

USE OF REINFORCEMENT IN CONCRETE PAVEMENTS

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SYNOPSIS

Four years ago the writer presented to the Highway Research Board an outline of the investigations of rigid pavements being conducted by the Corps of Engineers, U. S. Army.¹ In the interim these investigations have yielded many results worthy of discussion. Not the least interesting is the comparison of performance between reinforced and non-reinforced concrete pavements. Results of tests to date indicate that the use of reinforcing steel in concrete pavements produces structural benefits which are particularly advantageous in prolonging the useful life of overloaded pavements. In the cases studied however, it appears to be much cheaper to obtain at least equal benefits by increasing the thickness of pavement rather than adding the necessary quantities of reinforcing steel. It is concluded that for the conditions surrounding the tests, the use of reinforcement is not to be recommended.

DESIGN OF THE TEST PAVEMENT

Wheel Load: The design and production of the XB-36 prompted the investigation of the design of pavements for single wheel loads of 150,000 lb. The original version of this aircraft was mounted on two main gears, each consisting of a single tire and strut which, with a gross weight of aircraft of 300,000 lb., accounts for the wheel load. Later versions of this aircraft (the B-36) are mounted on two main gears, each consisting of twin-tandem tires and wheels mounted on a single strut, see Figure 1. Although the effects of this gear have been thoroughly investigated, these results are beyond the scope of this paper.

Method: Based upon the 150,000-lb. wheel load, design methods and observations were extrapolated to produce best estimates of design requirements for this load. These estimates were bracketed, resulting in the layout shown on Figure 2, built in the fall of 1944 in generally good weather taking 2½ months, at the Lockbourne Army Air Base near Columbus, Ohio. Non-reinforced slabs included for test are 15, 18, 20 and 24 in. thick with only certain 15-in. slabs supported by base course. The reinforced slabs are 12, 14, 15 and 16 in. thick and were placed directly on natural subgrade excepting the 15-in. slab which was supported by a base course. The steel included

ranges from 0.13 to 1.84 percent of the cross sectional area of the concrete; details are given in Table 1. The details of the steel, as distributed in accordance with load stresses (Table 1), are shown on Figure 3. The plain concrete pavement is divided by joints into slabs of two sizes; 12.5 ft. by 25.0 ft. and 25 ft. square. The reinforced pavement, with one exception is divided into slabs 25 ft. by 50 ft. Seventeen different joint systems are also included. Matching and auxiliary slabs were also included but not loaded for observation during traffic.

Subgrade: The subgrade at Lockbourne is a uniform silty clay containing a little sand and a trace of fine gravel. It has a Casagrande classification CH. Dry unit weight in place averaged 95 lb. per cu. ft., with a water content of 19.1 percent. The general physical properties of the subgrade are as follows:

Liquid Limit	= 42.2 percent
Plastic Limit	= 24.1 percent
Foundation Modulus (at field moisture)	= 114-156 lb. per cu. in.
Undisturbed soaked C.B.R.	= 4

The construction season was dry and the subgrade was found in unusually dry state. Subsequent measurements indicated that the water content of the subgrade increased to 24 percent with a corresponding decrease in foundation modulus to about 100 lb. per cu. in. The normal effective water table is but a few inches from the surface.

¹ R. R. Philippe "Structural Behavior of Concrete Airfield Pavements—The Test Program" *Proceedings*, Highway Research Board 1944.

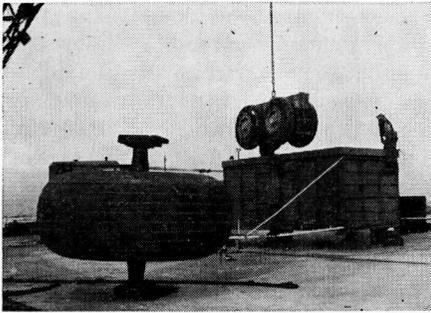


Figure 1. Loading Rig Used for Traffic Tests at Lockbourne Army Air Base. In left foreground is 110-inch wheel and axle, in background is twin-tandem gear mounted on single strut.

CONSTRUCTION

Placement Difficulties: Even though the construction of the slabs so designed was without precedent and was accomplished only by many unusual measures, these are not pertinent to the subject. Some difficulties however were encountered in placing the heavy wire mesh due to a permanent spring in the mats resulting from their manufacture. In some cases, it was necessary to keep the center of the mat high to keep the ends right and then work the center down as placement of concrete proceeded. Due further to limitations of available mesh it was necessary to resort to multiple layers which so closed the openings as to

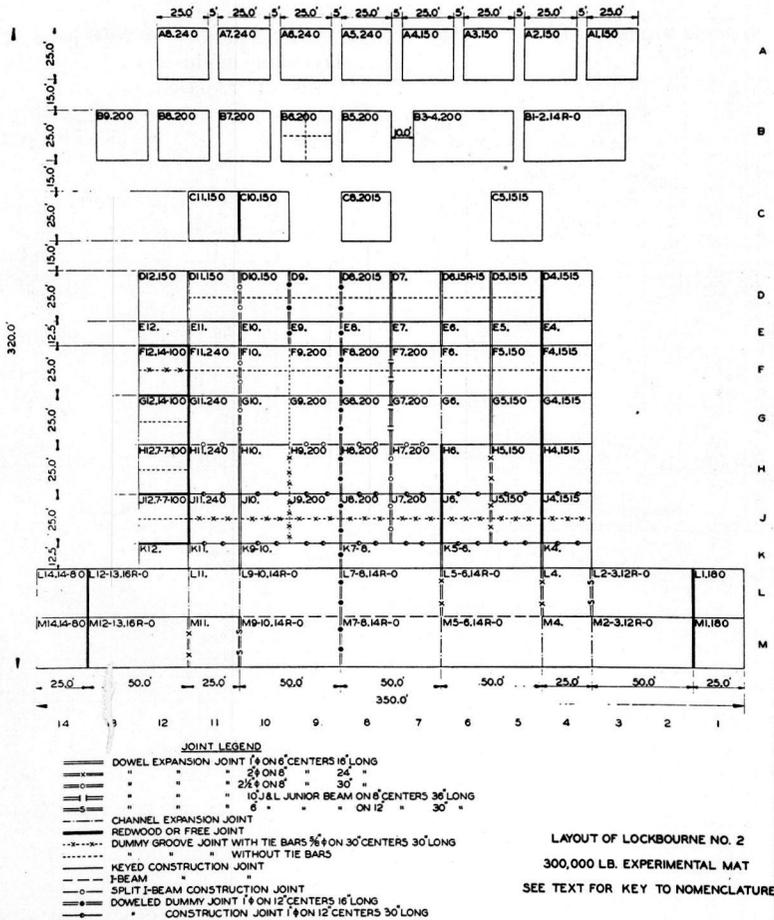


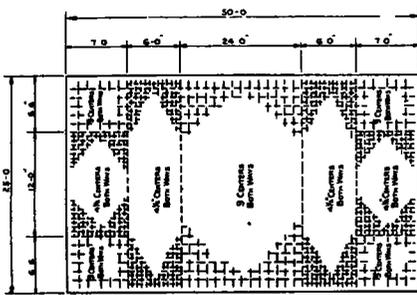
Figure 2. Layout of Lockbourne No. 2, 300,000 Pound Experimental Mat. The first two numbers following decimal point indicate slab thickness, third and fourth numbers denote thickness of base course.

TABLE 1
 LOCKBOURNE NO. 2—300,000-LB. EXPERIMENTAL
 MAT
 DISTRIBUTION OF REINFORCING STEEL

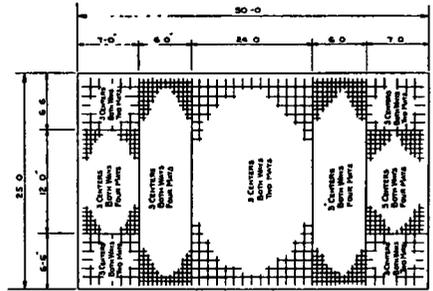
Slab Designation	Thickness of Concrete	Percent Area of Steel	Wire Gage No. or Reinforcing Bar Diameter	Weight per 100 sq. ft.		Wire or Bar Spacing	Number of Reinforcing Layers	
				Top	Bottom		Top	Bottom
<i>Wire Mesh Reinforcing</i>								
L2-3	12	0.82	0	425	425	3 x 3	2	2
L5-6	14	0.26	0	150	150	4 x 4	1	1
L7-8	14	0.70	0	425	425	3 x 3	2	2
M5-6	14	0.13	0	150	None	4 x 4	1	None
M9-10	14	0.35	1	265	265	4 x 4	2	2
L9-10	14		0 & 2	Distributed in Accordance with Load Stresses				
L12-13	16		0 & 2					
<i>Deformed Bar Reinforcing</i>								
M2-3	12	1.84	3	Distributed in Accordance with Load Stresses				
M7-8	14	1.43	3					
M12-13	16		1					

make it necessary to add water to the concrete for workability in embedding the mesh. As the result, some honeycomb was found at exposed pavement edges in the region of the mesh. Also, slight irregularities in mesh manufacture resulted in some uneven spacing in the multiple layers as placed. Although no structural variations are known to have taken place in installing bars, their placement too proved to be a tedious task. The following are the average of the measured properties of the concrete—28 day results:

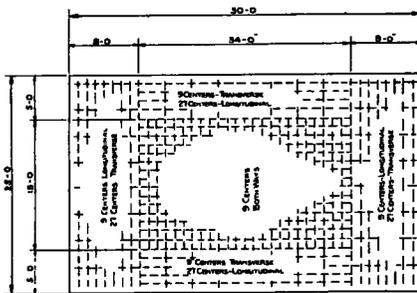
- Average placement slump = 2½ in.
- Flexural Strength = 750 psi.
- Comp. strength (Mod. cube) = 5950 psi.
- Dynamic modulus of Elasticity = 5.20 × 10⁶
- Density = 150.5 lb. per cu. ft.



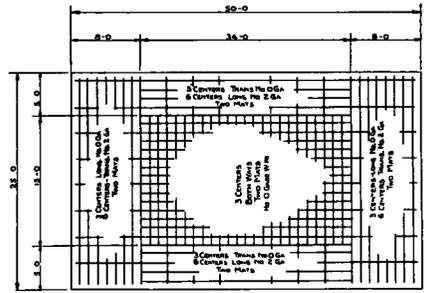
TOP STEEL
 1/2" ROUND REINFORCING BARS - DISTRIBUTED DESIGN



TOP WIRE
 STEEL WIRE NO. 0 GAGE - DISTRIBUTED DESIGN



BOTTOM STEEL
 1/2" ROUND REINFORCING BARS - DISTRIBUTED DESIGN



BOTTOM WIRE
 STEEL WIRE NO. 0 GAGE - DISTRIBUTED DESIGN
 EXCEPT AS INDICATED

Figure 3. Details and Distribution of Steel Reinforcing in Reinforced Concrete Slabs at Lockbourne Army Air Base.

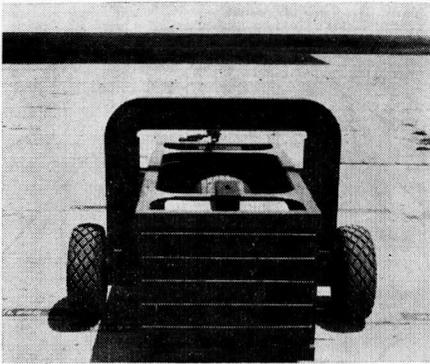


Figure 4. Loading Rig Used for Traffic Tests at Lockbourne Army Air Base. Rig is mounted on single wheel and loaded to produce 150,000 pounds on wheel assembly. Outrigger wheels are used for maneuvering.

were completed. A coverage is defined as complete application of the tire footprint area over the entire area of the test pavement.

At periodic intervals many pertinent measurements were made, including deflections and strains under the moving wheel load, temperature and temperature strains, and joint openings. The search for cracks was continuous, each crack being marked as it was discovered.

One coverage was completed before another was started so that it can be concluded that all 8,000 sq. yd. of surface were subjected to the same amount of traffic during variable weather and traffic conditions day and night, except when portions of the pavement failed so badly to disrupt, and thereby discontinue, traffic.

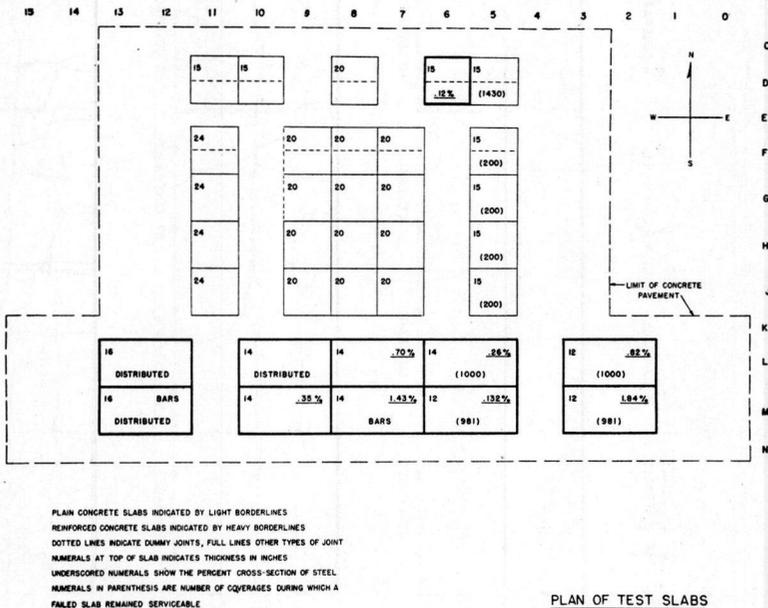


Figure 5. Test Area at Lockbourne Army Air Base Showing Coverages Required for Causing Failure of Certain Slabs.

TESTS OF THE PAVEMENT

The tests were carried on by observing the results of traffic on these pavements with a 150,000-lb. wheel load. A rig was built for this purpose and is shown on Figure 4. The rig traveled at about 5 m.p.h. and operated more or less continuously for a period of eighteen months, starting August 1945 and ending February 1947, at which time 2,000 coverages

TEST RESULTS

Complete Failure: Complete failure is defined as that condition where the slab becomes so badly distressed as to make further traffic with the testing rig inadvisable. The amount of traffic causing failure of the various test slabs is shown on Figure 5. The numerals in parenthesis on each slab represent the number of coverages at which traffic was discontinued.

15-INCH PLAIN CONCRETE SLABS ON 15" GRAVEL BASE
150,000 POUND WHEEL LOAD TRAFFIC

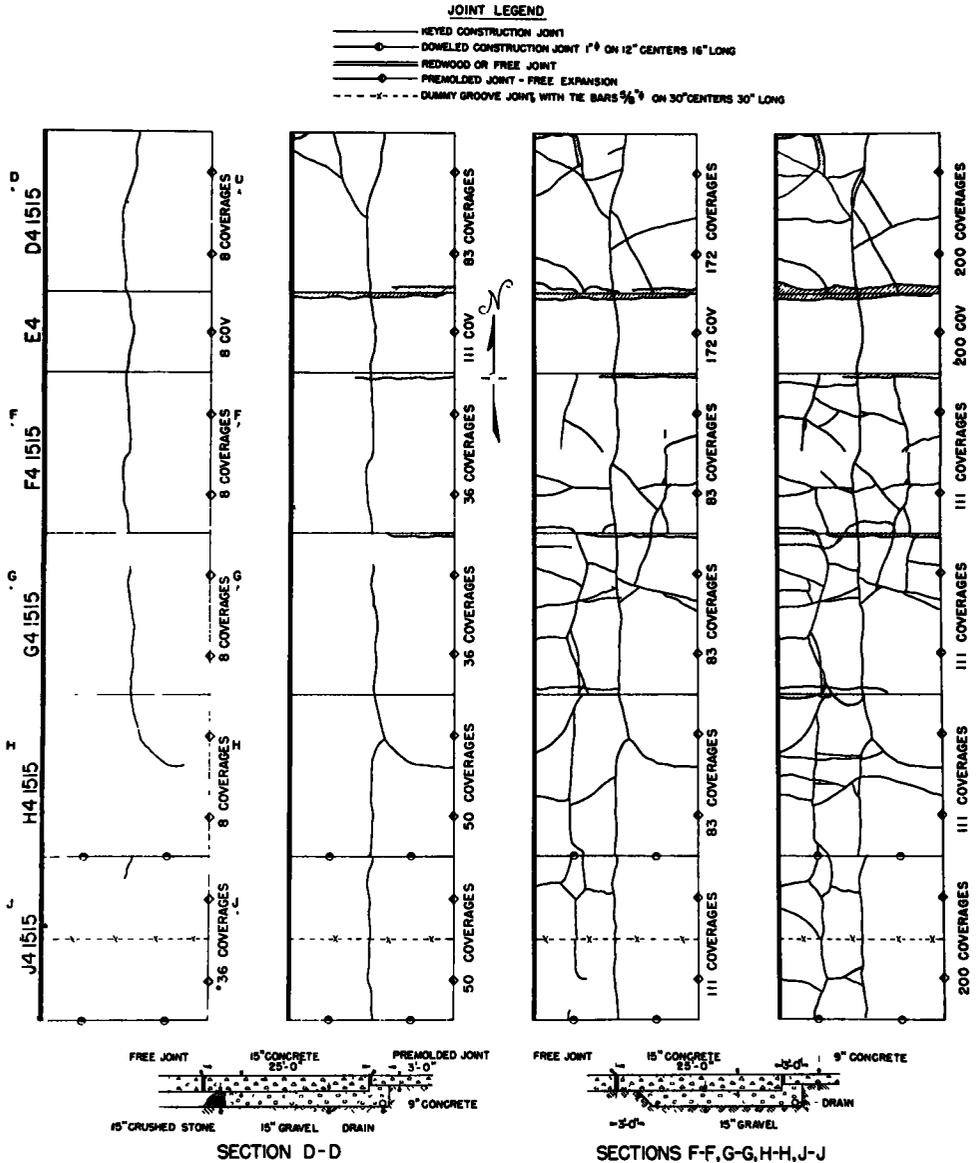


Figure 6. A Typical Crack Pattern Development at Lockbourne Army Air Base of a 15-inch Non-Reinforced Slab.

If no such numerals are given, the total traffic was carried. The numerals at the upper left hand corner show the thickness of the slab in inches. The numerals underscored give the percent of steel in the slab. In summary, the 15-in. non-reinforced slabs, with and without

base course, all 12 in. reinforced slabs, and the lightly reinforced slabs (less than 0.35 percent steel) failed.

Structural Failure: Before defining a structural failure it may be well to separate between

the reaction of a non-reinforced and a reinforced slab. Figure 6 shows the somewhat typical development of a crack pattern for a 15-in. non-reinforced slab on a 15-in. base course; the destruction is rapid and complete.

therefore, is not readily definable, as is well illustrated by Figure 7 showing a typical development. It is assumed however that when the pattern of cracks and the visible or measured deflections continue to enlarge with time,

12-INCH REINFORCED CONCRETE SLABS
150,000 POUND WHEEL LOAD TRAFFIC

JOINT LEGEND

- KEYED CONSTRUCTION JOINT
- PLAIN BUTT JOINT
- REDWOOD OR FREE JOINT
- KEYED CONSTRUCTION JOINT 1/2" x 4" TE BARS ON 18" CENTERS 30" LONG
- CHANNEL EXPANSION JOINT
- S DOWEL EXPANSION JOINT 6" JBL JUNIOR BEAM ON 12" CENTERS 30" LONG
- X DOWEL EXPANSION JOINT 2" x 4" ON 8" CENTERS 24" LONG

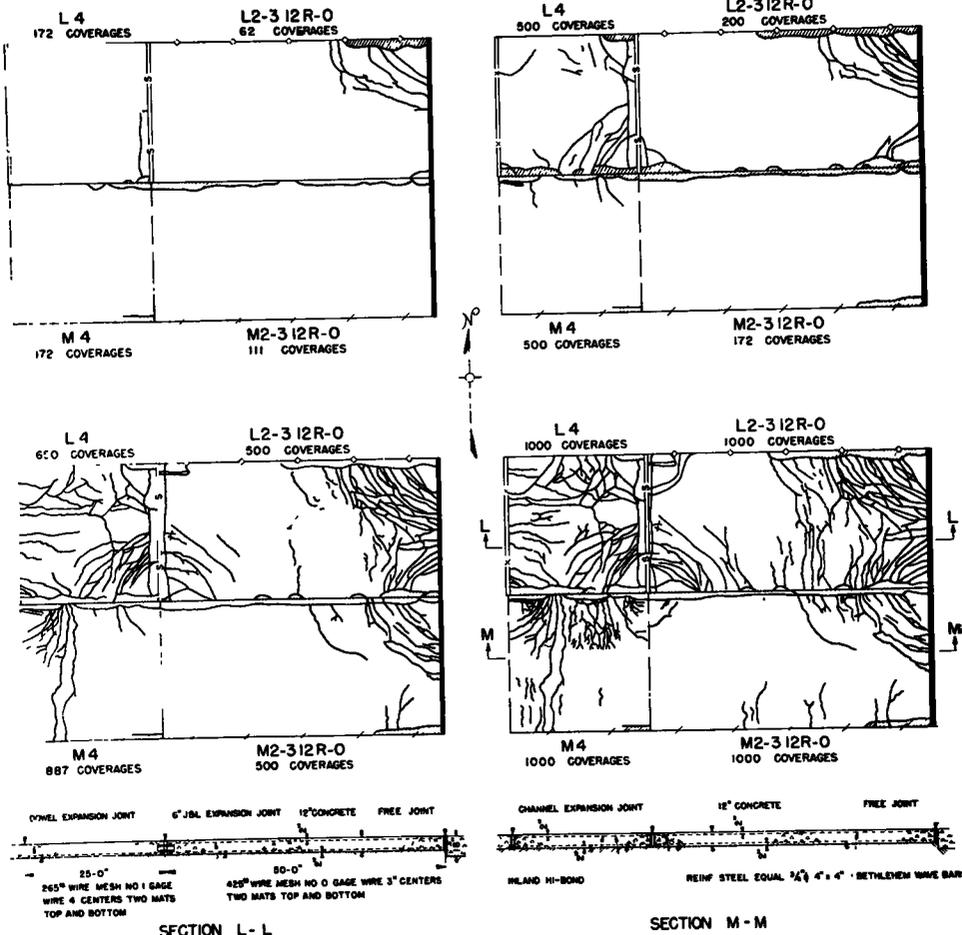


Figure 7. A Typical Crack Pattern Development at Lockbourne Army Air Base of a 12-inch Reinforced Slab.

It has been judged that the first slab-dividing crack is the condition of structural failure. In contrast, the development of a crack system is essential to the mobilization of stress in the steel of a reinforced slab. Structural failure,

the slab has failed. This admittedly is subject to judgement, which, in this case, will consequently prove of minor importance. Let us consider therefore, the development of overall crack patterns as shown by Figure 8 and

Figure 9. Figure 8 shows the crack pattern as it was observed after 620 coverages. Note the patterns already developing for the 12- and 14-in. reinforced slabs. Note also, the early

failure. It is further evident that the reinforced slabs are showing greater signs of distress, influenced undoubtedly by the pressure of a keyed construction joint. These results,

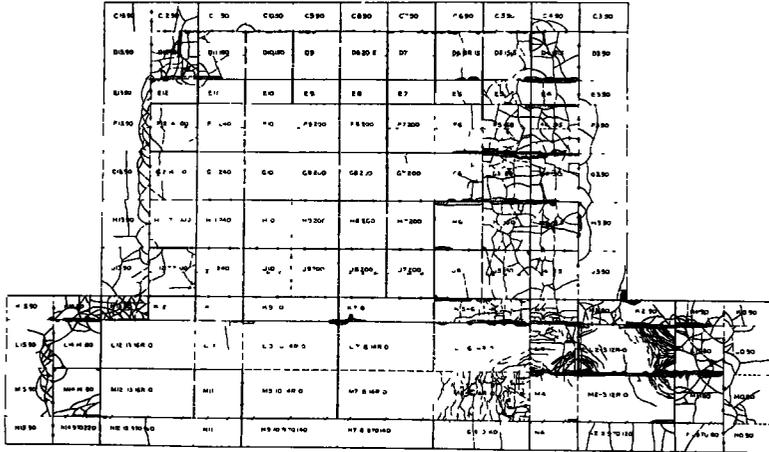


Figure 8. Overall Crack Pattern Development at Lockbourne Army Air Base. Test area has been subjected to 620 coverages of 150,000-pound wheel load traffic.

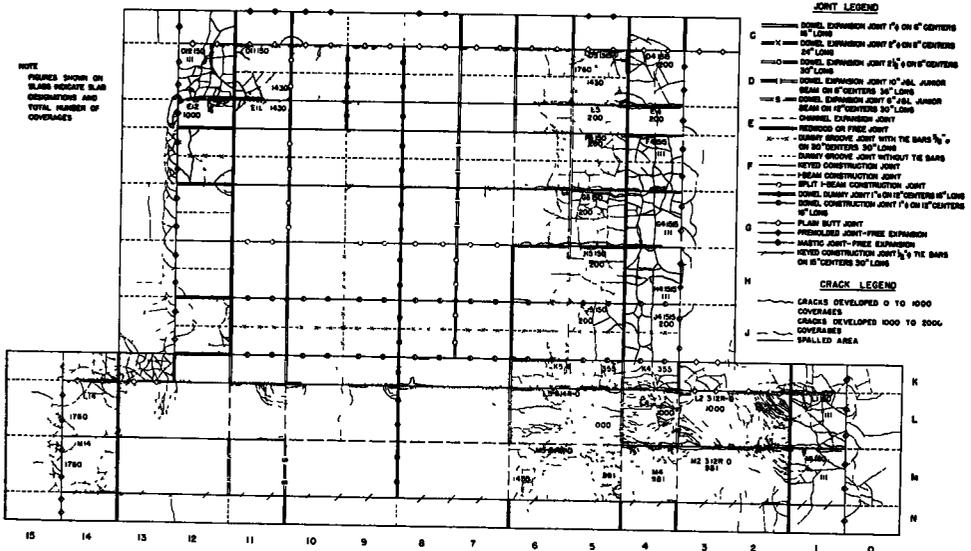


Figure 9. Final Crack Pattern Development at Lockbourne Army Air Base. Test area has been subjected to 2000 coverages of 150,000-pound wheel load traffic.

defects in the keyed construction joint which has proven a particular offender in reinforced pavements. Figure 9 shows the development after 2,000 coverages. Observe that none of the 20- or 24-in. non-reinforced slabs show

again summarized, show the 20- and 24-in. non-reinforced slabs to be satisfactory, the 14-in reinforced slabs with 0.35 percent steel or more and the 16-in. reinforced slabs, to be probably satisfactory.

DISCUSSION OF THE RESULTS

Structural Benefits: The information presented herein is but a very small part of all that obtained which is not even yet digested in form for concerted academic study. Of more immediate interest is the basic question of whether or not the use of reinforcement is beneficial. Structurally speaking the answer is undoubtedly "yes". Certainly, 12-in. reinforced pavements performed more satisfactorily than 15 inch non-reinforced pavements. Fourteen inch suitably reinforced slabs approached the performance of 20-inch non-reinforced slabs. Any more precise comparison is masked by the undue influence of keyed construction joints in reinforced pavements.

Life After Initial Break: Probably more significant in this study is the tenacity of reinforced pavement after initial overload. Progression of failure afterwards is very slow, with 12-in. reinforced pavements showing five-fold or more life under traffic than 15-in. non-reinforced pavements. It is regrettable that the benefits so indicated cannot be evaluated in terms of insurance against future overloads.

Cost Comparisons: These results indicate that of the slabs tested, the 20-in. non-reinforced slabs were satisfactory, and the lesser design, 15-in. non-reinforced slabs were unsatisfactory. On the other hand, 14 in. of concrete, reinforced top and bottom with 265 lb. wire mesh, or $\frac{7}{8}$ -in. 6 by 6 bars, performed satisfactorily, while 14 in. of concrete reinforced with 150 lb. wire mesh top and bottom did not. If we consider these two satisfactory designs as equivalent, then the cost of adding 6 in. of concrete should be compared with the cost of 265 lb. mesh, top and bottom. Bid prices on Patterson Field pavements were \$4.25 per sq. yd. for 21 in. pavement and \$4.95 per sq. yd. for 25-in. pavement; indicating 17.5¢ per yard for an added inch of thickness. Other comparative studies on costs in this range of thickness indicate a maximum probable of 20¢ per added inch per square yard. The probable maximum total cost of adding 6 in. of concrete at \$1.20 per sq. yd. is compared with the steel cost of \$2.80 per sq. yd. for the 265 lb. mesh, top and bottom (based on steel mesh at 6¢ per lb.). If steel placement costs are added, it is safe to say that the ratio of cost of additional concrete to steel is at least three to one.

CONCLUSION

The results of these investigations indicate that the use of reinforcement steel in concrete pavements produces structural benefits which are particularly advantageous in prolonging the useful life of overloaded pavements. In this case, however, it appears to be much cheaper to obtain at least equal benefits by increasing the thickness of pavement. It is concluded, therefore, for the conditions surrounding these tests, that the use of reinforcement is not to be recommended.

ACKNOWLEDGEMENT

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DISCUSSION

T. J. KAUER, *Director, Ohio Department of Highways*—In considering the comments made by Mr. Philippe in comparing plain and reinforced concrete it should be remembered that the data are the results of accelerated tests and that cracks were evidently given the same weight in comparing sections regardless of the width of the crack. Also no mention was made as to whether or not pumping was a factor. We believe that the conditions of concrete slabs for airports and pavements, assuming sound materials are used, are dependent primarily on age, type of subgrade and slab design.

The effect of age on concrete slabs varies considerably depending greatly on the effectiveness of the maintenance. Again assuming that sound materials are used and that the concrete is placed at air temperatures above 75 F. blowups are caused almost if not entirely by the gradual loss of expansion space provided by joints and cracks because of infiltration of incompressible material.

In our opinion the purpose of distributed reinforcement is not to increase beam-strength of the uncracked slab but merely to hold in tight interlock the faces of any cracks that may occur. Distributed reinforcement conserves the original load-carrying capacity of the slab by preventing the development of

wide open cracks when contraction occurs which in turn means that infiltration is kept to a minimum and prevents a crack from creating what would otherwise be two independent and free slab edges.

In February of 1949 some engineers of the Department inspected Lockbourne No. 2 and made the following observations:

"The 15-in. plain concrete without base course has failed. According to Mr. Philippe's paper, failure occurred at 200 coverages. Although not shown in his Figure 5, five of the sections of 15-in. concrete on 15-in. base course failed at 111 to 200 coverages. One 15-in. plain concrete on 15-in. base course section failed at an average of 1595 coverages. Many of the cracks in these sections are open, spalled and deformed. However, the 15-in. reinforced (0.127 percent steel) section is still serviceable after 2000 coverages. The cracks in this section are tight and show no deformation. There is slight spalling at one crack."

"Mr. Philippe reports that the 12-in. reinforced (0.82 and 1.84 percent steel) sections have failed, the lighter reinforced section after 1000 coverages and the heavier after 981 coverages. These two sections are separated by a keyed joint. There is some disintegration in the joint area and there are numerous cracks in the slabs. However, these cracks are tight and there is no spalling or visible deformation. In our opinion, the more heavily reinforced 12-in. sections are in better condition than the more lightly reinforced 15-in. section. Also, the more heavily reinforced is the better of the two 12-in. sections. In this comparison we have discounted cracks that are barely visible and have only considered the general appearance of the slab. We believe that, if failures in the area of the keyed joint had not occurred, the 12-in. reinforced section would have withstood additional coverages."

"In comparing the two 14-in. reinforced sections without base course and approximately the same number of coverages, the slab with 0.26 percent steel was considered to be in better condition than the slab with 0.132 percent steel. Here again, if it had not been for failures in the joint area, the more heavily reinforced section might have withstood additional coverages."

We agree that it may be more economical to increase the pavement thickness than to increase the supporting power of the base beyond certain limits. However, we should not forget that proper base courses under concrete pavements serve other purposes, such as eliminating pumping.

As to relative cost of extra thickness of concrete and distributed reinforcement, few figures are available. We question if the differential shown on the Patterson Field project would hold true at least on highway projects. The cost of distributed reinforcement (approximately 52 lb.) used in our highways would pay for less than 1½ in. additional thickness of concrete.

R. R. PHILIPPE, *Closure*—It must be stated that the studies in question were conducted on thick pavements with a wheel load of 150,000 lb. It is maintained that pavements of this type are in a different structural category than normal lightly loaded highway pavements. With heavy wheel loads the emphasis is on structural design, with questions of durability and workability of concrete taking an important but secondary position. In the past, the reverse has been true in highways; but gradually increasing highway loads are changing that situation.

Mr. Kauer rightfully introduces questions of size and type of crack, pumping, weathering, blowups and base course, but the author purposely avoided the discussion of these factors on the basis that each of these and other factors will be discussed in future papers. This presumably is a right of authorship where the choice exists of how inter-related material shall be presented. The discussor makes a particular point of introducing the question of base course, provoked possibly by the author's verbal opinions, but it is requested that discussion of this subject be postponed until the factual information is presented.

There is no particular disagreement with the results of the inspection by the Ohio Department of Engineers made in February 1949; as a matter of fact the results are verification of the information contained in the basic paper. What is not apparent from either source is the progressive increase of measured deformation with continuing traffic of the cracked sections; indicators of ultimate failure. Furthermore, there is little to be gained in

speculating what would have happened had joints not been present, for joints are a necessary evil and part of any rigid pavement.

Finally, the question of comparative costs is always subject to discussion. In the case of heavy airport pavements the accuracy of cost comparison is not too important because the apparent advantage shown by these studies of non-reinforced over reinforced

pavements of the same approximate cost is great. In the realm of highway pavements the evidence is not yet conclusive. Let us agree with Mr. Kauer's statement that "the cost of distributed reinforcement used in our highways would pay for less than 1½ in. additional thickness of concrete." Is there no doubt as to which alternative would be best under any given conditions?

THE FACTORS UNDERLYING THE RATIONAL DESIGN OF PAVEMENTS

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SYNOPSIS

A discussion of the pavement design problem is presented in four parts:

1-A. *Analysis of the pavement design problem.* A chart is presented illustrating the process of analysis by means of which relationships are established between all of the major and minor factors involved. The chart demonstrates that the problem of designing an adequate and economical pavement is logically subdivided into three separate or distinct problems and the solution to each must be reached by different methods and accomplished by different processes. The chart serves to illustrate and identify the essential properties or characteristics of traffic, pavement and foundation soils, all of which must be evaluated in order to accomplish an intelligent and comprehensive design.

1-B. *Behavior patterns developed in masses of granular materials under load.* The history of soil technology is traced briefly and comparisons made between the attempts to reach a solution by mathematical analysis and the empirical approach employing the experimental method. The meaning of certain common terms is discussed in order to focus attention upon the fact that soils consist of fragmentary matter and that soils mechanics involves the study of the conditions which exist at the point of contact between adjacent particles. The term "failure" as applied to soil masses is considered inadequate and misleading and it is emphasized that the capacity of soil materials to support loads is more adequately characterized as the "resistance" value. Resistance of soils or granular materials is due to friction between the solid particles and the cohesion or tensile strength furnished by films of moisture. Liquid films also cause lubrication and this reduction in particle friction is often responsible for an over-all reduction in resistance value. Diagrams and photographs are shown to illustrate the flow patterns developed by sands or clay materials under load.

2. *Mathematical relationship.* It is shown that traffic load effects are most nearly comparable to a strip loading and the most probable planes of slip are calculated for soils possessing different proportions of friction and cohesion.

Analysis of test track data indicates that the required thickness of pavement and base is proportional to the width of the loaded area, to the average tire contact pressure and to the log of the number of axle load repetitions.

The ability of the basement soil and the pavement to carry loads is directly proportional to the resistance value of the soil and to the bending strength or modulus of rupture of the pavement.

3. *Testing of soils and bituminous mixtures.* This part covers test procedures for evaluating and obtaining quantitative measurements of the essential properties of soils, photographs and sketches of test equipment, including special compactor, stabilometer, cohesiometer and swell pressure devices, together with