Theoretical Asphaltic Concrete Equivalences

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Theoretical asphaltic concrete equivalences were calculated on a continuous hourly or fourth-hourly basis for a 245-day period. For these calculations equivalence was defined as that thickness of base necessary to replace one inch of surfacing for equal deflection. Deflections were calculated using the layer elastic theory and the results of static and dynamic lab tests of the pavement materials in the frequency domain. The materials investigated were two asphaltic concrete surfacings and three asphaltic concrete bases. The effect of testing specimens with H/D ratios of less than two was investigated. The subgrade was that determined from the 1960 trenchings at the AASHO Road Test and the continuous hourly temperature data were those reported by the Asphalt Institute. Continuous 19-kip single-axle loadings moving at 50 mph were assumed for the principal calculations. The effects of different loadings were examined as functions of weight, speed, time, and contact area together with the effects of different subgrades and layer thicknesses. It was concluded that there is no unique equivalence and that the inclusion of a failure term is necessary to the theoretical calculation of equivalence for given materials, environment and loadings.

•THE objective of this study was the investigation of a theoretical approach, using laboratory test results, for determining the relative structural equivalences of asphaltic concrete surfacings to base materials in highway pavements. This problem is significant because of the possible geometries and diversities of materials available for use in pavements, the traditional approach to pavement design, and the relative insensitivity, as well as the time and money costs, of on-the-road performance-type tests. Similar studies of this problem in the past have been based on various criteria using average conditions, performance, etc., and the equivalences so determined can show a rather large range (1, 2, 3). In this study the criterion used to determine equivalence involves finding the increased thickness of a material that compensates for the deflection resulting from a unit thickness decrease in another material. The importance of deflection as a criterion was shown by the AASHO Road Test, in which deflection correlated as well with performance as did loadings and structural design (4).

The prediction of pavement deflections using the results of laboratory tests and the elastic layer theory has been of major interest in past work here. The results of comparisons of predicted and measured deflections have been reported (5, 6) and form the base for this study. The initial development of an approach to determining material equivalences using deflections was accomplished in work performed under a grant by the Asphalt Institute (7). That work showed the importance of variations in pavement-material properties with time-associated changes in temperatures, moisture contents,

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and densities. Based on that work it was concluded that there was no unique equivalence and that the theoretical determination of average equivalences must be based on climatic conditions as they actually vary with time.

Changes in pavement material properties with time, excluding the effects of aging, will vary with the pavement, its geographical location, and the time under consideration. Such changes are easily recognized in the rapidly changing temperatures in the asphaltic concretes and in the relatively slowly changing moisture contents and densities in the underlying layers. These changes are interrelated to some degree and in any study that considers the effect of such changes, it is necessary that the various data be compatible. Unfortunately no complete source of such compatible data is known and to investigate theoretically the equivalences of various asphaltic concretes for this study, it was necessary to devise a hybrid pavement-climate history. The resulting artificial conditions were composed of the hourly 12-in. asphaltic concrete temperature data reported by Kallas for 1964-5 in College Park, Maryland, and the subgrade conditions reported for the 1960 trenching studies of the AASHO Road Test (8, 9). For these conditions the equivalences of two asphaltic concrete surface and three asphaltic concrete base materials were investigated for those months in which the Road Test subgrade was not frozen.

Samples of the investigated materials have been tested in the laboratory and, using these test results, calculations of deflection under a 19-kip single-axle load moving at 50 mph were made using the three-layer elastic theory (10). These calculations were made for consecutive hours for 12-in. thick pavements composed of 3- and 9-in. thicknesses of surface and base materials. For each of these times 1 in. of the surface material was removed, in theory, and the amount of base necessary to bring the calculated deflection back to the original value was found by successive approximations.

While this study was restricted to asphaltic concretes in two constant layers, the methods used are believed applicable to such pavements in any number of layers. In that connection the greatest significance of this work may well be in the theoretical simulation of pavement response to moving loads with continuous time.

MATERIALS

The asphaltic concrete materials investigated in this study were the AASHO Road Test surfacing and base together with Ohio's T-35 surfacing and B-21 and B-35 bases. Complete laboratory test results for the Road Test surfacing, subgrade and base materials have been reported (5, 7) as have similar results for Ohio's T-35 and B-21 asphaltic concretes (6). As constructed for pavement service, the AASHO and the T-35 surfacings were composed of wearing and leveling courses. The preparation of laboratory test specimens of each of these materials involved the creation of a simulated mix in which the gradation of the aggregate was the average for the two courses. In addition, for the T-35 surfacing, data were available from tests on pavement cores in which the strain gages bisected the two courses. Samples of the Ohio B-35 base were tested as a part of this study.

Specimens of the B-35 base were taken from an in-service pavement using diamond core drills. This pavement, Hamilton Rd., was constructed during the fall of 1964 and the core specimens were taken on May 31, 1966. Figure 1 shows the average aggregate gradation of the B-35 base from extraction tests made during construction of the pavement. These tests gave an average asphalt content of 4.9 percent (of total mix) of a 70-85 penetration asphalt. Also shown for comparison in Figure 1 are the gradation curves of the other asphaltic concretes as well as average data from similar tests on the lab specimens.

The average core diameter from the Hamilton Rd. pavement was 3.75 in. and the average height was 7.5 in., of which some 3.5 in. were of the B-35 base and the remainder was of the surfacing. The surfacing layer was removed from the core specimens by sawing with a diamond saw, as was a thin layer representing the irregular bottom of the asphaltic concrete. This gave rather short test specimens 3.75 in. in diameter and 3.0 in. high or an H/D ratio of about 0.8.

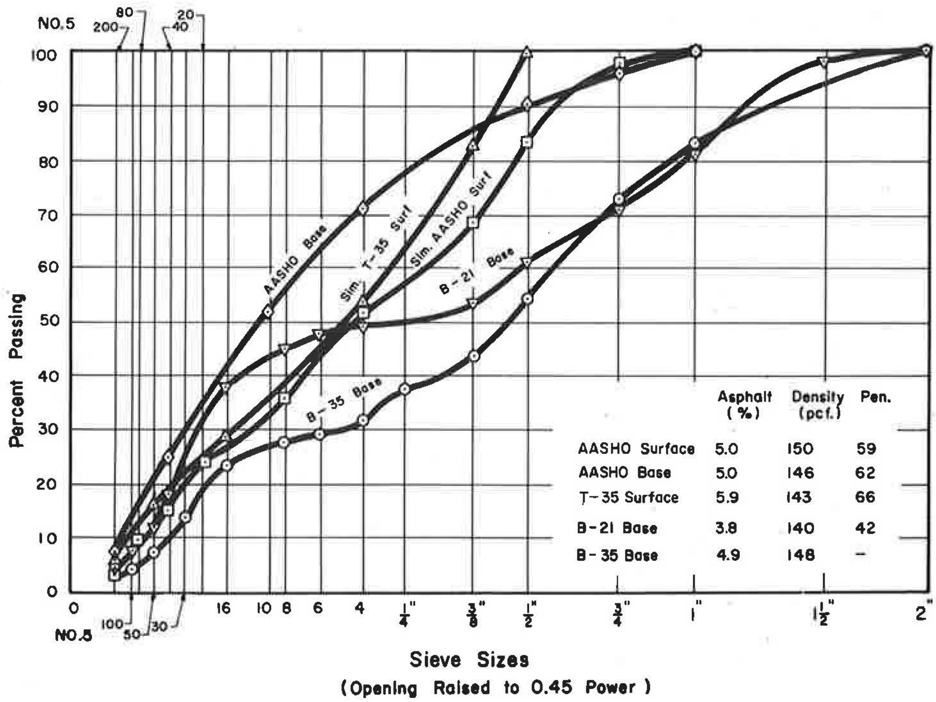

Figure 1. Aggregate gradations.

The B-35 core specimens were tested under dynamic loading to determine the variation in complex modulus $|E^*|$ and phase shift ϕ with changes in specimen temperature and in loading frequency. In these tests the asphaltic concrete specimens were subjected to simple axial compressive loading in the form of a sine wave and the resulting strain was measured with SR-4 gages mounted at specimen mid-height. These test procedures, involving relatively small loads and strains, and the analysis of the resulting data have been given in some detail previously (9). In brief, for unconfined dynamic compressive tests where steady-state sinusoidal loading is of the form $\sigma_v = \sigma_o \sin \omega t$ and the resulting strain is of the form $\epsilon_v = \epsilon_o \sin(\omega t - \phi)$, by definition:

$$|E^*| = \frac{\sigma_o}{\epsilon_o} \text{ and } \phi = \frac{t_1}{t_p}(360°)$$

where

$|E^*|$ = complex modulus,
ϕ = phase shift,
σ_o = amplitude of stress wave,
ϵ_o = amplitude of strain wave,
t_1 = time between homologous points on the two curves, and
t_p = period.

Before this study no tests of specimens with an H/D ratio of appreciably less than 2 had been performed here. Because of the relatively thin layer of the B-35 base in the Hamilton Rd. pavement it was necessary to investigate the feasibility of testing specimens with H/D ratios on the order of one.

End Effects

The effect of end conditions can be marked in test specimens with plane and parallel ends and H/D ratios of appreciably less than 2. This is a historic problem in elasticity,

as shown by the theoretical work of Filon in 1902 (11). There are two practical difficulties associated with testing short specimens. These involve the problem of achieving plane ends perpendicular to the axis of the specimen and the problem of eliminating the end restraint (or vice versa) that results when end platens are of different E and μ than the specimen. Past efforts to solve the latter problem have involved the use of segmented end platens, oiled membranes, low-friction membranes, combinations of these, etc. (12, 13, 14). For the purposes of this study a limited experimental investigation into these problems was undertaken.

To investigate the effect of specimen treatment and end conditions, a group of 16 asphaltic concrete test specimens was prepared that represented the range in materials that had been used in past studies. These capped specimens were 4 in. in diameter by 8 in. high and were mounted with $^{13}/_{16}$-in. active length SR-4 strain gages at sample mid-height. The specimens were repetitively tested over a period of several days to provide datum values of individual and average $|E^*|$ to which the effects from subsequent variables could be referenced. As a side variable in this test series, the effect of end irregularities (introduced by inserting feeler gages up to 0.050 in. in thickness) was investigated as well as the effect of using different end materials, such as $^1/_4$-in.-thick gasket-cork layers, 10-mil sheet Teflon, triaxial rubber membranes, etc. As would be expected there was no effect on average test values from the introduction of any of these conditions or materials at the ends of the capped specimens.

Eight of the 16 specimens were then used to investigate the effect of "freezing" (0 F) followed by annealing (1 hour at 150 F) on capped specimens. This question was of interest because it was expected that sawing would be better accomplished with frozen specimens. The results of these tests showed no effect on average $|E^*|$ as a result of freezing; subsequent experience with sawing indicated that it was as easy to saw unfrozen as frozen specimens and that the effects from sawing were similar.

Following these tests, the caps (only) of eight of the datum series were removed by diamond sawing. These specimens were then annealed at 150 F for 1 hour and repetitively tested at 88 F and 10.8 rad/sec over a period of several days. They were tested with steel end platens, with steel platens and feeler gages 0.004, 0.008 and 0.015 in. thick inserted (between sample and platen) directly over a strain gage as well as with the feeler gage at 90° from over the strain gages. There was no effect on average $|E^*|$ with steel end platens. There was no effect of end irregularity introduced by feeler gage below the 0.015-in. level. At that level there was a trend, barely significant, of slightly lower average $|E^*|$ with the feeler gage directly above the strain gage, and slightly higher average $|E^*|$ with the feeler gage away from the strain gages. There was no effect with cork alone nor was there any effect of feeler gage when used with cork. Other capping materials gave results similar to those with cork.

These specimens were then shortened by sawing to a height of $5^1/_4$ in., after which they were annealed and retested. At this point an effect from sawing was first observed in that first tests gave higher strains than did all subsequent tests. The latter gave values that were stable under repetitive testing performed daily for several days. Apparently some disturbance was caused by the sawing that was corrected in subsequent handling. At this time tests with cork showed no change from datum in average $|E^*|$ while tests with steel platens (only) gave individually erratic results that were somewhat higher in average $|E^*|$. Deviations of the ends of these samples from planes were estimated to be on the order of 0.002 in. from measurements made with an Ames dial by sliding the sample across plate glass. The difference in height across the specimens was on the order of 0.030-0.060 in. Tests with stacked triaxial membranes as well as those with stacked Teflon layers gave results intermediate between steel and cork, whether the layers were oiled or not.

After these tests the specimens were shortened by sawing to a height of 3 in. after which they were annealed and re-tested. The effect of sawing was again noted in first tests. Individual test results with steel platens were wildly erratic. Subsequent test results with two layers of $^1/_{16}$-in.-thick lab gasket rubber and with cork were consistent and were significantly lower than the datum test values; cork was somewhat better than rubber. In this later test series there was no effect of specimen rotation with respect to cork or rubber end materials. The results of tests using polyurethane foam caps

were similar to those with cork and rubber except that the average |E*| determined with foam showed no significant difference from the original datum tests.

From the results of these tests it was believed that both the foam and the cork showed promise as capping materials and that these two materials should be investigated at other test temperatures and frequencies with a larger number of test specimens. These tests were performed with results that, in brief, showed that the effects of these capping materials were variable under the different conditions of temperature and frequency. It was concluded that they could not be generally used as cappings for short asphalt concrete test specimens to eliminate end effects, even at the relatively low strain levels used in these tests. These results indicated that perhaps the only hope of solving the "like E and μ" problem with short specimens was to use caps of the same materials as the test specimens.

Following these findings the test datum specimens were ground at a local steel supplier with a Blanchard grinder. This equipment is rated to give ends out of parallel or of plane of less than 0.002 in. and the resulting surfaces were well within these tolerances. Check tests on these specimens, using the capping materials previously investigated, revealed the test-sequence effect first noted with sawing—the lower first-test value was again followed by recovery to the pregrinding value. Tests were performed using two of the datum specimens as caps while a third specimen, placed between the two capping specimens, was tested. The results showed that at the higher temperatures the resulting average |E*| were at datum values but that there was some effect of rotation of the caps with respect to the middle test specimen. It was suspected that the rotation effect was dependent on relatively small end-surface irregularities.

The ends of the capping and test specimens were carefully hand ground, using decreasing grit size down to No. 180, and retested at high and low temperatures. The results of these tests showed that the effect of rotation was more pronounced at the lower temperatures. Analysis of these data suggested that the rotation effect was strain-dependent; i.e., in tests at the higher temperatures and higher strains there was enough strain to overcome the effect of small end irregularities. This thesis was checked by performing tests at high temperatures at both low and high strains and the rotation effect that had been observed at low strains and temperatures was replicated. In these check tests the strain levels were about 30 and 120 microinches per inch—values that were comparable to those at which the effect was first noted. In check tests at the 40 F level it was not possible to achieve the higher strain level with the loading equipment available although lower strains could be attained. These tests did show, however, the same trend of decreasing dispersion in test values with increase in strain level. In these tests the strain levels were some 15 and 30 microinches per inch.

Based on analysis of all data it was concluded that hand-grinding to the No. 180 grit level brought the |E*| values to within ranges that were acceptable for the purposes of this study. One of the findings in this test series was that specimen ends, once prepared by grinding, must be maintained by keeping the specimen capped with plane surfaces. Asphaltic concretes are viscoelastic and surfaces ground plane will change with time and handling technique. In this study plate glass was used for this purpose and the insertion of 1- or 2-mil Teflon between the glass and specimen prevented bonding of the two.

This study was not exhaustive, by any means, and further research on the problem of testing short asphaltic concrete specimens at low strain levels is needed. Where specimens with fairly smooth ends and with H/D ratios on the order of 2 are available, or can be made, there is no particular problem as would be expected and as was experimentally confirmed in this study. If it is desired to test samples from in-service pavements, however, layer thicknesses and aggregate sizes will control the size of the specimens that can be used for such tests. For many pavements, such as the Hamilton Rd. pavement in this study, it will be necessary to test specimens with low H/D ratios. In these cases it will be necessary to use extraordinary techniques to minimize the end-effect problem.

For the tests of the Hamilton Rd. base specimens in this study the ends were ground through the No. 180 grit size as discussed previously. After each specimen was hand-ground it was stacked to give composite specimens composed of two central and active

specimens capped on the ends with inactive or capping specimens. First tests of these composite specimens were at 110 F and 10.8 rad/sec at which point the specimens, which had a tendency to bond, could not be easily separated. Following these tests the B-35 specimens were tested at other temperatures and frequencies and at the end of testing bonding was complete to the point that the composite specimens could be lifted by the top without separation. The average results of these tests are given graphically in Figure 2. Check tests for linearity of response (to increases in compressive stress) are not shown but gave results on the order of those of the other asphaltic concretes in this study.

Asphaltic Concretes

The study was concerned with the response of the different asphaltic concretes to a truck moving at 50 mph. With the truck loading represented by a cycle length of 6 feet, as used in past studies (5, 6), this is equivalent to a lab sinusoidal loading frequency of 77 rad/sec. The moduli response of the five asphaltic concrete materials to temperature change at this frequency is given in Figure 3. These data represent an interpolation for frequency and an extrapolation for temperatures higher than 110 F and lower

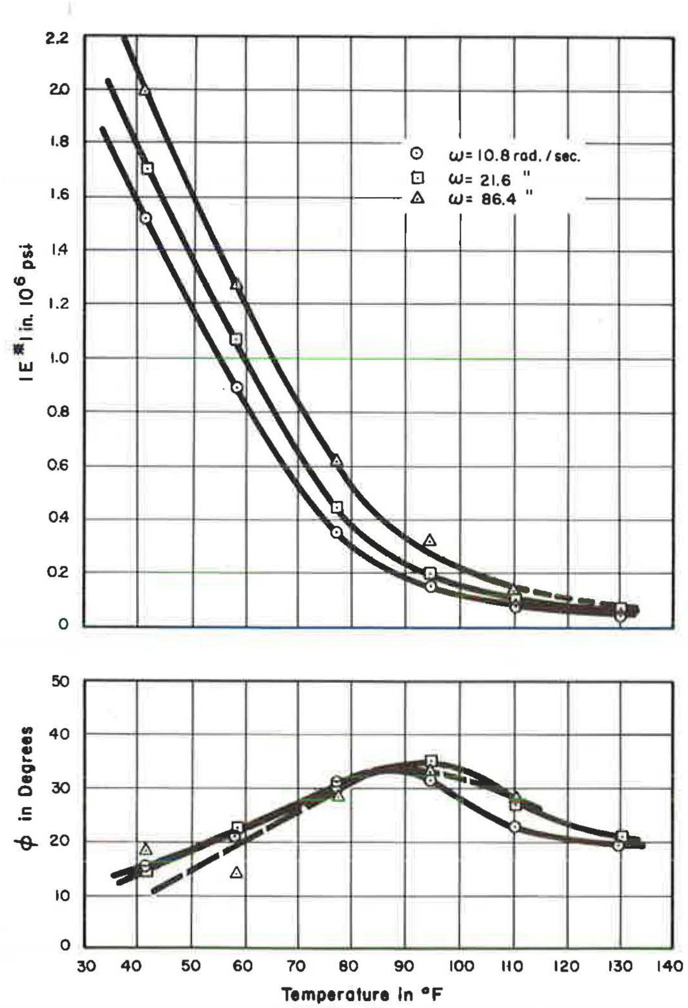

Figure 2. B-35 base results.

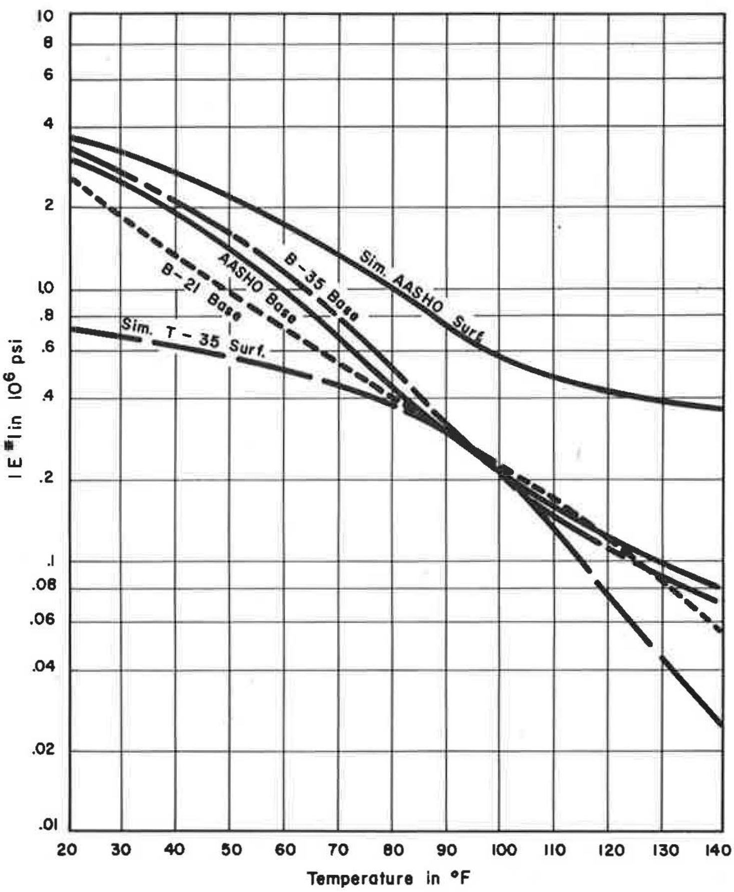

Figure 3. Complex moduli at 77 rad/sec.

than 40 F, except for the AASHO surfacing which was tested at temperatures between 120 and -20 F and the B-35 base which was tested up to 130 F. The data for each of these curves were fitted with polynomials for machine processing, so that each material was represented by two fourth- or fifth-order polynomial equations representing the laboratory test relation between $|E^*|$ and temperature at ω = 77 rad/sec.

Subgrade

The response of the subgrade to changes in saturation represents a similar interpolation for frequency and for the range in saturations involved in this study. This range was based on the results of the 1960 Road Test spring and fall trenching studies; the variation of saturation with calendar time was estimated. For convenience in processing, the data were reduced to an equation expressing the relation between subgrade modulus and AASHO Day for ω = 77 rad/sec:

$$|E^*| = 5.2587058 + 2.062026\,(10)^{-2}D - 1.8678979\,(10)^{-4}D^2 + 1.1368754\,(10)^{-6}D^3 - 4.0310894\,(10)^{-9}D^4 + 5.6703537\,(10)^{-12}D^5$$

where D = AASHO Day - 1370 (between 1370 and 1615), Day 1370 = April 1, Day 1615 = December 2, and $|E^*|$ is in $(10)^3$ psi. The range expressed in this equation is from about 5,300 to 6,400 psi.

Temperature Data

The source of the temperature data used in this study was that reported by Kallas for a 12-in.-thick asphaltic concrete pavement section at College Park, Maryland (8). The data consisted of hourly temperature measurements at the surface and at each 2-in. depth to the bottom of the pavement for a continuous 12-month period from June 1, 1964, to May 31, 1965. That portion of the data that included the calendar days represented by AASHO Days 1370 to 1615 was entered on punched cards for machine processing. Within this time period a relatively small amount of data was missing. The missing times were filled by inserting hourly temperatures from days with similar precedent temperatures. Interestingly, at the junction of the 1964 and 1965 temperatures (hour 2400 on May 31, 1965, and 0100 on June 1, 1964) there was no break in the trend of temperatures with time and no adjustments at this junction were necessary.

CALCULATIONS

For this study, equivalence was defined as that thickness of base that would compensate for the effect on deflection of decreasing the surface layer thickness by 1 in. The pavement section used consisted of 3 in. of asphaltic concrete surfacing and 9 in. of asphaltic concrete base. This structure was underlain by the subgrade represented in the data from the AASHO Road Test and was theoretically subjected to the temperature represented in the Asphalt Institute temperature data. Loading was a 9.5-kip wheel load moving at 50 mph for which the equivalent loaded area was 137 sq in. (R = 6.6 in.) and the equivalent laboratory test frequency was 77 rad/sec. Deflections were calculated using the "n" elastic layer solution developed by the Chevron Asphalt Co. This computer programmed solution was used as three layers with μ = 0.35 and the respective layer moduli, $E_i = |E_i^*|$ for ω = 77 rad/sec.

Equivalence

To calculate the equivalence of layer 1 to layer 2 (surface to base) for a given day and hour, the deflection under the center of the loaded area is calculated for that time. In this calculation E_1 is determined by the average temperature of the upper 3 in. (h_1) of the 12-in. pavement section, E_2 is determined by the average temperature of the lower 9 in. (h_2) and E_3 is determined by the AASHO Day. With this deflection known and E_3 constant, calculations are then made with h_1' = 2 in. and with variable base thickness, h_2', to find that thickness at which the deflection is the original value. In these calculations E_1' is determined by the average temperature of the upper 2 in. and E_2' is determined by the average temperature within the thickness under consideration. This procedure can be visualized as a graphical plot of deflection vs h_2' calculated with a surfacing thickness of 2 in. The intersection of the resulting curve with the original deflection (calculated with h_1 = 3 in. and h_2 = 9 in.) determines the equivalence which, for this pavement section, is the h_2' intercept minus 9. To determine the equivalence at the next succeeding hour this procedure is repeated using the different temperature gradient that normally exists in the asphaltic concrete at the different time. When h_2' is greater than 10 in., the temperature data are linearly extrapolated using the measured temperatures at the 10- and 12-in. depths.

With the data available in this study it was possible to determine the equivalences of two asphaltic concrete surfacings to three asphaltic concrete bases under the hybrid climatic conditions created for each hour of a 245-day period. For one set of materials (one surface and one base) this entails some 5,880 calculations of equivalence. To this end a computer program was developed that would calculate continuous hourly equivalences for the 245-day period.

In programming the calculation of equivalence, an iteration process was used to converge on the value of h_2' at which the deflection was the original value. To start this process a $\Delta h_2'$ of 1 in. is used, i.e., h_2' = 10 in. (in calculations for successive hours the first $\Delta h_2'$ tried is the equivalence for the previous hour). The deflection calculated with the first $\Delta h_2'$ is compared with the original value and if the deflections differ

by more than 0.00002 in., a new $\Delta h_2'$ is found using the empirically derived relation

$$\Delta h_2' = h_2' - 9 - \frac{\Delta W}{0.156}$$

where ΔW is the difference in the two calculated deflections. In successive iterations $\Delta h_2'$ is found by linear interpolation using the results of the last two calculations. The iteration process is discontinued at any point when the new $\Delta h_2'$ is less than 0.009 in. This process was relatively efficient and converged on the equivalence in an estimated average of 2½ trials in successive hourly calculations and in 3 trials in calculations for every fourth hour. No significant differences were found between computer solutions and relatively large-scale graphical solutions.

Because of the number of calculations involved in continuous hourly calculations it was desirable to investigate sampling plans that would reduce the total number of calculations without significantly affecting average equivalences while giving fairly

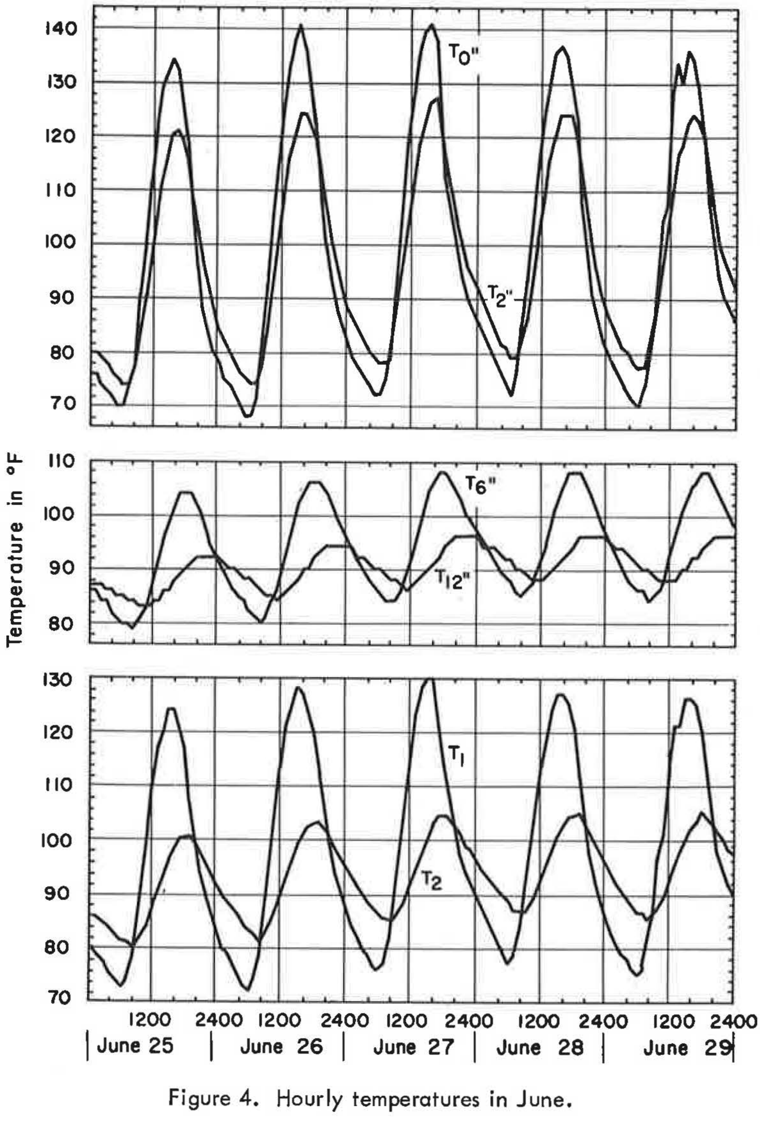

Figure 4. Hourly temperatures in June.

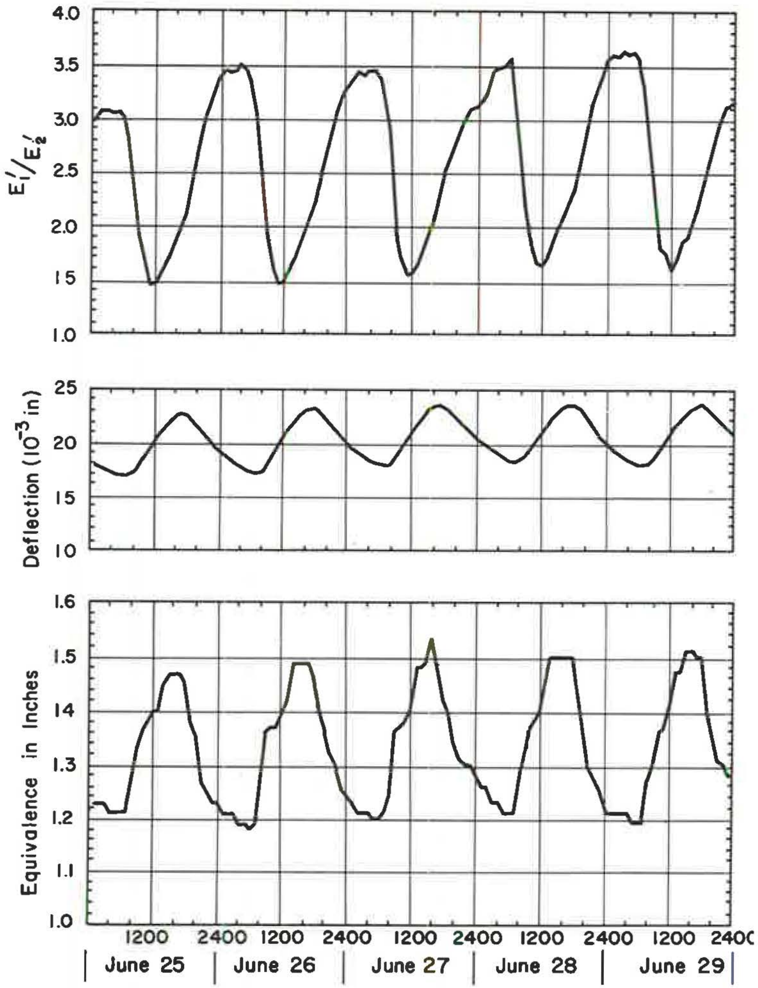

Figure 5. AASHO surface and base in June.

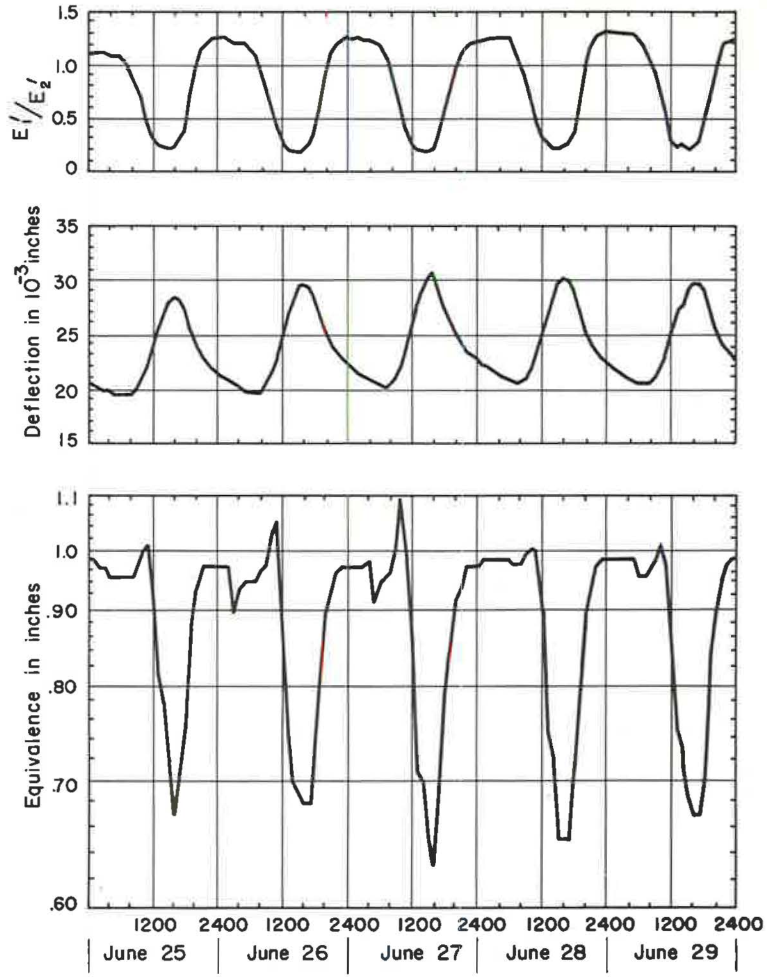

Figure 6. T-35 surface and B-21 base in June.

representative ranges in the resulting data. For this purpose seven 5-day blocks were selected that represented a 14 percent sample of the 245-day data. This selection was based on study (for all of the 5, 880 hours) of the trends with time of E_1, E_2 and E_1/E_2 using the Ohio T-35 surfacing and B-21 base lab test data. These trends were in the form of machine-plotted graphs, some 25 ft in length, in which 24 hours of data were plotted over a length of 1. 2 in.

The sampling plans investigated were based on sampling starting on any hour at frequencies of up to every sixth hour. The results of this study indicated that calculations made every fourth hour, starting on the fourth hour, were best. This plan gave a maximum positive variation in average equivalence in all 5-day blocks of 0. 003 in. and a maximum negative variation of 0. 001 in. Differences of this magnitude have no practical significance. Similar variations in high and low hourly equivalences (at any hour) were a positive 0. 00 in. and a negative 0. 11 in. for all 5-day blocks.

Variations in high and low equivalences with sampling plan reflect the success of the plan in proportionally sampling at the hours of critical temperature conditions relative to the two asphaltic concrete layers. For these data these hours vary in different 5-day blocks and no general statement can be made as to just when these times will occur. For any one 5-day block the critical hours would be expected to vary with the thicknesses of the layers under consideration and the respective moduli response to temperature changes in the two layers. In addition, for temperature data from other

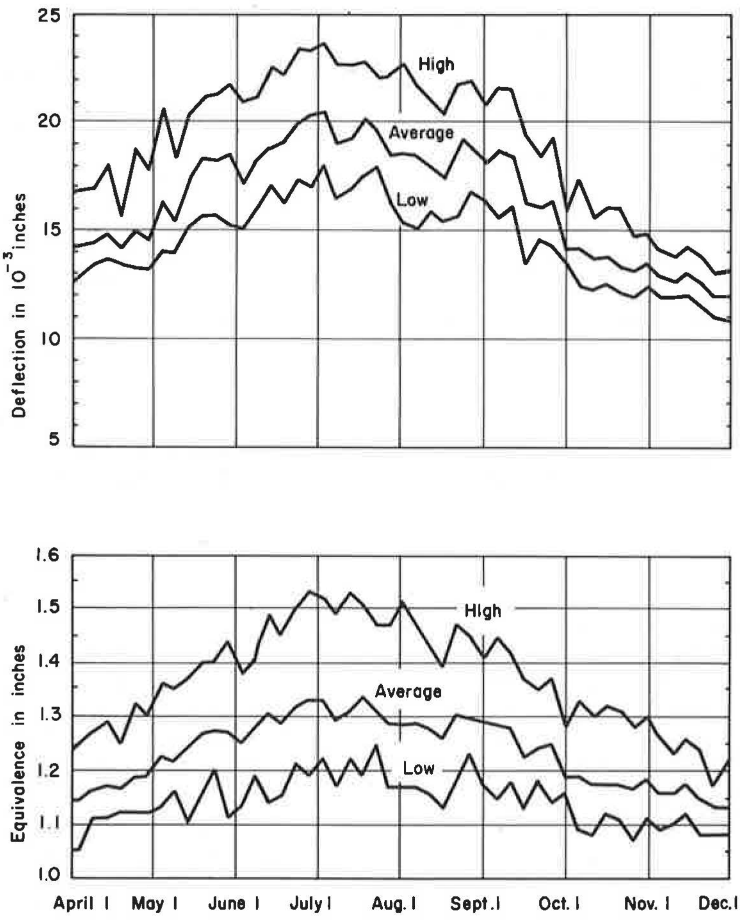

Figure 7. Five-day equivalences, AASHO surface and base.

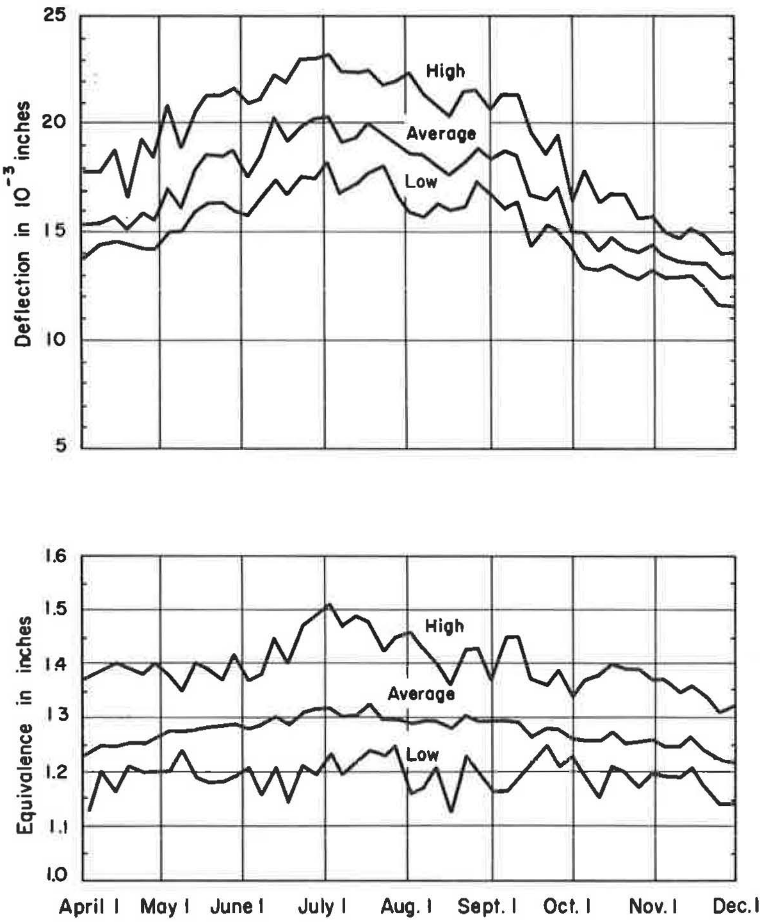

Figure 8. Five-day equivalences, AASHO surface and B-21 base.

sources at similar latitude, these times would be expected to be a function of the longitude in reference to the local time convention followed at the temperature recording sation, i. e., standard or daylight.

Typical Data

Figure 4 shows hourly temperatures at four pavement depths for a 5-day block beginning at 1:00 a. m. on June 25. Also shown in the figure are the corresponding hourly average temperatures for the upper 3 in. of pavement (T_1) and the lower 9 in. (T_2).

For the same time block Figure 5 shows the hourly deflections with the AASHO surfacing and base materials. Also shown are the moduli ratios of layer 1 to layer 2 at the thicknesses giving equivalence. The lower part of the figure gives the calculated hourly equivalences in which the 1 representing the surfacing in the ratio, 1: equivalence, is understood.

Figure 6 shows similar data for the same 5-day block with the T-35 surfacing and B-21 base. Equivalences below 1 in this figure are plotted to inverted scale; this results in a graphical presentation that is comparable to plotting equivalences greater than 1 to an arithmetic scale.

Average Equivalences

Figures 4 through 6 presented data for continuous hourly calculations over one 5-day block. To calculate equivalences for the full 245-day period, similar calculations were made for every fourth hour starting on the fourth hour in April 1; the effect of this sampling procedure on average and extreme equivalence was discussed earlier.

The data from the fourth-hourly calculations were treated in consecutive 5-day blocks. The results of this treatment are given in Figures 7 through 11 for all materials investigated. These figures show the 5-day average equivalences and deflections, plotted at the midpoints of consecutive 5-day blocks, for the different material combinations. For example, the average of all equivalences in Figure 5 is shown as the point, just before July 1, on the "average" curve of Figure 7. Shown in addition are the respective highs and lows within the successive 5-day blocks.

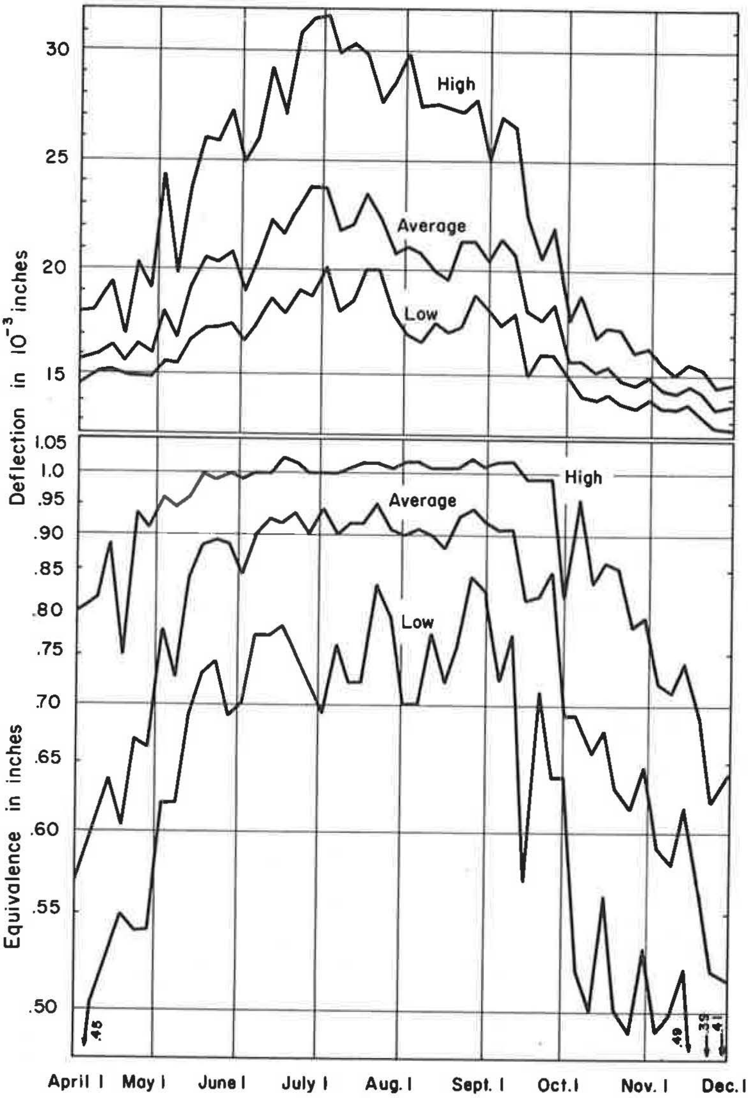

Figure 9. Five-day equivalences, T-35 surface and B-35 base.

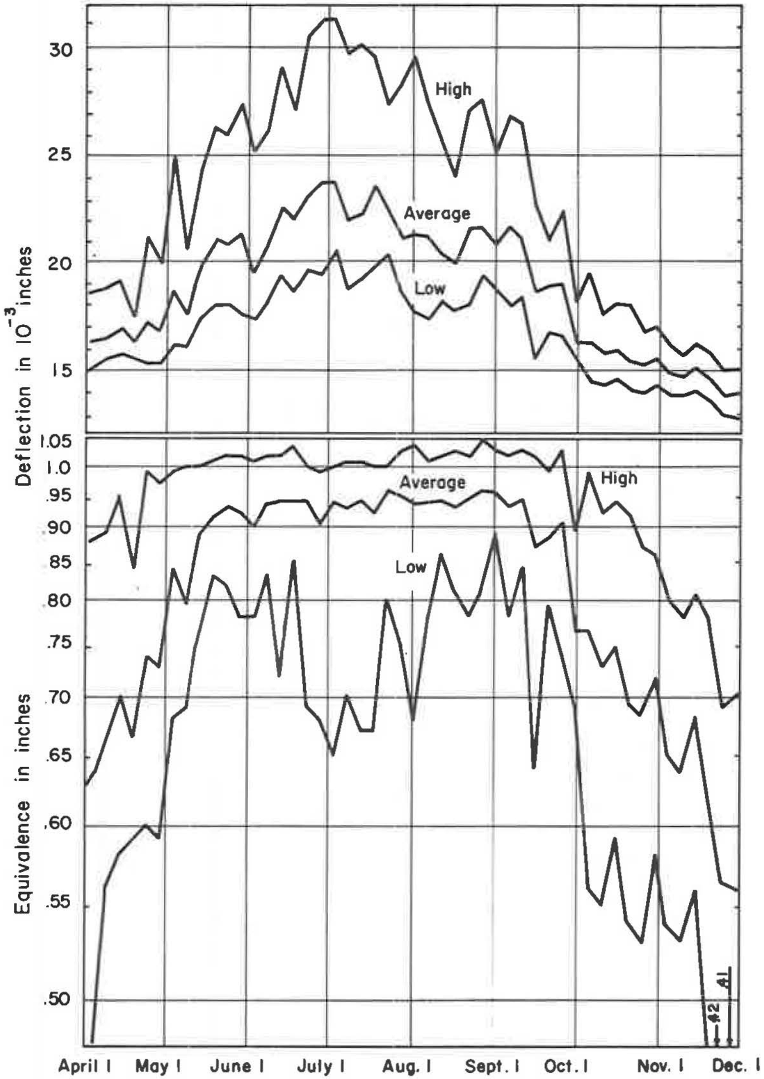

Figure 10. Five-day equivalences, T-35 surface and AASHO base.

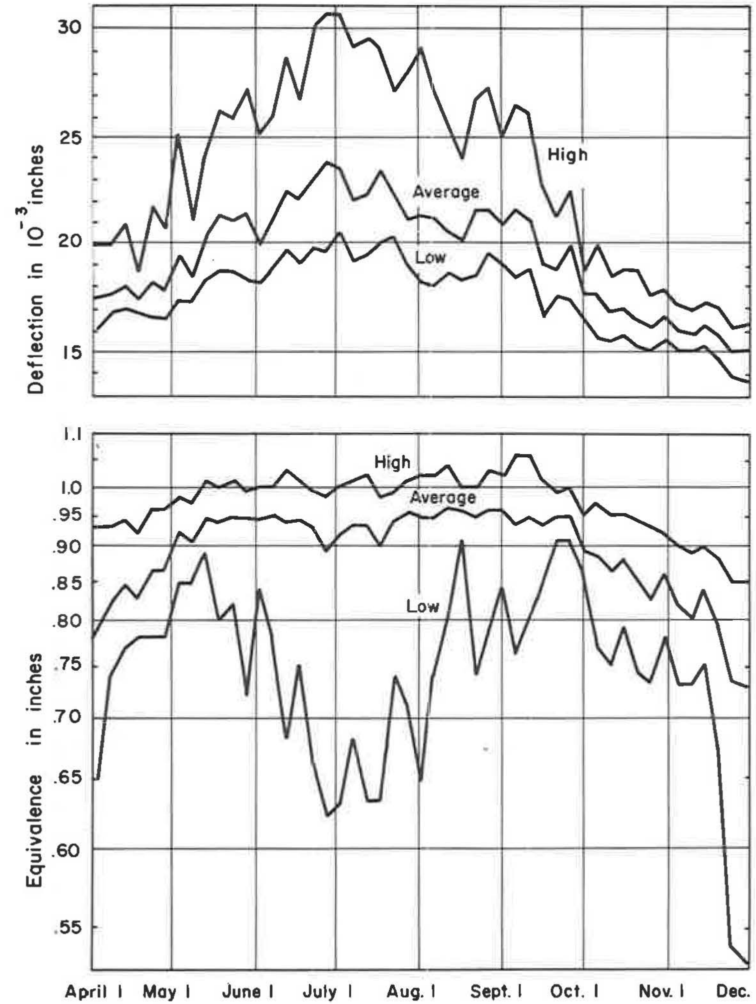

Figure 11. Five-day equivalences, T-35 surface and B-21 base.

TABLE 1

245-DAY DATA

Category	AASHO Surf. / AASHO Base	AASHO Surf. / B-21 Base	T-35 Surf. / B-35 Base	T-35 Surf. / AASHO Base	T-35 Surf. / B-21 Base
Equivalence (in.)					
Average	1.24	1.28	0.78	0.83	0.90
High (4th hour)	1.53	1.51	1.03	1.05	1.06
Low (4th hour)	1.05	1.12	0.39	0.41	0.53
Deflection (10^{-3} in.)					
Average	16.5	16.9	18.5	18.9	19.5
High (4th hour)	23.7	23.2	31.7	31.3	30.7
Low (4th hour)	10.9	11.6	12.5	12.7	13.6

The data may be further reduced to the average equivalence for the 245-day period. The results of this reduction are given in Table 1.

Costs

Equivalence calculations were made using the IBM 7094 computer with the hourly temperature data on magnetic tape and with moduli data in the form of equations as discussed. The average cost of fourth-hourly calculations for a 245-day period was about $1700 and required some 290 minutes of machine time when done in 25-day blocks. For the combinations of materials used a ± 10 percent variation was experienced. Had calculations for continuous hourly equivalences been made for all material combinations it is estimated that these would have cost some $5, 800 for the 245-day period on an average basis.

DISCUSSION

In these calculations combinations of two surfacings and three bases of asphaltic concrete were theoretically subjected to the same loading and "environmental" conditions of a 245-day period. Of the six possible combinations of these materials, five were investigated at constant thicknesses. With these combinations it is possible to directly compare the relative effect of the two surfacings with two of the bases. It is also possible to directly compare the relative effect of two of the bases with the two surfacings and of all three bases with respect to one surfacing.

245-Day Data

For pavements of the type studied, the trends of the 5-day average data (Figs. 7-11) indicate that equivalence varies seasonally, like deflection, with hot summertime conditions giving the highest values. For deflection this is different from asphaltic concrete pavements constructed largely of crushed stone; for these pavements springtime conditions normally give the highest deflections. Within these trends the data indicate that the three bases were substantially alike and that the largest differences were in the two surfacings. This is in qualitative agreement with the temperature-moduli curves of Figure 3. It is similarly in agreement with the trends of the 245-day average deflections and equivalences in Table 1. In the latter it is interesting that, with constant surfacing, higher deflections give higher equivalences and that the inverse is true for the inverse case, i.e., with base constant, higher deflections give lower equivalences. From the AASHO Road Test factorial sections (4, p. 137) it was concluded that:

> ...The performance of the flexible pavements was predicted with essentially the same precision from load-deflection data as from load-design information. Deflections taken during the spring when the subsurface conditions were adverse gave a better prediction of pavement life than those taken in the fall.

An extrapolation of that statement to an evaluation across the materials of this study is most attractive; however, it should be recognized that a number of factors must be considered before making such an extrapolation. These will be discussed in some detail in subsequent sections. Within this broad context, however, the data in Table 1 show that base equivalence is a function of the surfacing and suggest that the Road Test surfacing was substantially better than the T-35 surfacing. Within the bases, which were essentially alike, the averages suggest that the B-35 was slightly better than the Road Test base, which would be similarly rated with respect to the B-21 base. If deflections are ignored the apparent difference in average equivalence in the three bases has little meaning in a practical sense. If it is hypothesized that to compare equivalences

for the three bases, with common surfacing, it is necessary to set the three deflections equal, then it is possible to evaluate qualitatively this effect. Each of the three bases was used with the T-35 surfacing and the average deflections and equivalences increase in the same order. To reduce the deflections to that of the lowest, it is necessary to increase the other base thicknesses which, in turn, will increase the comparable equivalences with the net effect of making the differences in average equivalence greater than shown in Table 1. The validity of this hypothesis will be discussed subsequently.

The calculated equivalences of the AASHO Road Test surfacing to base materials can be compared with those estimated on the basis of performance at the Road Test. The Road Test staff did not make a mathematical (statistical) analysis of the performance of the base-experiment sections; however, on the basis of graphical analyses it was noted that for an 18-kip single-axle load at 10^6 applications to p = 2.5 (with 3 in. of surfacing and 4 in. of subbase), that 6 and 13 in. of the bituminous-treated and crushed-stone bases were needed, respectively (4, pp. 46, 58). Using these thicknesses and the Road Test equation for thickness index, $D = .44D_1 + .14D_2 + .11D_3$, this would indicate an equivalence ratio of 1: 1.45 (A. C. surface to A. C. base), or, as expressed in the convention of this study, an equivalence of 1.45. The 6 in. of bituminous base noted above is appreciably higher than that shown in the graphical data of Report 5 (4) and in a subsequent publication by Benkelman, et al (15), and it appears that the thicknesses were adjusted. In the graphical data and for equal performance at lower applications of this load, a range in comparable equivalences of from about 1.16 at 200,000 applications to perhaps 1.31 at 400,000 applications is indicated; at 1,000,000 applications an equivalence of about 1.26 appears more reasonable, based on the same data. At loads greater than 18-kip, similar ranges of 1.23 to 1.46 can be noted at 22.4-kip and of 1.34 to 1.67 at 30-kip. At 12-kip the equivalences are lower ranging from about 0.83 to 0.95. The 245-day average calculated equivalence of this study (1.24) compares favorably with these ranges as it does with the 1.29 advanced, indirectly, by the AASHO Design Committee (16).

It should be noted that the equivalence ranges cited here, both with varying load and within constant loadings, are anomalous with the thickness index equation in which equivalences are constant.

Representative Conditions

It is of some interest to examine the effect of shortening the calculations of this study by the use of a "representative" time or condition. Beginning with the hourly calculations, it is obvious that the time of day makes a significant difference in calculated equivalence and that, while there is at least one time that is representative of the average effect of all hours for that day, there is no obvious rationale that can be followed in its determination. In this connection it should be noted that this "representative" time will seldom correspond with an hourly observation. It follows that this finding can be expanded to include longer time periods without loss in net effect and that the concept of an "average" time, which can be taken as being representative of all times, has little if any real meaning. This is perhaps more easily visualized by examining "average" conditions. If, for example, average temperatures are calculated with depth for the data in Figure 4 (T_1 = 97.8 and T_2 = 93.5 F), and the 5-day average E_3 is determined, the use of these data does not predict the average equivalence for that time block. As a matter of fact those average temperatures never existed simultaneously in the trends of the recorded temperature data.

Biased Traffic

The hourly calculations of this study theoretically simulate a constant stream of trucks at all hours. If the traffic were actually biased as might happen, for example, with loaded mine trucks that operated only in the daylight hours, or with, perhaps, steel mill trucks leaving in the nighttime hours, the equivalences and deflections determined using only those hours would be expected to vary from those in Table 1. Some concept of the effect of time-of-loading variations is apparent in the continuous hourly data of Figures 5 and 6. The effect of similar but seasonal variations (June to November) are

TABLE 2

EFFECT OF LOWER SUBGRADE MODULI

Category	Deflection (in.)		Equivalence (in.)	
	E_3	$E_3/2$	E_3	$E_3/2$
Average	0.024	0.037	0.89	0.90
High	0.031	0.047	1.09	1.10
Low	0.020	0.031	0.63	0.69

far more dramatic but cannot be shown because of space limitations. Comparisons of this type are illustrative of some of the risks that may be involved in comparing the performances of in-service pavements at different locations. In this regard it is interesting that on the AASHO Road Test the daily 5-hour non-traffic period was shifted every two weeks but was always in the local time range of about 5 a.m. to 9 p.m.

Effect of Changed Subgrade

Equivalence could also be expected to vary with changed subgrade moduli. Such changes might result from different climatic conditions or with different subgrade soils. To investigate this effect, on a short time basis, the 5-day time block and conditions of Figure 6 were used (June, T-35 surface with B-21 base) except that the subgrade moduli, E_3, were fixed at one-half of those used in the calculations for that figure (6170 to 6190 psi). The resulting deflections were different as would be expected. The equivalences were closely the same, however, and a graph of the hourly calculations would show essentially no difference from the equivalences plotted in Figure 6 at the scale used. Table 2 gives the average and extreme data from these calculations and the corresponding data from Figure 6. These data indicate that calculated equivalences will not be affected by significant reductions in subgrade moduli even though total deflections are appreciably changed. If, however, subgrade moduli are increased by very large factors, interesting effects can be achieved. For this calculation the conditions at the hour of the low equivalences in Table 2 (hour 1600) were used. At that time $E_1 = 0.043$, $E_2 = 0.199$, $E_3 = 0.006$ or 0.003, all in 10^6 psi, and the equivalences were 0.63 and 0.69 in. for the two subgrade moduli respectively. If equivalence is calculated under the same conditions but with the subgrade modulus increased by a factor of ten ($E_3 = 0.006 \times 10^7$ psi), the equivalence becomes negative (about -0.35 in.) consistent with decreased deflection with decreased surface thickness. On the other hand, if the same conditions are used but with the subgrade modulus decreased by a factor of ten ($E_3 = 0.006 \times 10^5$ psi), the equivalence is 0.76 in., which is comparable with the 0.63 in. of Table 2.

Effect of Vehicle Speed

Equivalence would also be expected to vary with vehicle speed. The previous calculations represented a truck moving at 50 mph. The data in Figure 12 represent calculations for the same truck moving at 5 mph (a lab test frequency of 7.7 rad/sec). These hourly data are for the T-35 surfacing and B-21 base for a 5-day block in June and are directly comparable with the data in Figure 6 for the same time and materials. The 5-day average equivalence with the truck moving at 50 mph (Fig. 6) was 0.89 in. and at 5 mph (Fig. 12) was 1.03 in. Average deflections were 0.024 and 0.032 in., respectively. The larger deflections for the slower moving vehicle reflect the lower moduli that exist in all layers at the lower test frequencies. The lower vehicle speed resulted in a 20 percent decrease in E_3 while E_1 and E_2 were decreased by roughly 20 and 40 percent, respectively. It is interesting that the range of fluctuations in hourly equivalence is higher for the higher speed. Neither these nor the changes in average equivalence can be explained by changes in E_3 (a decrease of 20 percent vs the 50 percent of the "changed subgrade" calculations). The difference in average equivalences is, however, consistent with the nonproportional relative moduli shifts of the two upper layers (20 and 40 percent), i.e., the base layer was proportionally "weaker" and more thickness would be required. For in-service pavements this indicates that vehicle speed can affect equivalences and that the effect may be quite significant.

Effect of Thinner Base

Equivalence would also be expected to vary with changed base-layer thickness. The June 5-day time block of Figure 4 was used to investigate this effect on a short time

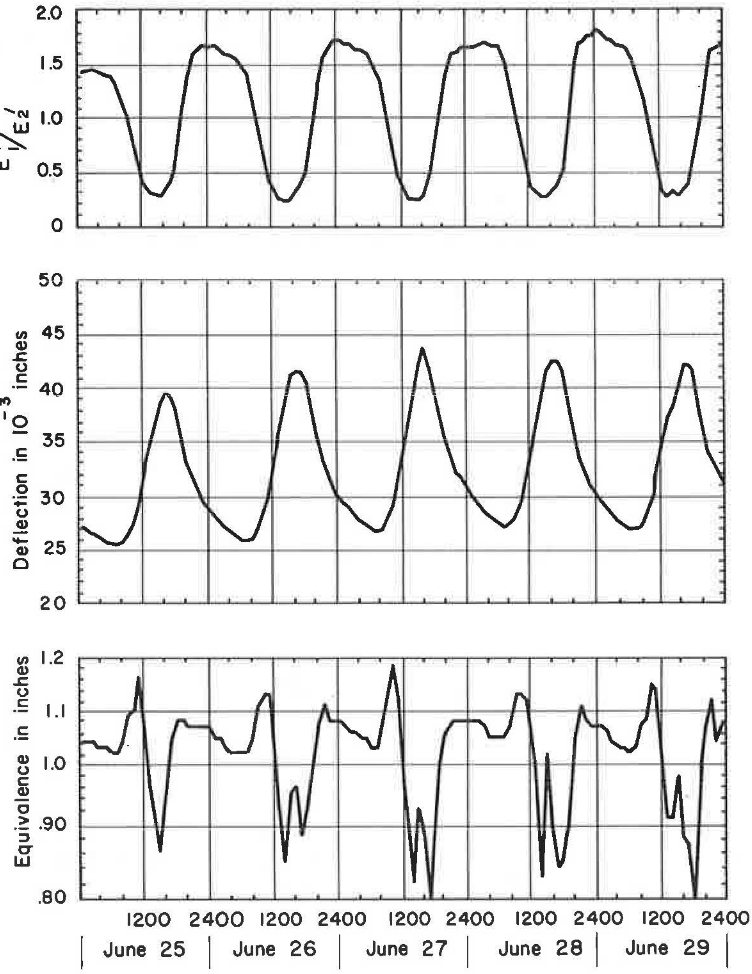

Figure 12. T-35 surface and B-21 base in June (5 mph).

basis. Materials were the AASHO surface and B-21 base, vehicle speed was 50 mph, layer 1 was 3 in. thick and the base layer thickness was fixed at 3 in. instead of 9 in. as used in all previous calculations. Figure 13 shows the average hourly temperatures of the 3-in. base layer and, for comparison, the same temperatures when the base was 9 in. thick. In both cases the surfacing was 3 in. thick. Also shown in Figure 13 are the resulting calculated hourly deflections, equivalences and moduli ratios at equivalence. Table 3 is a comparison of the average and extreme effects of the changed base thickness; in the table the 3-in. base thickness data are from Figure 13 and the 9-in. base data are from Figure 8.

TABLE 3
EFFECT OF THINNER BASE

Category	Deflection (in.)		Equivalence (in.)	
	3 in. Base	9 in. Base	3 in. Base	9 in. Base
Average	0.037	0.020	1.16	1.32
High	0.043	0.023	1.31	1.49
Low	0.031	0.017	1.06	1.19

For this time period, decreasing the base thickness by two-thirds roughly doubled the deflections while the effect on average equivalence was relatively slight. Two changes were effected in reducing the base thickness—the geometry change and the effect of this change on average temperatures and corresponding base moduli. If it were possible to effect only a thickness change with no change in base temperature and moduli (more con-

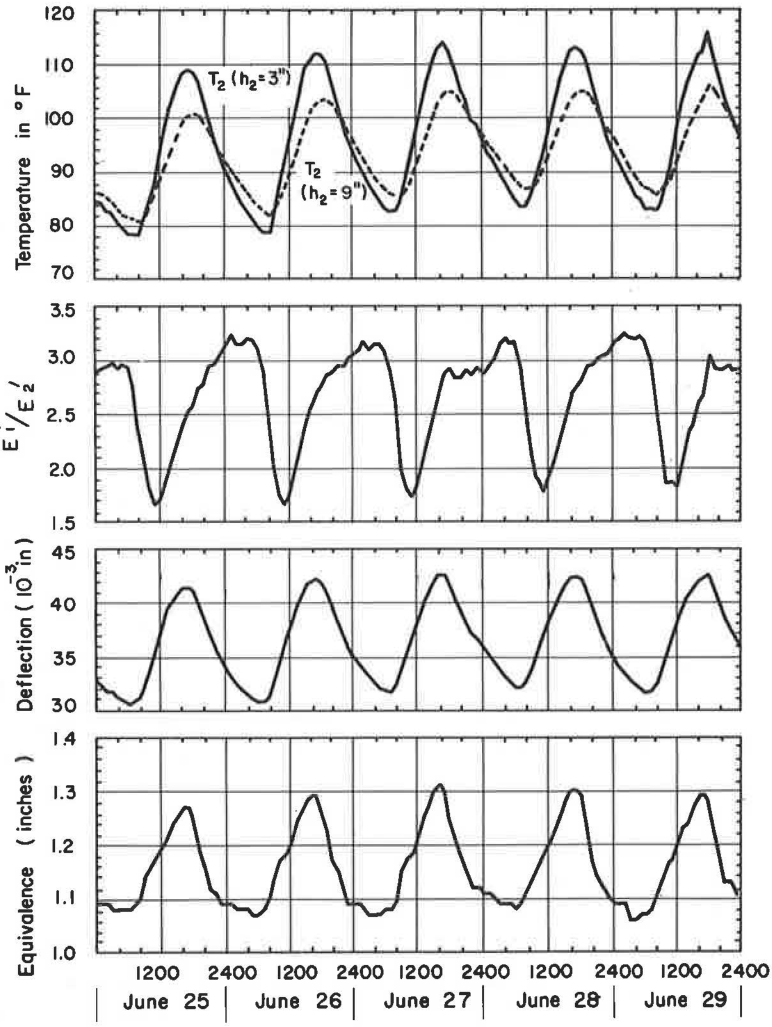

Figure 13. AASHO surface and B-21 base in June (h_2 = 3 in.).

sistent with a crushed-stone base), the effect of a thinner base layer would be a lower equivalence; i.e., the thicker the base layer the less efficient it is in replacing the surfacing as determined by deflection. Decreasing the base thickness in the data, however, changed the average base temperature and, on the average, this change resulted in a higher temperature in the thinner base as is shown by the hourly temperatures in Figure 13. This higher temperature in the thinner base results in lower moduli in the base which, all other things being equal, will require more base in the replacement of surfacing; i.e., a higher temperature causes a lower modulus which will result in a higher equivalence. For this 5-day block the effects of the geometry and temperature changes on average equivalence were in opposition with the thinner base tending to decrease equivalence and the changed temperatures tending to increase equivalence. The geometry effect was dominant and the net effect was a slightly lower equivalence than with the 9-in. base. While not investigated, the relative effect of a thinner base for other 5-day blocks would be expected to be different as a function of the relative temperature changes; however, this effect would be expected to be small.

To illustrate the geometry effect, equivalence was calculated for one point in time at which moduli were held constant while base thickness was changed from 7.9 to 11.1,

TABLE 4

EFFECT OF CHANGING LOAD AND RADIUS

Category	Deflection (in.)		Equivalence (in.)	
	L	L/2	L	L/2
Average	0.020	0.011	1.32	1.48
High	0.023	0.012	1.49	1.64
Low	0.017	0.009	1.19	1.34

then to 14.4 in. For this calculation: R = 7.04 in., p = 72 psi, h_1 = 3 in., $E_1 = .67(10)^6$, $E_2 = .31(10)^6$ and $E_3 = 4.08(10)^3$ psi and the resulting deflections were 0.033, 0.025 and 0.020 in. At these three thicknesses the equivalences were 1.22 in. at h_2 = 7.9 in.; 1.32 in. at h_2 = 11.1 in.; and 1.39 in. at h_2 = 14.4 in. These data indicate that with all other conditions constant, calculated equivalence increases at decreasing rate as base thickness increases.

Effect of Reduced Load and Contact Area

The effect of thickness changes with unchanged temperature can be secured by reducing the radius of the equivalent loaded area while holding contact pressure constant. To investigate this effect for a short time period, the June 5-day time block of Figure 4

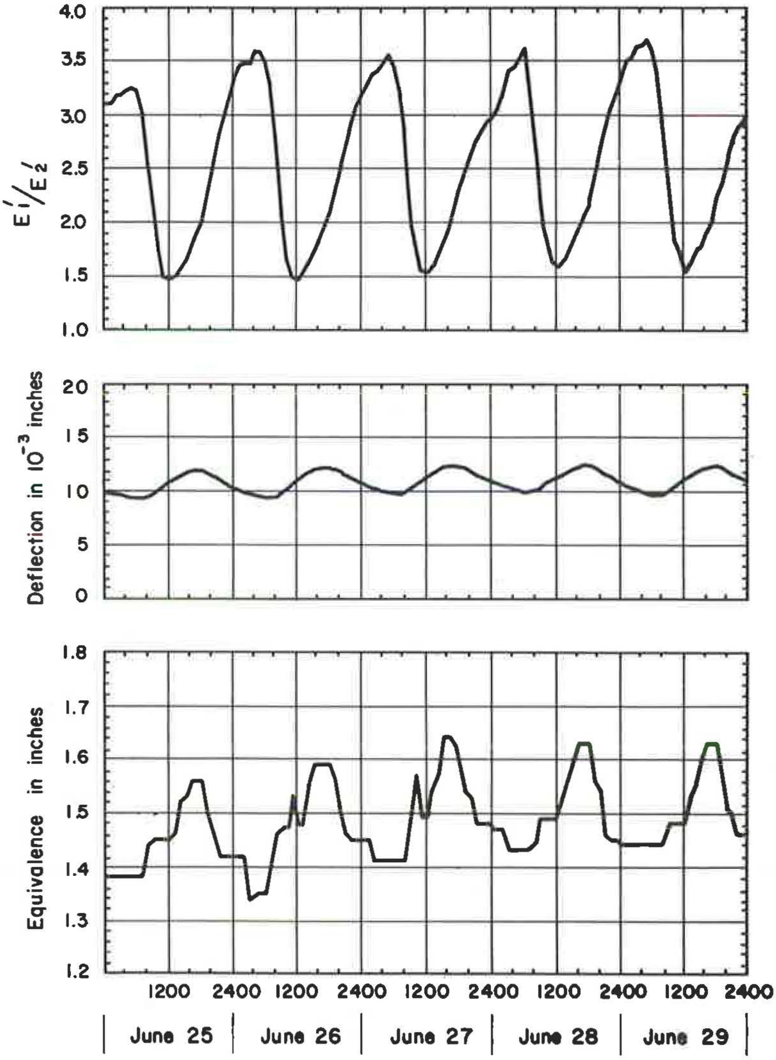

Figure 14. AASHO surface and B-21 base in June (L/2, $R/\sqrt{2}$).

TABLE 5

CHANGES AFFECTING DEFLECTION AND EQUIVALENCE

Change In:	Gives Change In:			
	Deflection (from changed)		Equivalence (from changed)	
Hour of determination	yes	(moduli)	yes	(moduli ratio)
No. of hrs. used for avg.	yes	(moduli)	yes	(moduli ratio)
Vehicle speed	yes	(moduli)	yes	(moduli ratio)
Load (constant cont. press.)	yes	(load and geom.)	yes	(geom.)
Load (constant cont. area)	yes	(load)	no	-
Surface material	yes	(modulus)	yes	(moduli ratio)
Base material	yes	(modulus)	yes	(moduli ratio)
Subgrade material	yes	(modulus)	no[a]	-
Surface material thickness	yes	(moduli and geom.)	yes	(mod. ratio and geom.)
Base material thickness	yes	(moduli and geom.)	yes	(mod. ratio and geom.)

[a]Not significant, in avg. equiv., for relatively large changes in moduli; can be significant in hourly equiv.

was used with 3- and 9-in. thicknesses of the AASHO surfacing and B-21 base, respectively. Vehicle speed was 50 mph and the only change from the conditions of Figure 8 was the reduction of total load by one-half and the effect of this reduction on radius at constant contact pressure ($1/\sqrt{2}$). The results of hourly calculations for these conditions are shown in Figure 14. The average and extreme equivalences and deflections are given in Table 4 together with the same results from the full-load case. The effect on deflection of decreasing the load by one-half was a decrease of about the same order as would be expected at constant pressure. Similarly, the effect on equivalence was an increase; this is consistent with the concept that the relative geometry change attained was qualitatively equivalent to proportional increases in the thicknesses of the layers with constant load, contact pressure and moduli. Had only the load been changed—i. e., a change in pressure with no change in contact area—no effect on equivalence would be expected even though deflections would show a change proportional to the change in load. Points such as these have interesting implications in considering material equivalences and pavement failure.

Equivalence and Failure

It was noted near the beginning of this discussion that for single-axle loadings at constant serviceability level, equivalences from the AASHO Road Test factorial sections were reduced to constants while those from the special base sections appear to vary with applications. To gain some insight into possible explanations of this apparent anomaly, Table 5 has been prepared to show those changes that affect equivalence and deflection in the theoretical work of this study. This table shows that any one of the listed changes will affect deflection and that the same is true for equivalence with the exceptions of load changes made without changing contact area and of, perhaps, changes in subgrade moduli. Considering the conditions at the Road Test and excluding the first three listed changes for purposes of discussion, it is of some interest to examine the loads, pressures and contact areas for the vehicles at the Road Test. These data, for the single-axle loadings, are shown in Table 6 (17). Contact pressures for the tandem axle loadings were very similar.

The data in Table 6 indicate that, at the Road Test, changes in load were accompanied by changes in equivalent radius and that, excluding Loop 2 (not in the special base experiments), these load changes were not accompanied by appreciable changes in calculated average contact pressure. Table 5 shows that these changes (load and radius at constant contact pressure) would be expected to affect deflection but that only the changed radii would be expected to change equivalence with constant materials at constant thicknesses. As noted, this effect would be expected to be relatively small. It should be reiterated, however, that for either of these conditions there would be a change in deflection. If deflection is a predictor of performance, the changed deflection would result in changed applications to failure for the two different loads. For a constant pavement design, an increase in load with no change in contact pressure would increase deflection, decrease the applications to failure and decrease the theoretical equivalence as a result of the geometry change.

TABLE 6

ROAD TEST TIRE DATA

Loop	Test Tire Load (lb)	Stnd. Load (lb)	Inflation[a] (psi)	Meas. Contact Area (sq. in.)[a]	Avg. Contact Press. (psi)[a]
2	1,000	1,065	24	36.6	29.1
2	1,500	1,580	45	37.4	42.3
3	3,000	2,980	75	45.4	65.7
4	4,500	4,580	75	67.8	67.5
5	5,600	5,150	75	77.7	66.4
6	7,500	6,780	80	97.3	69.7

[a]At standard load.

TABLE 7

ROAD TEST EQUIVALENCE DATA[a]

Category	Loop 2	Loop 3	Loop 4	Loop 5	Loop 6
Within loop regression coefficients					
D_1	.83	.44	.44	.47	.33
D_2	.25	.16	.14	.14	.11
D_3	.09	.11	.11	.11	.11
Within loop equivalences					
D_1	1	1	1	1	1
D_2	3.32	2.75	3.14	3.36	3
D_3	9.23	4.00	4.00	4.27	3
No. of test sections used	12	26	40	60	60
Avg. design h (in.)					
Surf.	2.5	3	4	4	5
Base	4.5	4.5	4.5	6	6
S. Base	4	6	8	8	12

[a]From Tables 2 and 10 of Reference 4.

For the same conditions, an increase in load with no change in contact area would have the same effects except that no change in equivalence would be expected. Obversely, at constant load, contact area and failure level, increased applications to failure will accompany increased base thicknesses and equivalences would be expected to increase as a result of the geometry change. If applications to some failure level are constant, it would be expected that increased loads at constant contact pressure, tending to give lower equivalence, would require increased base thickness, tending to give higher equivalence. Since these trends are in opposition the net effect of both geometry changes on equivalence could be rather small. No similarly general statements are possible for the changed load, area, and contact pressure conditions because both deflections and equivalences would be a function of the initial geometries (radius, h_1 and h_2) as well as of the moduli ratios, for constant materials.

The preceding relations were based on the assumption of constant materials with varying base thicknesses or applications. If only surfacing thickness is varied with applications, the given effects of the relative geometry changes on equivalence are reversed when E_1 is greater than E_2. With this addition it is possible to examine the Road Test main factorial equivalence data for some insight into the expected effect of the theoretical relations discussed.

The Road Test data for the main factorial sections are summarized in Table 7. If the regression coefficients for each loop in these data are multiplied by the number of sections used and these are summed and divided by the total number of sections, the results are the coefficients of D_1, D_2, and D_3 in the thickness index equation. On the basis of the data combined in Tables 6 and 7 it is apparent that the load changes at constant pressure across Loops 3-6 were accompanied by average layer thickness changes. The previous discussion suggests that the gross effect of these changes (radius and thickness) on equivalence would be in opposition on a qualitative basis and that roughly comparable equivalence ratios might be expected as is indicated in the data for these four loops. For Loop 2 the load and thickness changes were in the same qualitative direction but the contact areas were not changed as they were in the other loops. This could help to explain the difference in regression coefficients for this loop and the unusually high equivalence for the subbase material. These statements assume that the effect of changes in the Lane 2 tandem axle loadings across the loops were proportional, which appears reasonable in the absence of more data.

Within any one loop at the Road Test there were a large number of thickness changes; however, there are no readily available data with which to evaluate qualitatively, in a similar manner, the relation between the field data and the effects that would be theoretically expected. If it is assumed that in the analyses of the Road Test data the geometry effects were considered as a part of the spread or scatter in the data, then the measure of this scatter is an indication of the possible (but not at all probable) limits of these effects. Saying this another way, in developing the thickness index equation, it is not clear how the Road Test analyses may have considered geometry effects such as those discussed—whether these may have been included as a part of the load or of similar across-lane and loop parameters, or if such effects are perhaps implicit in the statistics. In any event, the scatter in individual data points was evaluated as a part of that analysis. This was given as ± 14 percent of D and includes effects from all causes, among which could be those resulting from geometry changes. If it could be assumed that all of this scatter was a result of the geometry effects, and this is taken in the base or D_2 coefficient, then for an 18-kip single-axle loading with $p = 2.5$ at 10^6 applications and D_1 and D_3 = 3 and 6 in. respectively, the coefficient of D_2 could vary from 0.10 to 0.18 about a ± 29 percent range. Similarly, except that D_3 = 16 in., the D_2 coefficient could vary from 0.05 t0 0.23, about a ± 64 percent range. For the Road

Test, geometry effects would be theoretically expected with changes in load, or surface thickness or in base and/or subbase thicknesses. On the basis of these calculations it is clear that the inclusive "scatter term" of the thickness index equation provides space for rather large individual effects among which may be the geometry effects that would be expected on a theoretical basis.

If materials are varied, the number of applications to some failure level will vary as is shown in the special base studies of the Road Test. In the Road Test analyses the concept that deflections predict performance was based on the main factorial sections, in which materials were constant, and was most nearly true for springtime conditions. Presumably this concept would hold for other materials so long as the materials are constant; however, it is not clear that this concept can be extrapolated across materials, i.e., equal deflections with different materials should not be expected to give equal performance, a priori. In this connection the Road Test findings noted that deflections in sections with gravel were somewhat lower than those with crushed-stone base even though the performance of the crushed stone was considerably better than that of the gravel base sections (4, p. 85). This is a subtle point: Had equal structural thicknesses given equal deflections under equal loadings, theoretical deflection-based equivalences would also have been equal, in the absence of failure criteria. Lower deflections for the gravel would indicate lower equivalence, on the same basis, and it would follow that equal thicknesses and loadings would give higher applications to failure for the gravel. This was not the case, however, and on this basis it seems clear that failure criteria are necessary to a theoretical evaluation of the equivalences of different materials. Summarizing this discussion of equivalence and failure, equivalence—as defined in this discussion—is a function of load and contact area, of the layer thicknesses, of the materials and environment, and of the number of applications to failure.

SUMMARY AND CONCLUSIONS

The 245-day theoretical data for the Road Test asphaltic concrete surfacing and base materials, the only such materials for which field performance data were available, gave a remarkably close estimate of the field results. Points of similarity in the theoretical simulation include the use of essentially the same materials, the use of only one load, close to the average, at comparable contact pressure and the use of common vehicle speeds insofar as the effect of the 35- to 50-mph vehicle speed shift affects moduli ratios. The main points of dissimilarity are the temperature regime used and, as a part of that, the representativeness of the length of time over which theoretical average equivalence was calculated. In regard to the first difference, there are no data with which to base an estimate of the differences between temperatures in the 12-in. asphaltic concrete pavements at Ottawa, Ill., in 1958-60 and those measured at College Park, Md., in 1964-65. It can be rationalized, however, that over the length of time used, the cumulative differences were probably not significant. A similar rationalization can be advanced for the representativeness of the length of time used in the calculations. The trend of five-day averages of Figure 7 indicates that a 365-day average equivalence would be lower. Had calculations been made for this longer time span it can be speculated that the total average equivalence would not have dropped below one and would most likely be higher. This would not represent a large change in consideration of the apparent spread in the field data cited for the special base studies.

For the remaining materials of this study the calculations show that the equivalence of a base is a function of the surfacing, and vice versa. Unfortunately there are no comparable sources of field performance data for these materials. Because of this it was necessary to seek other data relating deflection and performance for different materials. The AASHO Road Test data demonstrate that deflection-based equivalences have no causal relation to the number of applications to some failure level with different materials. This suggests that it is entirely possible to simulate theoretically two pavement designs of different materials that will give the same average calculated equivalence for the same loading and time history. For this, however, it would be expected that the number of applications to failure of the two would be different. On the other hand, the term equivalence implicitly assumes equal performance or applications to

failure and this, in turn, indicates that the theoretical determination of equivalences for different materials requires the inclusion of failure criteria. On this basis equivalence can be defined in the terms of this study by the following generalized equation:

$$\text{Equiv.} = f(L, V, T, A, H, E, C, N)$$

where

L = the loadings,
V = their velocities,
T = the times of their applications,
A = the contact areas,
H = the layer thicknesses,
E = the materials,
C = the climate or environment, and
N = the number of applications to failure.

This is an interesting equation. With the inclusion of the failure term to the concept of average equivalence, as anticipated in this study, it is clear that exactly those considerations that would be expected in a rational design formula are collected in the equation. With the exception of N, it is also clear that the tools and techniques necessary to such an approach are available and indeed have been used in this study, to some approximation. This points to the pressing need for research that will fill the blanks represented in the failure term. When these blanks are completely filled the need for equivalences will presumably have vanished.

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REFERENCES

1. Shook, J. F. Development of Asphalt Institute Thickness Design Relationships. Proc. AAPT, Vol. 33, 1964, pp. 187-220.
2. Skok, E. L., Jr., and Finn, F. L. Theoretical Concepts Applied to Asphalt Concrete Pavement Design. Internat. Conf. on the Structural Design of Asphalt Pavements, Univ. of Mich., Preprint Vol., 1962, pp. 575-604.
3. Burmister, D. M. Applications of Layered System Concepts and Principles to Interpretations and Evaluations of Asphalt Pavement Performances and to Design and Construction. Internat. Conf. on the Structural Design of Asphalt Pavements, Univ. of Mich., Preprint Vol., 1962, pp. 218-233.
4. The AASHO Road Test: Report 51—Pavement Research. HRB Spec. Rept. 61-E, 1962.
5. Coffman, B. S., Kraft, D. C., and Tamayo, J. A Comparison of Calculated and Measured Deflections for the AASHO Test Road. Proc. AAPT, Vol. 33, 1964, pp. 54-92.
6. Coffman, B. S. Pavement Deflections from Laboratory Tests and Layer Theory. Second Internat. Conf. on the Structural Design of Asphalt Pavements, Preprint Vol., Jan. 1967, pp. 664-708.
7. Coffman, B. S. A Method for Determining the Equivalences of Asphalt Concretes in Pavements. Unpublished report to the Asphalt Institute, Nov. 1965.
8. Kallas, B. F. Asphalt Pavement Temperatures. Highway Research Record 150, pp. 1-11, 1966.

9. Data System 4180. Trench Study, Main Loops, Flexible Pavement, Spring-Summer 1960. AASHO Road Test, Highway Research Board.
10. Burmister, D. M. The General Theory of Stresses and Displacements in Layered Systems. Jour. Applied Physics, Vol. 16, 1945.
11. Filon, L. N. G. On the Elastic Equilibrium of Circular Cylinders Under Certain Practical Systems of Load. Phil. Trans. Royal Soc. of London, Vol. 198, Ser. A May 1902.
12. Rowe, P. W., and Barden, L. Importance of Free Ends in Triaxial Testing. Proc. ASCE, Jour. S.M. & F. Div., Vol. 90, No. SM1, Jan. 1964.
13. Barden, L., and McDermott, J. W. Use of Free Ends in Triaxial Testing of Clays. Proc. ASCE, Jour. S.M & F. Div., Vol. 91, No. SM6, Nov. 1965.
14. Blight, G. E. Shear Stress and Pore Pressure in Triaxial Testing. Proc. ASCE, Jour. S.M. & F. Div., Vol. 91, No. SM6, Nov. 1965.
15. Benkelman, A. C., Kingham, R. I., and Schmitt, H. M. Performance of Treated and Untreated Aggregate Bases. Internat. Conf. on the Structural Design of Asphalt Pavements, Univ. of Mich., Preprint Vol., 1962, p. 129.
16. Langsner, G., Huff, T. S., and Liddle, W. J. Use of Road Test Findings by AASHO Design Committee. HRB Spec. Rept. 73, p. 411 (Appendix D), 1962.
17. The AASHO Road Test: Report 31—Traffic Operations and Pavement Maintenance. HRB Spec. Rept. 61C, Table 5, p. 16, 1962.