Composite Pavement Design for Roads and Streets

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This paper contains a brief review of the Corps of Engineers' development of one type of composite pavement design procedure for airfield pavements. This development is used as a basis for presenting a procedure for the design of composite pavement for roads and streets. Sufficient information is given for the direct application of this procedure. Adequate references are provided for more detailed study of this development and design procedure.

•THE method of composite pavement design given in this paper was originally developed for strengthening plain concrete airfield pavements with non-rigid overlays. The non-rigid overlays consist either of bituminous concrete only or of a high-quality base course surfaced with bituminous concrete. The development of this design method for composite airfield pavements (1) extended over the 10-yr period from 1945 to 1955. This method in its present form has been in use by the Corps of Engineers for the design and construction of military airfield pavements since 1955. The method was adapted in June 1961 to the design of composite pavements for roads and streets (2).

DESIGN DEVELOPMENT

Composite Pavements for Airfields

The background of the full-scale traffic testing and the analysis of the results leading to the design method for composite pavements is given by Mellinger and Sale (1). A knowledge of the manner in which failure occurs and the interaction of the components leading to failure is basic to this or any other method of design. Two conditions are involved in the design of composite pavements: (a) that the non-rigid overlay be of sufficient quality that the bituminous concrete or base materials, if present, will not fail providing the concrete base pavement gives adequate support; and (b) that failure starts in the concrete base pavement and progresses to the surface of the overlay. Failure, with this type of interaction of the overlay and base pavement, is defined as the condition where visible transient deflection of the overlay surface under the design traffic loading is in the order of 0. 75 to 1. 00 in., and permanent deflection or rutting of the surface is in the order of 1. 00 to 1. 50 in.

Therefore, the composite pavement design is related to the design procedure for plain concrete pavement for various degrees of failure. The design procedure for plain concrete pavements is given by Mellinger (3). Two advantages are obtained by placing a non-rigid overlay on a plain concrete pavement: (a) the rate of cracking or break-up of the base pavement is reduced; and (b) a greater degree of break-up or cracking of the base pavement can be permitted than would be feasible without the overlay.

Figure 1 shows three conditions of the concrete base pavement that resulted from traffic loading. The traffic was continued in the first case (a) after failure of the overlay surface, and stopped in the second case (b) at incipient failure; that is, when transient deflections of the overlay surface were in the order of 0. 75 in. or less. The last case (c) shows the condition of the base pavement when traffic was not sufficient to pro-

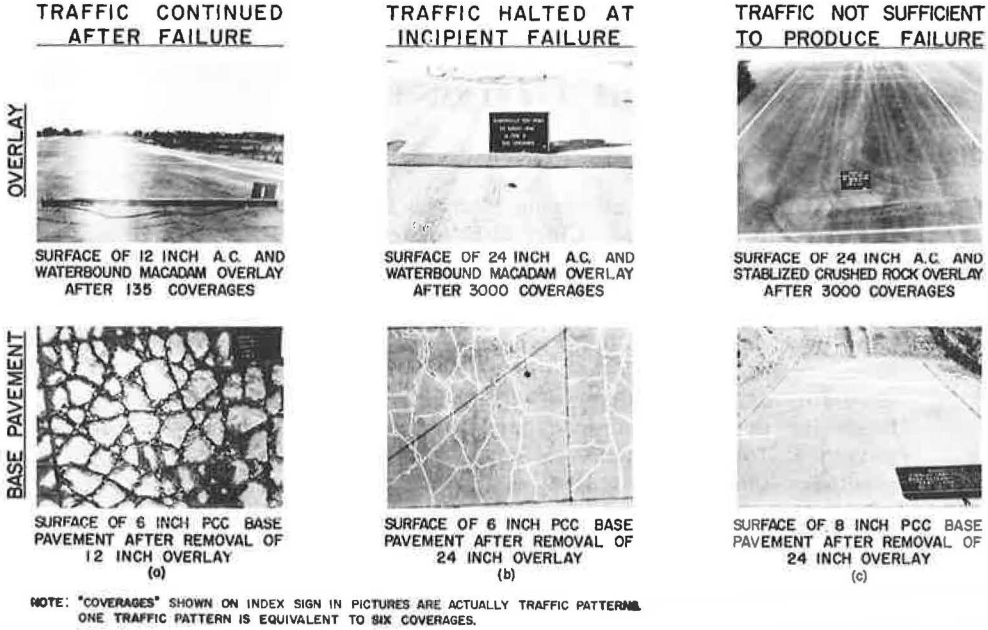

Figure 1. Typical after traffic overlay and base pavement conditions, Sharonville overlay test tracks.

duce failure. The base pavement was broken into pieces having an area of from 5 to 7 sq ft for the case where traffic was stopped at incipient failure, which was typical of the behavior of all 51 full-scale overlay test items which were subjected to traffic test loading. For these items, the thickness of the base pavements ranged from 6 to 12 in. and the thickness of the non-rigid overlays varied from 3 to 42 in. The thickness of the overlays composed completely of bituminous concrete varied from 3 to 20 in. Where base courses were used in the overlays, the base thickness varied from 5 to 38 in. with the thickness of the bituminous concrete surfacing being 4 in. in all cases.

Figure 2 shows a set of curves developed from full-scale traffic tests of plain concrete pavements. The percent of design thickness is plotted on semi-log paper against the number of coverages at which the pavement broke into pieces having an average area of roughly 7 sq ft. This is the condition of the base pavement at which a surface failure of the overlay is imminent. The following procedure was used to correlate the results of the traffic tests on the 51 full-scale overlay test items.

Using the procedures for the design of plain concrete pavements (3), the thickness of concrete h_d necessary to carry the wheel loading of the traffic for 5,000 coverages on each item was computed. This thickness was reduced by a percentage (percent standard design thickness) F, from Figure 2, depending on the number of coverages at which the test item failed. The design thickness (Fig. 2) is for the 5,000-coverage level. For example, Item No. 11 of the Sharonville No. 1 test track had a plain concrete base pavement with a thickness h of 6 in. and an all-bituminous-concrete overlay with a thickness t of 5.6 in. This item failed after 70 coverages of a 100,000-lb twin-wheel loading. The full concrete design thickness h_d required to carry this wheel load for 5,000 coverages is 16 in. The thickness of concrete required to carry this loading for 70 coverages and result in the condition of failure defined for the base pavement would be $F h_d$. Figure 2 establishes F as 51 percent in this case, the subgrade modulus k for this item being 100 pci. The dimension of concrete deficiency for the base pavement is given by $Fh_d - h$. In this case $Fh_d - h = 0.51 \times 16 - 6 = 2.2$ in.; that is, if

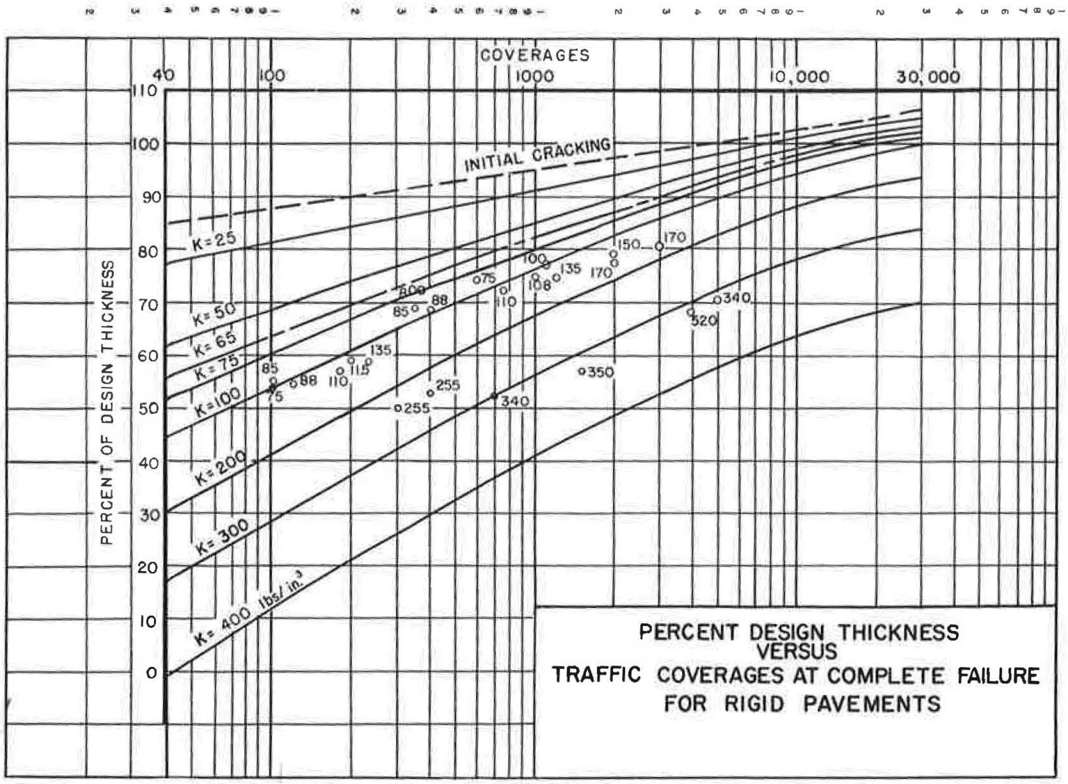

Figure 2.

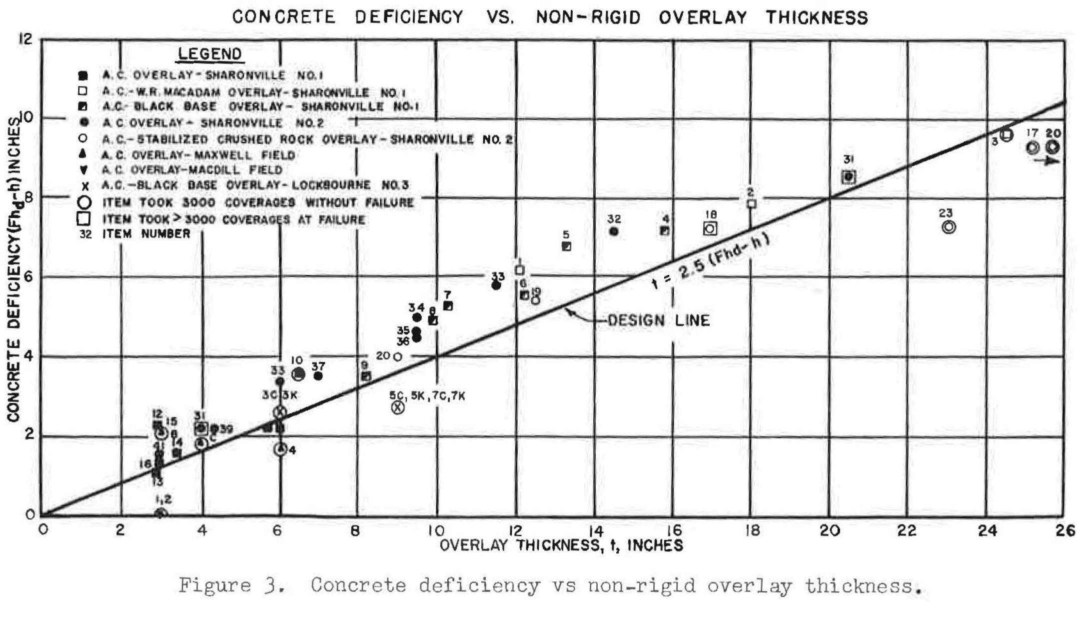

Figure 3. Concrete deficiency vs non-rigid overlay thickness.

the concrete base pavement had been 2.2 in. thicker, or 8.2 in. thick, it would have been reduced to the same condition after 70 coverages of the 100,000-lb twin-wheel traffic loading as it was after this same loading but having a 5.6-in. all-bituminous overlay. The dimensions, number of coverages at failure, subgrade modulus, and flexural strength of the concrete of the base pavement were known for each of the 51 overlay test items. Using this information, the concrete deficiency $Fh_d - h$ was computed for each item and plotted against the overlay thickness (Fig. 3). A straight line drawn through the origin and on the conservative side of the plotted values is also shown in Figure 3. This line is called the design line and is expressed by

$$t = 2.5\ (Fh_d - h) \tag{1}$$

in which t is the thickness of the non-rigid overlay; F is a modification factor which varies with the subgrade modulus k and coverages. Values of F can be obtained directly from Figure 2, or curves of different coverage levels for k vs F can be prepared (1, Fig. 6) from the information in Figure 2. Eq. 1 is used to design non-rigid overlays for airfield pavements. To design such overlays, the flexural strength and the thickness h of the existing concrete pavement and the subgrade modulus are used. With these values, the design thickness, h_d of a plain concrete pavement is determined for the new wheel loading at the desired coverage level. The design life of a plain concrete pavement is determined by the design coverage level. The number of aircraft operations per coverage will depend on the gear configuration of the aircraft and on whether the pavement is to function as a runway, taxiway or apron. The airfield pavement is designed to fail at the end of its design life. Failure is considered to have occurred in a plain concrete pavement when 20 to 30 percent of the slabs have 1 or 2 cracks in them and spalling starting at the joints and cracks. When h_d is modified by the factor F, a pavement thickness is obtained such that the pavement slabs would be broken up into pieces 5 to 7 sq ft in area at the end of the design life. This design life or coverage level is the same as that for the full thickness h_d. The modification factor, F, is always less than one.

RIGID PAVEMENTS FOR ROADS AND STREETS

The adaption of the foregoing procedures to the design of composite pavements for roads and streets requires a plain concrete pavement design procedure that provides for a pavement life definable in terms of load repetition or coverages. Such a procedure for designing concrete pavements has been given (2) and details of its development covered (4). Pavements for roads and streets are subjected to a much greater number of repetitions of traffic loading than are airfield pavements. Also, road and street pavements are subjected to a greater variety of mixed traffic than airfield pavements. Therefore, two modifications of the airfield pavement design procedure were required.

1. The curve for load repetition or coverage vs percent design thickness had to be extended to include the greater frequency of traffic on road pavements that would be encountered in a 25-yr life. This curve (Fig. 4) was developed from full-scale accelerated traffic tests of concrete airfield test pavements for a range of 40 to 30,000 coverages. The dotted portion of the curve indicates its extension beyond this range. This extrapolation is based on judgment as well as on a limited amount of data from laboratory research studies of the fatigue characteristics of concrete in flexure.
2. The second modification was necessary to provide a means of taking into account the effect of mixed traffic on coverage values. This modification was made by selecting a basic 18,000-lb single-axle loading with dual wheels and deriving an equivalent-coverage factor for selected vehicles using standard wheel configurations (4). Table 1 gives this conversion with respect to vehicle type, loading, and vehicle-operations per coverage, with the equivalent-coverage factor being shown in the last column.

A coverage is defined as a sufficient number of vehicle-operations to produce one application of the design stress over the entire width of the traffic area. The relation-

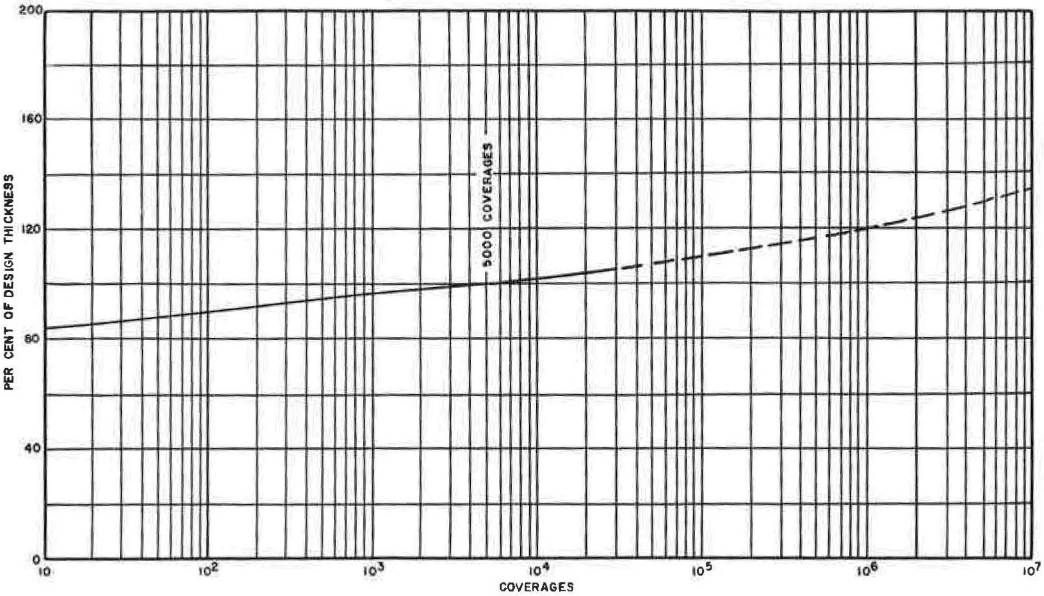

Figure 4. Rigid pavements coverages vs percent of design pavement thickness.

ship between operations (or applications) and coverages for each of the axle loadings (Table 1) is a function of the pavement lane width (11 ft), the width of the tire contact area, the number of wheels on the axle, the spacing of the wheels, and the degree of wander (or lateral distribution) of the traffic. The development of the values relating axle operations to coverages for each axle of the configurations of Table 1 has been described in detail (5).

To illustrate the use of Table 1, the case of the 3-axle truck is taken where 1.13 operations of this vehicle would be equivalent to 1 coverage of the standard 18,000-lb single-axle loading. The equivalent-coverage factor for this loading is 0.0288. On this basis, 1 coverage of the 18,000-lb single-axle basic loading would have the same effect stress-wise as approximately 1/0.0288 or 35 operations of the 35,500-lb 3-axle truck (4).

As an example of the further application, it is assumed that a pavement is being designed for the type of traffic distribution shown in the first three columns of Table 2. The number of operations for each vehicle type for a 25-yr (column 3) were converted to the number of equivalent coverages of an 18,000-lb single-axle loading by the equivalent-coverage factors (Table 1). For example, in the case of the 3-axle truck, the number of operations for 25 years is 9,125,000. The equivalent-coverage factors are for 1 operation of the various vehicles and not for 1 coverage. The equivalent number of coverages of the 18,000-lb single-axle load is obtained by multiplying the total number of operations of the vehicle by the appropriate coverage factor. The equivalent number of coverages, that is the number of coverages of the 3-axle loading that will have the same effect stress-wise as the standard 18,000-lb single-axle loading is obtained by multiplying 9,125,000 by 0.0288, the equivalent-coverage factor, which gives 263,000 equivalent coverages. The number of equivalent coverages computed for each vehicle type and total of the results are

TABLE 1

EQUIVALENT-COVERAGE FACTORS

Vehicle Type	Design Loading (lb)	Maximum Loading (lb)	Vehicle-Operations per Coverage	Equivalent-Coverage Factor
Passenger cars	3,900	4,500	4.79	1.4×10^{-10}
Panel and pick-up trucks	5,500	6,000	4.63	1.6×10^{-9}
2-axle trucks and buses	15,000	26,000	2.10	1.45×10^{-4}
3-axle trucks	35,500	44,000	1.13	0.0288
4-axle trucks	50,200	58,000	0.841	0.0444
5-axle trucks	62,400	68,000	0.677	0.0290

TABLE 2

EXAMPLE OF TRAFFIC SUMMATION FOR OBTAINING NUMBER OF EQUIVALENT COVERAGES FOR MIXED TRAFFIC

Vehicle Type	Avg. Operations per Day per Lane	25-Yr Operation per Lane	No. of Equivalent Coverages
Passenger cars	4,000	36,500,000	51.20×10^{-4}
Panel and pickup trucks	500	4,560,000	73.00×10^{-4}
2-axle trucks and buses	1,000	9,125,000	13.20×10^{2}
3-axle trucks	1,000	9,125,000	26.30×10^{4}
4-axle trucks	200	1,820,000	7.90×10^{4}
5-axle trucks	50	456,250	1.32×10^{4}
Total			356,520

TABLE 3

RELATIONSHIP BETWEEN RIGID PAVEMENT DESIGN INDEX AND EQUIVALENT COVERAGES OF THE BASIC LOADING

Rigid Pavement Design Index	Percent Thickness for 5,000 Coverages	Range of Equivalent Coverages	
		Minimum	Maximum
1	82.0	1	45
2	90.5	45	600
3	99.0	600	13,000
4	107.5	13,000	130,000
5	116.0	130,000	800,000
6	124.5	800,000	3,500,000
7	133.0	3,500,000	14,000,000
8	141.5	14,000,000	40,000,000
9	150.0	40,000,000	110,000,000
10	158.5	110,000,000	300,000,000

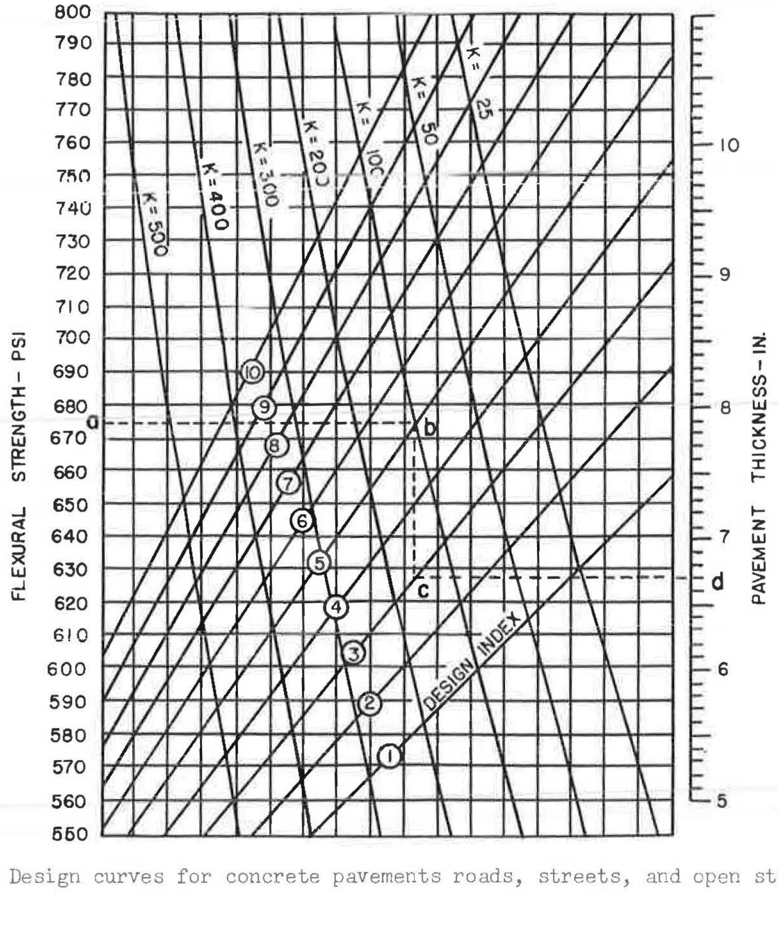

Figure 5. Design curves for concrete pavements roads, streets, and open storage areas.

given in the last column of Table 2. This gives about 356,520 equivalent coverages for the total volume of mixed traffic over the 25-yr period for the number of operations per day per lane selected. A pavement for the vehicle types and traffic volumes in Table 2 can now be designed on the basis of 356,520 coverages of the standard 18,000-lb single-axle loading. The design method consists of computing the critical stress at a free edge for the 18,000-lb single-axle loading by means of the Westergaard analysis (6). A uniform impact factor of 0.25 and the appropriate coverage design factor from Figure 4 is included in the stress computation. To simplify the procedure, Table 3 defines pavement design indices for coverage levels of the basic loading.

For example, the design index for the equivalent-coverage level computed in Table 2 is 5 since the range of equivalent coverages which this factor represents is between 130,000 and 800,000 (Table 3). The average coverage design factor for this range from Figure 4 is 1.16. With these factors established, the design chart (Fig. 5) can be prepared. The pavement thickness is determined by entering the chart with the flexural strength, as a, proceeding to the appropriate subgrade modulus line, as point b, then to the appropriate design index line, as c, and finally to the indicated pavement thickness, as point d. For example, to design a pavement when the 90-day flexural strength of the concrete will be 650 psi, the subgrade modulus 100 pci, and the traffic volume has a design index of 5, the thickness from Figure 5 is 8 in. If it were 8.25 in. or greater, a 9-in. thickness would be used.

COMPOSITE PAVEMENTS FOR ROADS AND STREETS

The foregoing method of plain concrete pavement design provides the basis for composite pavement design by making available a means of determining h_d for roads and streets for use in Eq. 1. However, one further modification of the information developed for airfield pavement design is necessary. The curves of Figure 2 were extended from the 30,000-coverage level to a 300,000,000-coverage level and curves for determining F, as given in Figure 6, for the design indices were obtained. Each curve represents a different equivalent-coverage level or design index, as defined in Table 3, and is numbered accordingly.

The formula for determining the non-rigid overlay thickness t of a composite pavement as developed from Eq. 1 for airfield pavements is

$$t = 2.5\ (Fh_d - Ch) \qquad (2)$$

in which h_d is the exact design thickness (to the nearest 0.1 in.) determined from Figure 5. Using the flexural strength of the existing rigid base pavement, the measured subgrade modulus k and the appropriate rigid pavement design index, the factor F is obtained from Figure 6. F is determined from the curve labeled with the same number as the rigid pavement design index. The C-factor is a coefficient depending on the structural condition of the rigid base pavement. Numerical values for C are determined as follows:

C = 1.00 when the rigid base pavement is in good condition or contains only nominal initial cracking,

C = 0.75 when the rigid base pavement slabs contain multiple cracks and numerous corner breaks.

The non-rigid overlay thickness t used in design should be determined to the nearest 0.5 in.

For example, there is an existing concrete highway pavement 6 in. thick that is to be strengthened by means of a non-rigid overlay to carry the volume of traffic defined in Table 2 for a 25-yr period. The existing pavement is in good condition so that a C-factor of 1.00 is used. The concrete has a flexural strength of 650 psi and the subgrade modulus is 100 pci. The rigid pavement design index for the increased traffic is 5. The full thickness of concrete h_d required to carry this increased traffic volume is 8 in. The factor F in Eq. 2 for a rigid pavement design index of 5 and a subgrade

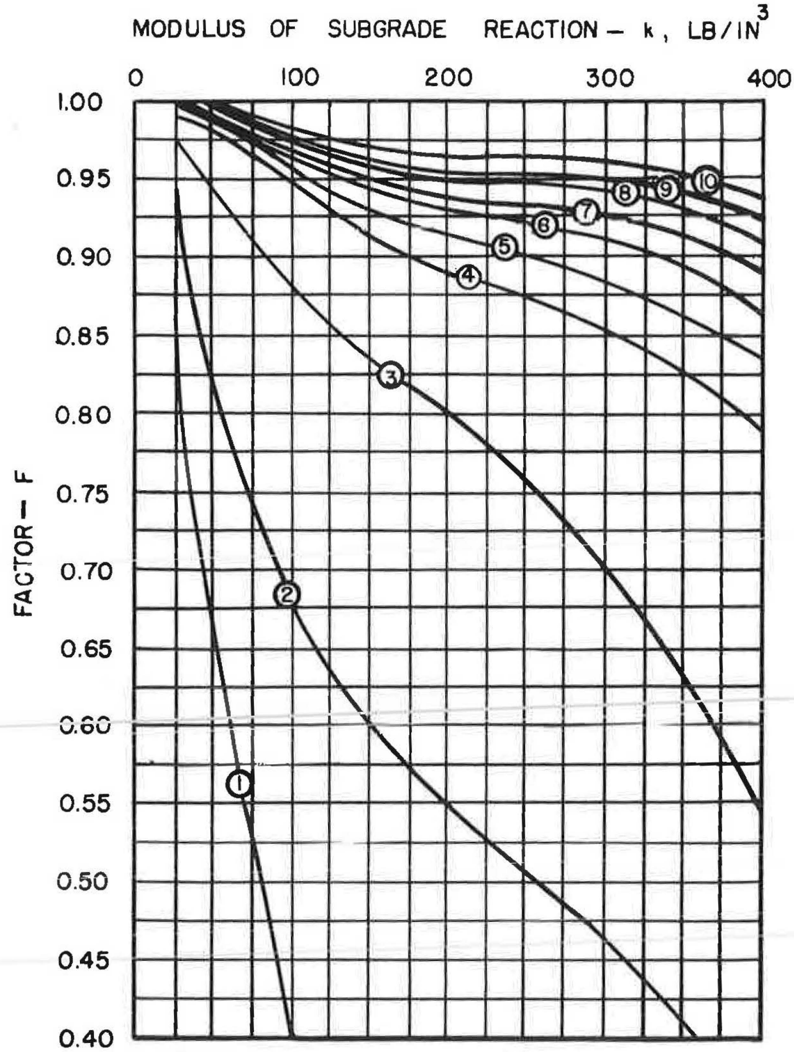

Figure 6. Composite pavement design factors.

modulus of 100 pci, as obtained from Figure 6, is 0.96. The non-rigid overlay thickness obtained using Eq. 2 is t = 2.5 (0.96 × 8 - 1 × 6) = 4.2 in. If the existing 6-in. concrete pavement has slabs containing multiple cracks and numerous corner breaks, a C-factor of 0.75 is used and the thickness t of the non-rigid overlay would be 8.0 in.

The two types of non-rigid overlays used in the actual construction of composite pavement are the overlay consisting entirely of bituminous concrete and the overlay consisting of a bituminous-concrete surface course over a granular base course (flexible overlay). Regardless of the type of overlay used, the thickness will be the same. The full-scale testing (1) indicated no difference in the performance of equal thicknesses of the two overlay types.

The all-bituminous-concrete overlay is used only when the combined thickness of a minimum 4-in. compacted base course and the required thickness of bituminous concrete surface course exceeds the design thickness t. There is no limitation, other than the economics of construction, on the maximum thickness of all-bituminous-concrete overlay that can be used. The bituminous concrete of the overlay is designed

and constructed in accordance with previously reported requirements (7). A tack coat is used between the rigid base and the all-bituminous-concrete overlay.

A minimum thickness of 4 in. is required for an all-bituminous-concrete overlay where it is used to increase the structural capacity of an existing concrete base pavement. The purpose of this limitation is to reduce to a minimum the reflection cracking resulting from movements occurring in the rigid base pavement.

When the overlay design thickness t is large enough to permit a 4-in. or more compacted base course plus the required thickness of bituminous concrete surface course, a flexible overlay may be used. The bituminous surface course will vary from 1.5 to 5.0 in., depending on the type of traffic. The base course should be a crushed aggregate material with a CBR of 100 for the full depth. Gradation and compaction requirements of the base course material are given elsewhere (7).

The flexible pavement design method may indicate a lesser thickness of overlay required than that given by Eq. 2, and this possibility must be considered when designing non-rigid overlays for rigid base pavements. This condition may occur when the existing rigid base pavement has a flexural strength of 400 psi or less, or if the modulus of subgrade reaction k exceeds 200 pci. Where such conditions prevail, the existing rigid base pavement is assumed to have a CBR of 100, and the required total thickness of pavement above the subgrade CBR is determined using the flexible pavement design procedure (7). The overlay design is then based on the method which requires the lesser thickness over the existing rigid base pavement.

SUMMARY AND CONCLUSION

The method for designing composite pavements is dependent on a suitable design method for plain concrete pavements. To present this design method for composite pavement for roads and streets wherein the effects of load repetition and the physical properties of the various components of the pavement are considered, it was necessary to devote a considerable portion of the paper to outlining the Corps of Engineers' design method for rigid pavement for roads and streets. This method of designing rigid pavement for roads and streets is important to the composite pavement design because it sets up the basis for evaluating the effects of mixed traffic by means of a standard axle loading.

The formula for determining the thickness of the non-rigid overlay is empirical; however, it is based on the definite trend indicated by the results of carefully conducted full-scale traffic tests (Fig. 3). The full-scale tests included a variety of overlay and base pavement thicknesses and a range of subgrade modulus from 50 to 370 pci, the predominate range being 50 to 100 pci. It is in the range of weak subgrade support that composite pavements have their greatest application.

In addition to taking into account the physical properties of the various pavement components and the effect of load repetition that can be translated into terms of pavement life, the design method is based on a limiting failure concept that is defined with respect to the interaction of the base pavement and overlay.

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