CORPS OF ENGINEERS DESIGN PROCEDURES FOR RIGID AIRFIELD PAVEMENTS

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The Corps of Engineers has prepared new design procedures for rigid airfield pavement design. Plain, reinforced, fiber-reinforced, prestressed, and continuously reinforced concrete pavements may be designed with these procedures. This paper describes the development of the Corps of Engineers rigid pavement design procedures, the assumptions and modifications required for each type of concrete pavement, and an example design of a medium-load airfield pavement.

Background

In 1979, the Corps of Engineers, U. S. Army, prepared a new rigid airfield design manual, TM 5-824/AFM 88-6, Chapter 3 (1), which provides design procedures for plain, reinforced, fiber-reinforced, prestressed, and continuously reinforced concrete pavements for Air Force airfields. This paper describes the basis of each procedure and an example design for a medium-load airfield pavement. Since the scope of this paper is limited, the reader is referred to the original manual (1) for details of jointing, reinforcing, compaction, etc.; to TM 5-818-2/AFM 88-6, Chapter 4 (2) for frost design; and to TM 5-822-7/AFM 88-6, Chapter 8 (3) for construction procedures.

Plain Concrete Pavement

Analytical Model

The Corps of Engineers has designed plain concrete pavements since 1946 by limiting the tensile stress at the bottom of the slab with the load adjacent to the slab edge (4). Dr. Westergaard's analytical model of a thin plate on a dense liquid foundation is used to calculate the magnitude of stress (5,6). Solutions of the Westergaard equations are available in the form of influence charts (7,8) and are also computerized (9). Static small-scale model tests (10) and strain measurements during full-scale traffic tests confirmed that this analytical model provided reasonable and conservative results.

The parameters considered in stress calculations with the Westergaard model are loading, concrete modulus of elasticity E, Poisson's ratio μ, slab thickness, and modulus of subgrade reaction k. Values for E and μ are generally selected as 27.6×10^6 kPa (4×10^6 lbf/in.^{2}) and 0.20, respectively. Representing the subgrade soil with a single value k is not accurate nor theoretically rigorous, but it is a useful approximation for practical rigid pavement design (5,11,12,13). The Corps of Engineers uses a field plate load test with a 76.2-cm-(30-in.-) diam plate conducted on in situ material to determine modulus values. Procedures for this test and a correction for saturation are published in MIL STD 621A (14).

A base course placed under a rigid pavement may perform functions such as drainage or serve as a construction platform, but it only affects the thickness design through changes to the foundation modulus. Four types of bases are recognized: unbound, stabilized, additive modified, and membrane encapsulated. Stabilized bases must meet the requirements of TM 5-822-4/AFM 88-7, Chapter 4 (15). Bases with stabilizers that do not meet these requirements are considered as additive-modified bases. The membrane-encapsulated bases consist of waterproof membranes placed around a base material to prevent water infiltration and weakening of the base (16).

A field plate load test on the surface of the base determines the design k value for additive-modified, bituminous-stabilized, membrane-encapsulated, and unbound bases. The design manual (1) includes limits on the maximum allowable value for the design k value of unbound bases. These limits are presented in the form of figures and are determined from the subgrade k value, the thickness of the base, and the type of material in the base. A design k value for stabilized layers under prestressed and continuously reinforced pavements is determined from another figure using the subgrade k, the modulus of elasticity of the stabilized material, and the thickness of the stabilized layer. A cement, lime, or fly ash stabilized base under a plain, reinforced, or fiber-reinforced pavement is treated as a low-strength pavement, and the pavement is designed by the following modified, partially bonded rigid overlay equation (17).

$$h_d = \sqrt[1.4]{h_{dc}^{1.4} - \left(0.00331\, h_b \sqrt[3]{E_b}\right)^{1.4}} \qquad (1)$$

where h_d = pavement design thickness, in centimetres; h_{dc} = required pavement design thickness without base, in centimetres; E_b = modulus of elasticity of stabilized base, in kilopascals; and h_b = thickness of base, in centimetres.

Load

During World War II, the Corps of Engineers undertook a series of tests to determine if load factors were needed to account for aircraft dynamic loads. The results of dynamic drop tests of aircraft gears on concrete slabs were inconclusive, but flight test results, summarized in Table 1 (18, p. 17), found normal aircraft landings to be less severe than the static loading. Later accelerated traffic tests for the C-5A cargo aircraft confirmed that static loads were as severe or more severe than moving loads up to 4.5 m/s (10 mph) (19). A joint Federal Aviation Administration and Corps of Engineers effort collected extensive information on the vertical pressure and the elastic and inelastic horizontal and vertical displacements of bituminous and concrete pavements to a variety of aircraft operations (20). Figure 1 (20, p. 87) shows a typical relatively flat response for rigid pavement, while the bituminous pavement had sharp peaks in response to static loads. Static aircraft loads are as severe as any loading that will occur under traffic, and a dynamic load factor is not needed for normal operations.

Table 1. Summary of World War II flight tests.

Operation	Load: Range (%)	Load: Average (%)
Static	-	100
Taxi	120-150	139
Normal landing	40-60	47
Hard landing[a]	149-202	173

[a] Considered more severe than normal aircraft operation; in worse cases caused mechanical damage to aircraft.

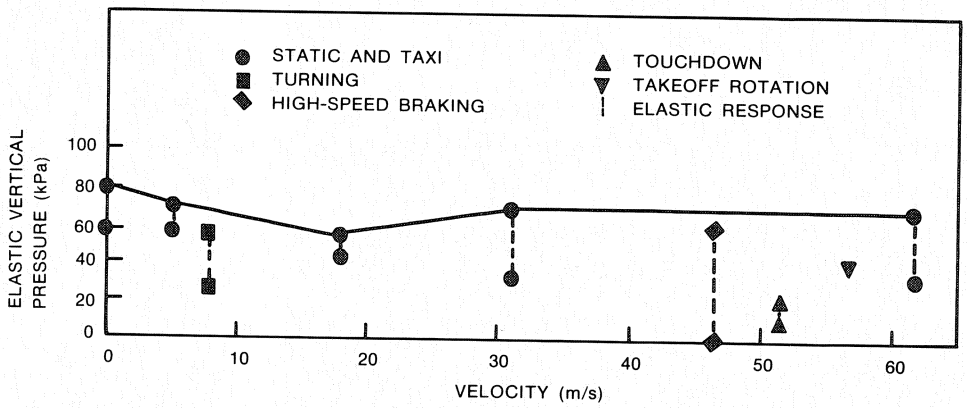
When aircraft loads are applied at the edge of slab, from 0 to 50 percent of that load will be transferred across the joint to the adjacent slab depending on the construction of the joint. Table 2 (21, p. 93-101) compares the efficiency of several types of joints used in accelerated traffic tests at Lockbourne Air Force Base, Ohio, where the keyed construction joint proved marginal under traffic and the others provided acceptable performance. Laboratory tests found that doweled joints could be constructed to obtain an initial load transfer near the theoretical maximum of 50 percent, but repetitive loading resulted in significant decreases in load transfer (22). The load transfer measured on airfields as shown in Table 3 ranges from no load transfer to a maximum of 50 percent with an average of 28 percent for doweled joints and 37 percent for keyed joints (23,24). The actual load transfer across a joint depends on many factors and is not constant. The Corps of Engineers design procedure allows a 25 percent load reduction to account for load transfer that is consistent with the results shown in Tables 2 and 3.

Aircraft Traffic

Current Air Force airfield design uses four traffic areas to account for variations in the intensity of loading on airfield pavements (12). Type A traffic areas are subject to heavy channelized traffic such as on taxiways or ends or runways; type B traffic areas are subject to more distributed traffic such as on parking aprons; type C traffic areas are runway interiors, which are subject to a reduced aircraft loading; and type D traffic areas are the outer, seldom trafficked edges of the runway. TM 5-824-1/AFM 88-6, Chapter 1 (25) describes these traffic areas in more detail.

Studies of airfield traffic distribution developed individual aircraft pass-to-coverage ratios, which relate the number of aircraft trips needed to cause one maximum stress application at every point in the traffic lane (26,27). For instance, 3.44 passes of a C-141A aircraft would cause one maximum stress repetition or one coverage on the highly channelized traffic lane of a primary taxiway, while on

Figure 1. Maximum elastic vertical pressure at 17.8 cm (7-in.) depth for a a rigid pavement under a B-727.



Note: 1 kPa = 0.145 lbf/in.^{2}; 1 m/s = 1.9 knots.

Table 2. Joint efficiencies from Lockbourne No. 2 tests.

Joint Type	Pavement Thickness (cm)	Number of Measurements	Joint Efficiency (%)[a] Range	Mean	Coefficient of Variation[b]
Keyed construction joint	30-61	19	27.5-95.0	72.6	0.26
Keyed with tire bars[c]	23-41	2	86.2-86.7	86.5	--
Doweled construction joint[c]	38-61	7	74.3-92.0	83.8	0.09
Dummy contraction joint[d]	38-61	10	79.0-92.3	88.2	0.05
Dummy contraction joint with tie bars[c,d]	38-61	6	84.5-93.2	89.1	0.04
Dummy contraction joint with dowels[c,d]	36-51	4	88.5-97.4	93.1	0.04

Note: 1 cm = 0.3937 in.

[a]Joint efficiency = $\frac{2 \times (\text{deflection unloaded edge})}{(\text{sum of deflections of loaded and unloaded edges})} \times 100$.

[b]Coefficient of variation = standard deviation ÷ mean.

[c]Dowels 2.5 x 41 cm (1 x 16 in.) at 30-cm (12-in.) spacing.
Tie bars 1.3 x 76 cm (1/2 x 30 in.) at 38-cm (15-in.) spacing.

[d]Dummy joints formed by inserting a steel blade into the wet concrete.

Table 3. Measured load transfer across doweled and keyed joints.

Location	Modulus of Soil Reaction (kPa/cm)	Pavement Thickness (cm)	Number of Measurements	Load Transfer (%)[a] Range	Mean	Coefficient of Variation
		Doweled Joints				
Beale AFB, CA	580	58	15	16.7-52.3	32.8	0.32
Dow AFB, ME	950	48	16	0.0-35.7	10.5	0.94
Ellsworth AFB, SD	580	58	16	30.4-50.0	40.6	0.12
Hunter AFB, GA	475	46	15	18.2-42.9	27.4	0.28
Lincoln AFB, NE	180	53	16	27.8-50.0	36.5	0.19
Lockbourne AFB, OH	200	30	11	7.4-23.7	15.8	0.37
March AFB, CA	270	41	15	20.0-47.4	32.0	0.24
McCoy AFB, FL	610	46	14	14.3-35.7	24.2	0.25
Tyndall AFB, FL	430	20-25	10	15.6-46.8	30.4	0.30
		Overall	128	0.0-52.3	28.1	0.43
		Keyed Joints				
Lincoln AFB, NE	180	53	2	35.9-36.1	36.0	--
McCoy AFB, FL	610	46	2	35.9-38.6	37.3	--
		Overall	4	35.9-38.6	36.6	

Note: 1 kPa/cm = 0.369 lbf/in.^{3}; 1 cm = 0.3937 in.

[a]Calculated from measured strains on loaded and unloaded edges of the joint.

a parking apron with a wider traffic lane due to increased aircraft wander 6.34 passes would be required for each coverage. Therefore, type A traffic area pavements must be thicker than type B pavements because the same number of passes of an aircraft will cause more stress repetitions in the type A pavement.

During and shortly after World War II, taxiways and the areas within the last 305 m (1000 ft) of runways were observed to fail sooner than the interior portions of the runways (28). Type C traffic areas are designed for nonchannelized traffic with the design load reduced 25 percent to take advantage of these observations. Type D traffic areas occur on airfields designed for the B-52 and C-141A aircraft and are designed for reduced load and traffic levels.

When the B-47 aircraft with the bicycle gear arrangement were introduced in the 1950's, unexpected pavement failures developed because of the highly channelized traffic and possible severe loading from the characteristic rocking or porpoising of these aircraft during high-speed braking (29,30). In an attempt to preclude further failures, new rigid pavement design criteria for the B-47 were issued in May 1955 to increase the design coverage level for type A traffic areas from 5,000 to 30,000 to account for heavily channelized traffic and to increase the design load 15 percent for possible additional loads resulting from the porpoising action of the aircraft (30). These were revised in February 1958 for the heavier B-52 to reduce the type A traffic area coverages to 10,000 because of a change in operational concept (30). Future investigations failed to conclusively determine if the 15 percent factor was needed; thus it may be overly conservative (13,31).

Design Factor

Moisture, temperature, and stress repetition have received considerable study and directly affect the rigid pavement performance. The Corps of Engineers accounts for these effects through a design factor defined as $DF = R/\sigma_e$ where DF = design factor; R = concrete flexural strength; and σ_e = maximum edge stress.

Accelerated traffic tests (19,32,33,34) have provided the basis for development and validation of the design factor and the relation between the traffic coverages and the design factor. These traffic tests defined three failure levels: (1) initial failure when a slab contains a single crack; (2) shattered slab when cracking divides the slab into 6 pieces; and (3) complete failure when cracking divides the slab into approximately 35 pieces. Air Force requirements for performance with minimum maintenance established the failure criterion for design as an initial single crack (13). However, condition surveys of active airfields and the performance of the accelerated traffic section revealed that slabs on a high-strength foundation continued to perform well after a single crack formed. To take advantage of this performance, slab thickness requirements were reduced as shown in Table 4 (12, p. 35) to allow some cracking to develop.

Table 4. Reduction in pavement thickness for high-strength foundations.

Subgrade Modulus, k (kPa/cm)	Reduction in Thickness (%)
540	0.0
810	4.6
1090	10.6
1360	19.2

Note: 1 kPa/cm = 0.369 lbf/in.^{3}.

Pavement thickness requirements can be expressed as a percent of standard thickness as illustrated in Figure 2. The standard thickness is calculated for a design factor of 1.3 at 5,000 coverages. The effect of the different failure criteria is shown in Figure 2 for a subgrade modulus of 540 kPa/cm (200 lbf/in.^{3}), as well as the pavement reduction for a modulus of 810 kPa/cm (300 lbf/in.^{3}) from Table 3. Data points for initial failure for k values of less than 680 kPa/cm (250 lbf/in.^{3}) from accelerated traffic tests were tabulated by Parker et al. (35) and are also shown in Figure 2. Complete curves for varying subgrade modulus for each failure criteria have been published by Hutchinson (36).

The initial crack failure criteria curves in Figure 2 show a sharply increased slope above 5,000 coverages. When the effects of highly channelized traffic from the B-47 and B-52 bombers were first discovered, it was necessary to project design curves from existing data at 5,000 to 30,000 coverages, which were far in excess of any trafficking data. A straight-line projection from available Corps of Engineers data fell well below other existing fatigue curves (Figure 3 (34, p. 29)). To bring the Corps criteria into closer agreement with the other fatigue projections, the line was adjusted upward to provide an additional 6 percent thickness at 30,000 coverages. Later limited accelerated traffic testing up to 35,000 coverages was not conclusive in developing new criteria for high traffic levels (34).

Design

Military airfields are designed for a specific aircraft and load. Charts for light load (F-4 aircraft), medium load (C-141A), heavy load (B-52), and short field (C-130) are included in the design manual (1). Charts for other aircraft also have been prepared. If necessary, the effects of mixed traffic can be analyzed (36). Figure 4 (1, p. 175) shows the design curve for medium-load airfields. All previously discussed factors, such as load transfer and effect of high-strength subgrades, have been accounted for in the chart except for design loads for type C and type D traffic areas. These loads must be reduced 25 percent from the gross load used for type A and type B traffic areas. An example design is presented later in the form of tables.

Reinforced Concrete Pavement

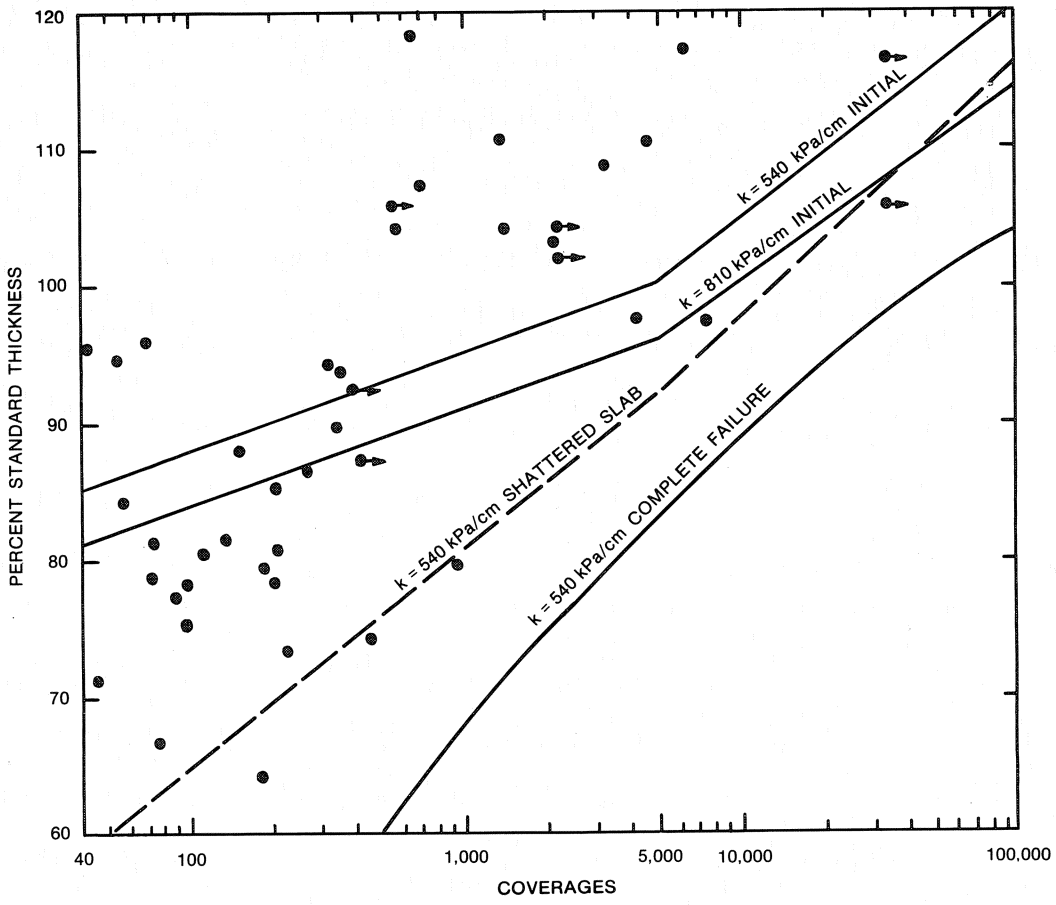
Basis of Design

During the Lockbourne accelerated tests, 14 items with steel reinforcement varying from 0.13 to 1.84 percent were trafficked with 27,200- and 68,000-kg (60,000- and 150,000-lb) wheel loads (32,37). Later, another 11 test items with steel reinforcement varying from 0.167 to 0.366 percent were tested at the Sharonville track (34). These tests found the reinforcing steel had no effect on the development of the initial crack in the slab. However, the further progression of cracking was slowed and the cracks were held tightly together. The failure criterion for these reinforced test items was changed from a single crack to spalling along the cracks to take advantage of this improved performance.

Design

Figure 5 (1, p. 184) shows the nomograph developed from the accelerated traffic tests. A desired

Figure 2. Pavement thickness requirement for varying traffic and failure conditions.



Note: 1 kPa/cm = 0.369 lbf/in.^{3}.

Figure 3. Effect of stress repetitions.

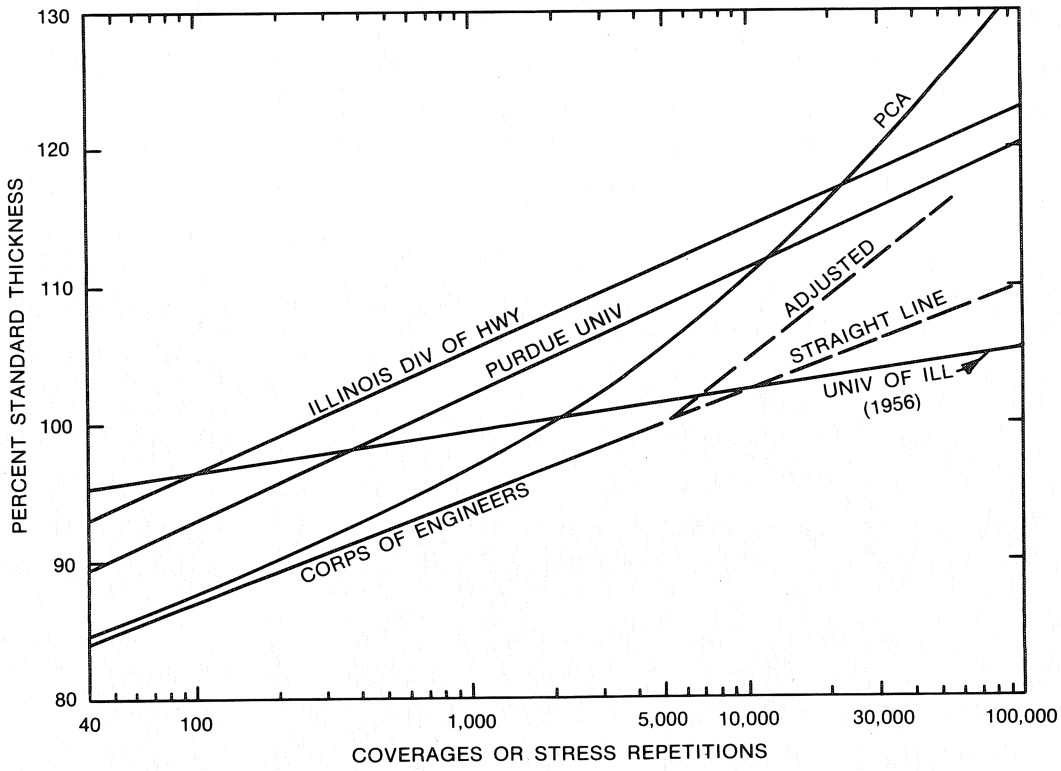
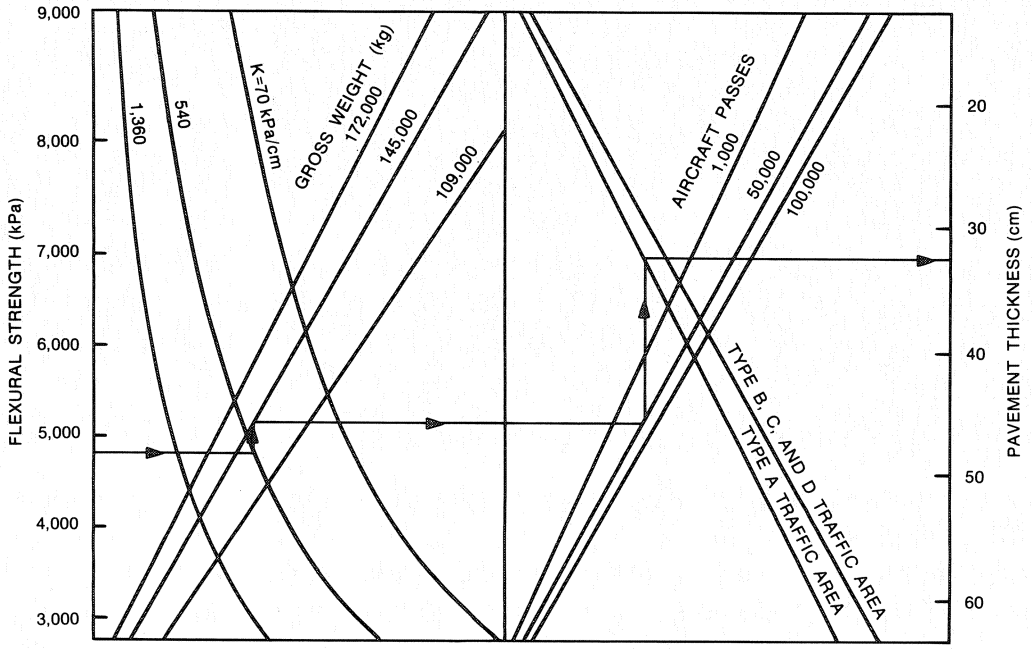
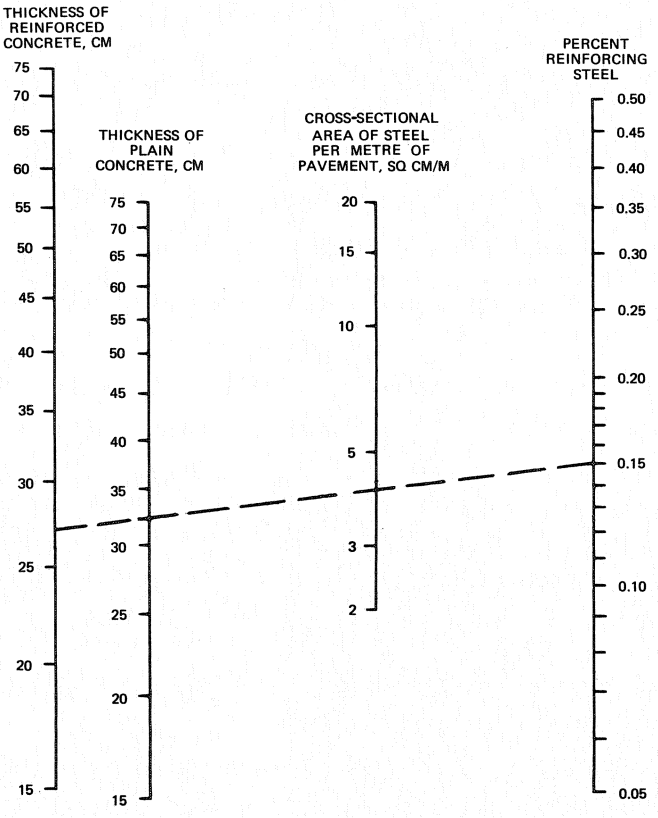


Figure 4. Design curve for plain concrete medium-load airfields.



Note: 1 kPa = 0.145 lbf/in.^{2}; 1 cm = 0.397 in.

Figure 5. Design nomograph for reinforced concrete pavement.



Note: 1 cm^2/m = 0.0509 in.^{2}/ft; 1 m = 3.28 ft; 1 kPa = 0.145 lbf/in.^{2}.

amount of steel reinforcing may be used to determine the required thickness of reinforced concrete, or the reinforced concrete thickness may be selected to determine the quantity of steel needed for this thickness. At least 0.05 percent steel must be used before any reduction in pavement thickness is allowed, and no additional benefit is allowed for steel in excess of 0.5 percent.

Fiber Reinforced Concrete

Properties and Applications

When short lengths of steel fiber are randomly dispersed in the concrete matrix, concrete flexural and tensile strengths increase, ductility and toughness increase, and dynamic strength increases. Improved flexural strength, typically 6200-9000 kPa (900-1300 lbf/in.^{2}) for field mixes, and increased resistance to spalling offer important potential advantages for fiber-reinforced concrete pavements (38). Observations of existing fiber-reinforced concrete pavements indicate that fibers on the surface corrode rapidly, but there are no data to indicate that fiber corrosion occurs within the slab or to determine the actual effects of fiber corrosion (38).

Parker (38) describes 11 fiber-reinforced concrete pavements built between 1967 and 1973. Other recent projects include a 10-cm-(4-in.-)thick fiber-reinforced concrete overlay for a tank parking apron at Fort Hood, Texas (39); 15 slabs of varying design subjected to bus traffic (40); and four airport applications described by Parker and Rice (41). These projects have provided useful experience and information on pavement performance and construction procedures.

Basis of Design

Accelerated traffic tests of four test items provided information needed to modify the conventional,

plain concrete design method for fiber-reinforced concrete. A fiber-reinforced slab has not reached its ultimate strength when a single crack forms; therefore, the failure criterion selected for fiber-reinforced concrete design was the opening of a crack under traffic to a width that allows water infiltration and loss of load transfer across the crack (38). Since the data available on fibrous concrete pavement performance are limited, no reduction in pavement thickness is allowed for high-strength foundations. Figure 6 (38, p. 164) shows the required thickness of fibrous concrete as a percent of standard thickness of plain concrete defined earlier. The relation of fiber-reinforced concrete thickness and coverages is assumed to be similar to plain concrete, and the location of the fiber-reinforced line was selected to provide a conservative relation for the limited available data.

Appreciable reductions in pavement thickness are possible with fiber-reinforced concrete (Figure 6), but these thinner slabs have higher deflections resulting in possible densification and shear failure in underlying material. Parker established a relation between measured elastic deflection of plain and reinforced concrete pavements, which provided acceptable performance of the entire pavement system with traffic coverages as shown in Figure 7 (38, p. 165). The relation for fiber-reinforced concrete was assumed to be similar, and the limited available data were used to locate the fiber-reinforced curve. Furthermore, Parker developed a relation between the deflection computed from the Westergaard analytical model and the measured deflections that allows the deflection for a given loading to be computed and checked against deflections which previously provided acceptable performance. The check on deflection ensures that a pavement designed on the basis of limiting stresses in the slab does not fail because of other factors not considered in the design model.

Design

Design curves for fiber-reinforced concrete have been developed for individual aircraft. First, a design curve, such as Figure 8 (1, p. 191), for medium load (C-141A) pavements is used to select a design thickness. This thickness is then used to determine a deflection (Figure 9 (1, p. 196)), which is checked against an allowable deflection for that aircraft loading. The original design manual (1) provides figures for determining allowable deflection for military airfields, and Parker (38) provides allowable deflection limits for a variety of military and civil aircraft. The minimum thickness for any fiber-reinforced concrete pavement is limited to 10 cm (4 in.) to avoid problems with placement and slab curling.

Prestressed Pavements

Behavior

A crack forms in a prestressed slab when the tensile stress on the bottom face exceeds the sum of the concrete flexural strength and the prestress compressive stresses. This cracking is the limit of elastic behavior of the slab and is the conventional point of slab failure. However, the prestressed slab will redistribute bending moments to increase the negative radial bending moment after this initial crack forms. When the load is removed, the prestress force closes the crack allowing continued service of the slab. Failure of the prestressed slab occurs when tensile cracking develops in the surface of the slab from the negative radial bending moments. A small increase in load or load repetitions then causes a punching shear failure. This behavior model for a prestressed slab in the inelastic range has been confirmed by model and full-scale accelerated traffic tests (42,43). The major benefit of the prestress is to allow the use of the slab in the inelastic range of behavior. A comprehensive review of prestress concrete pavement literature has been published by Hanna et al. (44).

Design

Sale, Hutchinson, and Carlton (43) used model and full-scale accelerated traffic tests of prestressed concrete slabs to develop an empirical design equation, which was later modified by Odom and Carlton (45) to be

$$P_d = \frac{280\ WNB}{wh^2} - R + P_s + P_t \qquad (2)$$

where P_d = design prestress, in kilopascals; W = total load, in kilograms; N = load repetition factor determined from Figure 10 (43, p. 61); B = load moment factor determined from Figure 11; w = ratio of multiple-wheel gear load to single-wheel load determined from Figure 12 (1, p. 206); h = design thickness of prestressed pavement, in centimetres; R = design flexural strength of concrete, in kilopascals; P_s = subgrade restraint stress, in kilopascals; and P_t = temperature warping stress, in kilopascals.

The form of equation 2 is based on the assumption that 5 percent of the aircraft load is on the nose gear and the remaining load is evenly distributed between the two main gears. If this assumption is not met, then the term 588P, where P is the actual gear load, should be substituted for 280W. Figures 11 and 12 require evaluation of the term A/ℓ^2 where A is the actual tire contact area and ℓ is the radius of relative stiffness calculated as

$$\ell = \left[\frac{Eh^3}{12(1-\mu^2)k}\right]^{1/4} \qquad (3)$$

The load moment factor B is an empirically determined relation of the initial cracking load, the load causing negative cracking on the surface of the slab, the distance r from the load to the negative cracking, the radial elastic moment calculated from Westergaard's interior loading at a distance r , and the maximum measured negative radial moment at a distance r . The development of this factor from the results of model tests is described in detail by Sale, Hutchinson, and Carlton (43) and Odom and Carlton (45). The selected model test data shown in Figure 11 had circular loaded areas. The elliptical load curve should be used for design.

The concept of replacing an actual multiple-wheel gear load with an equivalent single-wheel load, which produces the same critical tensile stress and greatly simplifies calculations, is described by Hutchinson (12). Sale, Hutchinson, and Carlton (43) used this concept and results of model tests to determine the relation for w in Figure 11 for military aircraft. Odom and Carlton

Figure 6. Performance criteria for fibrous concrete pavements based on first crack failure criterion.

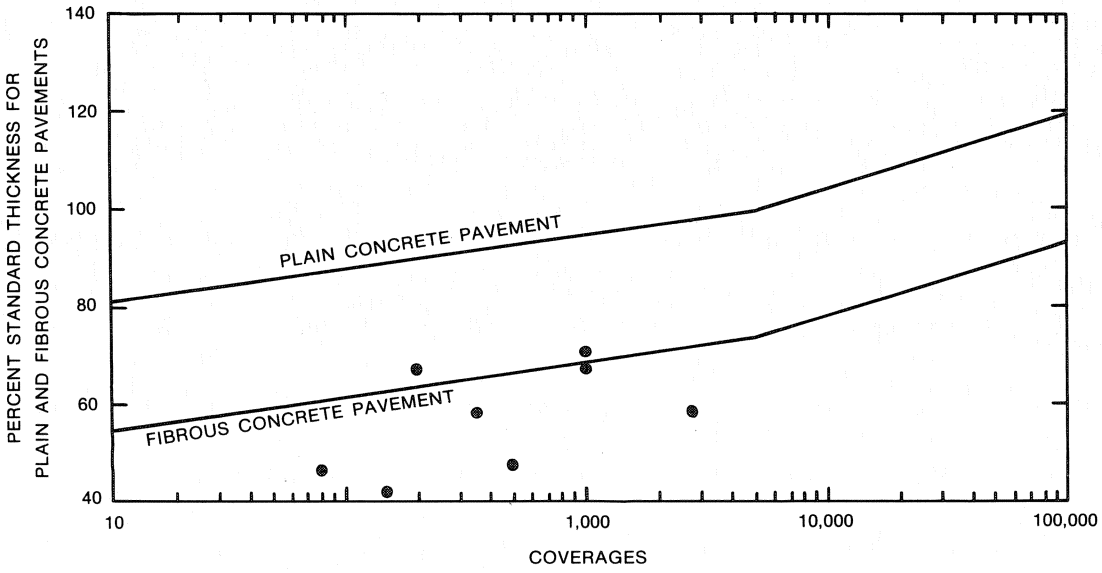
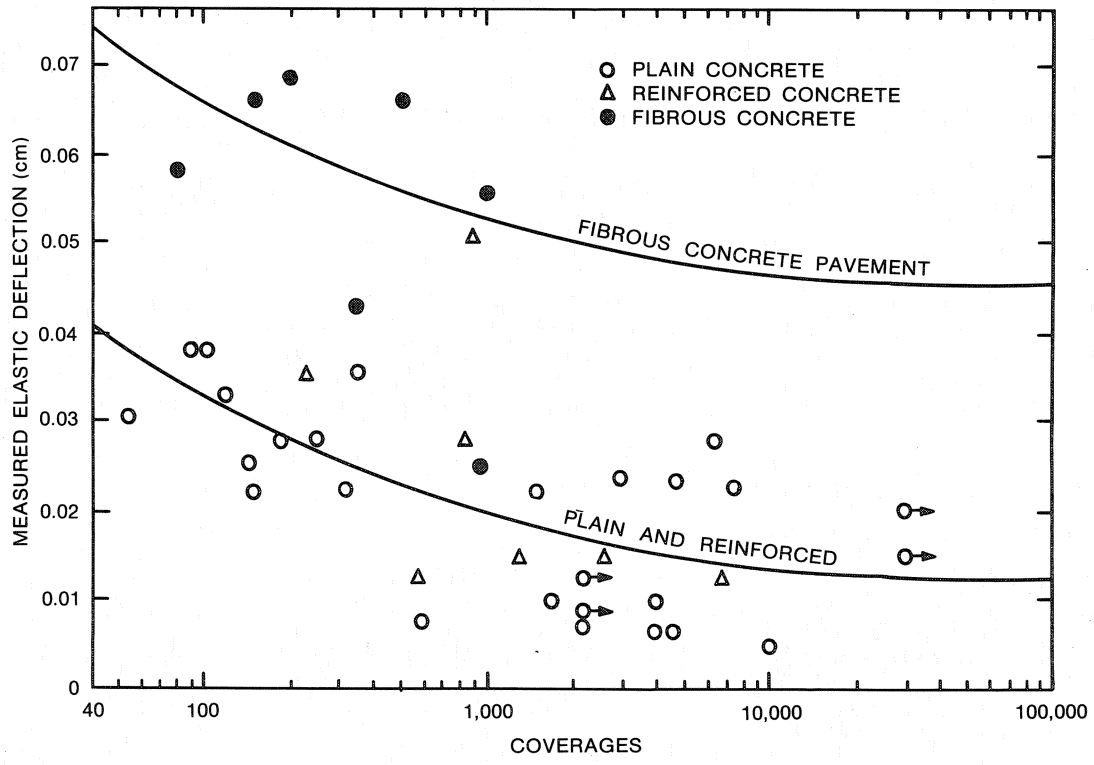
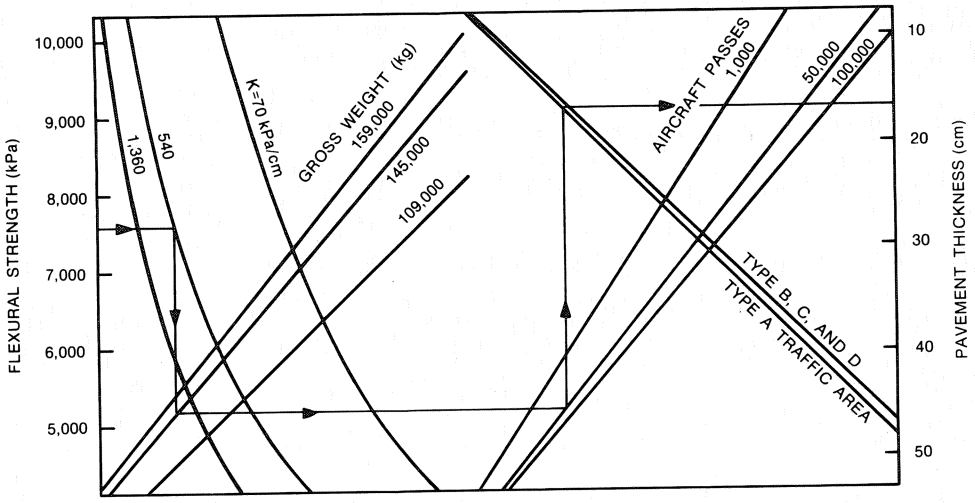


Figure 7. Relationship between measured deflection and pavement performance.



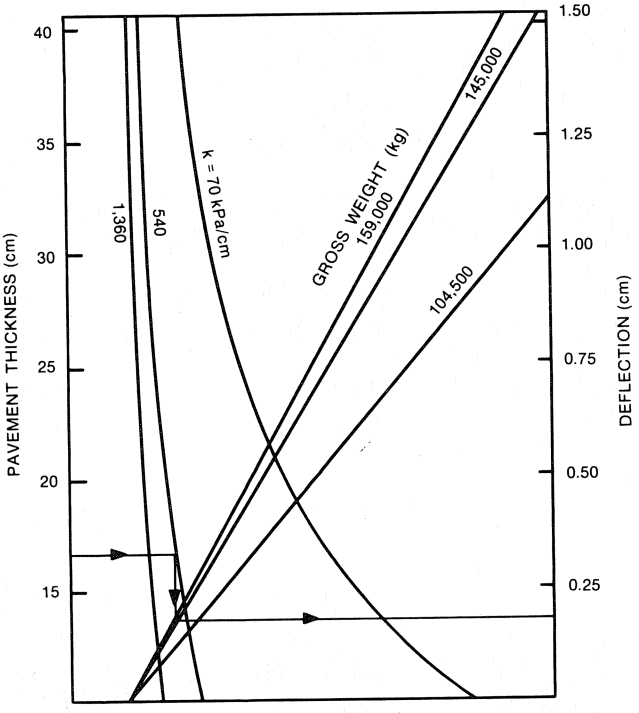
Note: 1 cm = 0.3937 in.

Figure 8. Design curve for fiber-reinforced concrete medium load airfields.



Note: 1 kPa = 0.145 lbf/in.^{2}; 1 cm = 0.3937 in.; 1 kg = 0.002 kip (mass).

Figure 9. Deflection of fiber-reinforced concrete, medium-load airfields.



Note: 1 kPa = 0.145 lbf/in.^{2}; 1 cm = 0.3937 in.; 1 kg = 0.002 kip (mass).

(45) analytically developed relationships for w for civil aircraft.

The design prestress must also counteract tensile stress developed from subgrade restraint P_s when the slab contracts because of temperature change and the warping stress P_t developed from the temperature gradient in the slab. These stresses may be calculated from the following:

$$P_s = 11.78\ C_f L \qquad (4)$$

$$P_t = \frac{Et\varepsilon_c}{2(1-\mu)} \qquad (5)$$

where C_f = coefficient of sliding friction, estimated 0.6 for design with friction reducing layer of sand, polyethylene, etc.; L = length (or width for transverse prestress) of slab, in metres; ε_c = concrete coefficient of thermal expansion, in centimetre per centimetre per degree Centigrade; and t = difference in temperature between top and bottom of slab, in degrees Centigrade.

The prestressing tendons must be stressed beyond the design prestress level to account for various tendon stress losses, estimated to be 20 percent, and frictional resistance between tendons and conduits. The reader is referred to References 1, 43, 44, and 45 for more detailed information on prestressing required for the tendons to overcome these losses.

Prestressed pavements are restricted to foundations with subgrade modulus k of 540 kPa/cm (200 lbf/in.^{3}) or higher and to a minimum thickness of 15 cm (6 in.). Prestressing is required in both longitudinal and lateral directions, and the design prestress may have a maximum value of 2,760 kPa (400 lbf/in.^{2}).

Continuously Reinforced Concrete Pavement

Basis of Design

Continuously reinforced concrete pavement depends on the reinforcing steel to transfer the load across cracks and to prevent widening of the cracks that form in the absence of transverse joints or because of the load. Experience with continuously reinforced pavement under aircraft traffic is very limited. Development of this design procedure is based on highway and airfield experience with continuously reinforced pavement and modifications of the plain concrete design procedure.

Austin Research Engineers, Inc., under contract to the U. S. Army Engineer Waterways Experiment Station developed a design procedure for continuously reinforced airport pavements (46) and later instrumented and evaluated the performance of a continuously reinforced runway at O'Hare International

Figure 10. Load repetition design factor versus traffic index.

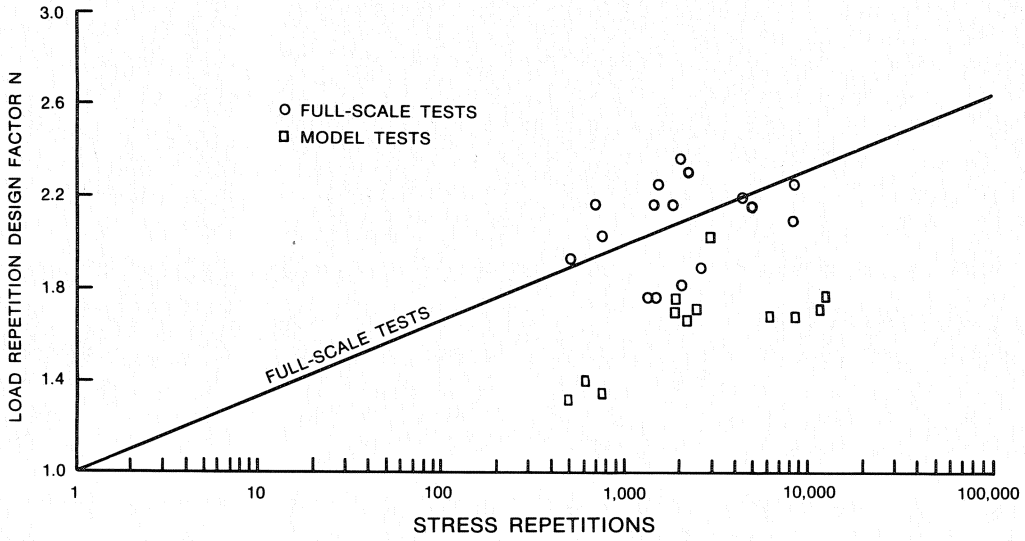
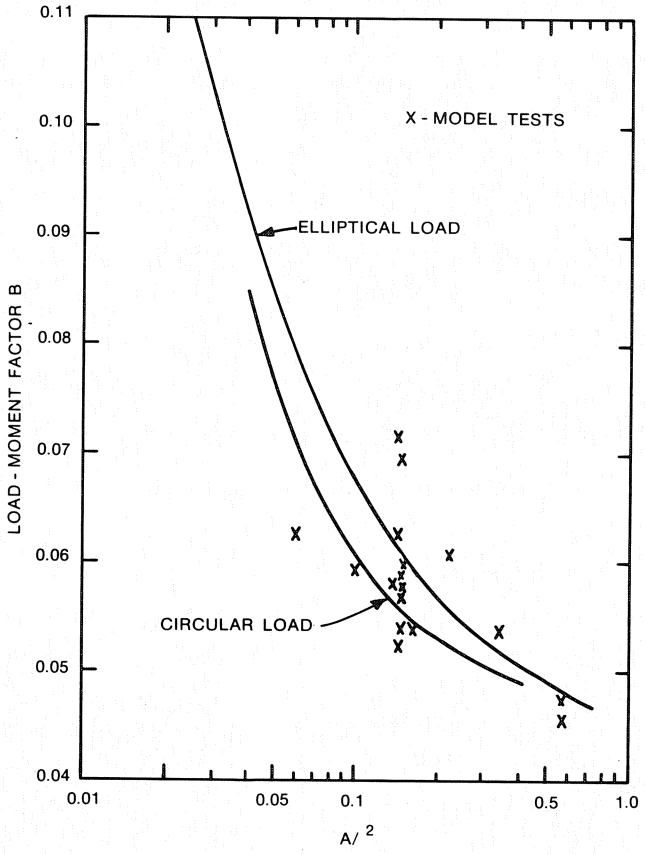


Figure 11. Load moment factor B .



Airport (47). Harvey (48) modified the original design procedure of Austin Research Engineers to reflect results of the O'Hare Airport study and to make the design procedure compatible with existing Corps of Engineers and Federal Aviation Administration design procedures.

Design

Design of continuously reinforced concrete pavement limits the load induced tensile cracking to acceptable performance levels. Harvey (48) developed a revised design factor based on cracking intermediate between initial and shattered slab failure conditions defined earlier. Tensile stresses were calculated for loads in the interior of the slab from an elastic, discrete element idealization (46). The revised design factor was used to develop Figure 13 (1, p. 201), which determines the allowable concrete flexural stress values. These values are then used with Figure 14 (1, p. 202) to obtain the required slab thickness.

The amount of longitudinal steel used in the continuously reinforced pavement must meet three separate requirements: (1) the American Association of State Highway and Transportation Officials steel requirement for continuous reinforcement, (2) the steel required to resist stresses from temperature changes, and (3) the steel required to keep shrinkage cracks tightly closed (46,48). Transverse steel is designed to resist subgrade frictional drag forces (46,48). These steel design equations have been modified in the design manual (1) to use the 90-day concrete flexural strength rather than the 7-day concrete tensile strength as used in References 46 and 48.

Large deflections due to the increased flexibility of continuously reinforced concrete pavements have caused problems with spalling, pumping, and premature pavement failure (46,48,49). Design based on limiting tensile stress provides no protection against deflection related problems. To avoid these problems, continuously reinforced concrete pavements must be at least 15-cm (6-in.) thick and must have a minimum 15-cm- (6-in.-) thick stabilized base.

Example Design

Table 5 provides the parameters needed with the other information in this paper for an example design of a medium-load military pavement. Sample designs for each pavement type are shown in Table 6 using these parameters both without a base and with a 15-cm- (6-in.-) thick lean concrete base. In practice, pavement thicknesses are rounded to the nearest 1/2 in. and to the nearest centimetre in Table 6.

Conclusions

The five design procedures summarized herein have been developed over the past 40 years and have

Figure 12. Ratio of multiple-wheel gear loads to single-wheel gear loads.

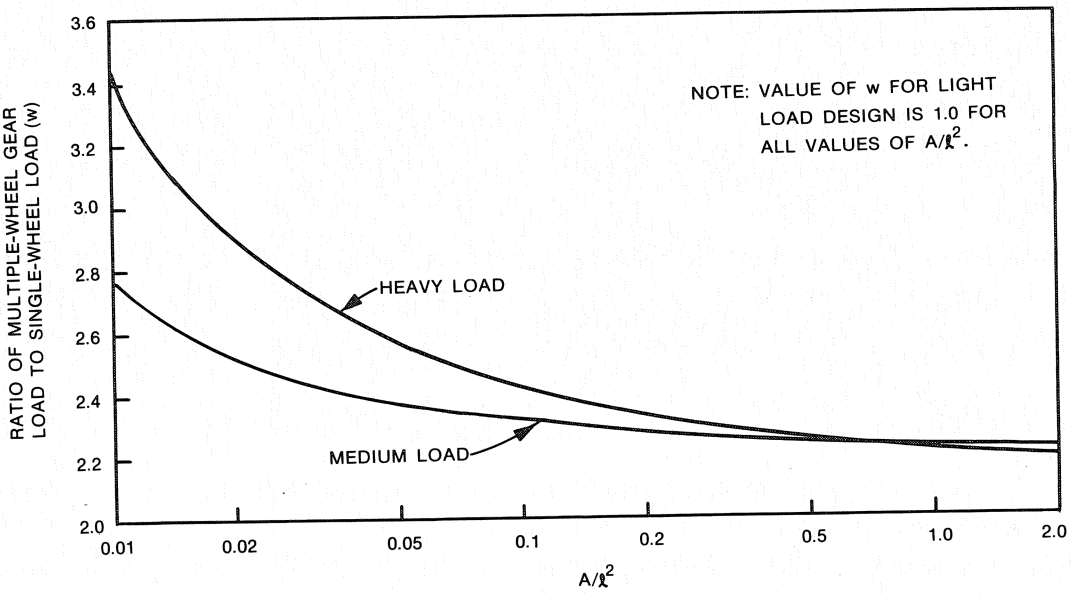
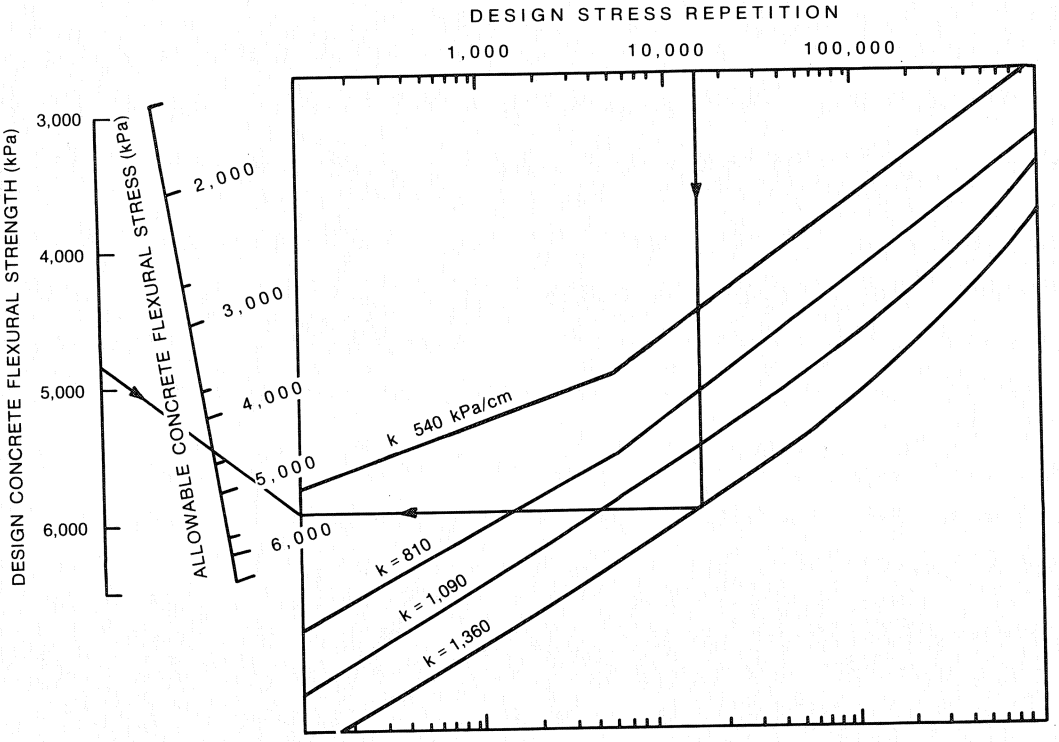
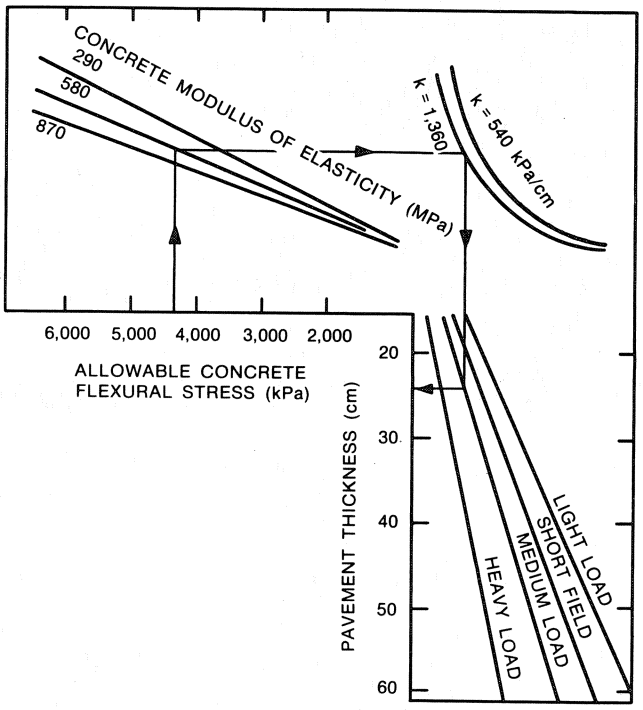


Figure 13. Allowable concrete flexural stress for continuously reinforced concrete airfield pavements.



Note: 1 kPa = 0.145 lbf/in.^{2}; 1 kPa/cm = 0.369 lbf/in.^{3}.

Figure 14. Required thickness of continuously reinforced concrete pavement.



involved numerous offices of the Corps of Engineers, as well as the U. S. Air Force and the Federal Aviation Administration among others. Preparation of the new design manual (1) gives the designer for Air Force airfields more options than he has had in the past to develop economical pavement designs within the specific requirements of his project. Maintenance requirements, scarce construction materials, restrictive grade requirements, or similar limitations may make alternative designs to plain concrete desirable. In the past, the Corps of Engineers has only allowed plain and reinforced concrete pavement for airfield design.

These design procedures are at various levels of maturity. The Corps of Engineers has extensive experience with plain concrete airfield pavement design. A review of the performance of 25 plain and reinforced concrete airfields by Hutchinson and Vedros (31) found that the Corps of Engineers procedures met the U. S. Air Force pavement requirements. Experience with fiber-reinforced, prestressed, and continuously reinforced concrete pavements is much more limited and future field experience will provide the information to further improve and refine these design procedures.

Table 5. Example design parameters.

1. Design Requirement - medium-load airfield for 50,000 passes

2. Aircraft - C-141A

   Weight - 145,000 kg, types A & B; 109,000 kg, type C

   $A = 1340\ cm^2$

(Continued)

Table 5 (Continued)

$$\text{Stress Repetitions} = \frac{\text{50,000 coverages}}{\text{pass-to-coverage ratio}}$$

Type A - 14,500 repetitions

Types B & C - 7,900 repetitions

3. Subgrade - k = 540 kPa/cm, no frost

4. Concrete -

   $E = 27.6 \times 10^6$ kPa, $\mu = 0.2$, R = 4830 kPa

   $\varepsilon_c = 10.8 \times 10^{-6}$ cm/cm per °C

5. Fiber Reinforced Concrete - R = 7590 kPa, allowable deflection 0.14 cm

6. Lean Concrete Base -

   $E = 13.4 \times 10^6$ kPa, h = 15 cm, surface k = 1360 kPa/cm

7. Continuously Reinforced Concrete - 0.69% steel

8. Prestress Design Parameters

h (cm)	k (kPa/cm)	A/ℓ^2	B	w	Traffic Area	N
20	540	0.225	0.0565	2.27		
18	540	0.263	0.0550	2.26	A	2.36
20	1360	0.357	0.0518	2.25	B&C	2.26
18	1360	0.418	0.0509	2.24		

Slab length - 122 m; temperature gradient - 0.22°C per cm pavement thickness

Note: 1 kg = 2.2 lb; 1 cm^2 = 0.155 $in.^2$; 1 kPa/cm = 0.369 $lb/in.^3$; 1 kPa = 0.145 $lbf/in.^2$; 1 cm = 2.54 in.; 1 m = 3.28 ft; and 1°C = 1.8°F.

Table 6. Comparative example designs.

Type	Base	Required Thickness (cm) A	B	C	%[a]	Remarks
Plain	No	33	29	23	100	--
	Yes	26	23	16	79	--
Reinforced	No	27	25	19[b]	82	0.15% steel
	Yes	22	19	15[b]	67	0.15% steel
Fibrous	No	17	16	12	52	Excessive deflection
	No	22[b]	22[b]	17[b]	67	--
	Yes	10[b]	10[b]	10[b]	30	--
Prestress	No	20	20	18	61	--
	P_d[c]	2810	2560	1950	--	--
	Yes	20	20	18	61	--
	P_d[c]	2370	2130	1610	--	--
Continuous	Yes	24	20	15	73	0.69% steel

Note: 1 cm = 2.54 in.; 1 kPa = 0.145 $lbf/in.^2$.

[a] % = percent thickness of type A traffic area with plain concrete with no base as denominator.

[b] Required minimum thickness.

[c] P_d = design prestress in kilopascals.

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