Evaluation of Rigid Pavement Performance

F.M. MELLINGER, Director, Ohio River Division Laboratories,
Corps of Engineers, U.S. Army

For over fifteen years the U.S. Army Corps of Engineers has been conducting an extensive investigational program in connection with the design, construction and evaluation of concrete airfield pavements. This program has given consideration to paving materials, construction methods, analytical methods of design, traffic on specially constructed test pavements, and the condition of existing concrete airfield pavements. The purpose of this investigational work on rigid pavement is to establish a realistic method of design and evaluation and to insure that the pavements constructed are in accord with the requirements of the design. From time to time these investigations have been reported in the Proceedings of the Highway Research Board and other technical publications (1) (2). This paper summarizes briefly the method for the design and evaluation of rigid pavements based on the Corps of Engineers studies. Although the evaluation of rigid pavement performance involves many factors, the approach taken in this paper is that the load carrying capacity of the pavement with regard to both the magnitude and the frequency of loading, must be of prime consideration before factors other than load can be viewed in their proper perspective.

● MANY TIMES during the life of an airfield it may be necessary, for various reasons, to have an evaluation of different sections of pavement. Pavements may be evaluated to estimate the life remaining in a section, to check and correlate design methods with pavement performance, to provide information for pavement strengthening programs, or to serve as a guide in aircraft operations. The U.S. Army Corps of Engineers, over its years of experience with rigid pavements, has developed a procedure whereby pavement performance can be predicted for a wide range of operating conditions. However, before presenting this evaluation method, some mention should be made of what constitutes pavement failure.

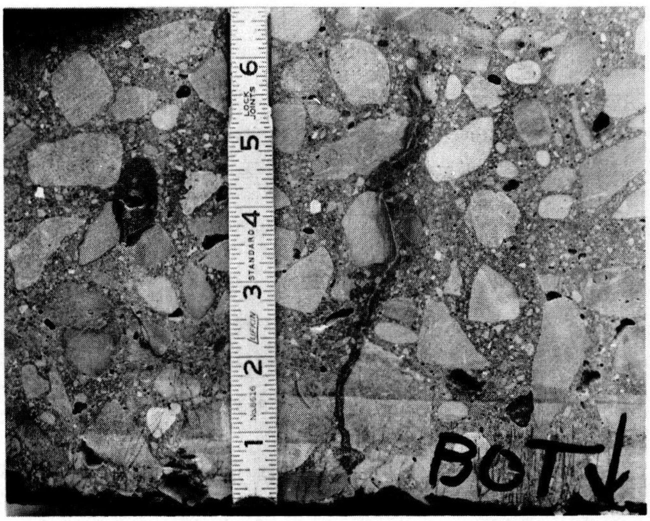
CAUSES OF FAILURE

Depending on the definition of pavement failure, the causes of failure, such as construction defects and over-loading, assume relative degrees of importance. However, with the advances in pavement construction technology, knowledge of concrete materials, and pavement jointing systems developed over the past thirty or more years, the number of failures due to causes other than over-loading by traffic should be small. This has been the trend observed for concrete airfield pavements constructed by the Corps of Engineers over the past fifteen years.

The most difficult as well as the most significant cause of pavement failure to evaluate is over-loading. Over-loading can occur over a period of several years as a function of the fatigue strength of the concrete and supporting media, or the loading may be so excessive that pavement failure results almost immediately. The latter case is not too difficult to evaluate. However, until the former becomes evident by excessive spalling at the joints and structural breaks in the pavement, over-loading is seldom detected; and, even when it is detected, the degree of over-loading still remains a difficult evaluation problem.

In the case of long-time over-loading the degree of over-loading is a problem because of the manner in which failure occurs. The failure is a function of the fatigue strength of the concrete as it fails in flexure at the base of the pavement slab. Minute cracks form which may extend up into the pavement about an inch, leaving the surface of the slab intact. Figures 1(a) and 1(b) show such cracking found in a beam cut from a 14-inch thick plain concrete pavement slab near a joint. This pavement had been subjected to 30,000 cycles of stress repetition by a 100 kip twin-wheel traffic loading. Figure 1(b) shows a close-up view of an unmarked crack extending upward 6 inches from the base of

(a) Cracking in base of 14-in. pavement slab after 30,000 coverages of 100 kip twin wheel load traffic.

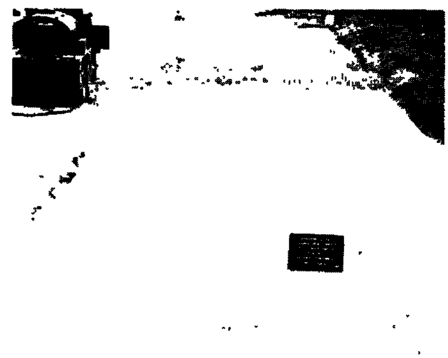


(b) Close up view of unmarked crack in above beam cut from 14-in. pavement.

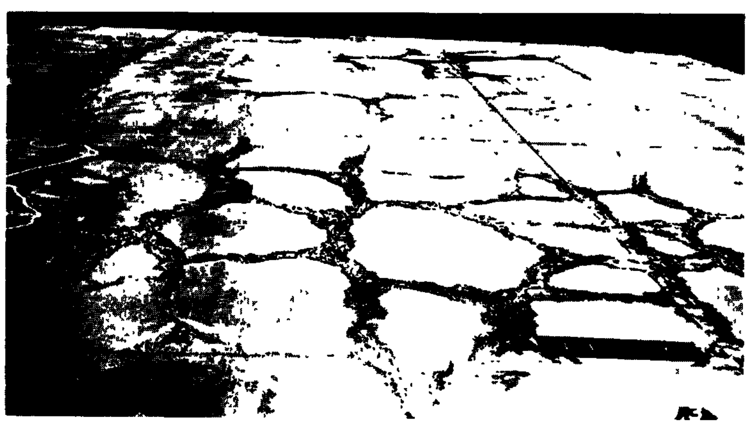
Figure 1. Evaluation of rigid pavement performance.

the pavement. This initial stage of failure is difficult to detect unless instrumentation is located in the precise area. When the crack finally reaches the surface in its development under repeated traffic loading, it generally appears as a hairline crack extending a foot or two inward from the joint. Even at this stage the pavement would not be considered failed. Only after one or two such cracks had developed on the surface for the full length or width of the slab and started to spall, would the slab be considered failed structurally. From the time the first minute crack occurs in the base of the pavement until the final crack pattern has developed, the slab would be considered satisfactory. This process can represent an appreciable part of the design life of the pavement, depending on the rate at which the cracking develops to its final stage. This rate will depend not only on climatic conditions, but also on the modulus of elasticity of the concrete, degree of subgrade support, and frequency of loading.

The detection and evaluation of this type of progressive failure is extremely difficult, even on controlled test pavements. In some cases the failure can be detected with deflection gages when an abrupt increase in deflection takes place. Strain gages also indicate slab failure if the gage located in the base of the slab contains the crack, an abrupt



(a) Failure condition of 16-in. plain concrete pavement after 24,663 coverages of 100 kip twin wheel load traffic.



(b) Complete failure of 12-in. plain concrete slab after 1,359 coverages of 150 kip twin tandem wheel load traffic.

Figure 2. Evaluation of rigid pavement performance.

increase in strain occurs or the gage fails. On the other hand, if the gage is located adjacent and normal to the crack, an abrupt decrease in strain will be observed. Strain gages located on the surface of the slab will give erratic readings as these initial cracks occur, and a general reduction in strain will be observed under continued load application.

The evaluation of the causes of pavement failure may be obvious in some instances but in all cases the question as to whether or not the pavement was over-loaded by the traffic and, if so, to what degree must be answered first. The mechanics of pavement failure and the materials with which pavements are constructed precludes a strictly theoretical approach. Certain empirical relationships must be established to evaluate the load capacity of a pavement. One such approach, as outlined in the following paragraphs, gives a basic design concept, the type of performance observations by which this concept is implemented, and finally the necessary information for translating the design concept into a design procedure for new pavements and an evaluation method for existing pavements.

DESIGN CONCEPT

The evaluation of pavement performance does not evolve from a few observations over a limited time. It must be founded on a basic design concept which takes into account the physical properties of the pavement and its supporting media. Over a period of years this concept will be modified on the basis of actual field performance and, when available, on the results of controlled full-scale traffic tests. The design concept is necessary since a great variety of observations of pavement performance must be correlated for the purpose of obtaining the most economical design applicable for a given set of conditions and a realistic evaluation of a pavement's capabilities while in service. The development of such a concept has been one of the chief objectives of the Corps of Engineers' Rigid Pavement Investigational Program for airfield pavements since early

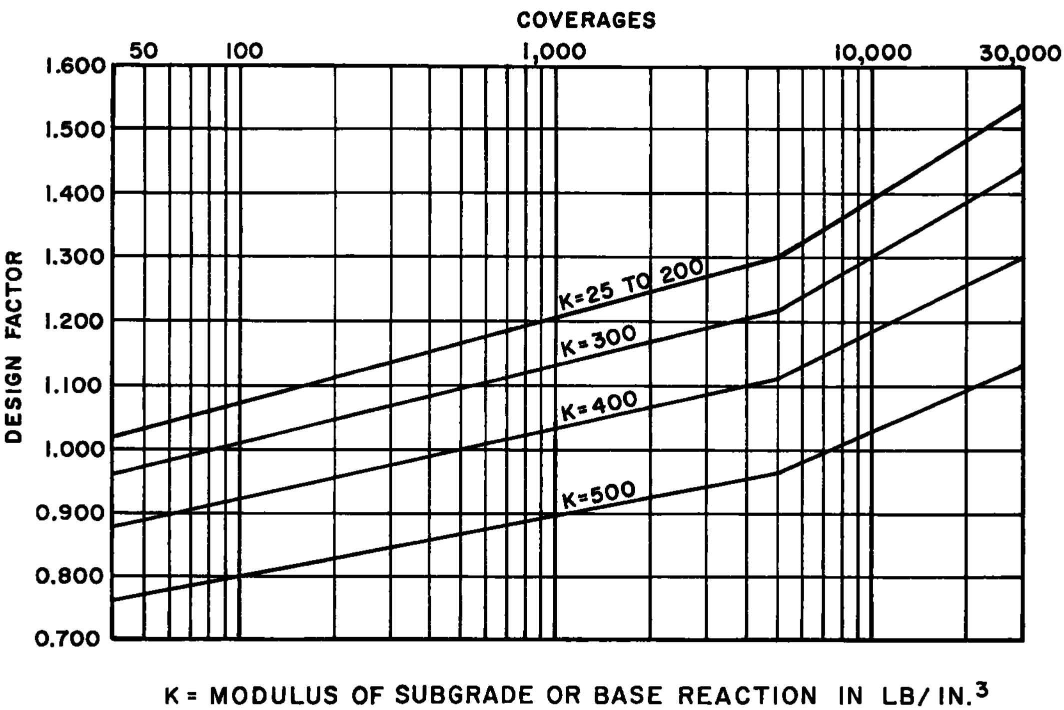


Figure 3. Rigid pavement design factors.

in 1943. Embodied in the design concept developed are the basic theoretical approach, the pavement loading for design or evaluation, the frequency and distribution of the design loading on the pavement, and the definition of what constitutes failure of the pavement.

Basic Theoretical Approach: In any theoretical approach certain idealized assumptions must be made. In order for Westergaard's equations (3) to be applicable to the computation of stresses in slabs supported on a subgrade, it must be assumed that within the range of action, the slab is elastic with single constant values for the modulus of elasticity and Poisson's ratio; that the thickness of the slab is constant; and that the reaction of the subgrade is a vertical pressure, equal, per unit of area, to a constant, "k", (4) times the deflection, the base being uniform in character and everywhere in contact with the slab. No concrete pavement ever constructed meets all these requirements, but the relative performance of concrete pavements agrees surprisingly well with theoretical formulae based on these assumptions. The basic formula used by the

Corps of Engineers is that for an edge or joint of a pavement slab that has no load transfer. The stress computed by this formula is reduced 25 percent for load transfer. Actual measurement of the efficiency of the various types of joint construction used for airfield pavements indicates that this percent is a representative value. This stress is then modified by a design factor, the selection of which is dependent on the number of load or stress repetitions and the modulus "k" of the subgrade reaction. For design the computed stress can be made equal to the flexural strength of the concrete by adjusting the slab thickness or, for evaluation, by adjusting the load.

Pavement Loading: The manner in which a pavement will be loaded is an important determination for any design concept since considerable economy can be effected through this factor. The pavement is generally designed for the heaviest aircraft which it is expected to carry in quantity; that is, the aircraft in continuous operation, not the occasional heavy load. The selection of the design load for pavements which handle military aircraft requires considerable judgment, since the weight of individual aircraft varies with the type of operation, as well as with take-off and landing. In the latter case, the difference in fuel load can be an appreciable percentage of the gross weight of the aircraft. In pavement evaluation work the problem is met where it is necessary to determine whether an existing pavement will support the operation of a specific type of military aircraft.

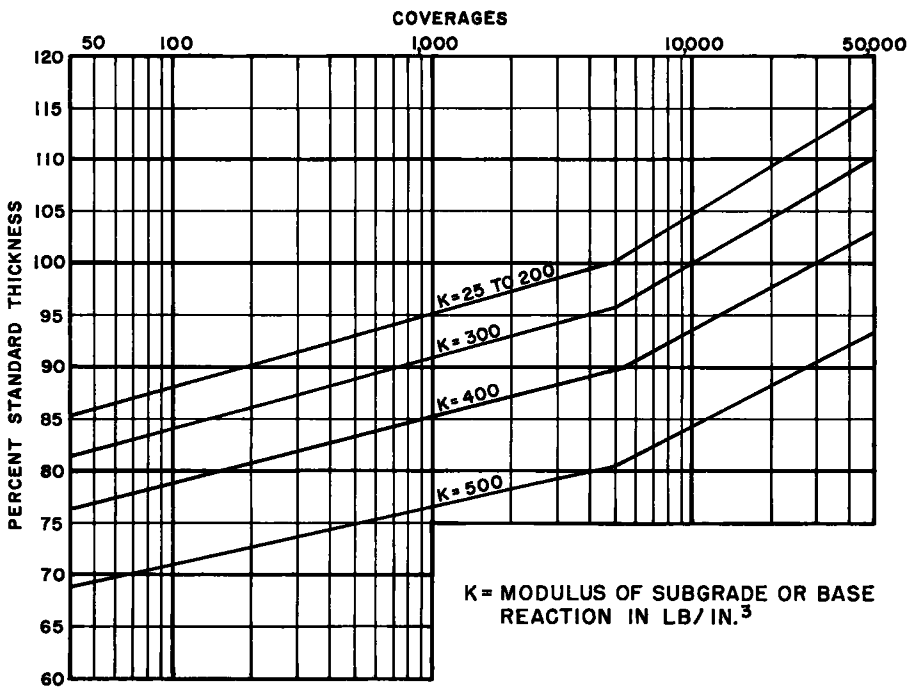


Figure 4. Rigid pavement useful life, 2 to 3 pieces, 1 slab.

Frequency and Distribution of Loading: Regarding the frequency and distribution of loading all possible information on the types of aircraft and their operational characteristics must be studied and considerable judgment exercised in the selection of the appropriate design factor which will determine the pavement life. The term coverage is used to relate the frequency and distribution of the design loading to aircraft operations. One coverage indicates one application of maximum stress at each point in the trafficked area of a pavement and is a function of the number of aircraft operations. In the case of evaluating an existing pavement for a given type of aircraft, the remaining pavement life would be defined by the additional number of coverages which the pavement could reasonably be expected to carry prior to failure.

Definition of Pavement Failure: A pavement facility such as a taxiway apron or runway on an airfield does not fail all at once, the process of failure is gradual. Actually,

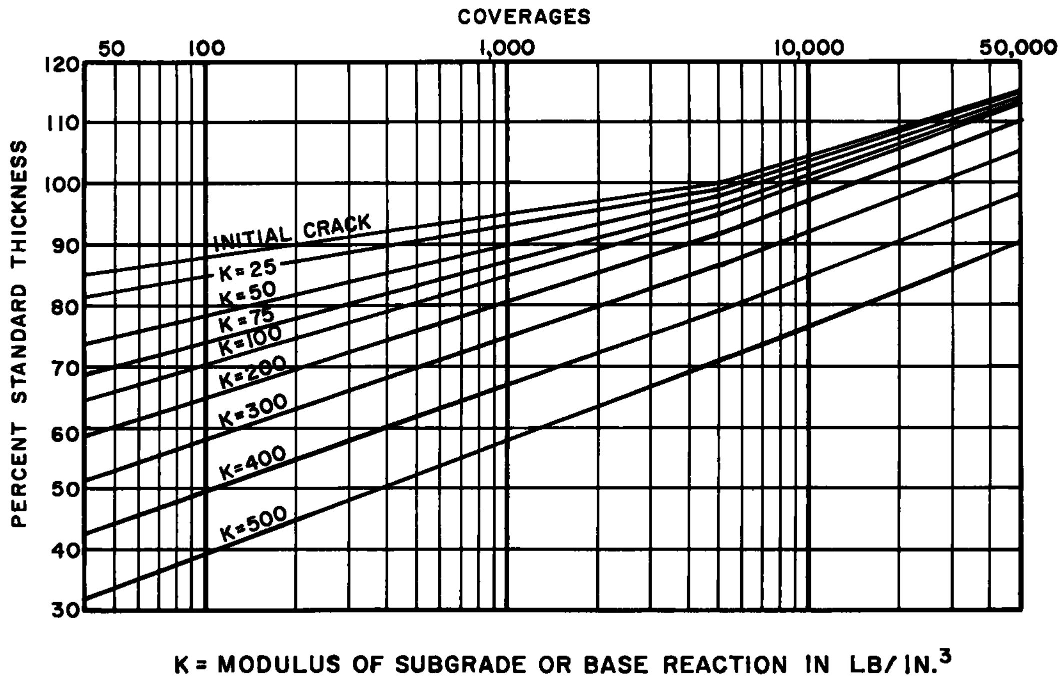


Figure 5. Rigid pavement complete failure, 6 pieces, 1 slab.

an airfield pavement is designed to fail from fatigue after a given number of coverages of the design loading predicted for a 10 to 20 year design life. This design failure is defined as one or two structural breaks or cracks occurring in 30 percent of the slabs in a pavement feature, with the cracks starting to spall. The appearance of a slab in this failed condition is shown in Figure 1(a). For some categories of evaluation, where the pavement is loaded beyond its design capacity, failure is defined as the case where at least 30 percent of the slabs are broken into six pieces and limited maintenance is required to keep the pavement surface suitable for aircraft operation. Figure 2(a) shows an individual pavement slab in this condition.

PERFORMANCE

The observation of pavement performance has one basic objective that is to provide the necessary information for the development of a design procedure. This observation of pavement performance is a continuing process, for once a design procedure is developed, the observation must continue for the purpose of checking and refining the design. Pavement performance is examined under different climatic conditions, and for different types of aircraft loading and operation. In addition, controlled traffic tests are made on specially constructed full-scale test pavements for a variety of loadings and pavement designs. These designs have included overlay pavements on concrete base pavements, reinforced concrete pavements, plain concrete pavements and, more recently, prestressed concrete pavements (5). Since 1943, full-scale traffic tests of pavements have included the loadings, gear configurations and types of pavement shown in Table 1. Not included in Table 1 are tests of rigid, flexible and prestressed overlay pavements (2) (5). The testing of specially constructed test sections under controlled traffic loading provides for a detailed study of the pavement and subgrade materials; also provided is the opportunity to measure strains and deflections at critical areas in the pavement. The information thus developed, in itself, is limited but, when correlated with periodic condition surveys of airfield pavements subjected to actual aircraft operation in areas representative of subgrade soils, construction materials and climate throughout the United States, it provides a good basis for a logically developed design procedure.

TABLE 1

SUMMARY OF TRAFFIC TESTS

Date	Gear Loading		Number of Test Items	Concrete Pavement	
	Weight, kip	Type Wheel		Thickness, in.	Type
1942-43	20, 37 & 60	Single	66	6 to 10	Plain & reinforced
1944-45	150	Single	120	9 to 24	Plain & reinforced
1946-47	150	Twin-Tandem	33	12 to 20	Plain
1955-56	100	Twin	15	11 to 20	Plain & reinforced

EVALUATION

Thus far a design concept with the various factors involved has been presented, with a brief outline of the general means by which information to implement this design concept is obtained. Now remains the method of incorporating this information in an overall design procedure. However, before proceeding, it is necessary to describe how a rigid pavement can be expected to fail under repeated traffic loading. Failure of a plain concrete pavement generally starts with a crack extending into a slab from a joint. This crack develops with traffic into a longitudinal crack, a transverse crack for the full length or width of the slab, or a corner break. The pavement is not considered as failed until the cracking has developed for the full length or width of the slab. Additional cracking and spalling at the cracks will develop with continued loading. The rate of this failure development will be dependent on the degree of subgrade support. If the subgrade has a high bearing value, the rate of failure will be slow; if the subgrade has a "k" value of less than 200 lb per in.^{3}, the rate of breakup will be relatively fast. This means that a greater degree of cracking or greater number of pavement breaks can be tolerated for a pavement on a high bearing value subgrade before it is considered failed than for a pavement on a weak subgrade. The theoretical formula for edge loading using a fatigue factor for load repetition only will not reflect this difference. Therefore, to correlate the theory with actual pavement performance, it is necessary to vary the fatigue or over-all design factor with the value of the subgrade modulus, as well as with coverages or stress repetitions. Variations in the design factors for different values of subgrade modulus are shown by the curves of Figure 3. This figure gives the design factors used by the Corps of Engineers with Westergaard's formula for stress at a free edge of a slab under load. The stress is reduced 25 percent for load transfer at a joint. This resulting stress multiplied by the appropriate design factor is set equal to the average flexural strength of the concrete to obtain the design thickness of the pavement for a specified loading. For example, if the pavement is to be designed for 5,000 coverages of the 100 kip twin-wheel loading on a subgrade having a "k" value of 200 lb per in.^{3} or less, the design factor would be 1.30. Assuming that the average flexural strength of the concrete will be 700 psi, the design thickness "h" of the pavement should be such that the load

TABLE 2

SUMMARY OF DESIGN FOR 100 KIP TWIN WHEEL GEAR LOADING

Subgrade Modulus "k", lb per in.^{3}	Flexural Strength of Concrete, psi	Design Factor		Pavement Thickness, in.	
		5,000 Coverages	30,000 Coverages	5,000 Coverages	30,000 Coverages
100	700	1.300	1.520	15	18
300	700	1.215	1.435	12	15
400	700	1.110	1.300	11	13
500	700	0.960	1.130	10	12

will produce a stress at a joint equal to the flexural strength of the concrete divided by the design factor (700/1.3 = 538 psi). Table 2 shows the effect on design when applying the design factors from Figure 3 to a 100,000 pound twin-wheel gear loading for different values of subgrade support. Table 2, with the foregoing definitions, indicates how the basic theory is modified by the design factors to obtain agreement with observed pavement performance and a specific definition of failure. The same principles can be applied in the evaluation of an existing pavement for an increase in loading or changes in aircraft operation. In this case it is desired to know the number of coverages of a given loading that a pavement can sustain until failure occurs, and how many coverages it will sustain until complete breakup of the pavement occurs. In the first case, initial failure is defined as "30 percent of the slabs in a trafficked area broken into 2 or 3 pieces by structural breaks," and complete breakup of the slab is defined as "50 percent of the slabs in the trafficked area broken into 6 pieces." Figures 4 and 5 respectively are used to evaluate for these two conditions. In these cases the percent standard thickness is plotted against coverages for different values of subgrade modulus, "k". The percent standard thickness is the thickness of the existing pavement divided by the standard thickness for the evaluation loading times 100. The standard thickness is the thickness required for the loading, using a constant design factor of 1.3 for all values of subgrade modulus. For values of "k" up to 200 lb per $in.^3$ this design factor of 1.3 represents the 5,000 coverages level, see Figure 3. For example, assume an existing pavement is 13-inches thick and in good condition, the subgrade modulus, "k", is 100 lb per $in.^3$, and the flexural strength of the concrete is 700 psi. It is required to evaluate this pavement for an aircraft having a maximum twin-wheel gear load of 100 kip. For this particular case, Table 2 gives the standard thickness as 15 inches (first row, column 5). The percent standard thickness would be (13 ÷ 15) x 100 or approximately 87 percent. The evaluation for the number of coverages to produce initial failure is given by Figure 4 as 50 coverages, while for complete failure Figure 5 gives about 1,500 coverages. These coverage numbers are then converted to aircraft operation numbers and the pavement life is predicted for each pavement feature, whether taxiway, runway or apron.

SUMMARY AND CONCLUSION

The evaluation of rigid pavement performance must begin with a design concept which relates the traffic loading and its frequency to the physical properties of the pavement and its supporting media. The significant factors and application of the method of design and evaluation given in this paper are:

1. For either the design or evaluation of a rigid pavement, a definition of the condition of the pavement at failure must be established. In some cases this definition can be more severe for evaluation than for design.
2. Methods of design or evaluation must be based on accurate and detailed observations of pavement performance.
3. Westergaard's theoretical formula for edge loading with an allowance for load transfer at a joint provides an accurate means for appraising the relative capacity of concrete pavements.
4. Where it is necessary to take into account load repetition and to alter the theoretical relationship of values of subgrade modulus, modification of the formula by design factors provides a means of obtaining agreement with actual pavement performance.
5. Although the design and evaluation factors given by Figures 3, 4, and 5 are set up for specific application they provide a scale which translates the results of many pavement tests and observations into usable form for continued evaluation of rigid pavement performance. Where controlled traffic tests are made on specially constructed test pavements these factors will provide a method for predicting failure or analyzing test results.

ACKNOWLEDGMENT

The investigational program on which the design and evaluation procedures given in this paper are based has been carried out by the staff of the Ohio River Division Laboratories, Corps of Engineers, U.S. Army. The program is directed and coordinated by members of the Airfields Branch, Engineering Division for Military Construction, Office, Chief of Engineers. This work was done under and by the authority of the Chief of Engineers, U. S. Army.

REFERENCES

1. Mellinger, F.M., Sale, J.P. and Wathen, T.R., "Heavy Wheel Load Traffic on Concrete Airfield Pavements," Proceedings of the Highway Research Board, 1957.

2. Mellinger, F.M., Sale, J.P., "The Design of Non-Rigid Overlays for Concrete Airfield Pavements," Proceedings of the American Society of Civil Engineers, Paper 979, Journal No. AT2, May 1956.

3. Westergaard, H.M., "New Formulas for Stresses in Concrete Pavements of Airfields," Transactions, American Society of Civil Engineers, 1948, Vol. 113, page 425.

4. U.S. Army, Corps of Engineers, "Airfield Pavement Design, Rigid Pavements," Engineering Manual for Military Construction, Part XII, Chapter 3, March 1954.

5. Mellinger, F.M., "Prestressed Concrete Airfield Pavements," Proceedings World Conference on Prestressed Concrete, San Francisco, California, July 29 to August 2, 1957.