the critical thickness design consideration for the HSSB layer is longitudinal cracking based on edge-corner wheel loading conditions. For HSSB materials, the controlling thickness design criterion is the flexural stress at the bottom of the stabilized material layer.

HSSB DESIGN CONCEPTS

The structural response and fatigue performance of the HSSB layer (for a given wheel loading) are influenced by the flexural strength, modulus, and thickness of the stabilized layer, the modulus and thickness of the AC surface course layer (if it is used), and the subgrade resilient modulus. HSSB materials of the same quality (strength, modulus) display similar structural responses. Thus HSSB thickness design concepts are independent of material type.

HSSB layer thickness can be established using an "intact layer" structural analysis approach (the HSSB layer is considered to be an "elastic layer," not an incompressible slab) and design concepts based on HSSB layer fatigue consumption (*1,9*). This approach is valid even though the HSSB layer may initially develop transverse shrinkage cracks. An adequate HSSB layer thickness prevents significant additional cracking [particularly the longitudinal outer wheel path cracking indicative of fatigue failure (*6–8*)] under traffic loading. HSSB fatigue life is estimated from the calculated stress ratio (SR). (SR = HSSB flexural stress at the bottom of the layer-HSSB modulus of rupture.) The mechanistic thickness design option in the American Coal Ash Association Flexible Pavement Manual (*5*) is based on these concepts and principles.

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HSSB DESIGN PROCEDURE DEVELOPMENT

General

The proposed HSSB thickness design procedure is predicated on the fatigue failure of an "intact" HSSB layer with a nominal AC surface course [maximum of approximately 10 cm (4 in.)]. In this type of pavement structure, the AC radial strains are compressive and subgrade stresses are low. Thus, AC fatigue and subgrade rutting are not significant design criteria. The only thickness design criterion is fatigue consumption in the HSSB layer for considering longitudinal crack formation.

The HSSB fatigue algorithm (SR versus log number load applications to cracking) proposed for use in the Illinois DOT HSSB thickness design procedure (9) is shown in Figure 1. [Additional fatigue algorithms are given by Thompson (*1*)]. The HSSB thickness requirement is very sensitive to the fatigue algorithm selected. The proposed procedure can easily accommodate other fatigue algorithms considered appropriate by the user agency.

Stress Ratio Calculations

The flexural stress at the bottom of the HSSB layer (σ) can be estimated from an algorithm developed by Thompson (*1*) from a comprehensive ILLI-PAVE HSSB data base. The ILLI-PAVE analyses were based on a 9,000-lb circular load (80 psi pressure) as a representation of one dual-wheel of the standard 18-kip (18,000-lb) single axle load. The ILLI-PAVE HSSB data base includes many representative HSSB pavement configurations, AC moduli, and HSSB moduli. The AC surface course thickness ranged from 0 (surface treatment) to 4 in. and HSSB thickness varied from 6 to 12 in.

The algorithm for estimating σ is

$$\text{Log } \sigma = 2.49 - 0.07 \text{ TEQ} + 0.0001\, E - 0.0083\, E_{Ri}$$

$$R^2 = 0.95$$

$$\text{SEE} = 0.059 \qquad (1)$$

(Note: The AC surface plus HSSB layer pavement section is converted to an "equivalent" HSSB thickness, TEQ.)

$$\text{TEQ} = T + T_{AC}\,(E_{AC}/E)^{0.33} \qquad (2)$$

Required inputs for Equations 1 and 2 are AC modulus (E_{AC}, ksi) and AC thickness (T_{AC}, in.); HSSB modulus (E, ksi) and HSSB thickness (T, in.); and subgrade resilient modulus (E_{Ri}, ksi). (NOTE: σ is in psi.)

AC modulus is significantly influenced by pavement AC temperature. Various procedures for estimating E_{AC}-mix temperature relations are presented in Appendix C4 of National Cooperative Highway Research Program (NCHRP) Project 1-26 (*10*). The Asphalt Institute AC modulus prediction procedure (*11,12*) is frequently used.

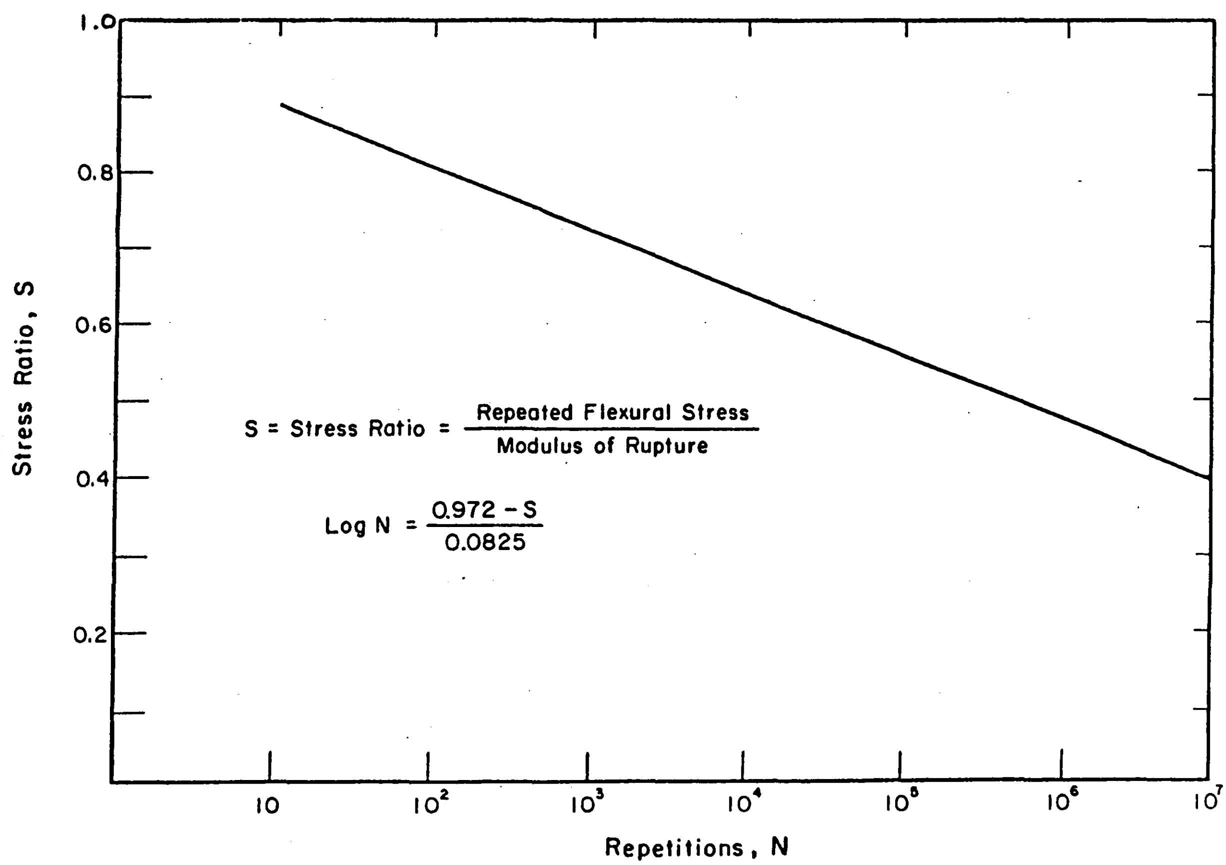

FIGURE 1 High-strength stabilized base fatigue algorithm (*9*).

A plot of E_{AC}/E versus $(E_{AC}/E)^{0.33}$ is shown in Figure 2. For typical AC mixtures and pavement temperature fluctuations representative of a temperate climate (such as the midwestern United States), an $(E_{AC}/E)^{0.33}$ value of 0.5 is recommended for general HSSB design calculations, although at times a higher value would be indicated. Portland Cement Association recommendations (*13*) support the general validity of the 0.5 "equivalency." Thus Equation 2 becomes

$$TEQ = T + 0.5\ T_{AC} \qquad (3)$$

For routine a priori thickness design purposes, approximate HSSB unconfined compressive strength—HSSB modulus and HSSB compressive strength—HSSB modulus of rupture relations are adequate (*1*). HSSB flexural strength can be estimated as 20 percent of the compressive strength. The HSSB modulus-compressive strength relation recommended for use in the proposed Illinois DOT procedure (*9*) is

$$E\ (\text{ksi}) = 500 + \text{Compressive Strength (psi)} \qquad (4)$$

Note: 1 ksi = 6.9 MPa.

Other HSSB modulus-HSSB strength relations are presented by Thompson (*1*).

Subgrade soil resilient behavior is characterized by the "resilient modulus," defined as

$$E_R = \text{DEV}/\epsilon_r$$

where

E_R = resilient modulus,
DEV = repeated deviator stress, and
ϵ_r = recoverable axial strain.

Repeated unconfined compression or triaxial testing procedures are often used to evaluate the resilient moduli of fine-grained soils

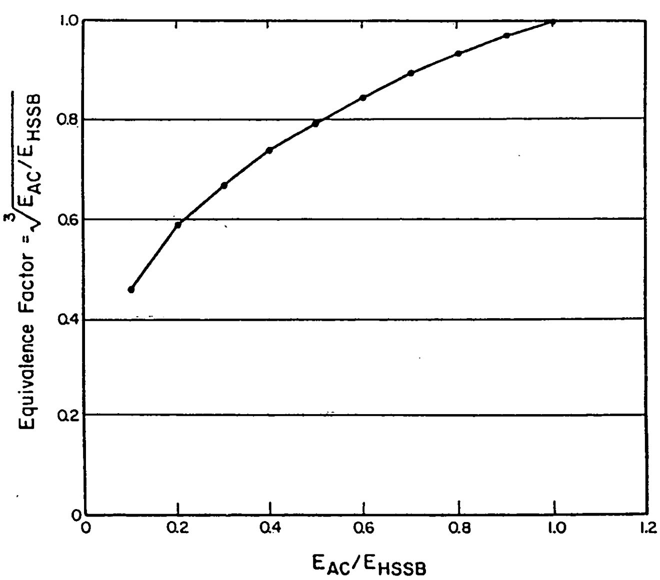

FIGURE 2 Equivalence factors for asphalt concrete surface.

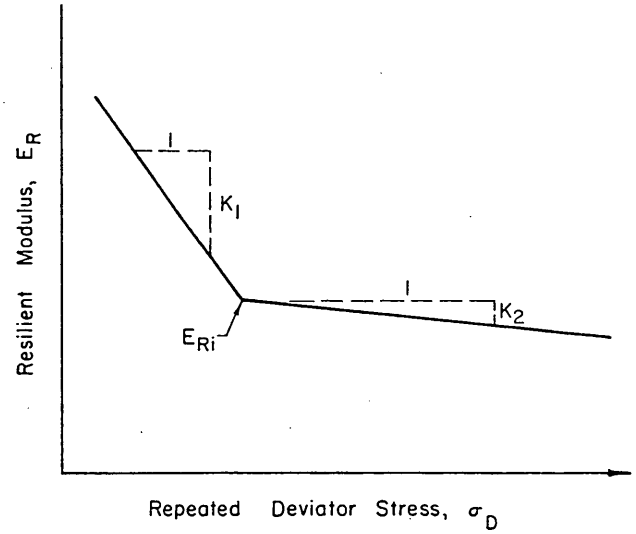

FIGURE 3 ILLI-PAVE stress-dependent fine-grained soil subgrade model.

and granular materials. Resilient moduli are stress dependent: fine-grained cohesive soils experience resilient modulus decreases with increasing stress, whereas granular materials stiffen with increasing stress level.

The arithmetic stress-dependent behavior model for fine-grained soils was used in developing the ILLI-PAVE HSSB data base (*1*). The model is shown in Figure 3. Extensive resilient laboratory testing, nondestructive pavement testing, and pavement analysis and design studies at the University of Illinois have indicated that the arithmetic model is adequate for flexible pavement analysis and design activities.

In the arithmetic model, the value of the resilient modulus at the break-point [at approximately 42 kPa (6 psi)] in the bilinear curve, E_{Ri} (see Figure 3) is a good indicator of a soil's resilient behavior. The slope values, K_1 and K_2, are less variable and influence pavement structural response to a smaller degree than E_{Ri}.

Subgrade E_{Ri} can be established from laboratory testing, local experience and information, nondestructive testing, or estimated from soil classification data. Note that the flexural stress estimate is not sensitive to the E_{Ri} input.

Thompson and Robnett (*14*) developed a simplified procedure for estimating the resilient behavior of Illinois fine-grained soils. A regression equation for predicting E_{Ri} at optimum water content and 95 percent of maximum dry density AASHTO (American Association of State Highway and Transportation Officials) *T*-99 is

$$E_{Ri}\ (\text{OPT}) = 4.46 + 0.098\ (\%\text{CLAY}) + 0.119\ (\text{PI})$$

where

E_{Ri} (OPT) = E_{Ri} (ksi) at optimum moisture content and 95% AASHTO *T*-99 maximum dry density,
% CLAY = Clay content (< 2 micron)
PI = Plasticity Index

Note: 1 ksi = 6.9 MPa.

Based on the extensive Illinois soils resilient testing data base Thompson and LaGrow (*15*) established typical "E_{Ri} decrease/1 percent moisture content increase" for various U.S. Department of Agriculture (USDA) textural classifications. The following values are useful for a priori pavement design activities:

USDA Textural Classification	*E_{Ri} Decrease/1% Moisture Increase (ksi/%)*
Clay, silty clay, silty clay loam	0.7
Silt loam	1.5
Loam	2.1

Note: 1 ksi = 6.9 MPa.

The E_{Ri} (OPT) estimate should be adjusted to reflect in situ moisture conditions. For the high water table conditions that predominate in Illinois, the in situ subgrade soil moisture content is almost always in excess of AASHTO T-99 optimum, and frequently is near 100 percent saturation.

The general E_{Ri} relationships shown in Table 1 were proposed by Thompson et al. (*16*) for the design of low-traffic volume airfield pavements. Various approaches that have been proposed for considering subgrade soil moduli are summarized in Appendix C5 of National Cooperative Highway Research Program Project 1-26 (*10*).

Examination of Equation 1 indicates that σ is primarily controlled by TEQ. Assuming a typical value for E_{Ri} of 3 ksi and estimating E from compressive strength (see Equation 4), Equation 1 is simplified to

$$\text{Log } \sigma = 2.515 + 0.0001S - 0.07 \text{ TEQ} \qquad (5)$$

where

TEQ = Equivalent thickness (in.),
σ = HSSB flexural stress (psi), and
S = HSSB compressive strength (psi).

Note: 1 psi = 6.9 kPa.

Considering the precision with which HSSB field strength can be estimated, the general variability of traffic loading conditions and field subgrade E_{Ri} values, and so on, Equation 4 is considered to be acceptable for routine a priori pavement design activities. A highway agency may select different typical values for E and E_{Ri} from those used previously or elect to apply Equation 1 to each particular set of project design conditions.

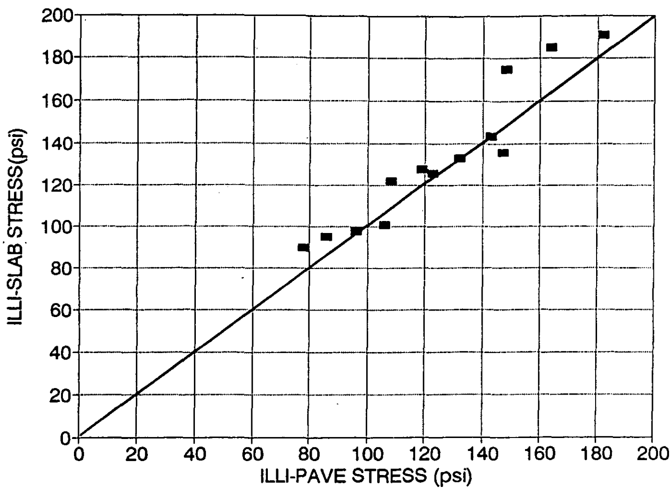

FIGURE 4 ILLI-SLAB/ILLI-PAVE stress calculation comparisons.

The interior flexural stress (Equation 1 or 5) is increased by 50 percent to account for edge loading and HSSB transverse cracking effects (*1*). ILLI-SLAB analyses (for the condition of no load transfer between adjacent slabs) were conducted in NCHRP 1-26 (Calibrated Mechanistic Structural Analysis Procedures for Pavements) for some typical HSSB sections (TEQ from 8 to 12 in.) to further consider the multiplier factor. An "equivalent k" (k—modulus of subgrade reaction—is the subgrade support input for ILLI-SLAB) was established for each section by analyzing the ILLI-PAVE load-displacement data for the "interior" loading condition. The comparison, see Figure 4, indicates the stresses estimated by applying the 50 percent multiplier factor to Equation 1 compared favorably with ILLI-SLAB stresses for a location 18 in. from the pavement edge.

In a prepared discussion of *Transportation Research Record 1095* (*6*), Ioannides considered the multiplier factor approach

TABLE 1 Estimated Subgrade Resilient Modulus Values (*16*)

	Design Subgrade E_{Ri}, ksi			
	High Water Table*		Low Water Table**	
AASHTO Soil Class	With Frost	W/O Frost	With Frost	W/O Frost
A-4; A-5; A-6	2.0	4.0	3.0	6.0
A-7	2.0	5.0	3.5	7.0

* Water table seasonally within 24 inches of subgrade surface

** Water table seasonally within 72 inches of subgrade surface

NOTE: 1 ksi = 6.9 MPa

based on Westergaard analysis procedures. For typical HSSB highway pavement sections (radius of loaded area/radius of relative stiffness = 0.15), his recommended value for the multiplier would be about 65 percent.

Because the HSSB design is based on an ''early life'' compressive strength (a conservative approach) and some load transfer will occur between adjacent slabs, it is recommended that for an a priori pavement design, the 50 percent multiplier factor be used for increasing the HSSB interior stress to estimate the edge stress. σ_F, the ''design flexural stress'' ($\sigma_F = 1.5\ \sigma$) should be used to calculate the SR for HSSB thickness design.

HSSB Compressive Strength

The proposed design procedure is predicated on the concept that HSSB modulus and flexural strength can be estimated from the cured HSSB compressive strength. HSSB strength development is dependent on many factors (HSSB mixture ingredients and proportions, mixing efficiency, field compaction, curing conditions: time-temperature-moisture, etc.). Freeze-thaw action typically effects an HSSB strength decrease. It is not possible to accurately predict (in a typical a priori design scenario) HSSB strength as a function of time after construction.

Examination of the input parameters in Equation 1 indicates the significant effect of HSSB modulus. In addition to the constantly changing (particularly in the early life of a HSSB pavement) HSSB strength and modulus, the AC modulus fluctuates with temperature. Thus the load-related HSSB flexural stresses also change with time. Cumulative damage accumulation for a range of SRs can be considered by using Miner's procedure:

$$\text{Fatigue damage (\%)} = P_i \tag{6}$$

$$P_i = (N_i/N_{Ti})100 \tag{7}$$

where

P_i = percent fatigue life consumption for SR_i,
N_i = number of 18k SAL applied at SR_i,
N_{Ti} = number of load applications to failure for SR_i from Figure 1, and
n = number of SRs considered.

Failure is assumed when the cumulative fatigue damage is 100 percent.

It is difficult to calculate an SR for a particular time and accurately predict the pavement life for several years hence. The application of load repetitions at a high SR (which may occur in the early curing stages when HSSB strength is low) will effect considerable fatigue consumption.

Although an ''iterative procedure,'' which considers that HSSB strength-modulus-time relations for the field-cured HSSB mixture is conceptually and theoretically sound, it is not practical for inclusion in an a priori HSSB thickness design procedure. To simplify the procedure and facilitate the practical application of mechanistic-based concepts, HSSB layer fatigue consumption is calculated on the basis of the HSSB properties (compressive strength and modulus) for specific mixture design procedures, curing conditions (temperature, time, etc.), and construction practices. The compressive strength associated with these conditions is the ''Field Design Compressive Strength'' (CS).

CS is the field strength equal to (or in some instances greater than) the strength at the time the pavement is subjected to traffic loadings. The design procedure is considered applicable to HSSB materials with CS greater than about 5 MPa (750 psi). CS is the most important design input. It is necessary for a highway agency to establish procedures and guidelines for selecting CS for the thickness design determination.

Some typical examples illustrating various approaches to selecting CS are

1. The American Coal Ash Association (*5*) suggests that for PSM base, CS is the compressive strength based on 56-day curing at 73°F (100 percent relative humidity).
2. The Portland Cement Association (*13*) indicates the 28-day strength is appropriate for soil-cement thickness design.
3. In the 1986 AASHTO Guide (*17*), a structural coefficient 7-day compressive strength relation is shown for cement-treated bases. (Note: Many cement-treated material mixture design approaches are predicated on 7-day moist curing.)

The criteria for establishing CS are not necessarily the same for all HSSB materials. For example, the 28-day cured strength of cement-treated materials is typically about 50 percent greater than the 7-day moist cured strength. PSM frequently do not show the initial rapid strength development with curing characteristic of cement-treated materials, but PSM-cured strength normally continues to increase for a significant time period after construction. There is considerable variability in the rates of cement-treated material and PSM strength increase with curing (time and temperature). The development of ''Cured Strength-Degree Day'' (DD) data and relations for typical mixtures used by a highway agency are helpful in selecting realistic and appropriate CS values. In the Illinois Department of Transportation (DOT) mix design procedure [see *Flexible Pavement Manual* (*5*)] for PSM (lime-fly ash-aggregate, cement-fly ash-aggregate), a strength-DD relation is established for each mixture design. The degree days are calculated on the basis of temperatures above 40°F. A typical PSM strength-DD relation is shown in Figure 5.

SIMPLIFIED HSSB THICKNESS DESIGN PROCEDURE

The information, concepts, and principles previously presented can be used to develop a simplified HSSB thickness design procedure. The procedure is based on Equation 5 and the assumption that the HSSB Field Design CS can be used to estimate the HSSB modulus (see Equation 4) and flexural strength (modulus of rupture = CS/5). Equation 5 was used to develop the HSSB Thickness Design Chart shown in Figure 6. Equation 1 and different estimates of the inputs (HSSB modulus, modulus of rupture, and subgrade E_{Ri}) can be used to develop more refined design charts.

To select the SR design value (see Figure 1), the estimated design equivalent single axle loads may be increased to attain an increased ''design reliability'' level. An AASHTO-type ''Traffic Multiplier'' approach concept (*17*) is a procedure that might be used. The required HSSB thickness is relatively insensitive to the design reliability factor. A 25-mm (1-in.) HSSB thickness increase is sufficient to increase the design reliability from 50 percent to a considerably higher level. The typical increase in HSSB long-term cured strength (a phenomenon that is not considered in the HSSB

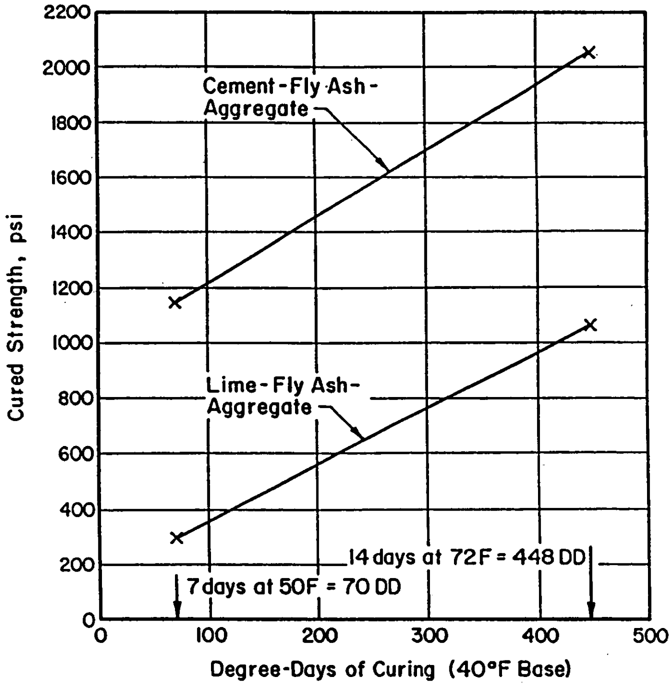

FIGURE 5 Strength-degree day relations for pozzolanic stabilized materials.

thickness determination process based on Field Design Compressive Strength) will effect a significant increase in the design reliability.

To limit early life fatigue consumption (HSSB strengths are low at this time), the HSSB pavement section must be adequate to effect an SR in the HSSB layer less than 0.65 before truck traffic loading. If the section is overloaded or fatigued at an early age, the "intact layer"-type structural behavior of the HSSB layer may be significantly reduced.

OTHER FACTORS INFLUENCING HSSB PAVEMENT PERFORMANCE

Historical performance and maintenance data for HSSB pavements should be considered in establishing policies for using HSSB pavements. The proposed HSSB thickness design procedure is based on an intact layer-HSSB flexural fatigue consumption approach. Other factors also influence the overall HSSB pavement performance.

- A TRRL report (*8*) indicated that, "for best performance, cemented roadbase should be laid in a single layer." The TRRL field survey data indicated the superior performance of "single-layer" versus "two-layer" construction. The degree of bonding achieved between the HSSB layers was probably the key contributing factor. If the required HSSB thickness exceeds the single-lift thickness that can be adequately constructed (primarily a full-depth adequate density consideration), special construction procedures are needed to achieve acceptable bonding between the HSSB layers.

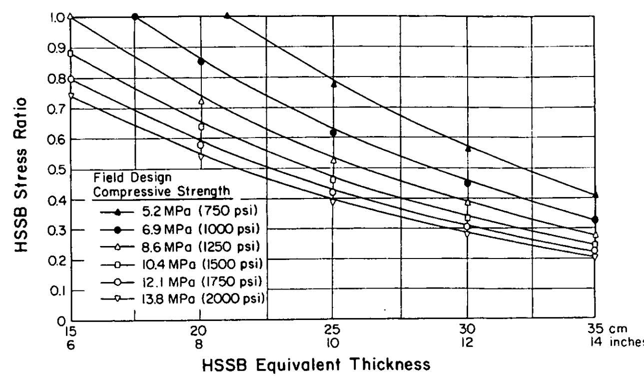

FIGURE 6 High-strength stabilized base equivalent thickness design chart.

- The performance of transverse cracks in the HSSB layer, HSSB material breakdown at transverse cracks, and pumping are major concerns. Increased pavement deflections may contribute to more rapid transverse crack breakdown and accompanying decreased load transfer at cracks, and increased potential for faulting and subgrade erosion or pumping. The Illinois DOT has implemented a policy for "sawing and sealing" joints in lime-fly ash and cement-fly ash base construction to improve joint performance. The Illinois DOT sawing and sealing detail for HSSB construction is shown in Figure 7.

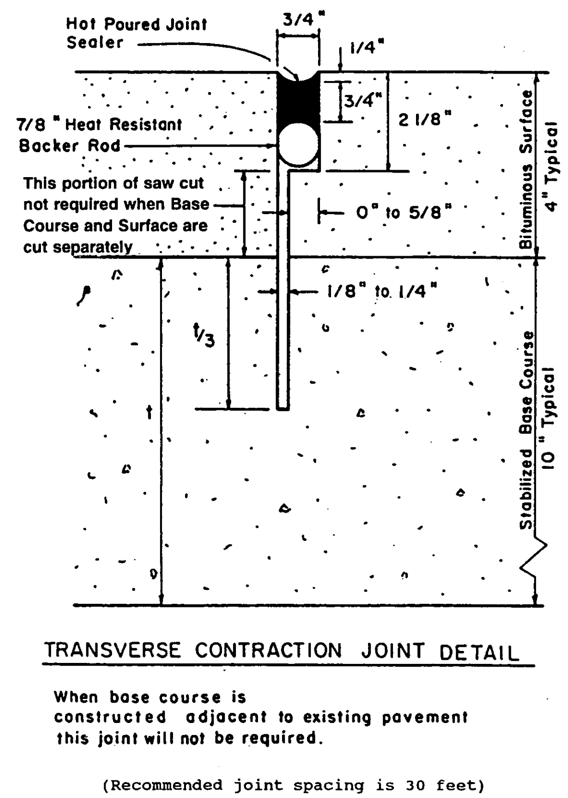

FIGURE 7 Illinois Department of Transportation high-strength stabilized base joint detail.

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