Structural Comparison of Two Cold Recycled Pavement Layers

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ABSTRACT

The structural strengths of two cold recycled pavements are compared. One recycled pavement section was built with foamed asphalt as a binder and the other with emulsion as a binder. Cores and deflection measurements were taken at different times after construction. The comparisons were based on results of tests on the cores, Dynaflect deflections, and strength indicators as well as developed AASHTO layer coefficients. The comparisons showed that the stiffness and strength of both recycled sections increased during the first 400 days after construction. The strength of the foamed-asphalt section increased more rapidly than that of the emulsion section during the first 250 days. The strengths and stiffnesses of the foamed-asphalt recycled section were slightly higher than those of the emulsion recycled section during most of the evaluation period, but the differences were small. Ranges of layer coefficients were developed that can be used in design of similar layers. These ranges indicate that the two recycled layers should perform about the same. The initial cost will therefore be the controlling factor in an economic analysis of these two types of recycled pavements.

Recycling of pavements has received widespread attention during the last 7 or 8 years, mainly because of energy and financial restraints. Recycling has the potential of reducing highway construction and rehabilitation costs. Actual cost savings can be evaluated only if the performance of the recycled section is known, because a proper economic evaluation can be conducted only when the initial as well as the life-cycle costs are known. An estimate of the performance of a pavement is essential in the effective comparison of alternatives and in pavement management. The major disadvantage of recycling, especially cold-asphalt recycling, is that relatively little is known about the performance of these layers. Practitioners (1,2) and researchers (3,4) recognize this problem. High-priority research needs in asphalt recycling involve the determination of material coefficients or the establishment of some limiting allowable strain or stress criteria. There are currently no such material coefficients or criteria available (3).

The determination of the performance of a recycled pavement is by no means an easy task. The performance is complex and influenced by a large number of factors. The performance of many of the conventional pavements is still not well understood. Performance of recycled pavements can be better understood and, it is hoped, predicted by further research and the monitoring of existing recycled pavements.

The structural strength of a pavement is an important indicator of its performance. The strength of a pavement material can be expressed in terms of resilient modulus (stiffness), Marshall stability, Hveem R-value, or deflection characteristics. These indicators have not been related directly to the performance of a layer, although some general relations have been developed (5). These indicators can be used successfully to compare the strength of the pavement layers but not to predict pavement life. The structural or layer coefficient used in the AASHTO design method for flexible pavements is currently the best single indicator of the performance of a pavement layer, although it is not perfect.

The AASHTO design method for flexible pavements is used by the majority of states in the United States (6). An equation relates the number of equivalent axle load applications to the structural number (SN) of the pavement. SN is an indication of the strength of the pavement. It is basically the sum of the strengths of the individual pavement layers. The higher the SN, the larger the number of loads that the pavement can accommodate before failure for given soil support and environmental conditions. The number of axle loads to failure can further be related to the number of years before functional failure will occur. The strength of the individual pavement layers is expressed in the AASHTO design method as the structural coefficient (a). Structural coefficients are dependent on a variety of factors, e.g., layer thickness, position in the pavement, thickness, and strength of surrounding layers, besides the strength of the layer itself. Coefficients range from about 0.05 for sandy-clay subbases to about 0.44 for hot-asphalt surface mixtures. The higher the coefficient, the greater the strength of the layer and the better it will perform.

RECYCLED PAVEMENT SECTIONS

The two cold recycled pavements compared in this paper were built during August and September 1981. The sections are contiguous and subjected to the same traffic and environmental conditions. Similar construction methods were used. The only difference was the binders used in the recycling: foamed asphalt and asphalt emulsion. A good comparison can therefore be drawn between the foamed-asphalt and emulsion cold recycled pavement sections.

After 5 in. (125 mm) of initial asphalt pavement had been removed, it was mixed with the binder and additional aggregate and relaid during recycling (7,8). A layer 1 in. (25 mm) thick of the initial pavement layer was left to protect the subbase during construction. The 5.5-in. (140-mm) recycled layer was overlaid with a 1.25-in. (40-mm) hot asphalt surface. Foamed asphalt was used on 4.2 miles (6.7 km) and emulsion on the remaining 4.7 miles (7.5 km). Various types of tests were conducted at approximately 10 days (September 1981), 250 days (May 1982), 375 days (September 1982), and 610 days (May 1983) after construction on the foamed-asphalt section. Similar tests were conducted at approximately 40 days (September 1981), 275 days (May 1982), 400 days (September 1982), and 640 days (May 1983) after construction on the emulsion section. The tests consisted of deflection measurements and the laboratory testing of core samples. The recycled pavement system further consisted of a granular subbase of approximately 4.5 in. (115 mm) on top of a sandy-silt subgrade.

STRUCTURAL COMPARISON

The main purpose of the structural comparison was to evaluate the performance of the two layers. A knowledge of the performance of the two recycled layers will assist pavement designers in future designs and the economic evaluation of such pavements. The layer coefficients are the most valuable in this regard.

Laboratory Strength Tests

Cores 4 in. (100 mm) in diameter and randomly selected were taken 10 and 375 days after construction on the foamed-asphalt recycled section and 400 days after construction on the emulsion recycled section. A large number of cores were broken to such an extent that they could not be tested. Only perfect samples were used. Strength characteristics were evaluated by means of resilient moduli, Marshall stabilities, and Hveem R-values. All tests were conducted at about 73°F (21°C) as specified by the Asphalt Institute for cold mixtures. The results are summarized in Table 1. Because only the unbroken cores could be used to determine the properties discussed, the average values obtained from these cores will probably be higher than the actual values. This will not influence comparisons between the recycled layers, however. Only a small number of specimens could be obtained to determine the Marshall stability, and the results should therefore be used with caution.

The asphalt mixture design methods proposed by the Asphalt Institute (9) usually specify a minimum Marshall stability and Hveem R-value among other parameters such as flow, coating, and so on, for cold asphalt mixtures. These specifications do not indicate what the service life of the pavement layers will be. This has to be accomplished by pavement design methods. The specifications only ensure that the layers will be stable under various traffic and environmental conditions. The foamed-asphalt and emulsion recycled mixtures both exceeded the required strengths.

The Marshall stability has been correlated with the structural coefficients for base courses (5), but because this was done for mixtures at 140°F (60°C), the relationships cannot be used here. What can be used is the increase in the structural coefficient as the Marshall stability increases. The foamed-asphalt mixture therefore appears to have a slightly higher strength based on performance if only the average values are considered. The differences in average values are, however, not significant at $\alpha = 0.05$ (t-test). The structural coefficients can therefore be assumed to be the same after 400 days, based on the Marshall stability.

The resilient moduli also have to be correlated with the structural coefficients and are used in mechanistic design procedures. By using the correlation of Van Til et al. (5) developed for asphalt-treated bases, the structural coefficient of the foamed-asphalt recycled layer increased from a value 10 days after construction of 0.10 to a value 375 days after construction of 0.26. A correlation by Tia (10) shows an increase from 0.25 to 0.38 for the foamed asphalt. The resilient moduli of the foamed-asphalt and emulsion sections are the same 400 days after construction at $\alpha = 0.05$ and the structural coefficients, based on these relations, will therefore be the same for the two layers.

The estimates from the laboratory test results indicated that the structural coefficients of the foamed-asphalt section increased after construction. Not enough information is available to discuss the rate of increase. The coefficients of the emulsion and foamed-asphalt sections are essentially the same approximately 400 days after construction.

Deflection Measurements

A Dynaflect was used to measure deflections of the pavement after construction at the indicated times in both lanes. The Dynaflect is widely used to measure pavement deflections (11,12). Properties of the deflection basin (Figure 1) used in the evaluation of the recycled layers were as follows:

1. Dynaflect maximum deflection (DMD) is the deflection at the center between the two steel wheels. This deflection can be converted to the Benkelman beam deflection by multiplying it by 20.63 (13). Other correlations are also available (11,14, 15). They all give basically the same answers.
2. Surface curvature index (SCI) is an indication of the stiffness of the surface course. SCI is defined as the difference between the deflections of the first and the second sensors.
3. The spreadability (SPD) is defined as the sum of the deflections of the five sensors divided by five times the maximum deflection and expressed as a percentage. The SPD is indicative of the distribution of loads by the pavement to the underlying layers.

High values of SPD but low values of DMD and SCI indicate stiff (or strong) upper layers. All three of these indicators are strongly influenced by factors other than the properties of the surface and base-course layers, e.g., subgrade strength and thickness of layers, and have not been correlated directly with material strength parameters, e.g., resilient moduli or structural coefficients. Another problem with the use of deflections to compare pavements at different times is that deflections are influenced by the asphalt temperature and the subgrade moisture

TABLE 1 Results of Laboratory Strength Tests

Specimen	Time after Construction (days)	Resilient Modulus N	Avg (psi)	SD (psi)	Marshall Stability N	Avg (lb)	SD (lb)	Hveem R-Value N	Avg	SD
Foamed asphalt	10	43	97,400	26,100	12	1,960	1,050	25	78.3	9.2
Foamed asphalt	375	12	333,000	84,000	3	2,900	100	10	82.0	9.0
Emulsion	400	14	247,000	82,000	5	3,300	790	11	84.5	5.6

Note: SD = standard deviation; N = number of samples; 1 lb = 4.448 N; 1 psi = 6.89 kPa.

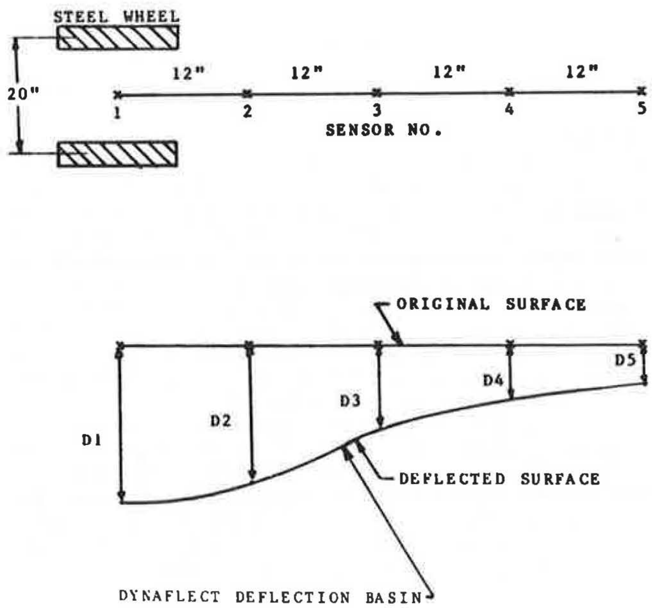

FIGURE 1 Dynaflect deflection basin.

content. Researchers in Kentucky (16) developed a method to adjust pavement deflections based on the asphalt pavement temperature. Because reliable pavement temperatures were not available, general correlations developed by Metwali (12) for Indiana were used. With these relations the DMD and SCI could be adjusted to a reference date (and thus a reference temperature and subgrade moisture content) based on the month of the year. The month after construction, September, was used as a reference. Metwali concluded that the DMD and SCI were influenced by seasons, but that the spreadability was not. Figures 2 to 4 show these changes in DMD, SCI, and SPD, respectively. All three indicators show that the stiffness of both sections increased during the first 400 days after construction because of densification under traffic and curing of the mixtures. The foamed-asphalt section was stiffer than the emulsion section. The rate of increase in stiffness, as indicated by DMD and SCI, was slightly higher for the foamed-asphalt section during the first 400 days. After that the rates of change in stiffness were almost equal. The stiffness (DMD, SCI) and load transfer capacity (SPD) of both sections decreased after about 400 days.

Both sections are in what Vaswani called the elastic phase of the pavement life (17). In this phase the consolidation or densification is almost negligible and the pavement layers behave more or less elastically. The deflections and stiffness indicators remain almost constant. The length of this phase depends on the type of material used, the traffic, and the environmental conditions. In Virginia this phase lasts about 5 years (17). The elastic phase is preceded by the consolidation phase in which the pavement layers, in this case the recycled layers, consolidate or densify. This phase lasted about 400 days (13 months) for both recycled pavements. Bandyopadhyay (4), in a study on recycled pavements in Kansas, found that the performance (and stiffness) of most recycled pavements improved during the first 7 or 8 months, after which they deteriorated. The elastic phase is followed by failure due to fatigue, in which cracks appear in the wheel path. The foamed-asphalt and emulsion sections are not yet in this phase.

Structural Layer Coefficients

Various methods can be and have been used to determine structural coefficients of pavement materials, but the most widely used are those based on the strains or deformations in the pavement and on the fatigue life of the material. The elastic-layer theory or finite-element method can be used to simulate the stresses, strains, and deformations in the pavement. The structural coefficients can be determined by comparing the strains, deformations, and fatigue life of the recycled pavement with those of a similar pavement with a standard AASHTO hot mixed asphalt layer in place of the recycled layer. The tensile strain at the bottom of the asphalt layer, the subgrade deformation, the maximum deformation at the surface, and the maximum compressive strain on top of the subgrade have been correlated with the number of load applications to failure (N_f). The tensile strain is an indicator of fatigue of the pavement. The deformations and compressive strain are indicators of the permanent deformation or rutting of the pavement. High permanent deformations lead to functional and eventually structural failure of the pavement. Functional failure can be defined

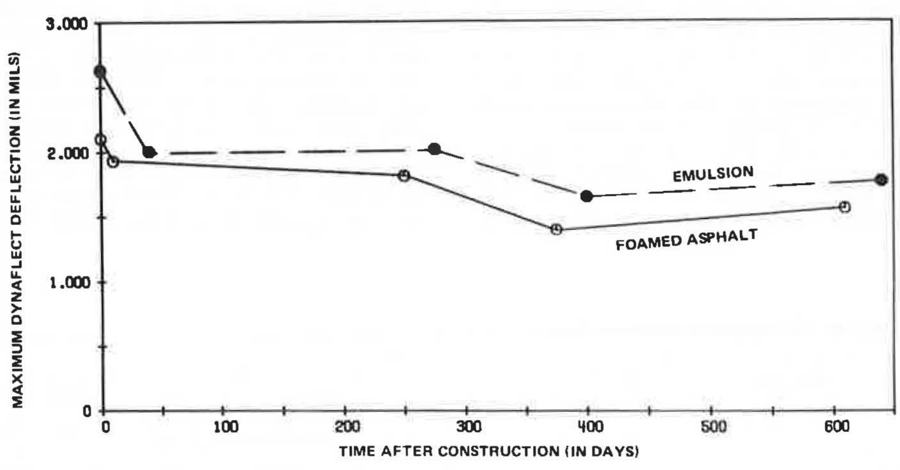

FIGURE 2 Comparison of DMDs.

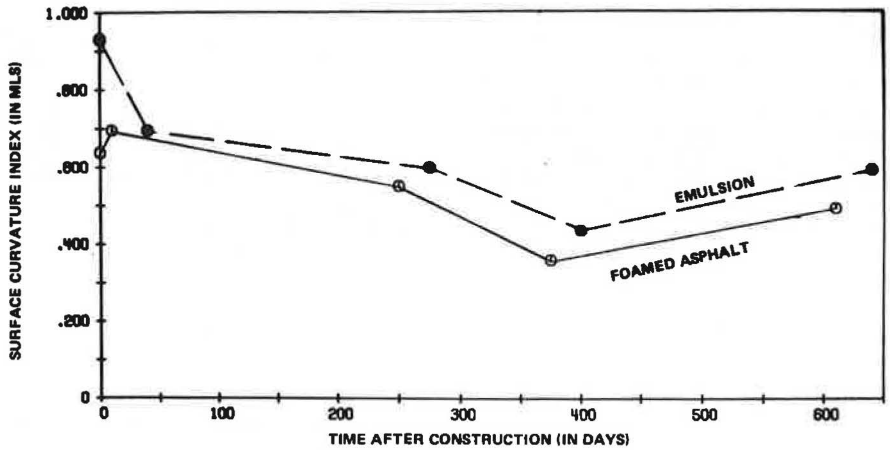

FIGURE 3 Comparison of SCIs.

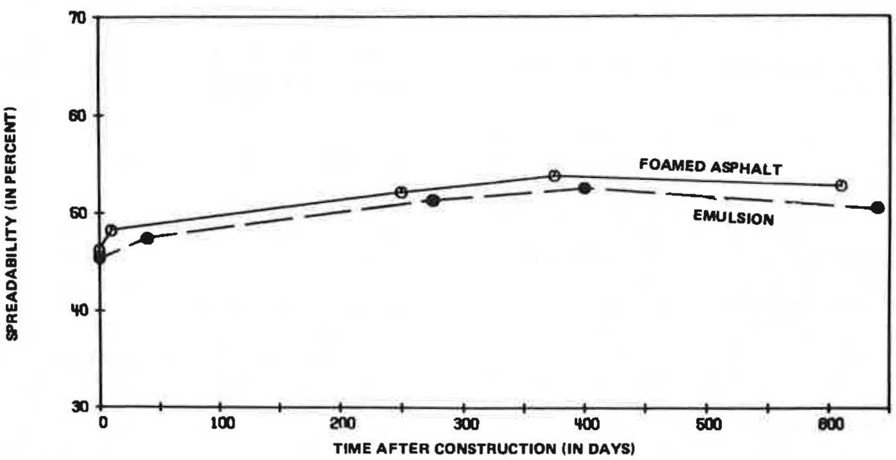

FIGURE 4 Comparison of SPDs.

as the condition at which the pavement will not be able to carry out its intended function without causing discomfort to passengers and high stresses on the vehicle, e.g., ruts. Different materials will have different load repetitions to failure. Pavements with the same number of load applications to failure will have the same service life and SN for similar climatic conditions, subgrade soil, and present serviceability indices according to the AASHTO design method. By replacing only the recycled layer with a standard AASHTO hot mixed asphalt layer the coefficients and thicknesses of the other layers will remain the same. Therefore

$$SN' = SN \quad (1)$$

where SN is the structural number of the pavement with the AASHTO layer and SN' is the structural number of the pavement with the recycled layer.

$$a' = a^*h/h' \quad (2)$$

where

- a' = structural coefficient of the recycled layer used as a base,
- a* = structural coefficient of the AASHTO asphalt layer = 0.44,
- h' = thickness of the recycled layer, and
- h = thickness of the AASHTO asphalt layer to give the same strain, deformation, or fatigue life.

The structural coefficient of a layer is influenced by the properties of the surrounding layers, the age of the pavement, the magnitude and frequency of load, the elastic parameters, and the thickness of the layer. The most important single factor is the elastic modulus of the layer in question. The best prediction of the true structural coefficients would be obtained if the in situ material properties and thicknesses of the pavement layers as well as the fatigue characteristics of all the layers were known. The strain or deformation criterion used in comparing the recycled layer with the standard AASHTO hot mixed asphalt layer should be the one that predicts the shortest service life and thus controls the performance. A large amount of testing is unfortunately necessary to obtain the necessary information.

A detailed description of the determination of the structural coefficients of the foamed-asphalt section is given elsewhere (18). The same method was used to determine the coefficients of the emulsion section. The first step was to determine the in situ elastic moduli of all the layers in the pavement at the different times the deflection measurements were taken. The layer thicknesses were measured before and during construction. Values of Poisson's ratio were assumed for the layers and they were assumed to remain constant. Constant elastic moduli were used for the asphalt layers. The granular subbase material and subgrade are stress-sensitive, and relationships obtained from the literature were used to relate stress in the pavement to the modulus of the layer. The relationships were of the following forms:

Granular material:

$$M_r = k_1 \theta^{k_2} \tag{3}$$

Subgrade material (clayey):

$$M_r = k_3 \sigma_d^{k_4} \tag{4}$$

where

M_r = resilient modulus,
θ = bulk stress,
σ_d = deviator stress, and
$k_1, \ldots, k_4$ = laboratory-developed coefficients.

Different coefficients were used for the different times of the year that the deflection measurements were taken.

A computer program based on the elastic-layer theory was used in this analysis to calculate the stresses, strains, and deformations in the pavement. This program, called BISTRO, uses constant elastic modulus values, and the moduli of the subbase and subgrade were adjusted manually after each run to incorporate their stress-sensitive behavior. A stiff subgrade layer was also introduced in the hypothetical pavement to simulate the pavement system more accurately. These methods have also been used by other researchers (19). An iteration process was used to determine the layer properties. In this iteration process the responses of the Dynaflect deflection basin were predicted by the program and compared with those from the actual deflection basin. With the layer thicknesses as well as modulus-strain relationships for the subbase and subgrade layers known, the moduli of the asphalt recycled and the surface layers could be determined through the iteration. A double wheel load of 9,000 lb (40 kN) at a pressure of 80 psi (550 kPa) was used in the program to induce the strains and deflections in the pavement system. The wheel spacing was 13 in. (330 mm). This is the same load as that used in the Benkelman beam test. These deflections, calculated by the program, were adjusted to Dynaflect deflections with the correlation factor mentioned earlier, because the Dynaflect applies a different load to the pavement system. The iteration process was terminated when the predicted deflection basin closely approximated the actual basin.

The tensile strains at the bottom of the asphalt layers, the compressive subgrade strain, and the maximum and subgrade deflections (Figure 5) were calculated with the properties of the recycled pavement known. These maximum strains were calculated under one of the wheels. The maximum strain does not always occur under one of the wheels, but the accuracy is sufficient for this study.

The next step was to replace the recycled layer with a standard AASHTO hot mixed asphalt layer and to calculate the required strains and deformations for different layer thicknesses. The moduli of the AASHTO layer were adjusted according to the average temperature observed each time the deflection readings were taken.

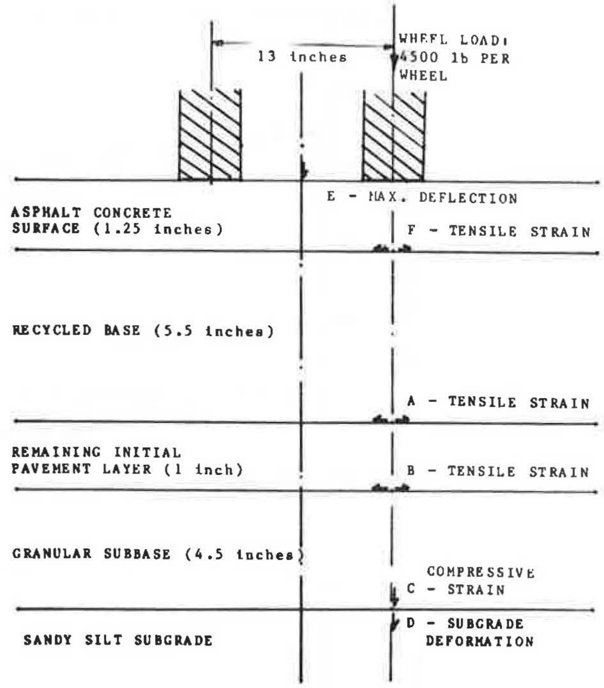

FIGURE 5 Pavement cross section.

The maximum surface deflection (20), the subgrade deflection (21), and the maximum compressive strain (20,22) have been correlated with the number of load repetitions to failure. The maximum tensile strain at the bottom of the asphalt layers has also been used to compare the recycled with the AASHTO layer. The same tensile strains will give the same performance only if the materials have the same fatigue characteristics. This will be the case for the remaining initial pavement layer, because it appears in both the recycled pavement and the pavement with the AASHTO layer. A certain tensile strain in the recycled layer will not indicate the same performance in the AASHTO layer, because their fatigue characteristics differ. The fatigue relationships are usually in the form of

$$N_f = k_1 (1/\epsilon_r)^{k_2} \tag{5}$$

where

N_f = number of loads to failure,
ϵ_r = maximum tensile strain, and
k_1, k_2 = coefficients.

Fatigue relationships were not developed for the recycled materials used in the construction of the road, nor are general relationships available for recycled materials. Relationships obtained from the literature for asphalt-stabilized base courses by Barksdale (23) and for asphalt base courses by Finn (24) were used for both the foamed-asphalt and emulsion recycled layers. Further relationships developed by Chevron (25) for emulsion mixes were used for the emulsion recycled layer, and relationships developed by Little and Epps (26) for foamed-asphalt mixtures were used for the foamed-asphalt recycled layer. The AASHTO layer was represented by two relationships, one each by Finn and by Witczak (27). Fatigue-life combinations that predicted coefficients of more than 0.50 or less than 0.05 were not considered to be applicable to the recycled layers and were deleted in the final analysis. Any of the strains, deformations, or fatigue characteristics can be used as a criterion to determine the coefficients, but the criterion that predicts the shortest service life will control the performance. The coefficients are sensitive to the criterion used, and unless the exact relationship of the criterion to the fatigue life for all the layers is known, a single coefficient cannot be determined. The relationships used were developed for materials not necessarily the same as those in this study. Various relationships were therefore used to develop a range of coefficients rather than a single coefficient for each recycled layer in this study. The following criteria were used in the development of these ranges:

1. The subgrade compressive strain, because it has been used widely in similar analyses;
2. The subgrade deformation, because it predicts the shortest service life;
3. The tensile strain at the bottom of the remaining initial pavement layer, which represents the maximum tensile strain in the asphalt layers and is independent of the fatigue life, because the same layer is used in the recycled pavement and the pavement with the AASHTO layer;
4. Three fatigue-life combinations (X2, Y1, and Y3), which gave coefficients between 0.05 and 0.50; the combinations used were as follows:
   a. The Finn relationship for the AASHTO layer with the Finn relationship for asphalt base courses (X2),
   b. The Witczak relationship for the AASHTO layer with the Barksdale relationship for the recycled layers (Y1), and
   c. The Witczak relationship for the AASHTO layer with the Little relationship for the foamed-asphalt recycled layer and the Chevron relationship for the emulsion layer (Y3).

The maximum deflection was found to be only a fair indicator of the structural strength or performance of the pavement (28).

Figures 6 and 7 show the comparison of the layer coefficients of the foamed-asphalt and emulsion recycled layers based on the maximum compressive strain in the subgrade and the maximum strain in the asphalt layers, respectively. Both Figures 6 and 7 show the same trends. The layer coefficients of the foamed-asphalt section increased rapidly during the first 250 days after construction. After 250 days they decreased slightly. The coefficients of the emulsion section increased the most between 250 and 400 days after construction, after which they also decreased slightly. Figure 8 gives the midpoints and the ranges of the coefficients determined by the six criteria listed (asphalt tensile strain, subgrade compressive strain and deformation, and three fatigue-life combinations). The coefficients of the two sections are basically the same from about 400 days after construction. The emulsion section took longer to reach its maximum strength and the strength increased more than the strength of the foamed-asphalt recycled layer. Coefficients for design purposes can be obtained from Figure 8. It is difficult to predict what the average layer coefficient over the life of the pavement will be with the limited information. The coefficient should be within the ranges of the coefficients determined for the sections after consolidation took place, that is, 400 days after construction. The coefficients to be used within the range depend on the pavement designer. Average values can be obtained by combining the ranges obtained at approximately 400 and 600 days after construction to get a new range and then taking the midpoint of this range. Such a procedure gave a layer coefficient of 0.31 for the foamed-as-phalt recycled layer and 0.29 for the emulsion recycled layer. It should be noted that these coefficients were developed for specific recycled layers. Caution should be exercised when they are used for other recycled layers.

CONCLUSIONS

All the strength indicators showed a rapid increase in strength during approximately the first 400 days after construction for both the foamed-asphalt and emulsion recycled sections. The rate of increase varied. The foamed-asphalt section gained most of its strength during the first 250 days, whereas the emulsion layer increased in strength gradually during the first 400 days. The strength as indicated by the deflection parameters showed that the foamed-asphalt layer had slightly higher strengths throughout the analysis period than the emulsion layer, but the differences were small. Full consolidation or densification was reached for both recycled layers during the first 400 days after construction.

The layer coefficient is the best single indica-

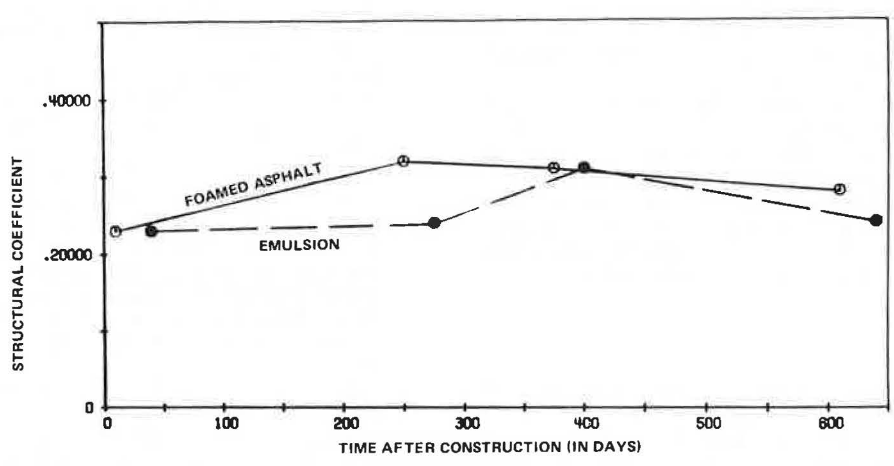

FIGURE 6 Comparison of layer coefficients: subgrade strain.

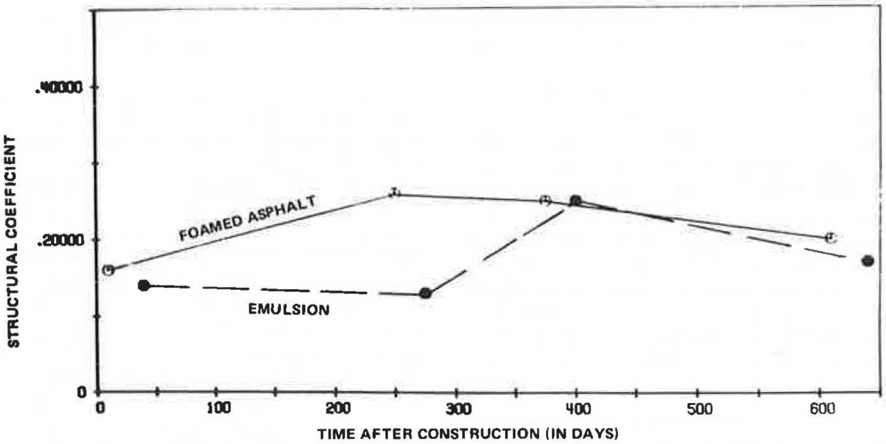

FIGURE 7 Comparison of layer coefficients: asphalt tensile strain.

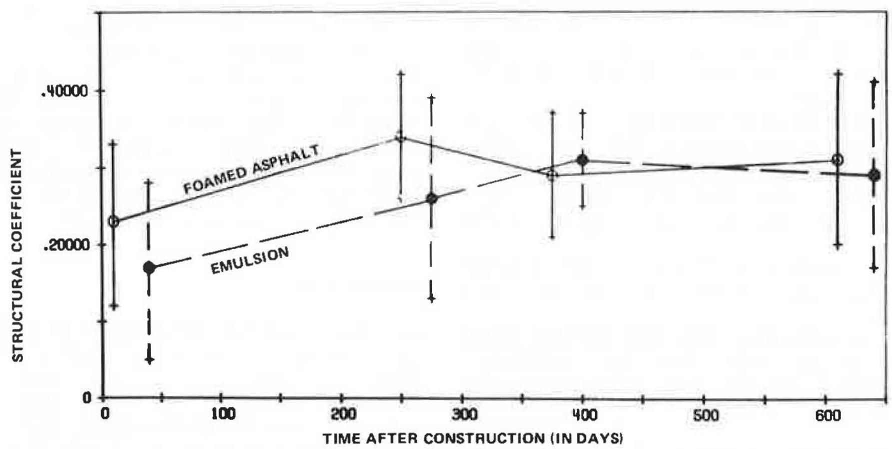

FIGURE 8 Comparison of layer coefficients: all criteria.

tor of the pavement performance. Figure 8 gives ranges of layer coefficients that can be used in the selection of layer coefficients for recycled layers similar to these used in the analysis. The midpoints are 0.31 and 0.29 for the foamed-asphalt and the emulsion recycled layers, respectively. Coefficients on the lower side of the range should be used in design, because both materials are new and their behavior has not been studied extensively. The structural coefficients of the foamed-asphalt recycled layer range from 0.20 to 0.42 and of the emulsion recycled layer from 0.17 to 0.41.

The coefficients are virtually the same, which indicates that the performances of the two recycled sections should be the same. The practical implication of the same performances is that any of the two binders, foamed asphalt or emulsion, can be used in cold recycling, because they will have the same service life. The most economical binder to use would be the one that has the lowest initial cost.

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