Heavy Wheel Load Traffic On Concrete Airfield Pavements

FRANK M. MELLINGER, *Director,*
Ohio River Division Laboratories, Corps of Engineers, U. S. Army;
JAMES P. SALE, *Airfields Branch,*
Engineering Division for Military Construction, Office, Chief of Engineers, U. S. Army; and
THURMAN R. WATHEN, *Chief of Field Investigations Branch,*
Pavement Division, Ohio River Division Laboratories, Corps of Engineers, U. S. Army

The advent of jet aircraft for military use has created many new problems for the airfield pavement designer. A few of these are blast effects, fuel spillage, heavier gross aircraft weights, a higher frequency of operation for individual aircraft, longer runways, and vast areas of pavement for parking aircraft. These are some of the problems with which the Corps of Engineers' Rigid Pavement Laboratory at Cincinnati, Ohio, is concerned. The great increase in pavement areas required by jet aircraft make it mandatory that the investigational program be continued to obtain the most economical solution for such problems.

Two factors which greatly influence the design of an airfield pavement are the magnitude of the wheel loadings and the number of repetitions of these loadings during the design life of the pavement. The testing described in this paper deals chiefly with these two aspects of the design problem. Two full-scale pavement test sections, one on a uniform subgrade of high bearing value, the other on a uniform subgrade of low bearing value, are described, and the results of accelerated traffic testing are presented and discussed. Each of the two pavement test sections contains comparable designs of plain and reinforced concrete pavements. Each test section was subjected to 90,000 repetitions of a 100,000-lb twin-wheel loading. Tentative conclusions are presented and discussed for equivalent plain and reinforced concrete pavement designs, as well as for the effects of load repetition on pavement life for both reinforced and plain concrete pavement. This provides the pavement designer with an additional tool of design which should be valuable in obtaining the most economical solution for the varied problems that must be solved in designing and constructing airfield pavements for current and future jet aircraft operation.

● BETWEEN 1941 and 1950, the Corps of Engineers' Rigid Pavement Laboratory at Mariemont, Ohio, developed and published design criteria for concrete airfield pavements for a range of loadings from 10,000 lb on single-wheel landing gear to 200,000 lb on twin-tandem (4-wheel) landing gear. The design curves were an adaptation of Westergaard's edge stress equations for concrete pavement and represented ten years of research and investigational work in theoretical analysis, model study, full-scale accelerated traffic tests, and observation of prototype airfield pavement performance. Westergaard's solutions (*1*) were modified in accordance with the various studies to account adequately for such factors as load transfer at joints, temperature stresses, and traffic repetitions.

Before adopting Westergaard's methods, considerable work was necessary in

developing test procedures and techniques for measuring certain physical properties of the foundation and pavement which were required in the solution of the equations; namely, the modulus of subgrade reaction, k, and the flexural strength of concrete. In the course of the investigation it was found that the methods of load application and the dimensioning of the test pavements had a marked effect on the test results. By correlating the results with the behavior of full-size concrete slabs under controlled conditions, the most favorable procedures were determined and established as standard.

Extensive studies were conducted to determine the effects of static, impact, and repetitive traffic loadings on concrete pavements. A joint program was initiated with the Army Air Corps to find which of those loadings was the most critical insofar as aircraft operation on actual airfield pavements was concerned.

The results of those early investigations showed conclusively that the most severe loading to which an airfield pavement is subjected is that of the repeated traffic of slow-moving aircraft, which occurs primarily on taxiways and the taxiway portions of aprons and runway ends. These findings are equally applicable for all types of airfield pavements, but discussions of design requirements for pavements other than those composed of portland cement concrete are not included in the scope of this paper.

Tests with military aircraft indicated that considerable impact could be produced by extremely "hard" landings, but that the normal "touch down" loading was only in the order of 65 to 80 percent of the static loading, due to the lift on the wing surfaces of the aircraft at landing speeds. Another consideration in discounting impact loads was the fact that the average weight of military aircraft during landing operations varies from only 50 to 75 percent of the takeoff weight. The characteristic of aircraft having considerable lift during landing and takeoff operations further served to allow a reduction in pavement thickness in the interior portions of runways.

Correlation of Test and Prototype Traffic

Having established the fact that repeated traffic loadings were the most critical, it was necessary to make a realistic determination of the frequency of traffic that had to be considered. Again, the Army Air Corps furnished traffic data for the normal operation of heavy bomber and cargo aircraft which generally control pavement design. Studies were then made to determine the typical lateral distribution of traffic on such pavement features as runways and taxiways. Correlating the results of these two studies, traffic records from prototype airfields were converted to traffic coverages in order to establish the number of traffic loadings to which pavement test sections should be subjected to be representative. Statistically, a coverage occurs at a point on a pavement surface when that point has been traversed one time by an aircraft wheel; or, more simply, when each point in a pavement has been subjected to one maximum stress. These studies indicated that 5,000 coverages were representative of from 10 to 20 years of prototype traffic; and this value, therefore, was selected as the design life of military airfield pavements.

The foregoing concepts were utilized in formulating the rigid pavement design curves prepared by the Corps of Engineers prior to 1951, and pavement performance definitely established the adequacy of these criteria. Rigid pavements designed according to these criteria were constructed throughout the United States and gave satisfactory performance under the traffic and loadings of such heavy aircraft as the B-17, B-24, B-29, B-50, and B-36. The behavior of these pavements failed to show many of the problems normally associated with highway pavements, such as elimination of poor quality base courses, pumping, faulting or slab displacement, and roughness. The reason for this is believed to be directly related to the relatively low number of stress repetitions on airfield pavements as compared to the high traffic frequencies and small lateral distribution on highway pavements. On the other hand, many mili-

tary airfield pavements were successfully carrying the sustained traffic of aircraft weighing more than 400,000 lb, with closely spaced individual wheel loads in excess of 50,000 lb and with tire inflation pressures approaching 200 psi.

Recent Problems

Beginning in 1951, two basic changes in aircraft design began to play important roles in airfield pavement requirements. The first of these was the advent of steerable landing gear, which gave pilots far greater control during taxiing operations; the second was the introduction of bicycle-type landing gear on the B-47 aircraft, which not only doubled the coverage rate in confined areas, but also produced an impact loading. Small irregularities in the pavement surface, coupled with an inherent rocking tendency in the aircraft, resulted in a "porpoising" action that offered a definite operational hazard to the pilot and subjected the pavement to a loading condition which had not been considered in design. The subject of pavement smoothness and the resulting effects on bicycle-geared aircraft is beyond the scope of this paper. However, the control of surface irregularities and small deviations from grade are given far greater consideration in current construction than formerly.

Unfortunately, the effects of these two factors were not anticipated, and it was not until two to three years of B-47 operation had occurred that problems began to develop in the so-called "heavy load" pavements. During this period the "heavy load" design had been established by the United States Air Force as a 100,000-lb twin-wheel loading, 37½-in. center-to-center spacing of wheels, with a contact area of 267 sq in. for each tire.

Because the loading and gear configuration on the B-47 aircraft almost exactly duplicated the design loading, there was every reason to believe adequate pavements were being produced. The first indications of distress in rigid airfield pavements became evident during the 1953 Condition Survey Investigational Program carried out by the Rigid Pavement Laboratory on a periodic basis at some 25 to 30 active Air Force bases. Pavements were beginning to show initial cracking on taxiways and runway ends, and many areas of pumping were developing prior to any other signs of distress. Past experience had never shown pumping to be a problem except on completely inadequate and overloaded pavements, and then only after considerable distress had been evidenced in the form of cracking and joint spalling.

In seeking reasons for those early signs of failure (by Corps of Engineers and Air Force definition, one crack in a pavement slab is considered failure) it immediately became apparent that the B-47 aircraft did not "wander" and distribute traffic over the width of a taxiway as had been the case with earlier aircraft, but rather it followed closely the centerline paint stripe. To casual observation, it appeared that each pass of the landing gear occurred over the same point. A rather elaborate study of these phenomena in 1955, using time lapse photographic technique, established the fact that during taxiing operations, 75 percent of all B-47 traffic occurred within a channelized boundary of about 7.4 ft, thus producing about six times the rate of coverage that had been experienced with earlier aircraft. Considering the outside dimensions of the twin-wheel gear (more than 4 ft), this channelization of traffic represented an average "wander" each side of the centerline of only 18 to 20 in.

Tentative Criteria for Channelized Areas

Steps were immediately taken to define the pavement areas which were being subjected to this channelized traffic condition and to adjust the design criteria to take care of the increased number of load repetitions. Several possibilities for making this adjustment were available. Previous accelerated traffic tests on test sections at Lockbourne Air Force Base (*2*) had established relationships between percent of design thickness for an initial cracking condition and coverages (Fig. 1, Curve ORDL Tests). This curve had only been validated for a level of

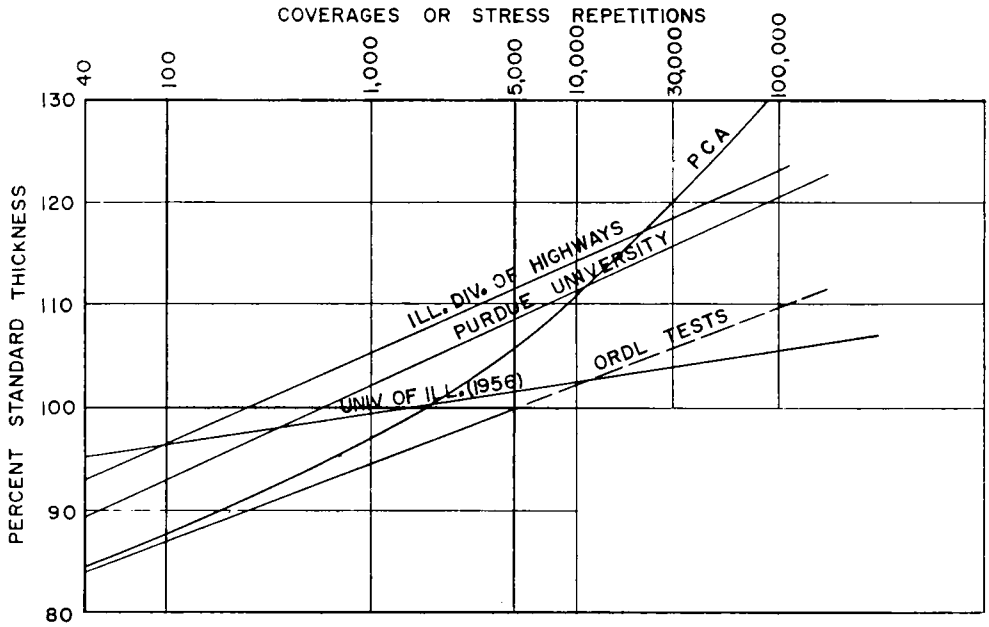

Figure 1. Fatigue curves for concrete pavements and beams.

5,000 coverages. An extrapolation of the curve to the 30,000-coverage level (which had been selected as representative for channelized areas) indicated an increase in pavement thickness of only 6 percent.

The extension of the ORDL curve appeared logical when compared to similarly scaled plots of fatigue tests on concrete beams loaded in flexure, as shown in Figure 1. These results of fatigue tests on concrete beams have been reported by the Illinois State Highway Department (*4*), Purdue University (*3*) and the University of Illinois (*5*). Also shown is the Portland Cement Associations' fatigue curve for pavement design. This latter curve had also been established for a high level of stress repetitions and indicates an increase in pavement thickness of about 15 percent in going from a 5,000-coverage level to a 30,000-coverage level.

Tentative design criteria for channelized traffic areas were established in March 1955. These called for a 12 percent increase in slab thickness over that required for the original 5,000-coverage level. Plans were made for the construction of two channelized traffic test sections, one on a foundation of high bearing capacity, the other on a foundation of low bearing capacity, to check further these tentative criteria.

Because the new channelized criteria produced unusually large pavement thickness requirements, it was decided to incorporate several test items of continuously reinforced concrete in the proposed test sections. Previous tests at Lockbourne had indicated strongly that the use of reinforcing in concrete pavements was difficult to justify economically (*8*).

However, these tests of reinforced concrete pavements did indicate advantages, such as fewer transverse joints and a reduction in thickness, over plain concrete pavement of similar design. These considerations, with the growing interest in prestressed pavements, made it necessary to develop further information on the behavior of reinforced concrete pavements compared to plain concrete.

DESIGN AND CONSTRUCTION OF TEST SECTIONS

The two test sections, one on a relatively high bearing value subgrade and the

other on a relatively low bearing value subgrade, were designed to bracket the requirements for a 100,000-lb twin-gear loading. The tire spacing of the twin-gear was 37½ in. center-to-center, with a contact area of 267 sq in. for each tire. The test sections, designated as Parts 1 and 2, were 25 ft wide, with no longitudinal joints, and about 600 ft long. The test items in each section varied from 50 to 65 ft in length. Each item was separated by a heavily reinforced concrete transition pavement 10 ft long.

Details of dimensions and reinforcing in the test items are given in Figure 2. The test sections were located on a government reservation near Sharonville, Ohio, a suburb of Cincinnati. This has been the location of the Rigid Pavement Laboratories full-scale pavement testing station since 1952. Former full-scale tests were conducted at Wright Field, Dayton, Ohio, and at Lockbourne Air Force Base, near Columbus, Ohio.

The low and high bearing value subgrades were carefully prepared to provide uniform conditions for the full length of the two test sections. The average measured physical properties of the subgrades for Parts 1 and 2 are given in Table 1.

TABLE 1
PHYSICAL PROPERTIES OF THE SUBGRADE

Property*	Channelized Traffic Test Track Part 1	Part 2
Subgrade modulus, k, lb/cu in.	50	300
Compaction, % modulus AASHO	92	97
Plastic limit, %	25-30	Non-plastic
Liquid limit, %	50-60	—
Classification, unified system	CH	GMd

* Properties determined in accord with Corps of Engineers procedures (*6*).

The test sections were built under a construction contract on the basis of plans and specifications similar to those prepared by the Corps of Engineers for airfield pavements. The low bidder was W. L. Johnson and Associates, Inc., of Columbus, Ohio. Construction was started in November 1955 and completed in January 1956.

Reasonably close estimates of the flexural strength of the concrete and its

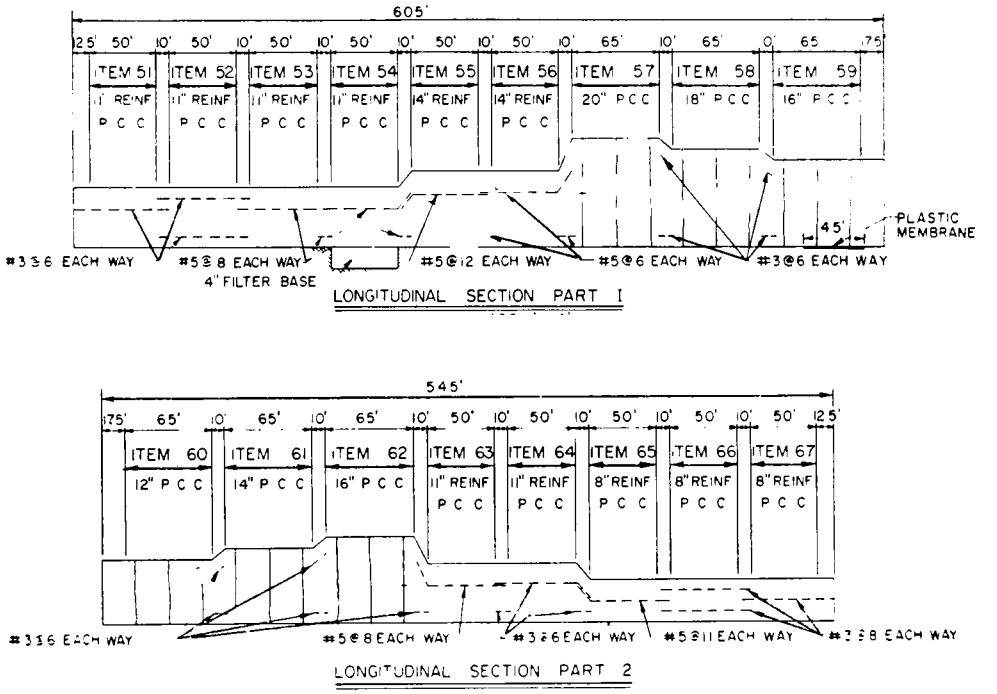

Figure 2. Design layout for channelized traffic test track, Sharonville, Ohio, 1955-6.

other physical properties were made for design purposes. These were based on previous experience with the available concreting materials. The mix design of the concrete and gradation of aggregates were in accord with normal Corps of Engineers requirements. The maximum aggregate size was 1.5 in. and the cement content was 5.5 sacks per cubic yard. The concrete was placed at a slump of 2 in. Test of field and laboratory beams indicated the physical properties of the concrete at the time the test sections were subjected to traffic from March through October 1956 to be as given in Table 2.

TABLE 2

PHYSICAL PROPERTIES OF CONCRETE AT THE TIME OF TRAFFIC TESTING

Property	Channelized Traffic Test Track	
	Part 1	Part 2
Flexural strength, psi	800	725
Poisson's ratio:		
Static	0.20	0.20
Dynamic	0.25	0.25
Modulus of elasticity, psi:		
Static	4.3×10^6	4.3×10^6
Dynamic	6.0×10^6	5.8×10^6

The flexural strength and static modulus of elasticity were determined from 6 x 6 x 36-inch beams loaded at the third point. The static value of Poisson's ratio was obtained from tests of 6 x 12-inch cylinders. The dynamic modulus and Poisson's ratio were determined from sonic tests of the concrete beams (*7*).

As indicated in Figure 2, each test section contained three plain concrete items, with the remaining items reinforced. The reinforced items were continuous, with no transverse joints. Generally, the steel was placed 4 in. below the surface of the concrete, with one exception in each section. In this latter case the quantity of steel was kept the same as an adjoining item, but one-half was placed 2 in. from the bottom of the slab and the other half, 2 in. from the surface.

In all cases equal amounts of steel were used in both the transverse and longitudinal directions. This was done because aircraft with various gear configurations may use an airfield; some gear configurations produce a maximum stress in the transverse direction, whereas others produce a maximum stress in the longitudinal direction. The steel was placed as prefabricated bar mats. The bar stock was rail steel having a tensile strength of not less than 80,000 psi and a yield strength of not less than 50,000 psi. It conformed to the ASTM test designation A16-54T for reinforcing steel.

Due to the limited number of test sections, only two percentages of steel were used; namely, 0.175 and 0.350 percent of the cross-sectional area of the pavement. The percent of steel and concrete thickness are summarized in the first three columns of Table 3. The type and location of the reinforcing steel is given in Figure 2.

It should be noted that in Part 1 the concrete thickness for the reinforced items was 11 and 14 in.; in Part 2 it was 8 and 11 in.

The plain concrete items in Parts 1 and 2 each contained three transverse contraction joints. In Part 1 the thickness of the plain concrete items was 16, 18, and 20 in.; in Part 2 it was 12, 14, and 16 in.

From the foregoing description of the design and construction of the test sections, it can be seen that the chief variables involved are subgrade support, pavement thickness, and amount and position of reinforcing steel. The selection of test items, as well as their design and construction, fully utilized previous experience of the Corps of Engineers obtained in actual airfield pavement construction and in the design, construction, and testing of full-scale prototype test pavements.

The instrumentation installed in the test items was the minimum necessary for obtaining information that would allow comparison between individual test items, as well as with results obtained from previous tests. The instrumentation consisted of deflection gages located at the center of each reinforced test item, and at the center and near a transverse joint in each of the plain concrete test items. Strain gages were placed normal to the direction of traffic in the non-reinforced test items at positions similar to the deflection gages. The deflection gages were of the type that provide a record of

TABLE 3
SUMMARY OF ITEM PERFORMANCE, 100,000-LB TWIN-WHEEL LOADING

Item No.	Thickness, in.	% Steel	Initial Crack		Coverages At Failure	Total Applied
			Type	Coverages		
			(a) PART 1			
51	11	0.167	Trans.	500	3,500	4,654
52	11	0.335	Trans.	584	7,963	11,863
53	11	0.349	Trans.	584	7,963	12,509
54	11	0.349	Trans.	831	7,963	12,509
55	14	0.183	Long.	2,604	31,279	34,650
56	14	0.366	Trans.	5,197	——	34,650
57	20	0.000	——	——	——	34,650
58	18	0.000	——	——	——	34,650
59	16	0.000	Long.	7,600	10,000	11,441
			(b) PART 2			
60	12	0.000	Long.	1,674	9,250	10,082
61	14	0.000	Long.	3,867	17,000	30,000
62	16	0.000	Long.	10,082	25,000	30,000
63	11	0.349	Trans.	6,676	——	30,000
64	11	0.167	Trans.	1,337	30,000	30,000
65	8	0.352	Trans.	908	1,800	2,488
66	8	0.345	Trans.	230	2,400	2,488
67	8	0.173	Long.	255	800	1,000

the permanent or plastic movement, as well as the dynamic or elastic movement. The strain gages provided measurement of dynamic strains only.

TRAFFIC TESTS

The traffic quantity scheduled for each test section was a minimum of 30,000 coverages or until failure of an individual test item occurred. The test items were so arranged that failure would occur in such order as to leave the remaining items open for further traffic. As may be seen from Figure 2, this was accomplished by placing the weaker items at either end of the test sections.

The traffic simulated that on a primary taxiway for B-47 operation; that is, all traffic was confined to the center 7.4 ft of the 25-ft wide test sections. Because the tire prints of the 100,000-lb twin-wheel loading were about 15 in. wide, three trips of the twin-wheel loading produced one coverage over the 7.4-ft wide traffic lane. Therefore, 30,000 coverages on a test item required 90,000 trips of the load rig. Figure 3 shows the load rig and the marked traffic lane of one of the test sections.

The load rig was a specially designed box with provision for mounting various aircraft gear configurations in the center. Weights were contained in the forward and rear portions of the box to produce the required 100,000-lb loading. The load box was stabilized by a yoke with outrigger wheels and was powered by a Tournapull, as shown in Figure 4. Regular 56-in. aircraft tires similar to those used on the B-47 were mounted on 37½-in. centers. The tires were inflated to 187 psi, which made the tire contact area 267 sq in. The tire prints were elliptical, having an aspect ratio of 1.6.

Part 2 was tested from March 10 to June 19, 1956; traffic was applied to Part 1 from June 22 to October 25, 1956. Traffic was considered completed on each test section when all items had either failed or had the minimum of 30,000 coverages. An item was considered to have failed when the cracks began to spall.

During traffic, plot plan and photographic records of cracks were kept with reference to the number of coverages. The deflection gages provided a record of permanent and transient deflections of the test pavements during traffic. In addition, periodic cross-sections of each item were obtained from level readings.

Application of traffic was accelerated by using two load rigs, similar to that shown in Figure 4, joined back-to-back.

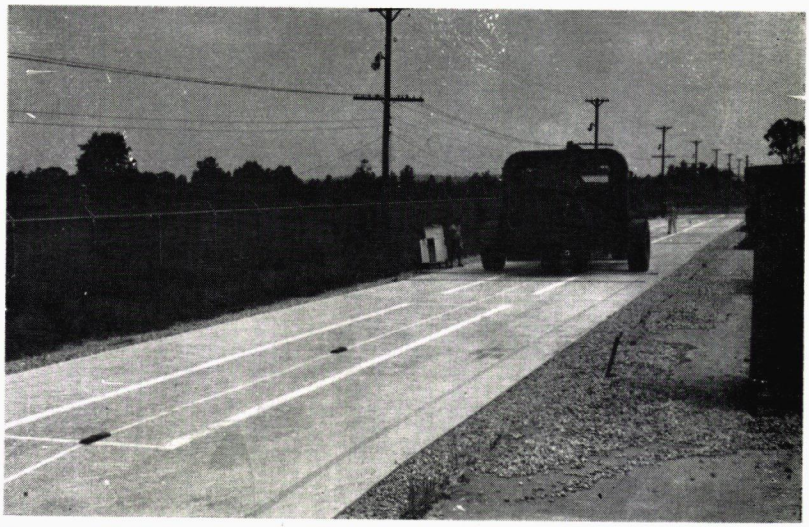

Figure 3. Load rig operating on Part 1. White lines show 7.4-ft wide boundaries of traffic lane at center of 25-ft wide pavement.

Figure 4. Specially designed load box with stabilizing yoke and Tournapull power unit.

This placed the two sets of twin load wheels 20 ft apart and they followed in the same path. The power unit of one rig pulled the assembly in one direction while the power unit on the other rig pulled the assembly back.

RESULTS OF TRAFFIC TESTS

Table 3 summarizes the more immediate results of the traffic tests. Columns 4 and 5 of this table indicate the type of initial crack and the number of coverages at which it occurred for each test item. In all cases the initial crack was longitudinal for the plain concrete items and was located close to the center of the traffic lane. In the case of the reinforced items, the initial crack was transverse with but two exceptions. These two exceptions occurred in Items 67 and 65, where the initial cracks were longitudinal and located just outside the traffic lane. The number of coverages at failure is given in Column 6 for each item, with failure being taken as the condition where

the crack or cracks present in the item start to spall. The final column of Table 3 gives the total number of coverages applied to each item.

Figure 5 shows typical crack patterns that develop in plain and reinforced concrete items. When traffic was continued on the reinforced concrete pavements beyond failure, areas about the size of the two tire prints are reduced to rubble, the maximum size being about 6 in. This occurred in Item 67 when 200 additional coverages were applied after failure at 800 coverages. In Part 1 the two reinforced 14-in. pavements withstood the full 30,000 coverages without failure, as did the two 11-in. pavements with similar reinforcement in Part 2. Also, in each case, the first crack appeared at about the same coverage level. This can be attributed to the higher bearing value of the subgrade of Part 2 and, partially, to the higher flexural strength of the concrete in Part 1. In Part 1 the 16-in. plain concrete item performed better than any of the 11-in. reinforced items, whereas in Part 2 the 11-in. reinforced items performed better than the 16-in. plain concrete pavement. In Items 52 and 66 the location of the reinforcement near the top and bottom of the pavement did not appear to have any advantage over similar amounts of steel located about 4 in. from the surface. The use of a filter course under Item 54 did not appear to provide any advantage under the conditions of the test.

Figure 6 shows a typical plot of pavement deflection vs coverages for Item 54. The lower curve gives the total deflection, but the upper curve indicates the permanent deflection, for one point in the traffic lane. The difference between the two curves shows the transient or dynamic deflection as the wheel load passes over the gage. The first crack appeared at a transient deflection of 0.115 in., and the first spall at 0.22-in. deflection.

Table 4 summarizes the maximum permanent, transient, and total deflections for the condition of the first crack and first spall. Also given is the coverage level for each condition. For purposes of comparison, deflections for items which did not crack or spall are included in the tabulation. As could be expected, the magnitude of the deflections was influenced more by the thickness of the pavement items than by the bearing qualities of the subgrade or by the presence or absence of reinforcement.

Figure 7 contains plots of permanent deflection for transverse sections across the reinforced items of Part 2 at 500 coverages. These plots show, to some extent, the effect of location and quantity of reinforcement for the 8-in. thick reinforced items. Item 67, which had the least amount of steel, had the greatest deflection at 500 coverages; Items 66 and 65, with twice as much steel, showed lesser deflection. In these last two items, the one with all steel at the center of the slab had less permanent deflection than the one where the amount of steel was the same but placed 2 in. from the top and 2 in. from the bottom of the pavement. However, Table 3 indicates that performancewise these two items were similar. It is believed that the greater permanent deflection of Item 66 over Item 65 can be attributed to the fact that the steel in the bottom of the slab was stressed beyond the yield point and lost some of its effectiveness.

The permanent deflection pattern transversely across the 14-in. reinforced items of Part 2 on the low bearing value subgrade was similar in configuration to that of the 11-in. reinforced items of Part 2, but slightly less in magnitude. In this case the controlling factor appeared to be the thickness of the pavement rather than the difference in subgrade support.

CONCLUSIONS

Of necessity, the conclusions drawn from these test results must be conservative. Further, due to the limited number of test items, results of prior tests of similar nature are used in conjunction with the evaluation of the performance of Parts 1 and 2 of the Channelized Test Track. One serious limitation is the absence of transverse joints in the reinforced items. This seriously limits con-

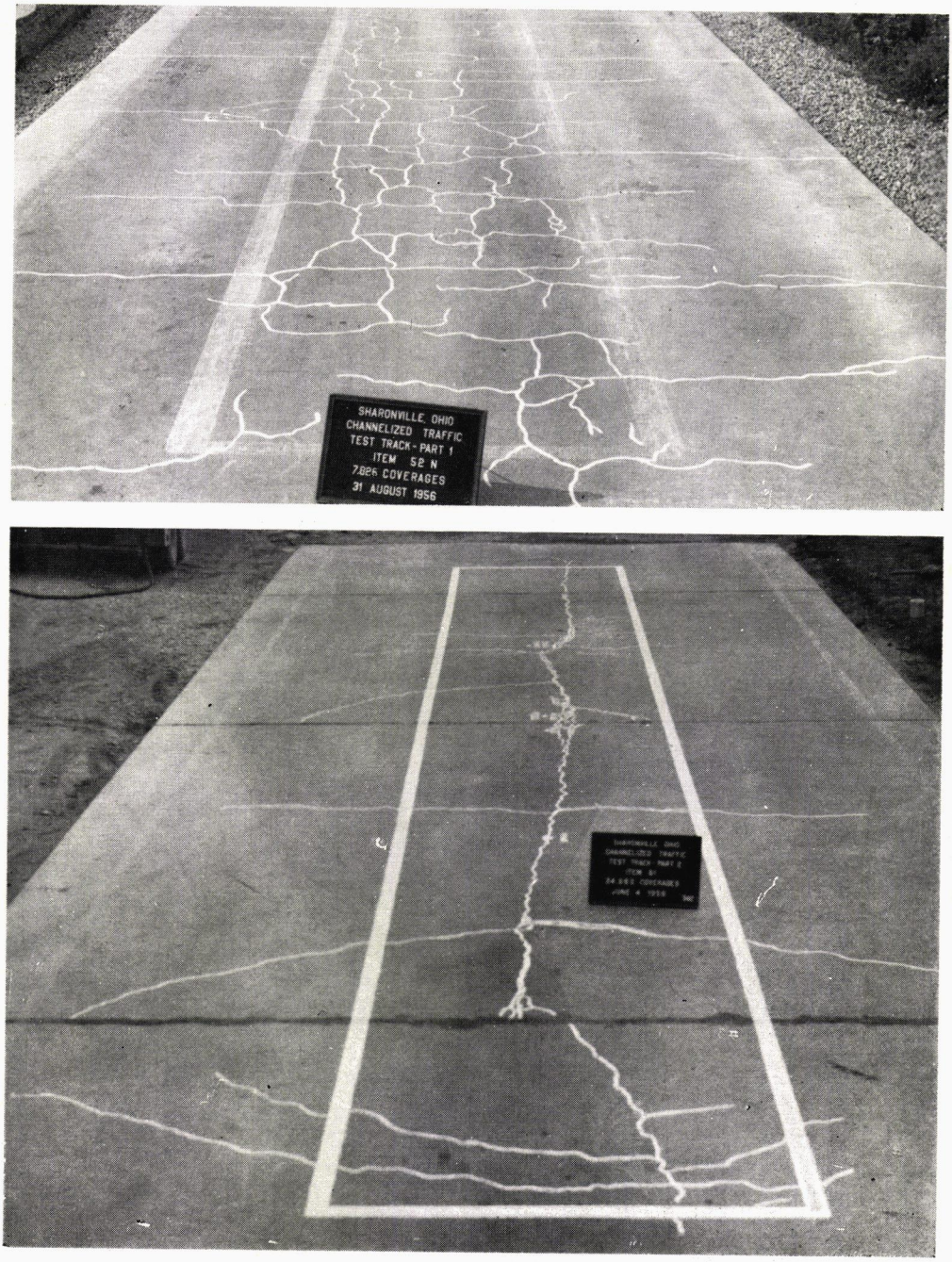

Figure 5. Typical failure of concrete pavement: (a) Item 52, 7,826 coverages, 11 in. thick, 0.335 percent steel each way; and (b) Item 61, 24,663 coverages, 16 in. thick, unreinforced.

TABLE 4
SUMMARY OF MAXIMUM DEFLECTIONS, 100,000-LB TWIN-WHEEL LOADING

Item No.	Pavement Thickness, in.	% Steel	First-Crack Deflection, in.				First-Spall Deflection, in.			
			Coverages	Permanent	Transient	Total	Coverages	Permanent	Transient	Total
					(a) PART 1					
51	11	0.167	500	0.05	—[1]	—	3,500	0.08	—[1]	—
52	11	0.335	580	0.05	0.05	0.10	8,000	0.08	0.05	0.13
53	11	0.349	580	0.06	—	—	8,000	0.12	—	—
54	11	0.349	830	0.04	0.11	0.15	8,000	0.17	0.16	0.33
55	14	0.183	2,600	0.04	0.06	0.10	31,000	0.07	0.07	0.14
56	14	0.366	5,200	0.06	—	—	—[2]	—	—	—
57	20	0	30,000[3]	0.17	0.06	0.23	—	—	—	—
58	18	0	30,000[3]	0.10	0.08	0.18	—	—	—	—
59	16	0	7,600	0.06	0.09	0.15	10,000	0.07	0.10	0.17
					(b) PART 2					
60	12	0	1,700	0.07	0.04	0.11	9,300	0.11	0.06	0.17
61	14	0	3,900	0.17	0.04	0.21	17,000	0.26	0.06	0.32
62	16	0	10,000	0.07	0.02	0.09	30,000	0.09	0.04	0.13
63	11	0.349	6,700	0.34	0.05	0.39	—	—	—	—
64	11	0.167	1,300	0.12	0.06	0.18	30,000	—	—	—
65	8	0.352	900	0.52	0.20	0.72	1,800	0.65	0.24	0.89
66	8	0.345	230	0.36	0.14	0.50	2,400	1.0	0.3	1.3
67	8	0.173	250	0.50	0.40	0.90	800	0.64	—	—

[1] Gage not working. [2] Not applicable. [3] Items 57 and 58 not cracked.

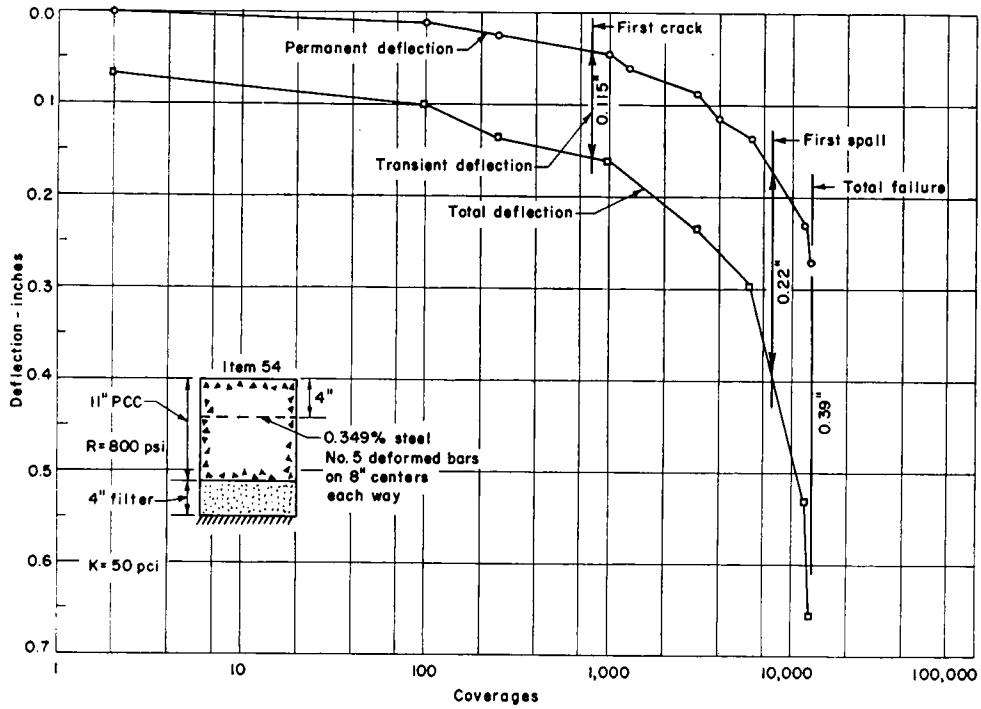

Figure 6. Deflection vs. coverages, reinforced concrete pavement, Item 54, channelized traffic test track, Part 1, Sharonville, Ohio.

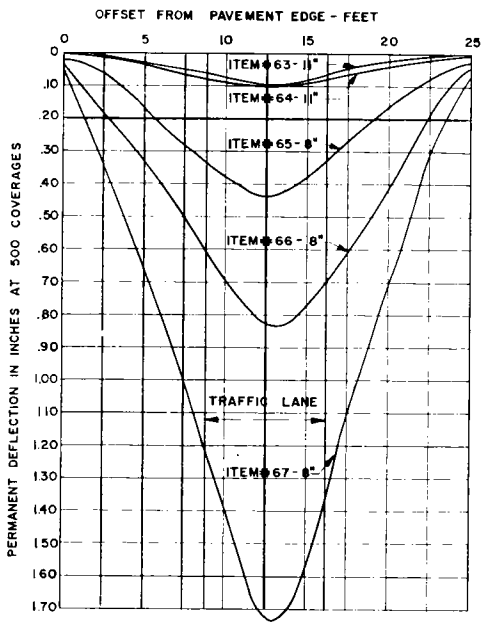

Figure 7. Average change in transverse section at 500 coverages of 100,000-lb twin-wheel load; reinforced items, Part 2.

clusions on which to base the design of reinforced concrete airfield pavements, where it is desired to reduce pavement thickness by the addition of reinforcement.

Prior to the design and construction of the channelized traffic test sections, a study of the results of previous traffic tests of plain and reinforced pavements (*8*) (*9*) was made for the purpose of determining possible reductions in pavement thickness where reinforcement was used. The results of this study are summarized in Figure 8, where the relationship between steel percentages and increase in effective slab thickness is shown. The effect of jointing both transversely and longitudinally is reflected in this plot. It will be noted that if plain and reinforced items having similar performance, as shown by Table 3, are plotted in Figure 8, the points will fall well below the curve. To illustrate the use of this curve, it will be noted that a 12-in. thick concrete pavement having 0.10 percent

steel area both transversely and longitudinally will perform as well as 13.8 in. of plain concrete. In Table 3 it can be seen that Item 54, which was 11 in. thick and had 0.35 percent steel each way, performed about as well as Item 59, which was a 16-in. plain concrete slab. This gives an increase in effective thickness of about 45 percent, whereas the curve of Figure 8 shows about 37 percent.

Figure 9 shows the tentative criteria established in March 1955 for designing concrete airfield pavements for a given coverage life. The design lines for a subgrade modulus equal to or less than 200 lb per cubic inch applies to Part 1, which had a subgrade modulus of 50 lb per cubic in.; the design line for a subgrade modulus of 300 lb per cubic inch applies to Part 2. The first line for a k of 200 lb per cubic inch or less predicts failure as a first crack in the pavement; the lower design line for a k of 300 lb per cubic inch allows the development of one to two cracks. This 4 percent reduction in thickness obtained in going from $k = 200$ or less to $k = 300$ resulted from observations of field performance and previous test track experience at Sharonville and Lockbourne. In these cases it was observed that when a pavement first cracked on a weak subgrade, due to traffic loading, the progression of failure was quite rapid. On subgrades of higher bearing value, the occurrence of the first crack could be reasonably well predicted by the ORDL curve of Figure 1 up to 5,000 coverages (this is identical to the k ≤ 200 design line of Figure 9), but the progression of

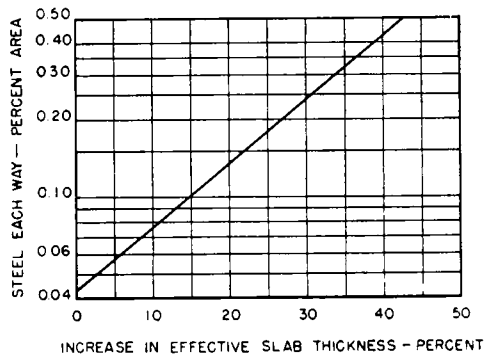

Figure 8. Effect of steel reinforcement on rigid pavements.

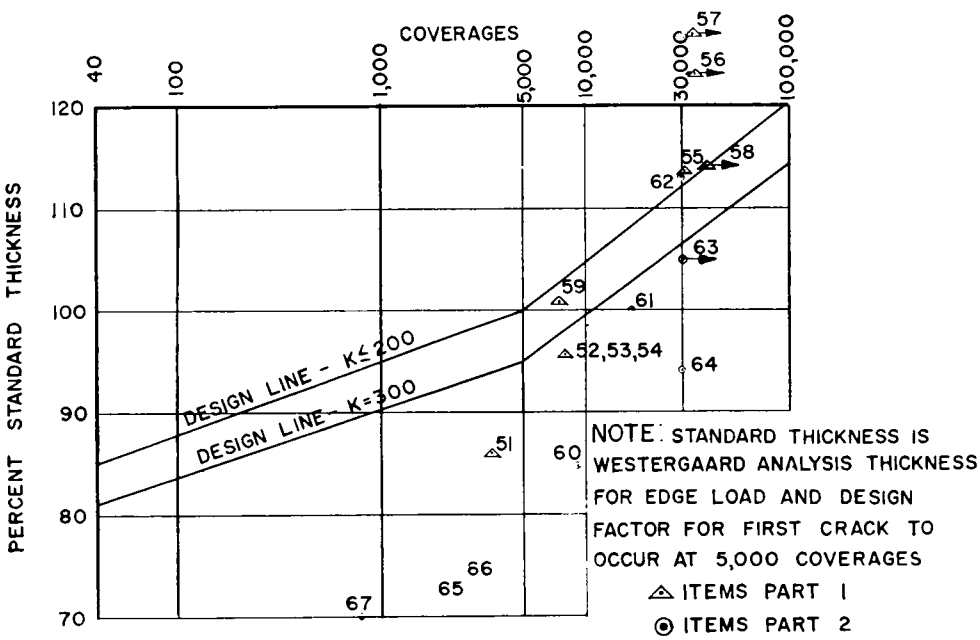

Figure 9. Design comparison with respect to coverages.

failure was much less rapid. Therefore, a greater advantage is given to subgrades of higher bearing value in the range of 200 to 500 lb per cubic inch when defining failure. This can be seen in the results of the present tests, shown in Table 3. Here the 16-in. plain concrete Item 59 first cracked at 7,600 coverages and was spalled and considered failed at 10,000 coverages. This item was on a subgrade having a $k = 50$ lb per cu in. Compare this with the 14-in. plain concrete Item 61 on a subgrade having a $k = 300$ lb per cu in. This item first cracked at 3,867 coverages, but did not reach a failed condition similar to that of Item 59 (at 10,000 coverages) until 17,000 coverages. Similar comparisons can be made between the 11-in. reinforced items in Parts 1 and 2.

Table 3 also indicates the effect of reinforcing steel in prolonging the life of a pavement after the first crack occurs. This is shown particularly well by the performance of 14-in. thick plain and reinforced Items 61 and 55 in Parts 2 and 1, respectively.

An attempt was made to summarize these effects by plotting the relative performance of each item in Figure 9. The items were all plotted as plain concrete designs by giving the reinforced items an equivalent plain concrete thickness based on the curve of Figure 8. With the exception of Items 62 and 55 the tentative criteria established in March 1955 are conservative from the standpoint of pavement life based on coverages or load repetition. Items 57 and 58 did not fail, and it was estimated that Item 64 was close to failure. All other points, with the exception of Item 59, were plotted at the coverage level indicated for failure in Table 3. Item 59 is plotted at the coverage level of the first crack and falls very close to the appropriate design line.

From considerations of grade change on runway ends when three thicknesses of pavement are used at 500-ft intervals, it is often desirable to reduce the design thickness of plain concrete by the use of reinforcement. This is particularly desirable when using rigid-type overlays to strengthen existing rigid or flexible pavements. The curve of Figure 8 has been tentatively proposed for accomplishing this with the following limitations:

1. No reduction in thickness shall be allowed for percentages of steel less than 0.05.
2. No further reduction in required thickness for non-reinforced rigid pavement shall be allowed over what is indicated for 0.5 percent reinforcement, regardless of the percentage of steel.
3. All longitudinal construction joints shall be doweled.
4. All transverse contraction or expansion joints shall be doweled.
5. The reinforcement steel shall not carry through any joint of the overlay, with the exception of longitudinal dummy joints, which may be required to match a joint in the base pavement.
6. The minimum thickness of reinforced rigid overlay shall be 6 in.
7. The maximum distance between transverse joints of a reinforced pavement on natural subgrade or base course shall not exceed 100 ft.
8. The percentage of steel used shall be the same both transversely and longitudinally.
9. Reinforcing steel shall be placed at a depth of $\frac{1}{4}h + 1$ in. from the pavement surface. where h is the thickness of the pavement in inches.

The following conclusions are based on the tests reported in this paper and on previous tests referred to herein:

1. Reinforcing does not materially affect the number of load repetitions required to produce the first crack in a concrete pavement.
2. The rate of progression of cracking after an initial crack is much slower in reinforced pavement than in non-reinforced pavement.
3. The cracks developed in reinforced pavement are held tightly together.
4. Nominal amounts of reinforcement in concrete pavements increase their useful life and may be used to reduce the thickness of concrete within the limitations given in the preceding discussion.

5. There is no advantage in placing reinforcement in the amounts considered near the bottom of a pavement slab.

6. Subgrade moduli in excess of 200 lb per cubic inch provide benefits by increasing pavement life over and above that indicated by the Westergaard theory.

7. The thickness of concrete for airfield pavements can be reduced in the major areas of the runway interiors and aprons by as much as 12 percent over that required for primary taxiways and runway ends.

ACKNOWLEDGMENT

The tests reported in this paper have been carried out by the staff of the Ohio River Division Laboratories as a part of the Corps of Engineers, U. S. Army, Rigid Pavement Investigational Program. This 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. WESTERGAARD, H. M., "New Formulas for Stresses in Concrete Pavements of Airfields." *Trans. ASCE,* 113:425 (1947).
2. PHILIPPE, R. R. AND MELLINGER, F. M., "Structural Behavior of Heavy Duty Concrete Airfield Pavements." *Proc. Highway Research Board,* 31:87-100 (1952).
3. HATT, W. K., "Researches in Concrete." Purdue Univ. Bulletin, 24:44-55 (1925).
4. CLEMMER, H. F., "Fatigue of Concrete." *Proc. ASTM,* 22:II, 408-419 (1922).
5. KESLER, C. E., "Effect of Speed of Testing on Flexural Fatigue Strength of Plain Concrete." *Proc. Highway Research Board,* 32:251-258 (1953).
6. U. S. Army, Corps of Engineers, "Airfield Pavement Design, Rigid Pavements." Engineering Manual for Military Construction, Part XII, Chapter 3 (Mar. 1954).
7. OBERT, L., AND DUVAL, W. I., "Discussion of Dynamic Methods of Testing Concrete with Suggestions for Standardization." *Proc. ASTM,* 41:1053 (1941).
8. PHILIPPE, R. R., "Use of Reinforcement in Concrete Pavements." *Proc. Highway Research Board,* 28:92-101 (1948).
9. U. S. Army, Corp of Engineers, "Lockbourne No. 1 Test Track, Final Report." (Mar. 1946).