From PCA for Airport Pavements

steel in all types of overlays are designed based on the overlay slab thickness. Otherwise, the design of tiebars and distributed steel in bonded and partially bonded overlays is based on the combined thickness of old and new slabs; and dowel design is based on the thickness of an equivalent slab (*h* in Formulas 10 and 11).

Reinforcement serves the same purpose in concrete overlays as it does in regular pavement. It is not required when joint spacings are short, but it is required in longer joint spacing to keep cracks from opening enough to present a maintenance problem. If the old pavement is extensively cracked, use of distributed steel or continuous reinforcement may be the most dependable method of minimizing uncontrolled cracking in unbonded or partially bonded overlays. (Bonded overlays, as mentioned, are for use only where the existing slabs are in good structural condition or where structural defects have been repaired.)

Continuously Reinforced Overlays

Because they are less susceptible to reflective cracking, continuously reinforced overlays offer an advantage over other overlays. For continuously reinforced overlays, a separation course is normally used over the existing pavement and the overlay thickness is determined as described for unbonded overlays. The amount of reinforcing steel is based on the overlay thickness requirements. Other design details are the same as for regular continuously reinforced concrete pavements.

A few partially bonded (no separation course), continuously reinforced overlays have been constructed. Partially bonded overlays should be used only if the existing pavement is in fairly good condition with short joint spacings so that joint movements will not greatly affect the overlay. A thinner overlay can be used because it is partially bonded, but additional steel may be required to prevent excessive crack opening.

Separation Courses

Some success has been experienced in preventing reflective cracking by use of a separation course between base slab and overlay. Not sufficient data are available, however, to establish the minimum thickness needed for the separation course to be completely effective. Indications are that any type of bond breaker will reduce the amount of reflective cracking. As discussed previously, use of a bond breaker or separation course requires a thicker overlay.

Concrete Overlays for Flexible Pavement

Concrete overlays have been used on flexible pavements for several years. They have performed well and demonstrate the feasibility of this type of construction.(47)

Design for a concrete overlay on flexible pavement is the same as design for a concrete pavement on grade. The modulus of subgrade reaction, *k*, is determined by plate-bearing tests made on the surface of the flexible pavement. Several agencies specify that no *k* value greater than 500 lb. per cubic inch be used in designing rigid overlays for flexible pavements. The limitation, however, appears to be arbitrary and more development work is needed to fully realize the advantages of this composite design.

APPENDIX A

FATIGUE CONCEPTS APPLIED TO TRAFFIC ANALYSIS

The purpose of this appendix is to provide engineers with a quantitative method for evaluating the effect of repeated aircraft operations on airport pavements. It applies to the design and evaluation of pavements at airports serving large volumes of heavy, multigeared aircraft of different types. When specific data on mixed aircraft traffic are available or forecast, this procedure can be used instead of using safety factors as described in Chapter 2. Its applications are:

- design for specific volumes of mixed traffic
- evaluation of future traffic capacity of existing pavements or of an existing pavement's capacity to carry a limited number of overloads
- evaluation of the fatigue effects of future aircraft with complex gear arrangements
- more precise definition of the comparative thicknesses of runways, taxiways, and other pavement areas depending on operational characteristics

Use of this quantitative method introduces three additional design parameters:

1. Traffic widths for taxiways, runways, and ramps
2. Variability of concrete strength
3. Downgrading of service life where a good subbase support is not provided

Coverages and Fatigue

The procedure described here was developed from a study and correlation(48) of two methods that reflect pavement design and performance experience at both civil and military airports. The first is the coverage method developed by the U.S. Army Corps of Engineers as part of their pavement design methodology for both rigid and flexible pavements.(49-53) It is based on pavement performance at military airfields and full-scale test track studies. The second is the fatigue method(54) used for highway pavement design. Based on concrete fatigue research, this method was applied early in the development of the Portland Cement Association's highway pavement design procedures. In a general way, the fatigue concept is also inherently part of airport design methodologies of the Federal Aviation Administration and the Portland Cement Association.

COVERAGES

The effect of the lateral distribution of traffic on runways and taxiways is taken into account in the Corps of Engineers' design procedure. That procedure uses the term "pass-coverage ratio" to refer to a conversion of the number of traffic operations to the number of design load repetitions; that is, a coverage occurs when each point of the pavement within the traffic lane has been subjected to a maximum stress by the operating aircraft. The following equation* relates coverages to the number of operations (passes) for a specific aircraft:

$$C = D \times \frac{0.75Nw}{12T} \qquad \text{(A1)}$$

where

C = coverages
D = number of operations at full load**
N = number of wheels on one main gear
w = width of contact area of one tire, inches
T = traffic width, feet

Fig. A1(49) shows the relationship between slab thicknesses and allowable coverages, developed by the Corps of Engineers.

The coverage curves reflect the following increases in the required pavement thickness for more than 5,000 coverages:(52)

Coverages	Increase in pavement thickness, percent
10,000	5
15,000	8
20,000	10
30,000	12

Traffic Width. T in Formula A1 expresses the traffic width within which the aircraft wanders—the transverse distribution of the traffic on runways and taxiways. Distribution curves are approximately bellshaped as shown in Fig. A2.(51)

Traffic width is considered as the width within which 75 percent of the main gear paths fall, and for practical purposes the Corps of Engineers assumes that the distribution is uniform within the traffic width. Traffic widths of 7.5 ft. for taxiways and 37.5 ft. for runways have been indicated by these studies.

FATIGUE

Concrete, like other construction materials, is subject to the effects of fatigue. A fatigue failure occurs when a material ruptures under continued repetitions of loads that cause stress ratios of less than unity. Since the critical stresses in concrete are flexural, fatigue due to flexural stress is used for thickness design; and the stress ratios are the ratios of flexural stress to modulus of rupture.

Flexural fatigue research on concrete has shown that, as stress ratios decrease, the number of stress repetitions to failure increases. It has also shown:

1. When the stress ratio is not more than about 0.55, concrete will withstand virtually unlimited stress repetitions without loss in load-carrying capacity. Hence, concrete has a flexural fatigue endurance limit at a stress ratio of approximately 0.55.
2. Repetitions of loads with stress ratios below the endurance limit increase concrete's ability to carry loads with stress ratios above the endurance limit, that is, concrete's fatigue resistance is improved.
3. Rest periods also increase the flexural fatigue resistance of concrete.

For thickness design purposes, the stress ratio for the endurance limit of concrete is reduced from 0.55 to a more conservative 0.50. Allowable load repetitions are shown in Fig. A3. The values are conservative with respect to flexural fatigue research on concrete.

Accumulation of the effects of repeated loads and mixed traffic is made on the basis of the Miner hypothesis(55) with sufficient conservatism to incorporate a very low probability of failure. Kesler,(56) in a summary of the fatigue properties of concrete, concludes that reasonable results can be obtained in this way. Ballinger's work(57) corroborated the Miner hypothesis but showed less reliable performance at high stress ratios of 0.70 or more; this is normally beyond the range used for pavement design purposes.

Use of these concepts for pavement design was initiated by PCA in 1933 and modified in view of additional information in 1966.(54) As discussed in Reference 58, the design procedure making use of the cumulative damage concept and the fatigue curve has given reliable thickness designs for highways and streets. These concepts, without specific use of the cumulative damage theory, have been applied to airport design since 1950.

---

*This equation is specified by the Corps of Engineers for tricycle-geared aircraft and applies to aircraft with single, dual, or dual-tandem gear configurations.

**Corps of Engineers defines D as cycles of operation where one cycle is one landing and one takeoff. Since landing weight is usually significantly less than takeoff weight, D can be considered to be the number of takeoffs or, more generally, the number of full-load passes.

LOAD REPETITION FACTOR

The load repetition factor (LRF) relates the number of aircraft passes over a given traffic width to an equivalent number of full-load stress repetitions that will give the same degree of fatigue consumption. The factor is analogous to the coverage factor used to convert aircraft operations to number of coverages.

Load repetition factors are determined from the complete stress profile and resulting fatigue consumption for various standard deviations of traffic distribution and for various ℓ values by a computer program that combines the PCA program for stresses,(20) the PCA fatigue curve,(59) and the normal probability curve. To save the designer the work of determining them himself, these factors are available from the Portland Cement Association. Table A1 lists factors for several aircraft. In a design problem, the expected number of full-load passes of a given aircraft is multiplied by the load repetition factor.

Table A1. Load Repetition Factors for Several Aircraft

	Load repetition factor (tentative design values)			
Aircraft	Taxiway		Runway	
	σ = 24 in.	σ = 48 in.	σ = 96 in.	σ = 192 in.
DC-3	0.12	0.07	0.05	0.03
B-727	0.41	0.23	0.13	0.09
DC-8 and B-707	0.83	0.46	0.25	0.17
B-747	0.58	0.38	0.33	0.28
C5A	0.74	0.61	0.37	0.25
B-2707*	0.52	0.39	0.22	0.16
Concorde	0.83	0.44	0.23	0.15
DC-10-10 and L1011	0.57	0.40	0.22	0.12
Future #4**	1.33	0.84	0.44	0.24

*12-wheel gear, spacing: 3 sets 22x44x22 at 44 in., 2 post, 265-in. tread.
**Projected 1 million pound aircraft, dual-tandem gear 44x56 in., 4 post (2 tracking), 426-in. tread.

Load repetition factors reflect the effects of the configuration of all wheels and gears. If trailing wheels or gear induce a substantially separate stress repetition (depending on wheel spacing and the radius of relative stiffness of the pavement) the effect is included in the load repetition factor. Additional gear, not trailing, are also included; these have negligible effect for traffic widths representing taxiways and greater effect for runway traffic widths.

VARIATION IN CONCRETE STRENGTH

Recognition of the variation of concrete strength is considered a realistic addition to the slab-thickness design procedure given in this appendix. Expected ranges of variations in the concrete's modulus of rupture have far greater effect than the usual variations in the properties of other materials—subgrade and subbase strength, layer thicknesses, etc. Typical ranges of variations in concrete strength are shown in Table A2.

Variation in concrete strength is introduced into the procedure by selecting a design modulus of rupture as follows:

$$DMR = MR_{90}\left(1 - \frac{V}{100}\right) M \qquad \text{(A2)}$$

where

DMR = design modulus of rupture, psi
MR_{90} = average modulus of rupture at 90 days, psi
V = coefficient of variation of modulus of rupture, percent
M = factor for the average modulus of rupture during design life, recognizing that concrete strength increases with age

Several combinations of V and M, along with load repetition factors computed from selected standard deviations of traffic distribution, σ, permit a close correlation of fatigue and coverage results. Selection of conservative values for all three factors (V, M, and σ) will result in excessive conservatism in the procedure.

Table A2. Variation of Concrete Strength

Rating of concrete control	Coefficient of variation, V, percent
Excellent	Below 10
Good	10 to 15
Fair	15 to 20
Poor	Above 20

Note: Table is from Reference 61 and is based on compressive strength tests. Variations in flexural strength are expected to be similar.

The following values, which give close correlation between coverage and fatigue relationships, are suggested for design purposes: realistic values* for V of between 10 and 18 percent; a conservative value* for M of 1.10; and values for σ of 24 in. for taxiways and 192 in. for runways.

WEAK FOUNDATION SUPPORT

When supported by firm subbase and subgrade foundations, pavements continue to give serviceability for some time after initial cracks have developed. This is reflected in Fig.

---

*References 60 through 63 discuss variations and gains in concrete strength and refer to other sources of information on these topics.

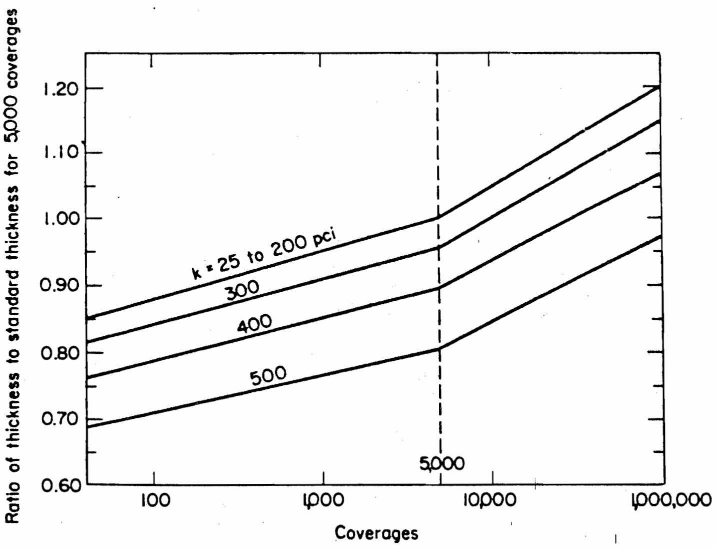

Fig. A1. Relation between pavement thickness and allowable coverages.

Development of Fatigue Procedure for Airports

To compare fatigue relationships with coverage concepts, the effects of the variables (for example, traffic width and aircraft gear configuration) had to be translated in terms of fatigue effects. It was found that an excellent correlation exists when some conservatism is used in the fatigue approach by recognition of a realistic degree of variation in concrete strength. An additional adjustment in the procedure reflects the experience of the Corps of Engineers with pavements built on weak foundations.

The effects of these factors, discussed in detail in Reference 48, are described briefly in the following paragraphs.

TRAFFIC WIDTH

In developing the correlation between fatigue and coverage procedures, the Corps of Engineers' traffic distribution curves were represented by normal distribution curves with various standard deviations. It was found that standard deviations of 24 in.* for taxiways and 16 ft. for runways fit the distribution curves, and these are suggested for design purposes. Thus, on taxiways, two-thirds of the time transverse placements of aircraft will fall within a 4-ft. width; on the central portion of runways, two-thirds will fall within a 32-ft. width. Data are provided for other standard deviations** in case the designer wishes to use different values based on results of traffic width studies currently in progress or proposed.

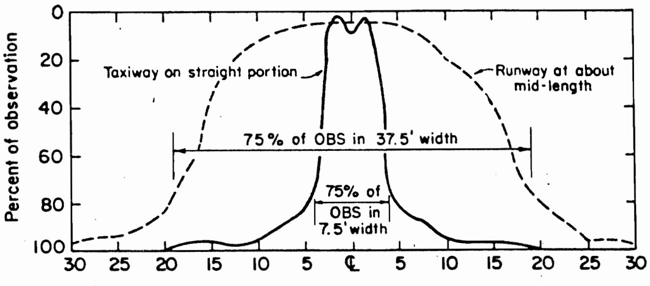

Fig. A2. Traffic distribution patterns for dual and dual-tandem gear aircraft.

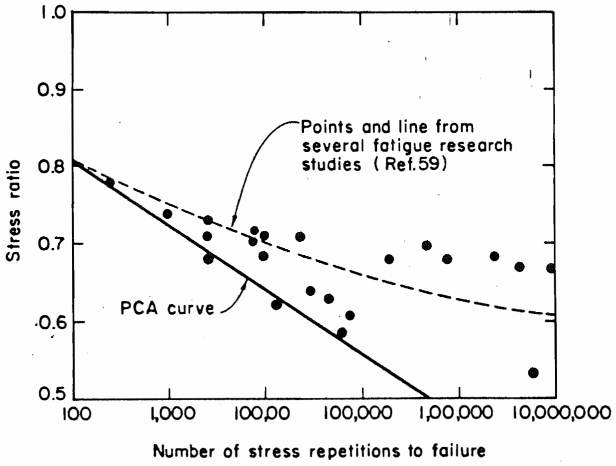

Fig. A3. Fatigue curve for concrete subjected to flexural stresses.

---

*For taxiways, a standard deviation of 40 in. fits the distribution curve in the sense that 75 percent of the traffic falls within a traffic width of 7.5 ft. However, a standard deviation of 24 in. more closely approximates the actual shape of the curve within the traffic width.

**The relation between traffic width, T, as defined by the Corps of Engineers, and the standard deviation of traffic distribution, σ, is: $\sigma = (0.88)T/2$.

A1(49) where more load repetitions are allowed for *k* values greater than 200 pci, which represent reasonably strong subbase and subgrade support. Conservatively, for pavements carrying high traffic volumes, this additional serviceability is not recognized in the fatigue design procedure.

If reasonably strong subbase and subgrade support is not provided, pavement failures may be due to causes other than flexural failure (such as excessive subgrade strains, excessive transient and permanent subgrade deformations, subgrade pumping) that lead to loss of support or nonuniform support and then to the secondary result of failure of unsupported slabs or joints.

It is interesting to note that theory and experience agree on the principle that stronger subgrade, subbase support provides more assurance that the pavement will behave as designed by flexural methods: As the *k* value increases, deflections and subgrade strains decrease at a faster rate than flexural stresses. An example is illustrated in Fig. A4. At safe flexural stresses, deflections and subgrade strains for a strong support are more likely to be within safe limits than for a weak subgrade where deflections and subgrade strains may be excessive even though slab flexural stresses are safe. This principle has greater effect for multiple-wheel gears.

Although it is not advisable to build a pavement to carry heavy multigeared aircraft on a weak subgrade, allowance is made for the subgrade-induced slab failure mode in the proposed procedure by adapting Corps of Engineers' curves for *k* values of 200 pci or less. These substantially reduce the allowable number of load repetitions for very low *k* values. To simplify use of this modification, the total fatigue consumption computed in Table A3 is increased by multiplying by a factor from Table A5 for the corresponding value of subbase, subgrade support.

For well-designed, heavy-duty pavements, a good subbase with a *k* value of at least 200 pci should be provided so that this modification would not apply.

Use of Fatigue Procedure, Mixed Traffic

DESIGN

An example of use of the fatigue method for analysis of mixed traffic is given in the design form shown here as Table A3. It was assumed that a specific forecast of aircraft types and expected number of operations* was made for the design life. (Data for several future and stretch aircraft also were assumed.) The design form conveniently incorporates aspects of the fatigue design method. Stresses are determined in the usual way from PCA stress charts for specific aircraft, and allowable load repetitions are listed in the table.

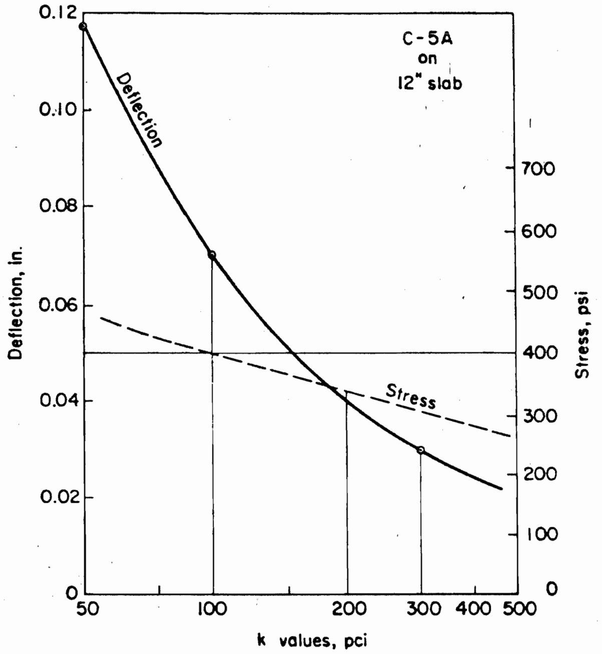

Fig. A4. Effect of foundation support on deflection and stress.

Total structural capacity used by all the aircraft,* column 8 of Table A3, should ideally not exceed 100 percent for an adequate design. For a 16-in. pavement, the structural capacity used is 83 percent; this represents an adequate design. If for a thickness of 15.5 in., however, more than 200 percent of the structural capacity is used, the design would be inadequate.

As explained, a good subbase should be provided for heavy-duty pavements carrying near-capacity traffic including multigeared aircraft. If the subgrade, subbase support value is low, experience indicates that the pavement's structural capacity is reduced. Due to failure in the foundation, the pavement may not be able to carry as many loads as predicted by flexural design methods. The factors in Table A5 are used to modify the structural capacity of pavements on foundations having *k* values of less than 200 pci. They are multipliers of the total structural capacity used computed on the design sheet. The basis for this modification is given in more detail elsewhere in this appendix.

EVALUATION

A similar analysis would apply for the evaluation of an existing pavement's future structural capacity, or to determine the capacity to carry a limited number of overloads where data on past traffic is known or can be estimated.

Load Repetitions and Safety Factors

It is of interest to compare numerical values obtained by

---

*Number of operations is expressed as full-load passes. This usually includes departures only because, for jet aircraft, arriving-aircraft gross weights are about 25 percent less than maximum gross weight. The lower stresses would not induce fatigue consumption unless the stress ratio were greater than 0.50. In special cases where arriving aircraft exceed this stress ratio, they can be included as separate aircraft of lighter weight.

*Landing gear of future aircraft may be widely spaced and may not track in the same path as other aircraft, or only the inboard gear may track in the path of other aircraft. In this case, separate summations may be appropriate for areas of highly channelized traffic.

Table A3. Pavement Design for Mixed Traffic

Pavement: Taxiway C
Traffic: 2 Million Departures

Slab thickness: 16.0 in.
k value: 300 pci
90-day modulus of rupture: 650 psi
$V = 18\%, M = 1.10, (1 - V/100)M = 0.90$
Design modulus of rupture (DMR) = 585 psi

Aircraft (1)	Stress, psi (2)	Stress ratio (3)	Expected number of departures (4)	LRF (5)	Fatigue repetitions (6)	Allowable repetitions (7)	Structural capacity used, percent (8)
Future #4*	354	0.61	1,500	1.33	2,000	24,000	8.3
B-2707**	332	0.57	9,600	0.52	4,990	75,000	6.7
DC-10-X†	330	0.56	32,000	0.57	18,200	100,000	18.2
L1011-X†	324	0.55	15,000	0.57	8,550	130,000	6.6
B747-X†	336	0.57	35,000	0.58	20,300	75,000	27.1
DC-8-63	305	0.52	57,500	0.83	47,700	300,000	15.9
B707	285	0.49	84,000	0.83	69,700	–	0
B747	280	0.48	38,000	0.58	22,000	–	0
DC-10-10	275	0.47	90,000	0.57	51,300	–	0
L1011	270	0.46	24,000	0.57	13,700	–	0
B727	265	0.45	387,000	0.41	158,000	–	0
Other	<270	<0.50	1,227,000	–	–	–	0
						Structural Capacity Used, Total	82.8

Columns 1 and 4 – From traffic projection
Column 2 – From PCA design charts
Column 3 – Stress ÷ DMR
Column 5 – Values from Table A1
Column 6 – Column 4 X Column 5
Column 7 – Values from Table A4
Column 8 – Column 6 ÷ Column 7 X 100

*Projected Future Aircraft No. 4, 1 million lb. gross weight, gear 44x56 in., 4 post (2 tracking).
**12-wheel gear, spacing: 22x44x22 at 44 and 44 in.
†Projected future stretch versions, gross weight assumed 20 percent greater.

Table A4. Stress Ratios and Allowable Load Repetitions

Stress* ratio	Allowable repetitions	Stress ratio	Allowable repetitions
0.51**	400,000	0.63	14,000
0.52	300,000	0.64	11,000
0.53	240,000	0.65	8,000
0.54	180,000	0.66	6,000
0.55	130,000	0.67	4,500
0.56	100,000	0.68	3,500
0.57	75,000	0.69	2,500
0.58	57,000	0.70	2,000
0.59	42,000	0.71	1,500
0.60	32,000	0.72	1,100
0.61	24,000	0.73	850
0.62	18,000	0.74	650

*Load stress divided by modulus of rupture.
**Unlimited repetitions for stress ratios of 0.50 or less.

the fatigue procedure with the recommended values of safety factors used in conventional design problems. For this purpose, safety factors have been computed by the fatigue procedure for a taxiway and runway for two operational levels: (1) capacity traffic, and (2) occasional operations of the design aircraft.

Pavement	Total operations	LRF	Fatigue repetitions	Working stress ratio	Safety factors
Taxiway	4 million (capacity)	0.83	665,000	0.50	2.0
	100,000 (occasional)	0.83	16,600	0.62	1.6
Runway central portion	4 million (capacity)	0.17	136,000	0.55	1.8
	100,000 (occasional)	0.17	3,400	0.68	1.5

(Assumptions: DC-8 and B-707 are design aircraft; 40 percent of operations are design aircraft and 50 percent are departures; $\sigma = 24$ and 192 in.)

These safety factors, computed as the reciprocal of the allowable stress ratio based on the fatigue analysis, are in reasonable agreement with those specified in Chapter 2.

Slab Thicknesses for Critical and Noncritical Areas

Further use of the fatigue method is illustrated by the following example computing thicknesses of pavements for a runway, taxiway, and apron. (Assumptions: B-747 aircraft; 175,000 departures; foundation k value of 300 pci; design modulus of rupture of 630 psi.)

Pavement	Traffic width as σ	LRF	Fatigue repetitions	Working stress ratio	Slab thickness, in.
Taxiway, apron, runway ends, and turnoffs	24 in.	0.58	102,000	0.55	13.5
Runway, central portion (excluding turnoffs)	16 ft. (192 in.)	0.28	49,000	0.58	13.0

In this example for a Boeing 747, the slab thickness for noncritical areas is 96 percent of that for critical areas. This value will vary depending on the wheel configuration of aircraft. For example, for a DC-8 and B-707 the value is about 90 percent, which is in reasonable agreement with Corps of Engineers and Federal Aviation Administration design recommendations.

It is important to note that, for mixed traffic and a greater proportion of design aircraft with complex gear, the required slab thickness for runways would approach that for taxiways.

The fatigue procedure is intended primarily as a method for handling mixed traffic. The examples in this section for a single aircraft are given to demonstrate reasonable agreement with past design experience.

Table A5. Adjustment for Weak Foundation Support

k value, pci*	Multiply "Structural Capacity Used" in Table A3 by:
50	8.0
75	5.4
100	3.7
150	1.9
200	1.0

**k* value on surface of foundation layer(s).

APPENDIX B

ADJUSTMENT IN ℓ VALUE FOR HEAVY-DUTY PAVEMENTS

This appendix provides a needed modification for the computation of stresses, deflections, and subgrade pressures for thick airport pavements carrying heavy aircraft with multiwheeled landing gear. The need for this modification arises from the question of evaluating the effect of a subbase in the analytical model of the pavement system.

Basis for Adjustment

Conventional methods of computing pavement response to loads, either by the dense-liquid subgrade assumption or the elastic-solid subgrade assumption, assume that the subbase and subgrade reaction is evaluated by a single modulus, *k* or *E*. By this assumption, the radius of relative stiffness, ℓ, is decreased when a subbase layer is used since the subbase and subgrade support is greater than that for the subgrade alone. This concept has satisfactorily given the approximate pavement response under past conditions of load configurations and pavement thicknesses. However, for emerging and predicted future aircraft with complex gear configurations and for multiwheeled gear operating on thick pavements, an adjustment is appropriate.

When a subbase is used, especially a strong subbase, it is understood intuitively that the load-spreading capability of the pavement is increased—in effect, that the radius of relative stiffness is increased. The significance of this for multiwheeled landing gear is that the effects of wheel interaction are increased, rather than decreased as conventionally assumed. While the effect of one or two closely spaced wheels may be approximated with no correction applied, the effect of additional wheels nearby is underestimated. The degree of error increases with the number of wheels in the landing gear, with increased ratios of subbase to subgrade strength and with increased subbase thickness.

As a result, an adjustment in the design procedure has been developed and is recommended for use in heavy-duty pavement design. The adjustment has negligible effect for single- and dual-wheel landing gear, some effect for dual-tandem gear, and substantial effect for aircraft with more than four wheels per gear.

Computations of stresses, deflections, and subgrade pressures are carried out based on the assumption that the radius of relative stiffness, ℓ, is increased by the factor indicated in Fig. B1. The figure represents the results of a study