PERFORMANCE OF HEAVY-LOAD PORTLAND CEMENT CONCRETE (RIGID) AIRFIELD PAVEMENTS

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INTRODUCTION

The question of the adequacy of design criteria for heavy-load rigid airfield pavements has often been raised and more often than not answered by a review and reiteration of the studies and data used in the criteria development. The best answer to the question lies in a review of how well the pavements have performed under actual aircraft usage. This paper presents the results of an analysis of the performance of the pavements at 12 military airfields which were designed and constructed using Corps of Engineers (CE) developed heavy-load criteria. The analysis consists of a prediction of the allowable traffic for the aircraft that have used the pavements using the CE criteria which is then compared to the actual traffic results to obtain a measure of the life of the pavement that has been expended. The percent of life used is then compared to the condition of the pavements to assess the adequacy of the criteria. While this paper is limited to an analysis of only heavy-load airfield pavements, similar analyses can be performed for medium- and light-load airfield pavements or, for that matter, to highway pavements.

BACKGROUND

Since the early 1940's, some 300 military airfield pavements have been designed and constructed using CE developed criteria. These include pavements for aircraft loadings ranging from as little as 2500 lb gross weight to the world's heaviest aircraft grossing 770,000 lb and included the B-52 aircraft grossing about 500,000 lb, the most severe from a pavement stress standpoint. Pavements have been constructed throughout the world and thus encompass a wide variety of foundation types, construction materials, and climatic conditions.

To assist in the development and validation of the design and construction criteria, periodic condition surveys have been conducted on a continuing basis at selected airfields to evaluate their performance. These surveys have provided the feedback loop which has enabled the CE to continually update and modify the criteria that have been developed from theory and short-term accelerated full-scale traffic loading tests. In many instances, the survey results have provided the data for criteria change and there have been substantial benefits from the surveys applicable to the evaluation, maintenance, and management of pavement systems.

RIGID PAVEMENT DESIGN CRITERIA

Only a summarization of the basic aspects of the CE developed criteria will be included herein since the criteria and their development have been well documented in various technical papers, reports, and manuals.[1-4] The criteria can be divided into four areas: reponse model, materials characterization, performance criteria, and equivalent thickness determinations.

Response Model

The basis for the CE design criteria is limiting tensile stress in the concrete using edge loading. The free edge stress is computed using the Westergaard equations[5] solved by influence charts.[6,7] Provision is made for a reduction of the computed free edge stress when load transfer devices are used in the joints of adjoining slabs. The CE

criteria permit a 25 percent reduction in the free-edge stress when specified load transfer devices are used; however, other values are permitted when it can be demonstrated that they are applicable. The tensile stress due to an applied wheel load can be computed using

$$\sigma_e = \frac{6q\ell^2 N(1-LT)}{10{,}000\ h^2} \quad (1)$$

where: σ_e = maximum tensile stress, psi

q = tire contact pressure, psi (assumed equal to wheel load divided by tire contact area)

$\ell = \sqrt[4]{\frac{E\ h^3}{12(1-\mu^2)k}}$, radius stiffness, in.

E = modulus of elasticity of concrete, psi

h = concrete thickness, in.

μ = Poisson's ratio

k = modulus of foundation reaction, psi/in.

N = block count from influence charts[6] or computer program[7]

LT = effective stress relief from load transfer device in joints

Material Characterization

The coefficient of subgrade reaction, more commonly referred to as the modulus of foundation reaction, k, is determined by a 30-in.-diam plate-bearing test[8] performed on the surface of the material on which the portland cement concrete will be constructed. The measured k value is adjusted when applicable to account for the effects of soil saturation and frost melting. Properties of the concrete required are the modulus of elasticity, E, Poisson's ratio, μ, and modulus of rupture, R. These properties are determined by third point loading tests on beams. For pavement quality concrete meeting CE specifications, the E and μ properties are relatively constant and values of 4×10^6 psi and 0.20, respectively, are used; however, other values can be input.

Performance Criteria

The response model yields the edge stress for a single application of the applied load and thus does not account for the fatigue effects associated with stress (load) repetitions or the effects of stresses associated with environmental or climatic changes. To account for these influencing parameters relationships between traffic coverages (stress repetitions) and design factor (DF) were established. These relationships, shown on Figure 1, have been developed from traffic tests to failure of a wide range of pavement thicknesses, foundation types and strengths, and aircraft gear configurations and loadings. Traffic coverages is the manner used to represent the number of maximum stress repetitions induced in the concrete by aircraft traffic. The conversion of aircraft passes to coverages is a complicated statistical procedure which is dependent upon such characteristics as the wander width of the aircraft traffic, tread dimension of main landing gears, wheel spacing , and tire width. Pass-to-coverage ratios have been developed for most military[9] and civil[10] aircraft based on traffic distribution studies at both military airfields and civil airports. The DF is the ratio of the concrete flexural strength R to the computed edge stress σ_e.

$$DF = \frac{R}{\sigma_e} \quad (2)$$

The test sections were trafficked and the performance, as measured by structural cracking visible on the surface of the concrete, was recorded. Many of the test sections were trafficked until the individual slabs were cracked extensively and reduced to sizes that were in danger of being "punched" into the foundation. The results from these tests were used to develop the performance criteria shown in Figure 1. Based upon using agency decisions, the performance criteria (DF versus coverages) for the initial failure condition were selected as the basis for design. This decision was based on the desire for a pavement facility that would provide continual operational capability with low maintenance requirements. The initial failure (Figures 1a and 1c) presumes that the trafficked slabs will experience one crack per slab for k values up to and including 200 psi/in. and two cracks per slab for k values in excess of 200 psi/in. during the design life. Another relationship (Figures 1b and 1d) that has been used in pavement performance analysis, is the "shattered slab failure," which presumes that the trafficked slab will crack into about six pieces during the design life. A third failure condition (not shown) is "complete failure," which represents extensive cracking of the individual slabs and a condition which begins to represent a hazard to aircraft operations. During the conduct of these traffic tests, it was noted that the smoothness of the test items was generally relatable to the structural conditions; i.e., as the slab cracking progressed, the roughness increased. No quantifiable relationship emerged from the results and it was apparent that the cracking-roughness relationship was dependent upon such things as foundation type and strength, concrete thickness, rate and method of load application, etc. Thus the using agencies and the CE have continued to rely on slab cracking to sufficiently define the functional condition of the pavement systems. The performance criteria have been well documented at coverage levels up to 5000; however, for economic reasons, few test sections have been subjected to high levels of traffic. The change in the slope of the performance criteria at the 5000 coverage level was made prior to available test results and was guided by results of fatigue tests on concrete beams and the desire for a degree of conservatism in the areas of the unknown. Likewise, the relationship for bicycle gear aircraft was developed, without supporting test results to account for dynamic-load effects resulting from the aircraft "porpoising" motion inherent with this type gear arrangement. Subsequent test data have neither supported nor negated these modifications to the performance criteria conclusively and therefore the criteria have not been changed.

Environmental and climatic effects were active during the traffic testing and thus the performance criteria include, to a degree, the results of these effects although not in a quantifiable manner.

Equivalent Thickness Determination

The criteria given thus far have been for a single thickness of plain (nonreinforced) concrete on a foundation composed of unbound (unstabilized) materials. Through the use of the full-scale accelerated traffic test sections, methods have been developed for equating multiple thicknesses of concrete (rigid overlay), asphaltic concrete and concrete (nonrigid overlay), and reinforced jointed concrete to an equivalent single-slab thickness which would exhibit approximately the same performance as the multiple-layered or reinforced sections. These relationships are all given in references 1 and 2. During the performance analysis, a few pavement facilities composed of rigid overlay, nonrigid overlay, and reinforced jointed pavements were encountered and the equivalent single thickness was determined in accordance with reference 2 and analyzed based on the equivalent thickness.

CONDITION SURVEY PROGRAM

The most recent comprehensive surveys at heavy-load airfields were made in 1972 and the results of those surveys form the basis for determination of the performance described in this paper. Surveys were performed at the 25 heavy-load airfields shown on Table 1. A summarization of pertinent physical properties of the pavement and foundation conditions is also shown on Table 1. In addition to the inspection of the physical condition of the pavements, information regarding the amount of maintenance that has been required was obtained and operational personnel were queried, through questionnaires and interviews, regarding the functional adequacy of the pavements.

For the analysis of performance, fairly detailed records of aircraft usage (i.e., aircraft type, loading, volume, and facilities used) are required. While some information of this type is available at each airfield, the detailed data required are maintained and reported

by the using agency only at selected airfields. The detailed traffic data required for the performance analysis were available for only 12 of the 25 airfields. These are indicated on Table 1.

Structural Condition

The physical condition inspection conducted during a condition survey is detailed as described in Appendix III of reference 11. The airfield pavements are first divided into features depending upon design loading, thickness, construction, slab dimension, usage, etc., and each feature is then inspected, slab by slab, recording the number and type of defects by slab and paving lane number.

Pavement defects are divided into two types: minor and major. Minor defects are considered to be those caused primarily by environmental or climatic conditions and deficiencies in materials or construction details. Normally they do not detract from either the load-carrying ability or functional condition of the pavement. Defects such as popputs, "D" cracking, uncontrolled contraction cracking, shrinkage cracks, map cracking, small corner or joint spalls, minor surface scaling, etc., are recorded as minor defects. Major defects are those which are indicative of overloading and/or fatigue failures which may impair the load-carrying ability of the pavements and may detract from the functional conditions of the pavement. Cracks extending the depth and from one edge of slab to another are considered to be major defects. Slabs which have been divided into six pieces by structural cracking are recorded as shattered. Settled or faulted slabs, pumping joints, surface scaling or joint spalling, when in the opinion of the surveyor have reached a severity to create an annoyance or hazard to normal aircraft operations, are recorded as major defects. Otherwise they are considered to be minor defects.

The results of the condition survey may be presented several ways. Normally, the structural condition of each pavement feature survey is rated based upon the percent of slabs in the feature that contain major and minor defects. The ratings are:

Condition Rating	Percent Slabs Containing Major Defects		Percent Slabs Containing Minor Defects	
	k = 25-200	k = >200	k = 25-200	k = >200
Excellent	0-2	0-10	0-10	0-20
Very good	2-10	10-20	2-20	10-30
Good	10-20	20-30	10-30	20-40
Fair	20-30	30-40	20-40	30-50
Poor to failed	>30	>40	>40	>50

For this paper, these same condition ratings have been applied to the entire primary heavy-load pavement system for each airfield surveyed and are shown on Table 1. Likewise, the condition of each pavement facility considered in the performance analyses was rated and is shown in Table 3. The structural condition of each runway and taxiway facility is shown by histograms of percent defects for each paving lane in Figures 3 and 4. An examination of these histograms reveal, as would be expected, that the most used paving lanes show the highest percent slabs containing major defects. These most used lanes of pavement are the four center lanes of runways (generally 100-ft width) and the center lane of taxiways (especially when the primary using aircraft have bicycle type main gears). Although histograms for all aprons are not shown, there is some indication of high usage of some lanes in the apron facilities, but the distribution of defects is fairly widespread, indicative of the wider distribution of traffic on these facilities.

Functional Condition

The functional condition, or the ability of the airfield pavement to perform its intended mission of providing a safe operational surface for aircraft ground operations, was obtained by querying the operational personnel (pilots, etc.). These were handled by personal interviews and in some cases by formalized questionnaires. Although several questions were posed, the primary items used to assess the functional condition of the pavement were (a) roughness as determined by personal comfort, (b) roughness as determined

by instrument instability, (c) roughness attributable to differential frost heave, (d) overall pilot rating considering roughness, skid resistance, direction control, and visibility. The results are highly subjective and, more often than not, highly dependent upon the history of the operational personnel assignments. That is, if the pilot was previously operating from expediently constructed airfields (turf, landing mat, etc.), he would invariably rate the heavy-load pavements as very smooth and excellent operational surface. If the pilot had been operating entirely from more permanently constructed airfields, he may rate the same pavement as moderately rough. Until more quantifiable methods are developed and used to rate the functional conditions, the opinionnaire type ratings must be carefully analyzed. The results of the functional ratings are shown summarized on Table 1. If no complaints about the operational surface were voiced by operational personnel, the pavements were rated excellent. If any complaints were received, the pavements were rated as good. If at least 25 percent of those questioned complained about the conditions of the pavements, they were rated as fair and if more than 25 percent complained they were rated as poor. As shown on Table 1, none of the heavy-load pavements were rated below good in 1972.

Maintenance

One of the most difficult aspects of evaluating the performance of pavements is to assess the effects of maintenance. While records regarding the amount of maintenance are available at most airfields, the exact type of maintenance is not always identified nor is it possible to assess how the maintenance, or more importantly how the lack of maintenance, has affected the overall performance of the pavements. For example, it is not unusual for local maintenance personnel to remove and replace isolated slabs that have been cracked (usually shattered) into several pieces. While the maintenance records show this in the form of costs, the exact location is not always available and may not have been recorded during the condition survey. Although this would have some effect, it is sufficient to generalize that the limited amount of slab replacement would not have a dominate effect upon the results of the performance analyses. An analysis of the maintenance performed shows that the major portion is for joint and crack sealing and patching of spalls, pop-outs, and "D" cracking, each of which help prolong the useful life of the pavements. Other types of maintenance performed include slab removal and replacement, mudjacking, correction of drainage problems, retexturing or resurfacing slippery surfaces, and occasional grinding or resurfacing because of roughness. The maintenance requirements shown on Table 1 have been based primarily on available cost records and thus are not indicative of the type of maintenance unless otherwise noted. A rating of low indicates that generally the maintenance costs have been below $100,000 per year; a rating of medium reflects maintenance costs ranging from $100,000 to $200,000 per year and high reflecting costs exceeding $200,000 per year. There are, of course, exceptions to the generalized ratings since a resurfacing program, slab removal and replacement program, mudjacking, etc., would reflect high costs in any one year. Nevertheless, it is generally found that the maintenance rating and structural conditions are related.

PERFORMANCE ANALYSIS

Only the pavement facilities at each airfield on which the volume and movement of traffic were fairly well known were used for the performance analysis. Generally speaking, these facilities include the primary runway and connecting taxiways, parallel taxiway, apron taxiway, and parking apron as shown shaded in Figure 2. In some cases, the apron pavement was not considered because it was impossible to delineate the traffic usage. For purposes of analysis, the runways were subdivided into the first and second 500 ft at each end of the runway and runway interior. The thickness, flexural strength, and modulus of foundation reaction, k, were obtained for each individual pavement facility from the reported results of previous test programs. Those pertinent physical properties are summarized in Table 1 as ranges of values; however, the properties applicable to each pavement facility were used for the analysis. Other influencing properties such as modulus of elasticity and Poisson's ratio of the concrete and stress relief due to load transfer (LT) mechanisms in the jointing systems were assumed constant and equal to 4×10^6 psi, 0.20, and 25 percent, respectively.

Life Capability Analysis

Each pavement facility was analyzed to determine the number of traffic coverages that it could sustain for each type and weight of aircraft that had used the facility. Combining equations 1 and 2 yields a relationship useful for determining allowable traffic coverages.

$$DF = \frac{10000\ h^2\ R}{6q\ell^2 N(1-LT)} \qquad (3)$$

The DF was computed for each pavement facility using the physical properties of the pavement materials for that facility. The computed DF and the k value were then used to enter the appropriate performance criteria, Figure 1, depending on aircraft landing gear type (bicycle or tricycle) to determine the allowable coverages (C_{al}) of that aircraft. An example of the results of this type analysis for the runway ends and interior pavements is shown on Table 2.

Traffic Analysis

Although rather detailed traffic records are available for the airfields selected for the performance analysis, some assumptions regarding the weights and distribution of the using aircraft on the individual pavement facilities were required. The traffic records list the volume of using aircraft by type and load range. It was assumed that the aircraft, in any load range, take off at the maximum weight and land at the minimum weights listed for that load range. The percentage of operational cycles (takeoffs and landings) that occur in each direction on the runway is available for each airfield. It was then assumed that all aircraft operations originate at the apron and, based upon the directional use of the runway, proceed to the runway end by way of the parallel taxiway and end connecting taxiway. On takeoff, each aircraft passes over the first and second 500-ft ends and runway interior but is airborne before it reaches the 1000 ft at the opposite end. On landing, it was assumed that 25 percent of the touchdowns occurred in the second 500 ft of the runway end and the remaining 75 percent in the runway interior. The landing aircraft then proceed to the end of the runway, turn off on the end connecting taxiway and proceed back to the apron by way of the parallel taxiway. These assumptions are supported by the traffic distribution study reported in reference 10. Based on these assumptions, the number of passes by each of the using aircraft on each pavement facility were determined. An example product of the traffic analysis is shown on Table 2. The actual coverages (C_{act}) of each aircraft type and load were obtained using pass-to-coverage ratios reported in reference 9.

Life Used Analysis

The percent life used by each type and weight of using aircraft for each pavement facility was determined by dividing the actual coverages (C_{act}) by the allowable coverages (C_{al-I} or C_{al-s}) for each failure condition. An example of the results of this analysis is shown on Table 2. The effects of aircraft load can readily be seen from this type analysis. A reduction in gross aircraft load (i.e., landing weight as compared with takeoff weight) significantly reduces the life used on a pavement facility. Likewise, light aircraft or aircraft with high flotation type landing gears (such as the C-5A) have little effect on pavements designed and constructed for heavier, more critical loaded aircraft. The total life used by the operating aircraft is then the summation of that used by each individual aircraft. A summarization of the life used by pavement facility at each airfield analyzed is shown by Table 3 along with the percent of slabs that contain structural defects and the assigned structural rating.

RESULTS OF PERFORMANCE ANALYSIS

The results of the performance analysis presented herein cannot be considered to be the product of a rigorous analysis because of some simplifying assumptions that have been necessary and the lack of precise input data. It is believed, however, that the results are sufficiently accurate to indicate the overall validity of design criteria as measured by pavement performance.

Table 3 summarizes the results of the performance analysis. The percents of life used for both the initial and shattered slab failure conditions are shown along with the percent slabs that contain major defects and the assigned structural rating. The percent of slabs containing major defects is based upon the 1972 condition survey and considers only the slabs falling within the trafficked width of the pavement facility (i.e., 100-ft width for runway facilities, 25-ft width for taxiways, and the full width for aprons). The distribution of defects over the total width of the runway and taxiway facilities is

shown by the histograms in Figures 3 and 4. The percent life used based on the initial failure criterion, which is the performance criteria used for the design of heavy-load rigid airfield pavements, is shown plotted versus the percent slabs containing major defects in Figure 5. A similar plot can be made for the percent life used based on the shattered slab failure criterion using the data in Table 3.

Figure 5 depicts the performance of some 117 separate pavement facilities representing a fairly wide range of thickness, concrete strength, modulus of foundation reaction, environmental conditions and usage. There were also eight reinforced concrete and one rigid overlay of rigid pavement included in the analysis. As expected, it was found that the percent life used was dictated by the aircraft operating at or near their maximum operating weight and more specifically by the B-52 and/or B-47 aircraft which generally produce the higher stresses in the concrete. These same aircraft operating at or near their minimum weights had little effect on the calculated percent life used. Similarly, aircraft such as the KC-135, C-141, KC-97, and lighter had only a minor or negligible effect on the calculated percent life used.

An examination of Figure 5 shows what, at first, appears to be a wide scattering of data; however, there are logical explanations for some of the data that appear to be abnormalities. For example, some of the facilities showing a large percent of slabs containing major defects at relatively low percents of life used are at airfields where differential heave resulting from frost penetration is known to have cracked some slabs. Likewise. abnormal weather and other conditions during placement and curing of the concrete is known to have caused some slab cracking. Since the number of slabs cracked by such non-load induced factors is not known, no attempt was made to adjust the data points for these airfields when plotting Figure 5.

The use of the data shown on Figure 5 in determining the adequacy of criteria becomes very complex because of variations in pavement strength and induced stress which are known to exist. The effects that variability has upon a performance analysis such as this can be hypothesized as done in reference 12; however, while some information is available regarding the coefficient of variation of many of the influencing parameters, the quantitative effects of these variances on performance becomes a complex study within itself and beyond the scope of this paper. If it is assumed that there is no variability, the CE criteria would predict that at 100 percent life used, 100 percent of the slabs would show at least one crack per slab for k values 200 psi/in. or less and two cracks per slab for higher k values. If only the variability of the concrete flexural strength, R, which is only one parameter affecting the overall strength of the pavement, is considered, the CE design criteria would predict performance similar to that shown by the solid line in Figure 5. This relationship is developed by assuming a normal distribution of R with a coefficient of variation of 7 percent and assuming that the distribution of slabs having any given R is the same as the distribution of R values in the concrete. The performance criteria (Figures 1a and 1c) were used to develop the solid line relationship shown on Figure 5. Since the allowable coverages for any given load producing cracking is dependent upon the ratio of R and induced stress, σ_e, and the percent life used is the ratio of actual to allowable coverages, the percent slabs that would crack at any given percent life used can be determined. It will be noted that the performance criteria result in a family of relationships of percent life used versus percent slabs containing major defects; however, for k values of 200 psi/in. or less, the band of relationships is quite small. For k values greater than 200 psi/in., the relationship falls to the right of the solid line relationship on Figure 5 but the exact locations on this plot cannot be determined. This is because the CE criteria consider failure as two cracks per slab for k values in excess of 200 psi/in. instead of the one crack per slab assumed for lower k values and the abscissa scale of Figure 5 considers one crack as being a slab containing major defects. To position the percent life versus percent slabs containing structural defects for the high k values, data regarding the percent life used to progress from one to two cracks per slab and the ratio of slabs containing one crack to two cracks per slab for any given percent life used is needed but is not available. Thus it can only be said that, according to the CE criteria, the performance of pavement facilities with k values in excess of 200 psi/in. should fall to the right of the solid line in Figure 5.

If the variability of the other parameters which affect pavement strength were considered, along with the variability of factors affecting induced stress and considering the fact that there is variability in the CE performance criteria, since they were developed using

traffic test data, the predicted life versus percent slabs containing major defects for k values of 200 psi/in. or less would be represented by a fairly wide band such as that shown hatched in Figure 5. Similar bands, falling to the right, would exist for k values higher than 200 psi/in. As noted in Figure 5, the band shown is considered conceptual since the exact band width can only be determined by a comprehensive analysis considering the effects of the variability of all influencing parameters. Nevertheless, the band shown illustrates the general shape and location that the results of the performance analysis should take according to the CE design criteria. The percent life used versus percent slabs containing major defects relationships may be more aptly termed "deterioration ratio" or "deterioration functions."

If the results of the analysis are viewed in this context, the following generalized conclusions can be drawn:

a. The overall shape of the performance data follows the shape that would be predicted by the CE design criteria (hatched area for k values 200 psi/in. or less) assuming variability in pavement strength and induced stress.

b. Data falling to the left of the hatched band on Figure 5, and especially that in which the calculated percent life used is around 100 percent or higher with only a small percent of slabs containing major defects, indicates a degree of conservatism in the design criteria.

c. Data falling on or close to the ordinate, especially for the lower percents of life used, is considered normal and commensurate with the concept of normal distribution of parameters affecting the performance.

d. Data clustered on the abscissa at very low percents of life used indicates some degree of unconservatism in the design criteria. However, since the criteria does permit some cracking to occur in pavements constructed on high-strength foundations before reaching 100 percent life used, the performance of these facilities should not be construed as representing a significant degree of unconservatism.

e. The data falling to the right of the hatched area at indicated k values in excess of 200 psi/in. is considered to be in the right general area according to the criteria; however, conclusions regarding whether they indicate conservatism or unconservatism in the criteria cannot be made since the locations of the predicted relationship cannot be established on this plot.

f. The performance analysis of the eight reinforced jointed concrete facilities and the one rigid overlay of rigid pavement facility indicate that these facilities fall into the same general data trend as the plain concrete facilities which supports the adequacy of the CE criteria for these types of pavements.

The results of the performance analysis indicate that the CE developed design criteria produce pavements which must be considered adequate from strictly a structural standpoint and therefore fulfills the user requirements of providing a safe operational surface with low maintenance. The functional condition evaluation, although very crude appears to generally agree with the structural performance analysis. This is, in no case did the operational personnel rate a pavement below good which agrees with the fact that the computed percent life generally is less than 100 percent and the percent of slabs containing major defects is generally less than 30 percent. The functional rating, being based on rideability, is primarily a rating of the runway facilities. As shown by Table 3, only in a few instances were any of the runway pavement facilities given a structural rating of less than good (less than 30 percent slabs containing major defects). The exceptions to this were some facilities constructed on k values in excess of 200 psi/in., which indicates that the criteria permitting some cracking to occur on high strength foundations is valid.

SUMMARY

All things considered, the performance analysis, coupled with the structural rating, functional rating, and maintenance history, indicates that the CE developed design produces a pavement which meets the user stated requirements (i.e., safe operational surface and low maintenance). The analysis tends to indicate some conservatism, especially for

the designs for high coverage levels, which appear to be supported by the functional ratings but not as well supported by the maintenance records. This indicates that the user requirements should be reexamined to determine whether the structural requirements should be relaxed, which is implied by the performance analysis and functional evaluation, at probably an increase in maintenance requirements. In any case, a comprehensive analysis of the overall effects of variability in pavement strength and induced stress on performance is needed.

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Table 1

Summarization of Pertinent Data on Rigid Heavy Load Airfield Pavements Surveyed in 1972

Airfield and Location	Major Using Aircraft	Years in Service	Subgrade		Base			Concrete		Maintenance Requirement*	Overall Condition Rating*	
			Classification	Range of k psi/in.	Classification	Range of Thickness in.	Range of k psi/in.	Range of Thickness in.	Range of Flexural Strength psi		Structural	Functional
Plattsburgh AFB, N. Y.**	B-47, B-52, KC-135	15	SP-SM	345-425	--	--	--	13-14	800	Low†	Excellent	Good
Pease AFB, N. H.**	B-47, B-52	16	SM-SP	150	SW-SM-SP	34	425	14	715-740	Low	Good	Good
Altus AFB, Okla.**	B-47, B-52, KC-135	14	CL-ML	75-125	SM-SC††	4-6	150-200	16-23	770-825	Low to Medium†	Excellent	Excellent
March AFB, Calif.	B-47, B-52, KC-135	9	CL-ML	75-100	GW-GP	0-30	100-450	13-25‡	700	Low	Excellent	Good
Dyess AFB, Tex.**	B-47, B-52	9-20	CL-CH-SC††	100-125	GW-GC-SC††	0-27	175-350	15-27	750-800	Medium to High†	Very good	Excellent
Westover AFB, Mass.**	B-47, B-52, KC-135	15	SM-SP	150-200	SP-SM	33	350	15	800-860	Low	Very good	Excellent
Wright-Patterson AFB, Ohio	B-36, B-52, KC-135	16-25	CL-GM	25‡‡-350	GP-GW	0-24	350	15-21§,*	760-850	Medium to High†	Excellent	Good
Kinchlow AFB, Mich.	B-52, KC-135	13	SP	300	GW	0-9	300-350	15-24‡,§	760-800	Low	Excellent	Excellent
Ellsworth AFB, S. Dak.	B-36, B-47, B-52	16	CL-CH	25‡‡-150	GW-GP	4-32	25‡‡-375	15-23‡,§,§§	715-825	Medium†	Good	Good
K. I. Sawyer AFB, Mich.	B-52. KC-135	15	SP-SM	300-350	AC/GW	0-500	350-500	14-20‡	725-800	Low†	Excellent	Excellent
Wurtsmith AFB, Mich.	B-52, KC-135	13	SP	250	--	0	--	15-21	780-890	Low	Excellent	Good
Castle AFB, Calif.**	B-47, B-52, KC-135	17	SM-SC	150-200	SM-AC/GW	6-27	225-350	16-18‡,§§	700-770	Medium†	Very good	Good
Minot AFB, N. Dak.**	B-52, KC-135, C-141	15	CL	25‡‡-125	GW	54-57	315‡‡-450	15-18	670-750	Low†	Very good	Good
Beale AFB, Calif.**	B-52, KC-135, C-141	14	CL-GC	150-350	GW	6	200-375	18-25	675-730	Low	Excellent	Excellent
Grand Forks AFB, N. Dak.**	B-52, KC-135, C-141	14	CL-SP-SM	25‡‡-200	GW-SP	48-58	120‡‡-400	18-24	750	Low	Very good	Good
Dow AFB, Maine** (Bangor International)	B-47, B-52, DC-8	14	CL	25‡‡-100	SW-SM	34-47	35‡‡-420	15-21§	750-770	Low	Very good	Excellent
Loring AFB, Maine**	B-47, B-52, KC-135	17	CL	25‡‡-125	GW	48-55	300‡‡-425	15-19	600-700	Medium†	Poor	Excellent
Mather AFB, Calif.	B-52, KC-135	14	CL-GC	125-225	GW	3.5-6	200-320	15-22‡,§	700-880	Low	Excellent	Excellent
Carswell AFB, Tex.	B-36, B-47, B-52	16	CL	75-100	GW††	0-7	75-150	15-27§§	715-850	Medium	Excellent	Excellent
Glasgow AFB, Mont.**	B-52, KC-135	13	CL	25‡‡-125	GW	17-55	100‡‡-400	17-26§	760-810	Low	Good	Excellent
Malmstrom AFB, Mont.	KC-135, C-141	20	CL	25‡‡-125	GW	20	105‡‡-250	16-19	800-960	Low	Very good	Good
Forbes AFB, Kans.	B-47, KC-197, C-135	20	CL-CH	25‡‡-75	SP-GW	0-8	25‡‡-125	16-24	775-800	High†	Very good	Excellent
Whiteman AFB, Mo.	B-47, KC-197, KC-135	22	CL-CH	25‡‡-75	GW	0-4	25‡‡-100	15-25‡	800-900	Medium†	Very good	Excellent
Lockbourne AFB, Ohio	B-47, KC-97, KC-135	16	CL	25‡‡-75	GW	0-6	25‡‡-125	16-27§§	750-800	Medium†	Excellent	Excellent
McConnell AFB, Kans.	B-47, KC-135, B-52	20	CL-CH	25‡‡-75	SP	0-6	25‡‡-100	15-17	800	Medium†	Very good	Good

* Pertains only to pavement facilities included in performance analysis (see Figure 2).
** Sufficiently detailed traffic records available for performance analysis.
† Some slab removal and replacement has been performed.
†† Stabilization used for some construction.
‡ Includes equivalent thickness of rigid overlay pavement.
‡‡ k value during frost melting period.
§ Includes equivalent thickness of reinforced pavement.
§§ Includes equivalent thickness of nonrigid overlay pavements.

Table 2

Example of Performance Analysis--Plattsburgh AFB, New York

Aircraft		Actual Passes and Coverages, Allowable Coverages, and Percent Life Used by Using Aircraft on Each Runway Facility																	
		17 End of NW-SE Runway						Interior of NW-SE Runway						35 End of NW-SE Runway					
Type	Load kips	Passes	C_{ACT}	C_{AL-I}	C_{AL-S}	% L_i	% L_s	Passes	C_{ACT}	C_{AL-I}	C_{AL-S}	% L_i	% L_s	Passes	C_{ACT}	C_{AL-I}	C_{AL-S}	% L_i	% L_s
B-52(A)	480	402	247	1,100	10,000	22.5	2.5	402	247	28,000	70,000	0.8	0.3	402	247	550	7,500	44.9	3.3
B-52	370	2,897	1,777	37,000	90,000	4.8	2.0	4,457	2,229	6×10^5	9×10^5	0.4	0.2	1,560	957	25,000	65,000	3.8	1.5
B-52	300	1,560	957	5×10^5	7.6×10^5	0.2	0.1	4,457	2,229	$>1 \times 10^6$	$>1 \times 10^6$	<0.2	<0.2	2,897	1,777	3×10^5	5×10^5	0.6	0.4
B-47	200	31,525	20,079	34,000	85,000	59.0	23.6	48,411	17,228	6×10^5	1×10^6	2.9	1.7	17,051	10,860	25,000	70,000	43.4	15.5
B-47	104	16,886	10,755	$>1 \times 10^6$	$>1 \times 10^6$	--	--	48,246	17,169	$>1 \times 10^6$	$>1 \times 10^6$	--	--	31,360	19,974	$>1 \times 10^6$	$>1 \times 10^6$	--	--
KC-135(A)	300	478	142					478	142					478	142				
KC-135	270	7,810	2,324					12,016	1,983					4,206	1,252				
KC-135	125	4,206	1,252					12,016	1,983					7,810	2,324				
C-135	180	2,156	642					3,317	987					1,161	346				
C-135	115	1,161	346					3,317	987					2,156	642				
KC-97	150	18,284	5,362					28,130	4,604					9,846	1,611				
KC-97	100	9,846	2,887					28,130	4,604					18,284	5,362				
C-141	323	113	33					174	27					61	18				
C-141	115	61	18					174	27					113	33				
C-5A	712	2	1					2	1					--	--				
C-5A	535	--	--					2	1					2	1				
MISC*	100	34,820	7,077					53,570	5,446					18,750	3,811				
MISC*	50	18,750	3,811					53,570	5,446					34,820	7,077				

Note: C_{ACT} - Actual coverages subjected by using aircraft.

C_{AL-I} - Computed allowable coverages for initial failure criterion.

C_{AL-S} - Computed allowable coverages for shattered slab failure criterion.

% L_i - Percent of initial failure life used by actual traffic.

% L_s - Percent of shattered slab failure life used by actual traffic.

Same procedure used for analysis of performance of taxiways and aprons.

* Miscellaneous aircraft composed of C-124, C-133, C-119, C-140, B-57, T-29, F-4, F-111, etc.

Table 3

Summarization of Life Used Versus Structural Condition

Airfield	Facility	Percent L_i	Percent L_s	Percent of Slabs Major Defects	Structural Rating
Plattsburgh AFB, N. Y.	1st 500-ft runway	86.5	28.2	10.0	Excellent
	2nd 500-ft runway	66.4	23.9	6.0	
	Runway interior	4.3	2.4	3.9	
	2nd 500-ft runway	26.5	17.7	0.0	
	1st 500-ft runway	92.7	20.7	0.0	
	Taxiway	171.1	47.7	14.0	
		276.2	43.5	7.1	
		126.7	34.9	14.6	
		116.0	25.6	18.6	
	Apron	27.9	11.4	2.5	
Glasgow AFB, Mont.	1st 500-ft runway	<0.1	<0.1	2.5	
	2nd 500-ft runway	0.1	<0.1	8.8	
	Runway interior	<0.1	<0.1	3.4	
	Runway interior	181.2	9.1	26.3	Good
	Runway interior	<0.1	<0.1	12.2	Excellent
	2nd 500-ft runway	0.1	<0.1	6.3	
	1st 500-ft runway	<0.1	<0.1	7.5	
	Taxiway	0.1	<0.1	2.9	
	Taxiway*	94.2	4.7	51.4	Poor
	Taxiway	2.6	1.4	2.1	Excellent
	Apron	<0.1	<0.1	9.6	Excellent
Pease AFB, N. H.	1st 500-ft runway	86.2	34.1	48.8	Poor
	2nd 500-ft runway	52.1	20.6	35.0	Fair
	2nd 500-ft runway	17.6	7.0	16.3	Excellent
	1st 500-ft runway	46.7	11.5	16.3	Excellent
	Taxiway	232.9	73.1	85.5	Failed
	Apron	141.5	37.0	10.6	Excellent
Beale AFB, Calif.	1st 500-ft runway	9.1	4.6	0.0	
	2nd 500-ft runway	74.2	30.8	0.0	
	Runway interior	12.7	6.0	0.0	
	2nd 500-ft runway	18.5	7.7	0.0	
	1st 500-ft runway	2.3	1.1	0.0	
	Taxiway	6.4	4.0	0.0	
	Taxiway	1.0	0.6	0.0	
	Taxiway	3.5	1.7	0.0	
Westover AFB, Mass.	1st 500-ft runway	90.1	30.7	0.0	
	2nd 500-ft runway	72.8	24.8	0.0	
	2nd 500-ft runway	59.6	20.2	2.5	
	1st 500-ft runway	73.8	25.1	6.3	
	Taxiway 1A	90.1	30.7	52.0	Poor
Castle AFB, Calif.	1st 500-ft runway**	67.5	30.0	2.7	Very good
	2nd 500-ft runway	171.6	66.7	18.8	Good
	Runway interior	144.7	55.1	23.8	Fair
	2nd 500-ft runway	32.5	5.6	68.8	Failed
	1st 500-ft runway	13.1	5.1	2.5	Very good
	Taxiway	38.4	21.3	15.0	Good
Loring AFB, Maine	1st 500-ft runway	154.6	34.8	95.0	Failed
	2nd 500-ft runway	135.3	28.8	58.8	Poor
	2nd 500-ft runway	9.0	3.7	61.3	Poor
	1st 500-ft runway	4.0	2.4	20.0	Very good
	Taxiway	154.6	34.8	89.7	Failed
	Taxiway*	2.4	1.2	66.7	Failed
Altus AFB, Okla.	1st 500-ft runway	102.2	40.9	2.5	Very good
	2nd 500-ft runway	84.6	33.8	0.4	Excellent
	Runway interior	0.5	<0.1	0.1	
	2nd 500-ft runway	1.9	0.8	0.0	
	1st 500-ft runway (200 ft)	0.4	<0.1	0.0	
Altus AFB, Okla., Cont'd.	1st 500-ft runway (300 ft)	56.0	19.6	0.0	Excellent
	Taxiway	110.0	44.0	2.6	Very good
		57.2	23.4	6.6	Very good
		0.5	<0.1	0.0	Excellent
		0.5	<0.1	0.0	
Bangor International, Maine (formerly Dow AFB)	1st 500-ft runway*	<0.1	<0.1	0.0	
	2nd 500-ft runway*	0.5	0.1	0.4	
	Runway interior*	3.5	0.2	12.7	Very good
	2nd 500-ft runway*	0.4	0.1	0.0	Excellent
	1st 500-ft runway*	<0.1	<0.1	0.0	Excellent
	Taxiway*	<0.1	<0.1	13.3	Very good
		0.4	0.1	16.0	Very good
		0.7	<0.1	71.2	Failed
		0.4	0.1	81.3	Failed
		<0.1	<0.1	43.4	Poor
		0.4	0.1	16.6	Very good
		89.5	14.9	0.0	Excellent
	Apron	61.9	12.3	0.0	Excellent
	Apron	61.9	12.3	1.6	Excellent
Grand Forks AFB, N. D.	1st 500-ft runway	0.4	0.2	40.0	Fair
	2nd 500-ft runway	2.3	1.2	5.0	Excellent
	Runway interior	27.7	8.6	12.3	Very good
	Runway interior	79.8	15.0	27.3	Good
	2nd 500-ft runway	7.1	2.7	6.3	Excellent
	1st 500-ft runway	2.7	0.4	0.0	
	Taxiway	2.5	1.3	0.0	
		13.4	5.8	7.4	
		10.4	4.3	0.0	
		2.9	0.4	0.0	
		2.9	0.4	0.0	
		<0.1	<0.1	2.3	
		<0.1	<0.1	22.5	Good
		<0.1	<0.1	5.1	Excellent
	Apron	<0.1	<0.1	19.4	Very good
Minot AFB, N. D.	1st 500-ft runway	0.8	0.2	12.5	Very good
	2nd 500-ft runway	5.4	2.0	7.5	Excellent
	Runway interior	9.4	3.3	26.7	Good
	Runway interior	32.4	8.8	13.3	Very good
	2nd 500-ft runway	4.7	1.6	37.5	Fair
	1st 500-ft runway	0.7	0.3	11.3	Very good
	Taxiway	1.2	0.5	5.3	Excellent
		4.5	1.3	38.2	Fair
		1.5	0.6	43.8	Poor
		1.5	0.6	25.4	Good
		0.9	0.4	26.9	Good
		0.3	0.1	14.3	Very good
		0.2	<0.1	7.1	Excellent
	Apron	9.9	4.8	3.0	Excellent
	Apron	16.9	10.2	29.5	Good
Dyess AFB, Tex.	1st 500-ft runway	1.1	0.6	6.3	Very good
	2nd 500-ft runway	52.6	18.6	14.3	Good
	Runway interior	1.7	0.9	9.6	Very good
	Runway interior	0.9	0.5	0.7	Excellent
	2nd 500-ft runway	318.3	77.5	6.3	Very good
	1st 500-ft runway	318.3	77.5	16.3	
	Taxiway	6.4	3.2	16.7	
	Taxiway	<0.1	<0.1	1.7	
	Taxiway	<0.1	<0.1	6.2	
	Apron	187.7	81.0	5.5	
	Apron	471.2	105.0	7.5	

* Reinforced jointed rigid.

** Rigid overlay of rigid pavement.

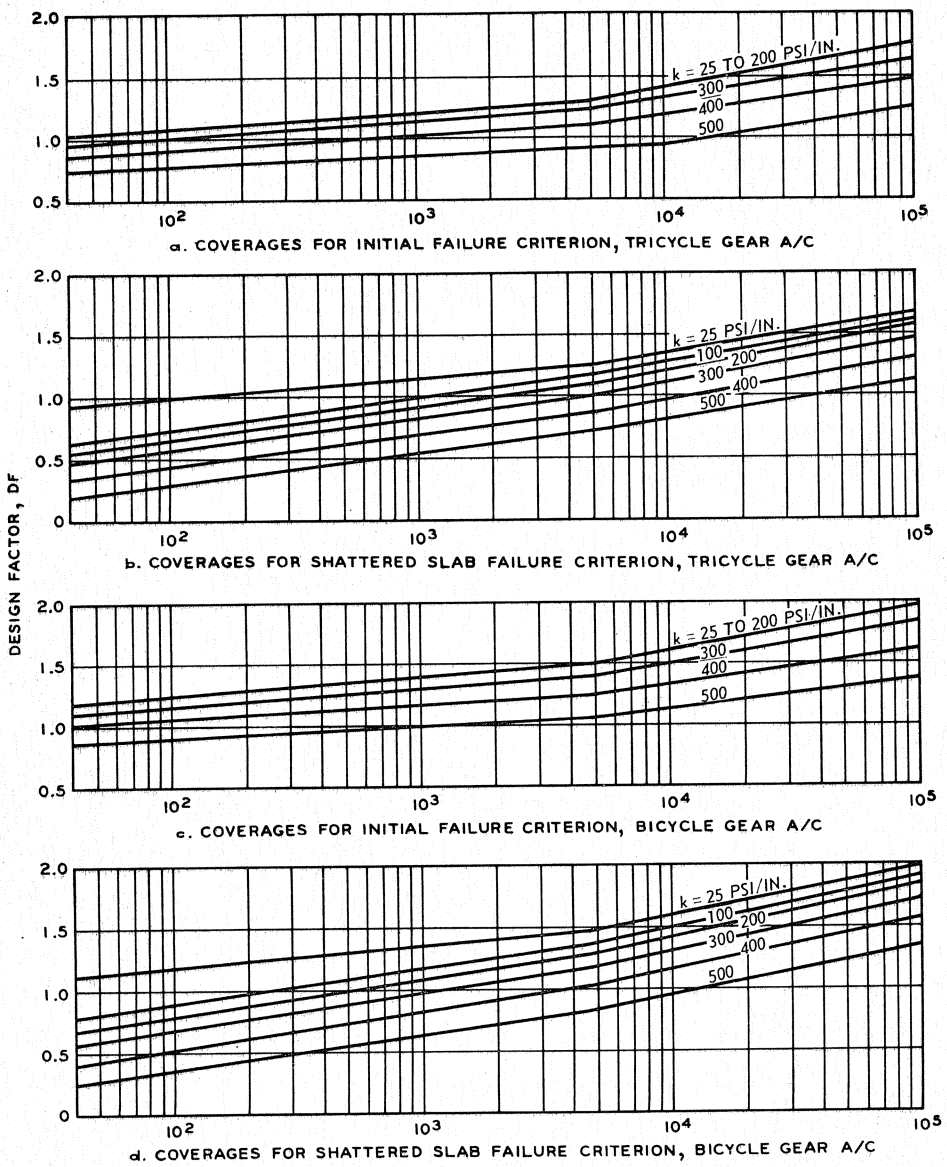


Figure 1. Performance criteria

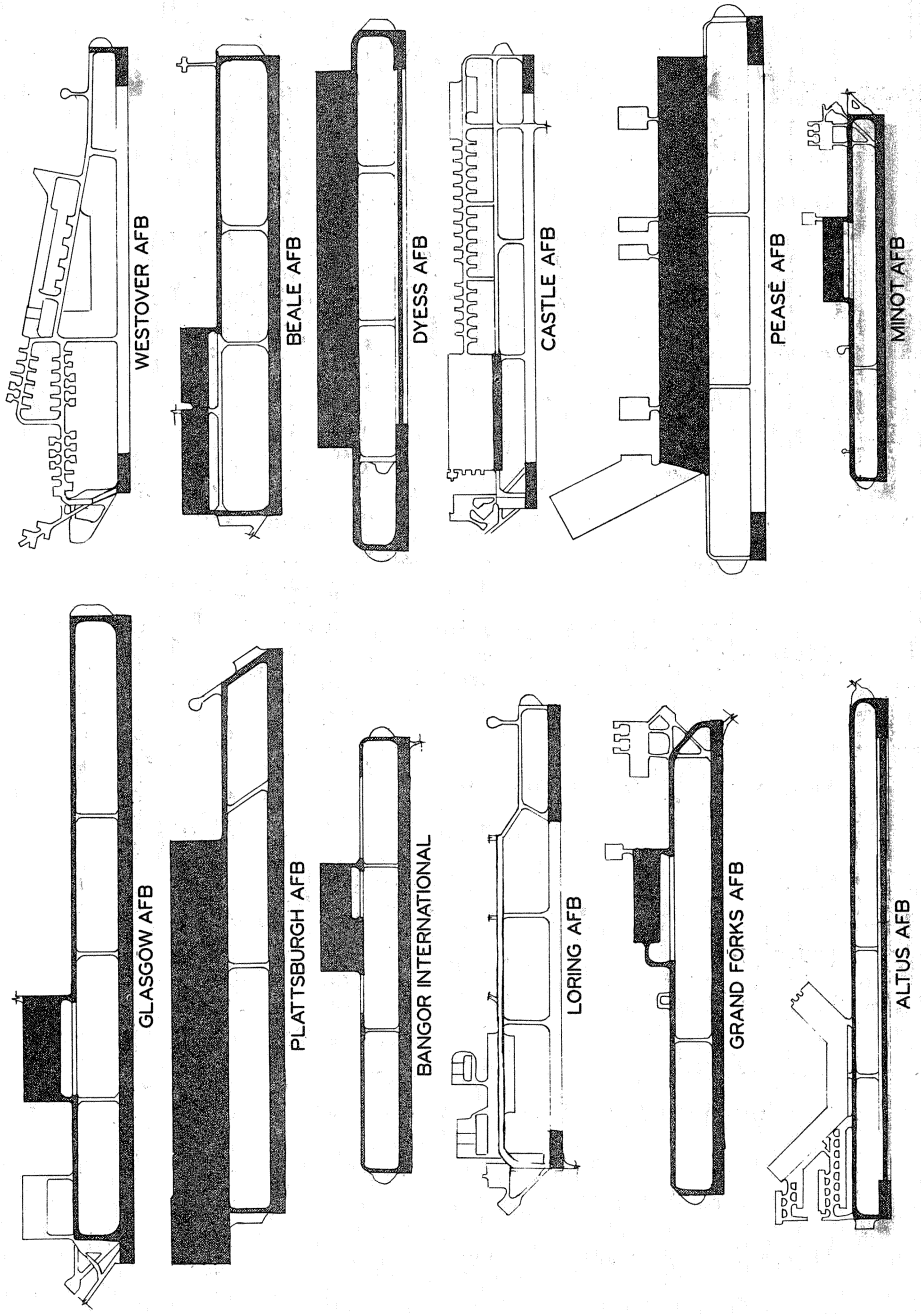


Figure 2. Airfield layouts

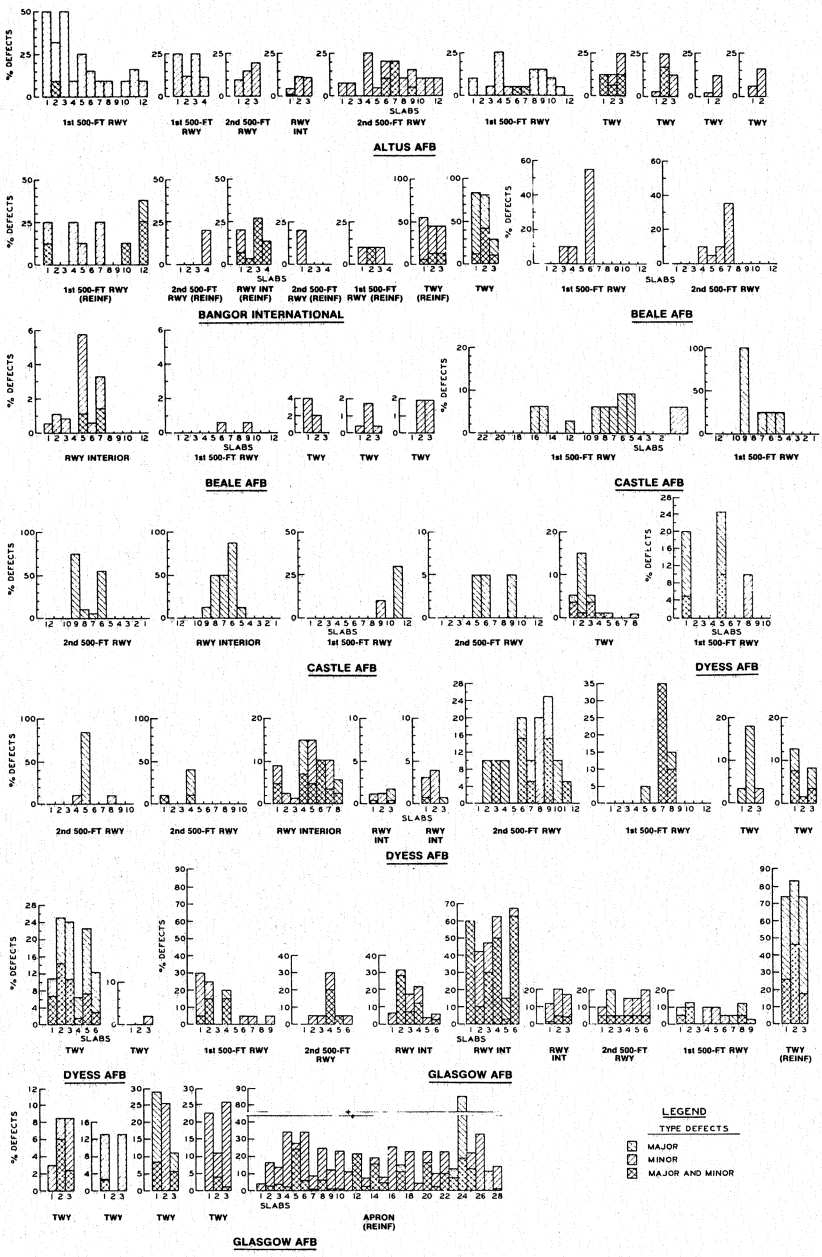


Figure 3. Histograms of pavement defects

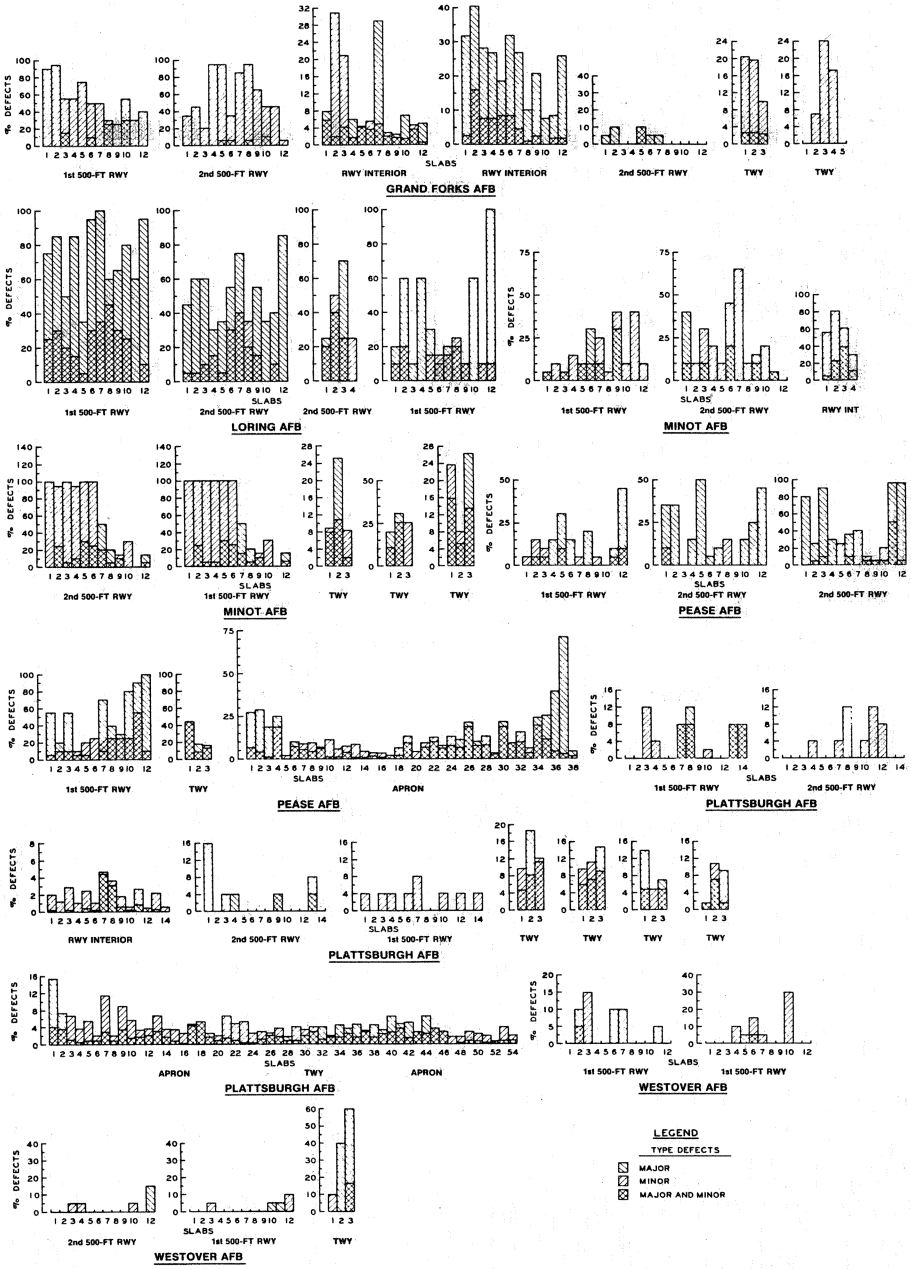


Figure 4. Histograms of pavement defects

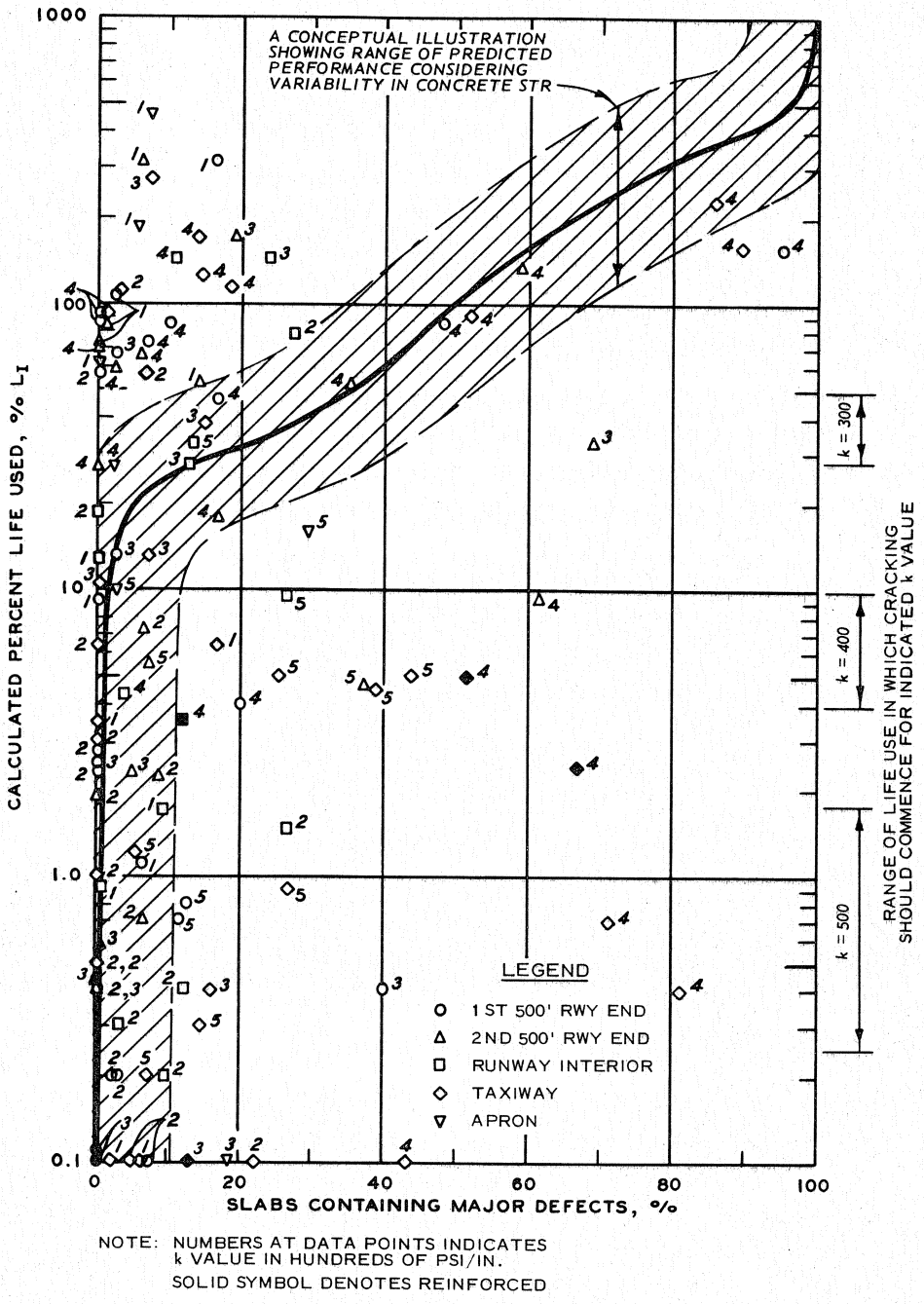


Figure 5. Results of performance analysis