CORRECTING PAVEMENT PUMPING BY MUD JACKING

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SYNPOSIS

This report covers some field experiments designed to correct the pumping action of rigid pavement slabs. In 1942 a performance survey on a portion of U.S. 30 between U.S. 41 and Valparaiso, Indiana, was made by representatives of the Joint Highway Research Project covering detailed analyses of pumping conditions on twenty-four miles of this road. Among other things the results of the survey showed that all of the experimental subgrade treatments (with the exception of the water-saturated section) were successful in minimizing or eliminating pumping and that pumping prevailed on untreated sections where the pavement was constructed on silty-clay soils.

Following this survey, a series of joints in a two-mile section near the Lake-Porter County line was selected for treatment by mud jacking. Treatment of these joints was performed in October and November of 1942. Four mixes were used:

1. Mix A; 77 per cent soil, 7 per cent RC-3, 16 per cent cement.
2. Mix B; 77 per cent soil, 7 per cent Road Oil, 16 per cent cement.
3. Mix C; 77 per cent soil, 7 per cent Tar, 16 per cent cement.
4. Mix D; 79 per cent soil, 3½ per cent Tar, 17½ per cent cement.

Even though work was hampered by cold weather and numerous equipment breakdowns, a total of 434 cu. ft. of mix was pumped under fifty pumping joints (an average of 8.7 cu. ft. per joint) in twelve working days.

Several performance surveys of this two-mile section have been made since treatment to determine the permanence of the treatments. The most recent survey (Oct.-Nov. 1944) showed that pumping had been reduced considerably. However, the installation of subgrade drains on U.S. No. 30 between S.R. 49 and S.R. 53 together with a particularly dry year (1944) made it difficult to rate the success on the basis of pumping alone. The settlement at the joints of both treated and untreated slabs showed considerable success for mud-jack treatment. It was found that the average settlement of the outer edges of treated slabs was 0.093 in. as compared to 0.194 in. for the untreated slabs. Further, it was found that 68 per cent of the treated slabs had settled 0.125 in. or less as compared to 53 per cent for untreated slabs.

A crack survey showed that mud jacking had been successful in reducing the expected number of cracks on this two-mile section. The data further show that cracks within 13 ft. of a joint are caused by slab movement and pumping, and that cracks in the middle third of a slab are from causes other than pumping. Of the four mixes used, those treated with Mix A and Mix D contained less cracks than those treated with Mix B and C.

Early in 1942 a performance survey was made on a portion of U.S. No. 30 located between U.S. No. 41 and a point just south of Valparaiso, Indiana (1).[a] A report of this survey stressed the seriousness of the pumping action taking place on the outside lanes of parts of this road - not five years old at that time. The report further contained suggestions for methods of treating pumping joints and presented an outline for a research program for the continuation of pumping studies. The results of this performance survey and others in Indiana and other states were presented at the November, 1943, Highway Research Board meeting in Chicago (2).

Among the new studies were suggestions for treatment of the slabs by mud jacking and by the installation of French drains. As a result of this report, arrangements were made to conduct mud-jacking research on a section of this road near the Lake-Porter County line. A two-mile section of road was selected for experimentation in which various mixes of soil, cement, and bituminous materials were to be forced under some of the slabs that had settled due to pumping action.

In October and November, 1942, 50 pumping joints were treated by mud jacking. The remainder of the joints in the two-mile section were left for comparative purposes. In addition, several joints were treated by draining with various types of drains. This report is a detailed study of that two-mile section of U.S. No. 30 under observation showing how both the treated and untreated slabs have performed during the two-year period following treatment.

U.S. HIGHWAY NO. 30

This report is concerned with a portion of U. S. No. 30 - a four-lane-divided-concrete pavement in Lake and Porter Counties extending from U.S. No. 41 to Valparaiso, Indiana, a distance of about 24 miles. This portion of roadway is of modern design in which the 200-ft. right-of-way contains two, 22-ft. slabs separated by a 44-ft. dividing strip and a 56-ft. strip on either side of the pavement. The pavement slabs are 9-in. - 7-in. - 9-in. in section, are reinforced with steel mesh, and were constructed with joints. The first portion of this road was constructed in 1937 and the last was completed in 1940. Several experimental-subgrade-treatment sections were installed on the western end of the road. Seven types were employed including saturating the subgrade with water, treating with bituminous materials (AES-1, T-C, MC-1), and replacing the subgrade with granular materials (sand, limestone dust, and crushed limestone).

The soils and topography of the area crossed by U.S. No. 30 owe their engineering characteristics to glacial activity. The road crosses or follows a large glacial deposit known as the Valparaiso Moraine. The topography varies from level to quite rolling. The topography near Valparaiso is somewhat rugged as the road crosses lake beds, terraces, sand dunes, and morainic deposits. From the junction of S.R. 330 to U.S. No. 41 the topography is level to moderately rolling and near U.S. No. 41 it becomes more rolling as the road crosses a series of sand dunes. The engineering characteristics of the soils contained in this area vary according to their origin and

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/a Numbers refer to the list of references at the end of the report.

topographic position. The soils of the morainic areas vary from granular materials to silts, clays, and silty clays. The drift soils of the moraine proper contain a considerable amount of shale fragments which weather readily to silty clay and clay. In general, the presence of this weathered shale has produced a plastic, poorly-drained soil in both the upland flat and the rolling moraine, the only difference being that the weathered profiles of the soils on the upland flat to rolling topography are much more developed and extend to greater depths than do the weathered profiles of the soils in the more rolling morainic areas. However, in some of the more rolling (nearly rugged) areas, the soils vary considerably. Some highway cuts show laminated soils while others contain silt, clay, or gravel pockets intermixed - all of which tend to add to the complexity of the engineering problems. Frost heaving occurs where the grade intersects or comes within a few feet of silt deposits and pumping occurs in areas of impervious, plastic, silty clays.

The dunes of both the east and west ends of this 24-mile section consist of windblown sand and are of post-glacial origin. The highway also crosses a few muck deposits near Valparaiso.

MUD JACK RESEARCH

Several states have tried mud jacking with soil-cement-bituminous mixtures as means of correcting pavement pumping. A description of some of the mixtures used by several states is given in the "Wartime Road Problems," No. 4, on pumping corrections, published by the Highway Research Board(3). The results of the April, 1942, performance survey showed the need for continuing studies on this section of U.S. No. 30 particularly in conducting research in mud jacking several pumping slabs.

Through co-operation with the LaPorte District and the Valparaiso Sub-district, many drainage and mud-jacking experiments were installed on a portion of U.S. No. 30 near the Lake-Porter County line for the purpose of combating pumping. Field operations were started on October 21, 1942, and were completed on November 23, 1942. Even though the research was conducted under adverse weather conditions accompanied by numerous equipment failures, the following was accomplished during 12 working days:

1. 36 French drains were installed.
2. 50 joints were treated by mud jacking.
3. 434 cu. ft. of mud-jack mixture were pumped under faulted slabs.

In June, 1942, 47 drains were installed by maintenance crews at some of the more severely pumping joints. During October and November, 1942, many of these drains were inspected and it was found that several were effective in stopping pumping. However, in locations of flat topography where drainage conditions were poor, many of the drains had clogged and the joints were pumping again.

The two-mile section selected for treatment contained soils that, for the most part, are similar in origin, texture, and engineering characteristics. Since traffic, rainfall, and soils do not vary in this section, the principle variables incorporated in the project were: the proportions and ingredients of the mud-jack mix; the operation procedure; the design of the drains installed; and the stone sizes in the drains.

The mud-jacking equipment used in conducting this research consisted of the following (See Figs. 1 and 2.):

1. Ingersoll-Rand air compressor operating at about 80 pounds, mounted on a truck.

2. A compressed air drill, operated at about 80 pounds and equipped with several 2¼-in. drill bits.

3. Mud jack apparatus consisting of a pressure chamber mixer, hose, nozzle, and various compressed-air fittings and lines all mounted on a heavy four-wheel trailer.

4. A 500-gallon water tank mounted on a truck.

5. Various types of small concrete mixers.

6. Regular highway maintenance truck for transporting soil, stone, and cement supply.

7. Tar kettle.

8. Wheelbarrow, spades, shovels, auger, and miscellaneous tools.

The soil used in conducting the mud-jacking research consisted of 46-per cent sand, 34-per cent silt, and 20-per cent clay. This soil was found to have a liquid limit of 29.3 and a plastic limit of 22.2. In choosing soil for this purpose an attempt was made to select material free from organic acids and solids.

The mixes used are shown in Table I. Four different mixes, A, B, C, and D, were employed in the entire project. Three different bituminous materials, A, B, and C, were used. These were RC-3, road oil, and tar, respectively. The fourth mix, D, contained one-half as much tar as mix C. The percentages were calculated on a dry-weight basis. However, for convenience in the field, the materials were proportioned in calibrated five-gallon buckets. For the first three mixes, A, B, and C, the percentages of materials remained the same. They were: soil - 77 per cent; bituminous materials - 7 per cent; and portland cement - 16 per cent. On a bucket basis, this was roughly eight, five-gallon buckets of soil; one, five-gallon bucket of bituminous material, and one bag of cement. Mix D called for one-half of a five-gallon bucket of tar.

Table I.

MUD-JACK ADMIXTURES USED AND WORK RECORD

Mix	Parts	Field Use - 5 gal. Bkt.	% by Vol.	Days	Joints Pumped	Cu. Ft. Pumped	Av. Mix per Joint
A	Soil	8 - 5 gal. Buckets	77	3	7	105.8	15.1
	Water	3-4 - 5 gal. Buckets					
	RC-3	1 - 5 gal. Bucket	7				
	Cement	1 Bag	16				
B	Soil	8 - 5 gal. Buckets	77	5	22	150.4	6.8
	Water	3-4 - 5 gal. Buckets					
	Road Oil	1 - 5 gal. Bucket	7				
	Cement	1 Bag	16				
C	Soil	8 - 5 gal. Buckets	77	2	16	128.4	8.0
	Water	3-4 - 5 gal. Buckets					
	Tar	1 - 5 gal. Bucket	7				
	Cement	1 Bag	16				
D	Soil	8 - 5 gal. Buckets	79	1	4	37.4	9.4
	Water	3-4 - 5 gal. Buckets					
	Tar	½ - 5 gal. Bucket	3½				
	Cement	1 Bag	17½				
Note:	1 joint "B" + "C" Mix			1	1	12.3	12.3
			TOTALS	12	50	434.3	8.7

Average joints per day................................ 4+
Average mix per joint................................ 8.7 cu. ft.
Average mix per day..................................36.2 cu. ft.
Drains installed in June, 1942.........................47
Drains installed in Oct.-Nov., 1942....................36

For convenience in making future observations of the treated joints, large letters, A, B, C, and D were painted on the pavement opposite each joint indicating which mix was used.

It was found that the amount of mixing water needed depended on the prevailing air temperature and the amount of water in the soil. If the weather was warm, it was noted that the bituminous materials mixed readily with the soil and water. When the weather was cold, the hot bituminous material did not mix readily with the soil and water. The chilling of the bituminous material seemed to stiffen the mix, thus requiring more water to obtain a creamy consistency. In addition, the bituminous material would become stringy and difficult to mix and pump.

The best mixing procedure developed was as follows:

1. A soil-water mix was made in which just enough water was added to obtain a fluid mix.

2. Bituminous material and additional water were added as needed, to obtain a uniform mix.

3. The cement was added. (The consistency should be such that the mix can be readily pumped through the hose and under the pavement.)

4. It was found that prolonged mixing should be avoided.

The following is a description of operations as they were performed on a typical joint during the experimental work.

1. Holes were drilled at desired joints.

2. A trench was dug along the pavement where pumping was severe.

3. If a drain was desired, or if there was considerable water under the pavement, a lateral trench was dug to the ditch line.

4. The mixture was then poured into the mud-jack hopper.

5. Air pressure was gradually applied which forced the mixture through the hose and under the pavement.

   Note: It was found that if too much pressure was suddenly applied, the mix would blow out the sides and out the cracks and other holes in the pavement and raise the pavement too fast, which in one case broke it.

6. A small amount of mixture was pumped in each hole, gradually raising each side to grade. On several occasions the material could be seen extruding in a long ribbon from under the pavement (in the open trench, (See Fig. 3). When this condition was reached before the slab was raised to the desired elevation the trench would then be filled and compacted in order to confine the mud-jack mixture.

7. As soon as the mud-jack nozzle was withdrawn from the hole in the slab, large wooden wedges were driven in the holes. These prevented the mixture from being forced out on the pavement by the pressure of the slab weight. The holes were left plugged about six or seven hours (See Fig. 4).

8. Traffic was kept off for a period of about two days. This allowed the mixture to harden.

Many methods of operation were tried. Included were the following:

1. Mud jacking without pre-draining the joint.

2. Mud jacking with pre-drainage of the pumping area.

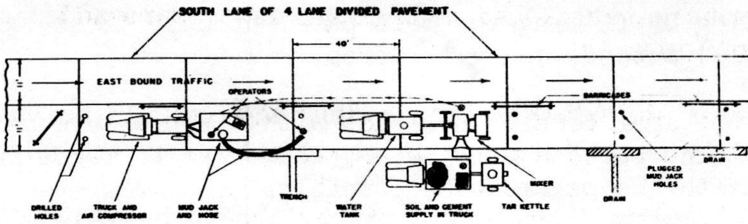


FIGURE 1. DIAGRAM SHOWING EQUIPMENT LAYOUT FOR MUD-JACK RESEARCH ON U. S. 30.

FIGURE 2. MUD-JACKING EQUIPMENT - AIR COMPRESSOR, MUD-JACK, WATER TANK MIXER, TAR KETTLE, AND SUPPLY TRUCK.

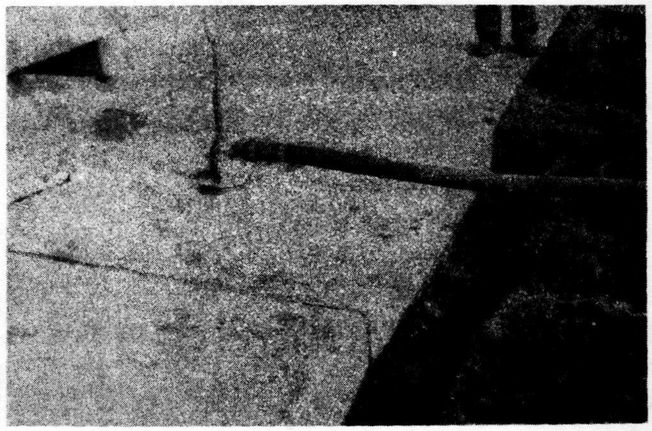


FIGURE 3. SUCCESSFUL MUDJACKING. HERE THE SLAB HAS BEEN RAISED TO GRADE AND A LONG RIBBON OF THE MUD-JACKED MIXTURE IS SEEN EXTRUDED FROM BENEATH THE SLAB.

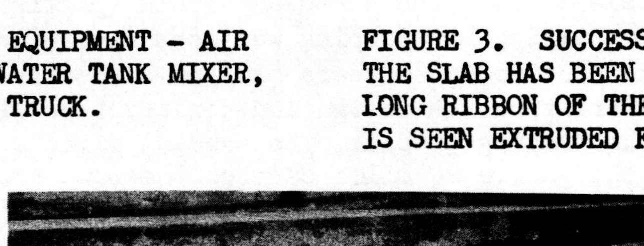


FIGURE 4. THE HOLES WERE PLUGGED TO PREVENT THE SLAB FROM SETTLING AND SQUEEZING OUT THE MIX UPON COMPLETION OF MUD-JACKING.

3. Mud jacking by filling the left pavement hole first, and then the right (edge hole) second, and vice versa.

4. Venting the area beneath the slab with air pressure before pumping the mixture. The purpose of this procedure was to force as much water out from beneath the pavement as possible.

5. Admixture variations, such as tar, RC-3, and road oil.

6. Mud jacking at a joint with and without supplemental drainage.

7. Drainage without mud jacking.

8. Some severely pumping joints were left untreated.

The four types of drains used in this project were: dry well; French drain with a lateral at the joint; French drain with a lateral below the joint; and French drain consisting of a lateral only.

1944 PERFORMANCE SURVEY OF 24 MILES

In October 1944, two and one-half years after the first survey and two years after mud jacking, another survey was made of U.S. No. 30. A detailed survey of the entire 24 miles was not made, but several pictures were taken to show the condition of many of the joints. It was observed that pumping had progressed at a rapid rate and had become a serious problem. Both the north and south (particularly the outside) lanes were suffering from pumping but pumping was more severe on the south lane. At present, this 24-mile pavement is seven years old and has served as an excellent "test track". Because of the variations in design and construction of the highway, it has been possible to study the pumping problem, its causes, effects, and, to a limited extent, its cures. Since the entire 24 miles carries the same amount of traffic (with the exception that the south lane carries the heavier truck traffic) and receives the same amount of rainfall, it has been possible to evaluate the various types of subgrade soils. A visual inspection of the 24-mile section showed no pumping on the natural sand section, the 6-in. sand section, or the 3-in. stone stabilization section. Pumping was very slight at a few of the joints on the limestone, AES, and the TC sections. Pumping was exceptionally severe on the water-saturated section and several of the slabs had settled sufficiently to warrant patching. Figures 5 and 6 show the condition of one of the slabs on the water-saturated subgrade in October, 1944.

Pumping was found to be severe in the silty-clay drift areas. Figures 7 and 8 are views of the same joint taken in 1943 and 1944 and show the extent of the failure of some of the severely pumping joints on drift soils. One section of this road, constructed on silty-clay drift, contained a total of 50 patched slabs in a distance of 2700 ft. (See Fig. 9).

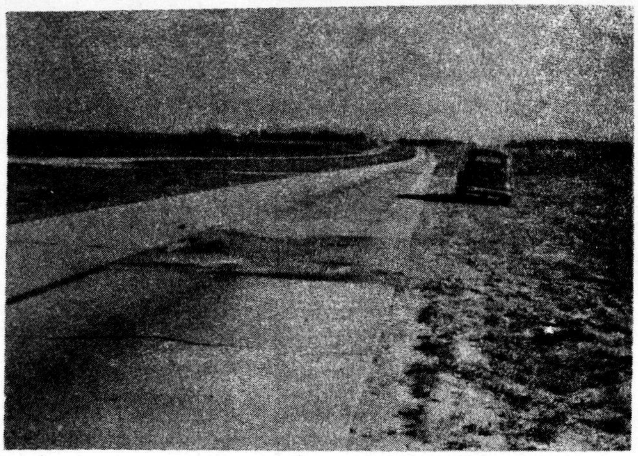


FIGURE 5. PERFORMANCE IN THE WATER-SATURATED SUBGRADE SECTION IN OCTOBER 1944.

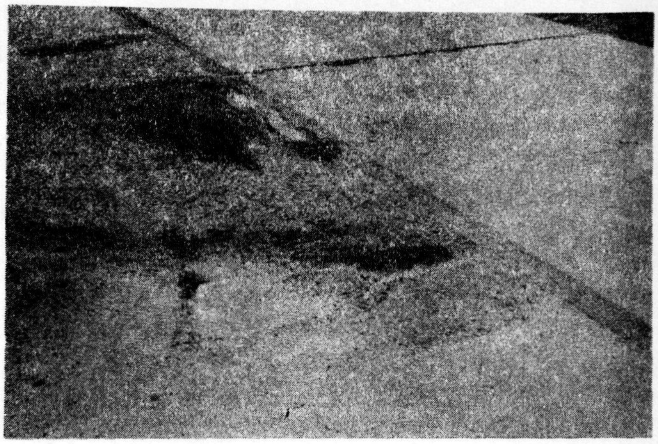


FIGURE 6. CLOSE-UP OF A JOINT IN THE WATER-SATURATED SECTION (OCTOBER, 1944).

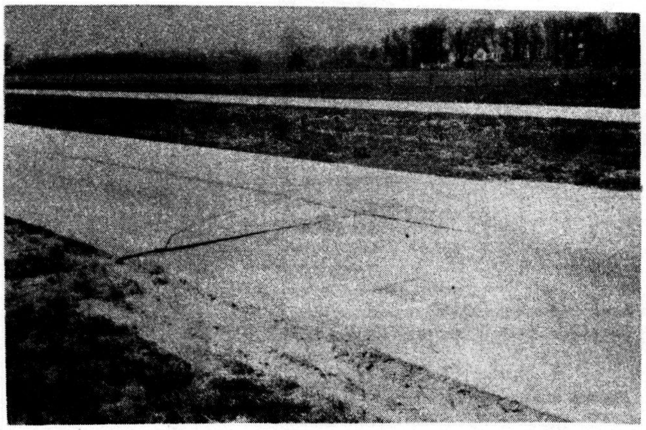


FIGURE 7. VIEW OF A SEVERELY PUMPING SLAB IN DRIFT SOIL OF THE VALPARAISO MORAINE IN NOVEMBER, 1943.

FIGURE 8. VIEW OF THF PATCH ON THE SAME SLAB (FIGURE 7) IN NOVEMBER, 1944. PUMPING IS STILL SEVERE.

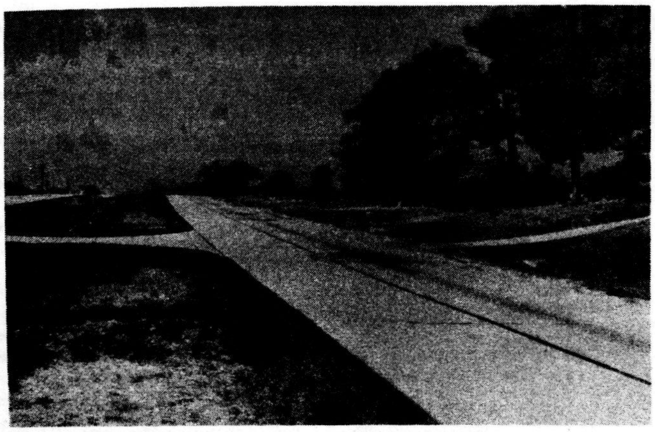


FIGURE 9. A SERIES OF PATCHES AT JOINTS OF SLABS THAT HAVE SETTLED DUE TO PUMPING. ON ONE SUCH SECTION A TOTAL OF 50 PATCHES WAS COUNTED IN 2700 FEET.

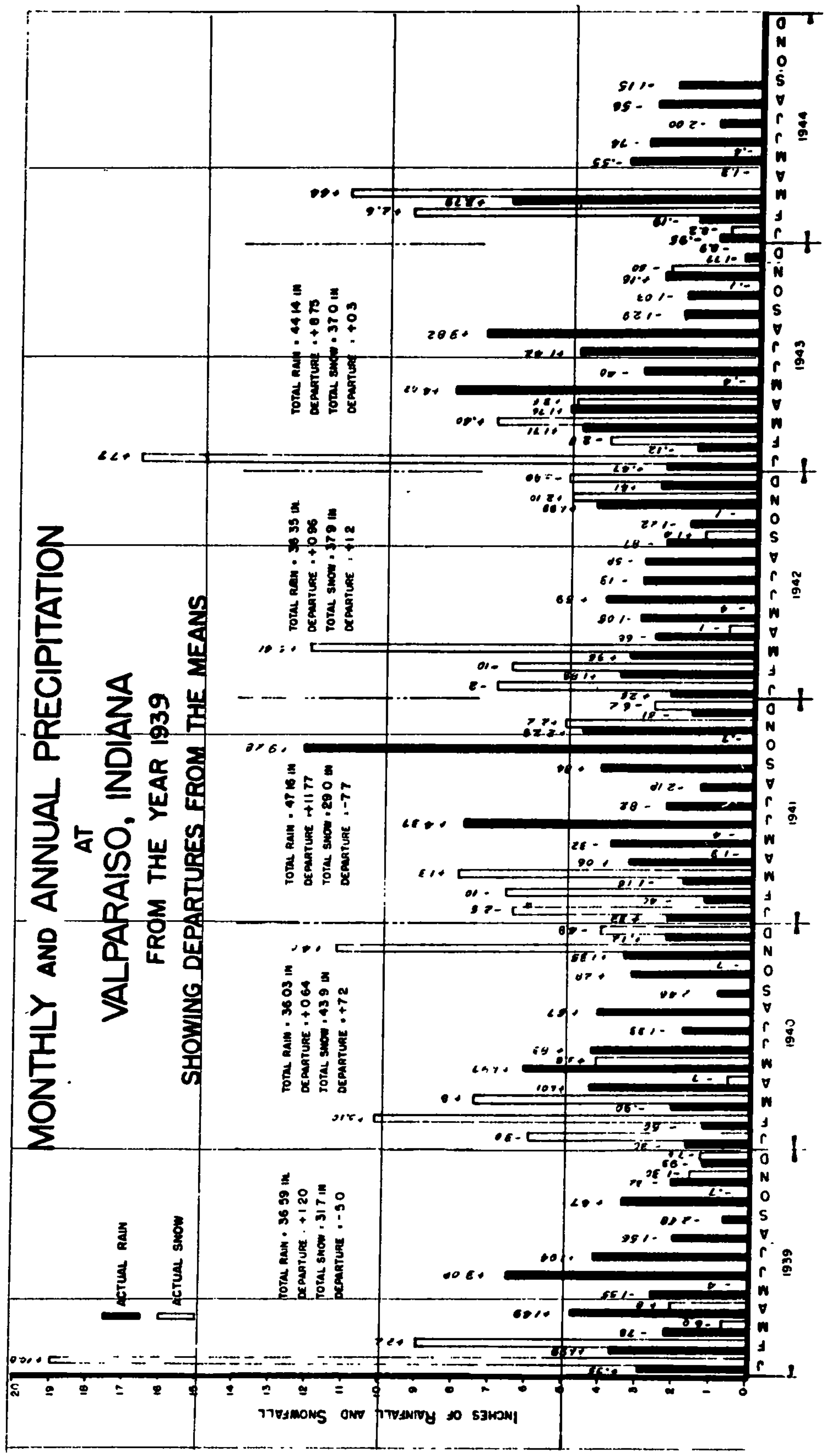

MONTHLY AND ANNUAL PRECIPITATION
AT
VALPARAISO, INDIANA
FROM THE YEAR 1939
SHOWING DEPARTURES FROM THE MEANS
ACTUAL RAIN
ACTUAL SNOW
TOTAL RAIN · 36 59 IN.
DEPARTURE · +1 20
TOTAL SNOW · 31 7 IN
DEPARTURE · -5 0
TOTAL RAIN · 36 03 IN
DEPARTURE · +0 64
TOTAL SNOW · 43 9 IN
DEPARTURE · +7 2
TOTAL RAIN · 47 16 IN
DEPARTURE · +11 77
TOTAL SNOW · 29 0 IN
DEPARTURE · -7 7
TOTAL RAIN · 36 35 IN.
DEPARTURE · +0 96
TOTAL SNOW · 37 9 IN
DEPARTURE · +1 2
TOTAL RAIN · 44 14 IN
DEPARTURE · +8 75
TOTAL SNOW · 37 0 IN
DEPARTURE · +0 3
INCHES OF RAINFALL AND SNOWFALL
1939
1940
1941
1942
1943
1944

FIGURE 10.

PERFORMANCE SURVEYS OF THE MUD-JACK SECTION

In the October, 1942, survey, previous to mud jacking, all cracks were stationed and counted, and all joints were rated as to degree of pumping (slight, p-1; moderate, p-2; severe, p-3). Six months after treatment, in May, 1943, another performance survey was conducted on the same two-mile section. In this survey new cracks were stationed and counted and again the joints were rated according to degree of pumping.

The next survey was conducted in October, 1944 (just two years after treatment) during which time pumping was found to be slight. The results of this survey were somewhat difficult to evaluate since drainage had been installed beneath the outside edge of the slabs for the major portion of the road from Valparaiso to U.S. No. 41. These drains and a deficiency of rainfall during the months of May to September, 1944, may account for the fact that pumping was not observed at the time of the October survey. During that period 14.26 in. of rain fell, which was 72 per cent of the normal rainfall for that period (a deficiency of 4.53 in.). See Figure 10 for a rainfall curve covering the period 1939 to 1944.

In view of these two conditions, a rating of the degree of pumping during that survey cannot be taken as a measure of the success or failure of treatment. However, a crack survey was also made in which the development of all new cracks was observed in both the treated and untreated section. (For purposes of comparison, a detailed crack survey was made on the 6-in. sand experimental section.) In addition, the settlement at each joint, inner edge and outer edge of the slab, was noted for both treated and untreated joints.

On November 6, 11, and 27, similar surveys were conducted (pumping only) since that area was receiving rainfall. These three additional surveys were made for the purpose of studying the effectiveness of the drainage system.

Table 2 shows a comparison of the 1942, 1943, and the 1944 pumping surveys. Table 3 contains results of pumping surveys of the 50 treated joints only. Tables 4 and 5 contain a summary of the settlement survey made in 1944 for both the treated and untreated joints. Table 6 is an analysis of cracking in cut and fill areas. Figures 13 to 22 are photographs of typical treated and untreated joints. Figure 23 is a distribution of cracks in 59 slabs constructed on the 6-inch sand section. Figures 24 to 34 are a set of distribution curves that help in the analyzing of the cracking of slabs with respect to pumping.

Pumping Surveys

The first performance survey of the two-mile mud-jack section made in October, 1942, prior to treatment, showed that 69 per cent of 277 joints were pumping. (There are 280 joints between station 610+10 and 722+86, but three in the Deep River Bridge are not included.) Of that number, 31.7 per cent were pumping slightly, 26.7 per cent moderately, and 11.2 per cent severely. (See Table 2). Table 3 shows the results of a pumping survey of the 50 joints that were treated later. This table shows that all

Table 2.

PUMPING SURVEY OF 2-MILE SECTION OF U.S. 30
(This table shows the number and percentage of joints pumping between stations 610+10 and 722+86. The table includes 50 joints treated by mud jacking.)

Degree of Pumping	OCTOBER, 1942 Before Treatment		MAY 6, 1943 6 Months After		OCTOBER 11, 1944 2 Years After	
	No.	Percent	No.	Percent	No.	Percent
0-None	84	30.3	96	34.6	259	93.5
1-Slight	88	31.7	112	40.4	7	2.5
2- Moderate	74	26.7	57	20.5	5	1.8
3-Severe	31	11.2	11	3.9	0	0
4-Very Severe	0	0	1	0.5	6	2.1
TOTALS	277	99.9	277	99.9	277	100.9

Degree of Pumping	NOVEMBER 6, 1944 After 0.71 in.*		NOVEMBER 11, 1944 0.71+0.43= 1.14 in.		NOVEMBER 27, 1944 1.14+1.21=2.35 in.	
	No.	Percent	No.	Percent	No.	Percent
0-None	260	93.8	259	93.5	256	92.4
1-Slight	7	2.5	6	2.1	12	4.3
2-Moderate	3	1.0	4	1.4	5	1.8
3-Severe	1	0.5	1	0.5	1	0.5
4-Very Severe	6	2.1	7	2.5	3	1.0
TOTALS	277	99.9	277	100.0	277	100.0

*The October 11, 1944, survey showed that pumping had practically stopped. Between October 11 and November 6, a total of 0.71 in. of rain fell and another survey was made. Between November 6 and 11 an additional 0.43 in. of rain fell, and another survey was made. The last survey was made on November 27 after an additional 1.21 in. (total 2.35 in.) of rainfall.

Table 3 – PUMPING SURVEY OF 50 JOINTS TREATED BY MUD JACKING

Degree of Pumping	OCTOBER, 1942							MAY 6, 1943						
	Before Mud Jacking							Six Months After Treatment						
	Mix					Total		Mix					Total	
	A	B	B+C	C	D	Joints	%	A	B	B+C	C	D	Joints	%
0–None	0	0	0	0	0	0	0	3	9	1	7	1	21	42
1–Slight	0	5	1	8	2	16	32	3	9	0	5	3	20	40
2–Moderate	1	8	0	6	2	17	34	1	4	0	2	0	7	14
3–Severe	6	9	0	2	0	17	34	0	0	0	2	0	2	4
4–Very Severe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	7	22	1	16	4	50	100	7	22	1	16	4	50	100

Degree of Pumping	OCTOBER 11, 1944							NOVEMBER 6, 1944						
	Two Years After Treatment							After 0.71 inches Rain*						
	Mix					Total		Mix					Total	
	A	B	B+C	C	D	Joints	%	A	B	B+C	C	D	Joints	%
0–None	6	20	1	16	4	47	94	5	20	1	16	4	46	92
1–Slight	0	0	0	0	0	0	0	1	0	0	0	0	1	2
2–Moderate	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3–Severe	1	2	0	0	0	3	6	0	0	0	0	0	0	0
4–Very Severe	0	0	0	0	0	0	0	1	2	0	0	0	3	6
TOTAL	7	22	1	16	4	50	100	7	22	1	16	4	50	100

Degree of Pumping	NOVEMBER 11, 1944							NOVEMBER 27, 1944						
	0.71" + 0.43" = 1.14" Rain							1.14" + 1.21" = 2.35" Rain						
	Mix					Total		Mix					Total	
	A	B	B+C	C	D	Joints	%	A	B	B+C	C	D	Joints	%
0–None	5	20	1	15	4	45	90	5	18	1	15	4	43	86
1–Slight	1	0	0	0	0	1	2	1	2	0	1	0	4	8
2–Moderate	0	0	0	1	0	1	2	0	0	0	0	0	0	0
3–Severe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4–Very Severe	1	2	0	0	0	3	6	1	2	0	0	0	3	6
TOTAL	7	22	1	16	4	50	100	7	22	1	16	4	50	100

*The October 11, 1944, survey showed that pumping had practically stopped. Between October 11 and November 6, a total of 0.71 in. of rain fell and another survey was made. Between November 6 and 11 an additional 0.43 in. of rain fell, and another survey was made. The last survey was made on November 27 after an additional 1.21 in. (total 2.35 in.) of rainfall.

TABLE: 4 SUMMARY OF SETTLEMENT SURVEY

Settlement in Inches	UNTREATED - 227						TREATED - 50					
	INNER			OUTER			INNER			OUTER		
	NO	%	ACC %	NO	%	ACC %	NO	%	ACC %	NO	%	ACC %
0	73	32.7	32.7	58	26.1	26.1	24	48	48	24	48	48
1/8	96	31.8	74.5	63	27.5	53.6	13	26	74	10	20	68
1/4	35	15.3	89.8	42	21.3	74.9	6	12	86	2	4	72
3/8	7	3.0	92.8	27	18.8	83.7	1	2	88	4	8	80
1/2	5	2.2	95.0	19	8.2	91.9	2	4	92	5	10	90
5/8	1	0.4	95.4	5	2.2	94.1				0		
3/4	2	0.9	96.3	2	0.9	95.0				1	2	92
7/8				1	0.4	95.4						
1				2	1.0	96.4						
PATCH*	8	3.4	99.8	8	3.4	99.8	4	8	100	4	8	100
TOTAL	227	100 %	100 %	227	100 %	100 %	50	100 %	100 %	50	100 %	100 %
AV.	0.123"			0.194"			0.098"			0.093"		

*See Text for Patch Explanation.

TABLE 5 - SUMMARY OF SETTLEMENT SURVEY
50 MUD-JACKED JOINTS

Settlement	MIX "A"						MIX "B"					
in	INNER			OUTER			INNER			OUTER		
Inches	NO.	%	ACC %	NO.	%	ACC %	NO.	%	ACC %	NO.	%	ACC %
0	5	71	71	4	57	57	10	45	45	9	41	41
1/8	1	14	85	2	28	85	5	23	68	4	18	59
1/4							3	13	81	1	5	64
3/8							1	5	86	2	10	74
1/2										3	13	87
5/8												
3/4												
7/8												
1												
PATCH*	1	14	99	1	14	99	3	13	99	3	13	100
TOTAL	7	99	99	7	99	99	22	99	99	22	100	100
AV.	0.02"			0.03"			0.08"			0.13"		

*See Text for Patch Explanation
(1 Joint - Mix B+C Had Not Settled)

Settlement	MIX "C"						Mix "D"					
in	INNER			OUTER			INNER			OUTER		
Inches	NO.	%	ACC %	NO.	%	ACC %	NO.	%	ACC %	NO.	%	ACC %
0	5	31	31	8	50	50	3	75	75	2	50	50
1/8	5	31	62	2	12.5	62.5	1	25	100	2	50	100
1/4	4	25	87	1	60	69						
3/8				2	12.5	81.5						
1/2	2	12.5	99.5	2	12.5	94						
5/8												
3/4				1	6	100						
7/8												
1												
PATCH*												
TOTAL	16	100	100	16	100	100	4	100	100	4	100	100
	0.16"			0.19"			0.03			0.04		

*See Text for Patch Explanation
(1 Joint - Mix B+C Had Not Settled)

TABLE 6 - COMPARISON OF CRACKS IN CUT AND FILL ON A TWO MILE SECTION OF U.S. 30

Date	Pavement Data	Cut	Fill	All
	No. Slabs	134	143	277 *
Oct.	No. Cracks	222	244	466
1942	No. Cracks Per Slab	1.65	1.70	1.68
	No. Slabs	134	143	277
May	New Cracks	11	19	30
1943	No. Cracks	233	263	496
6 Mo.	No. Cracks Per Slab	1.73	1.83	1.79
	No. Slabs	134	143	277
Oct.	New Cracks	110	91	201
1944	No. Cracks	343	354	697
2 Yr.	No. Cracks Per Slab	2.59	2.47	2.51

*There are 280 slabs in the section under observation. 3 of these are in the Deep River Bridge.

of the joints selected for treatment were pumping, and that one-third of them were pumping slightly, one-third moderately, and one third were pumping severely.

On May 6, 1943, six months after treatment, another pumping survey was conducted on the 277-slab section. This survey showed that of the 277 slabs, 65.3 per cent were pumping (Table 2). However, of the 50 slabs treated (Table 3), 42 percent were not pumping, 40 percent were pumping slightly, 14 percent moderately, and 4 per cent were pumping severely. Of the 68 percent of the joints pumping moderately and severely in 1942, only 18 percent were rated as pumping similarly in 1943.

Two years after treatment, the October, 1944, survey showed that 93.5 percent of the 277 slabs in the experimental section were not pumping (Table 2). A survey of the 50 treated joints showed that 94 percent were not pumping. Three of the 50 treated joints had failed to the extent that they had to be patched. However, study of the original work record shows that the failures are reasonable and might be expected (See Appendix for details).

Following the October, 1944, survey, three additional surveys were made at intervals of approximately one week since that area was receiving rainfall. Study of Table 3 shows that the additional rainfall caused a slight increase in pumping on both the treated and untreated joints.

It is difficult to measure the success of mud jacking by pumping surveys, since the effects of the relatively dry weather and the drainage installations are not known. However, pumping (or evidences of pumping) was noted at joints on other areas of the entire 24 miles of road.

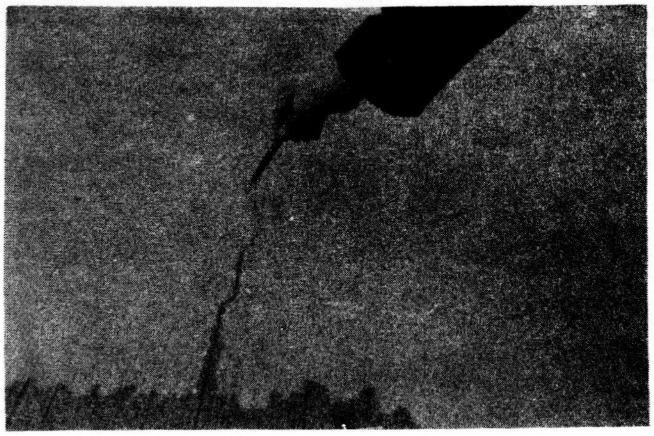


FIGURE 11. FIRST STAGES OF CRACKING DUE TO SLAB PUMPING.

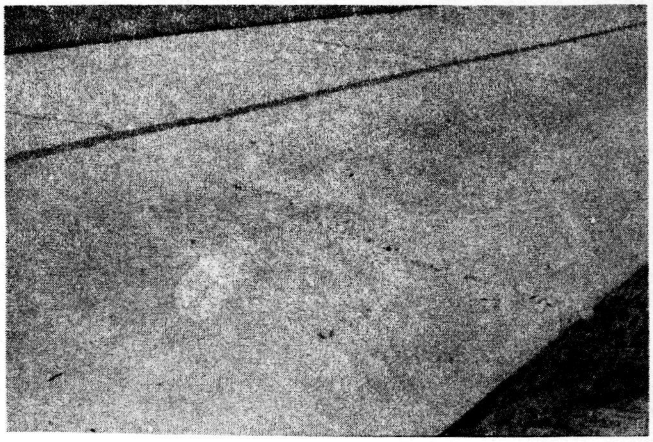


FIGURE 12. ADVANCED STAGES OF CRACKING IN WHICH SPALLING OCCURS CAUSED BY SEVERE SLAB MOVEMENT.

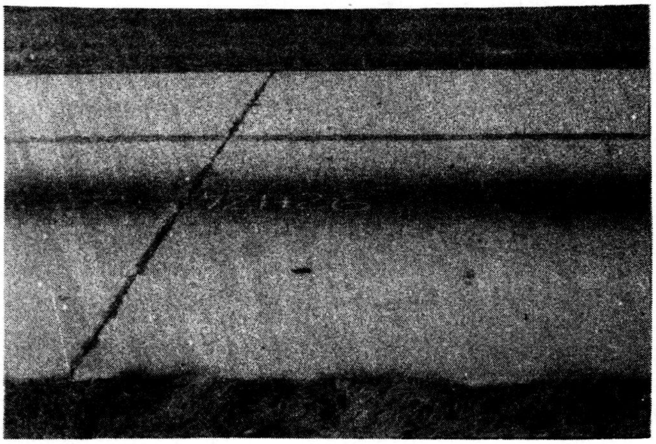


FIGURE 13. SUCCESSFUL MUD JACKING. THIS JOINT TREATED WITH MIX "A" HAD NOT SETTLED OR PUMPED DURING TWO YEARS OF SERVICE.

FIGURE 14. SEVERE PUMPING AT AN UNTREATED JOINT IN THE SECTION OF PAVEMENT IN WHICH JOINTS WERE TREATED WITH MIX "A"

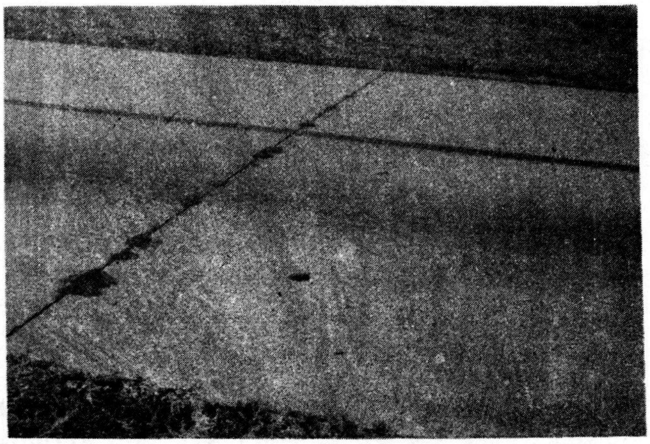


FIGURE 15. A SLAB TREATED WITH MIX "B" THAT HAS GIVEN TWO YEARS OF GOOD SERVICE.

FIGURE 16. AN UNTREATED SLAB (IN THE AREA IN WHICH THE JOINTS WERE TREATED WITH MIX "B") THAT HAD SETTLED 3/4 OF AN INCH.

FIGURE 17. THIS SLAB TREATED WITH MIX "B" HAD FAILED DUE TO AN EQUIPMENT FAILURE DURING TREATMENT.

FIGURE 18. THIS IS A VIEW OF THE FIRST CRACK PAST THE JOINT IN FIGURE 17.

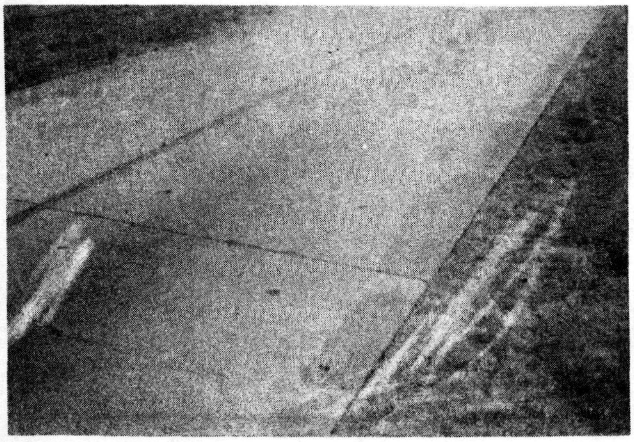


FIGURE 19. THE JOINT AT STATION 662+86 (MIX "C") HAS PERFORMED SATISFACTORILY FOR TWO YEARS.

FIGURE 20. THE JOINT AT STATION 662+46 (ADJACENT TO SLAB IN FIG. 19 WAS NOT TREATED AND HAS GIVEN TWO YEARS OF UNSATISFACTORY PERFORMANCE.

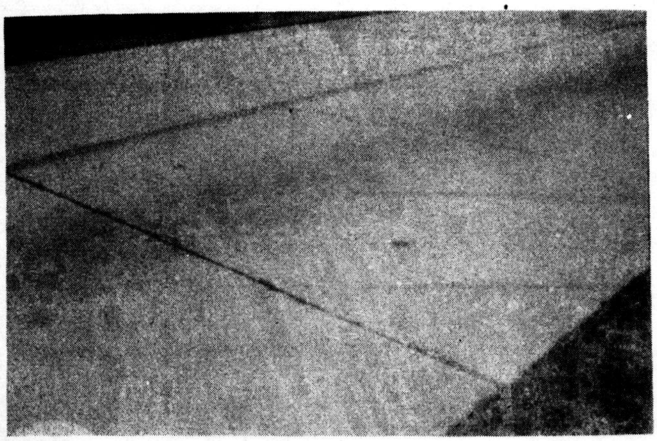


FIGURE 21. ANOTHER SUCCESSFULLY TREATED JOINT (MIX "C").

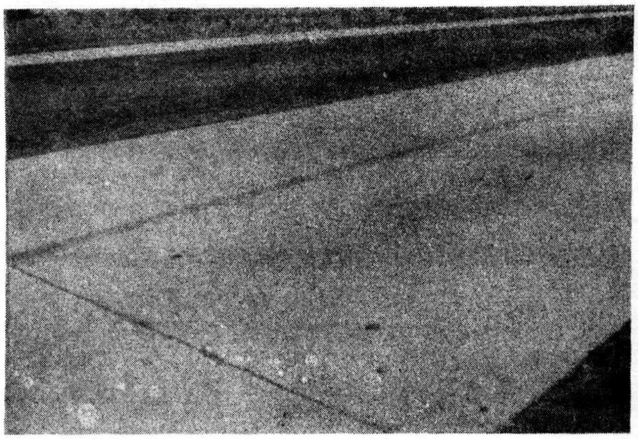


FIGURE 22. THIS JOINT, TREATED WITH MIX "D", PERFORMED SATISFACTORILY DURING TWO YEARS OF SERVICE.

Settlement Survey

Since the success of mud jacking could not be determined by rating the joints as to the degree of pumping, the settlement at each joint of both treated and untreated joints was measured. Since all slabs treated by mud jacking were raised to grade at the time of treatment, it is believed that this might be used as one measure of the success of treatment. The results of this survey are contained in Tables 4 and 5. Table 4 shows the settlement at the joints of the inner (centerline) and outer (shoulder) ends of all untreated slabs as compared to settlement of 50 mud-jacked joints. The table shows that the average settlement of the outer edge of 227 untreated slabs was 0.194 in. as compared with 0.093 in. for the 50 treated slabs.[/b] The inner slabs had settled 0.123 in. for the untreated slabs and 0.098 in. for the treated slabs. The table shows that settlement at the outer edge of the slab is greater than the settlement at the inner edge. (This corresponds favorably to severity of pumping with respect to the shoulder and centerline.) Some of the untreated slabs had settled as much as one inch. (A few that were patched obviously had settled to a much greater degree but were not measured).

Comparing percentages of slabs settling in increments of one-eighth inch showed that 48 percent of the outer slabs of treated joints had not settled, and 20 percent had settled one-eighth inch. This means that in two years, 68 percent of the treated slabs (outer edge of the joints) had settled one-eighth inch or less. These data can be compared to 26 percent of the untreated joints that have not settled and 27 percent that had settled one-eighth inch; or, that 53.6 percent of the untreated slabs had settled one-eighth inch or less. It should be pointed out that the percentages are based on the total number of cases and that eight untreated joints and four treated joints requiring patches are included; also, that the table for the treated joints includes all four mixes, some of which have failed more than others.

Table 5 compares the settlement at the joints by mix design. This table shows that both mixes "A" and "D" were effective in stopping settling at the joints. Of the seven joints treated with mix "A", one had failed and required a patch (equipment failure), four had not settled (outer portion), and two had settled an eighth-inch. Of the four joints treated with mix "D", two had not settled and two had settled only an eighth-inch. The joints treated with mix "A" had an average settlement (outer) of 0.03 in. and the joints treated with mix "D" had an average settlement of 0.04 in.

Comparison of the settlement of joints treated with mix "B" and "C" shows that those treated with "C" had settled the most. The average settlement of both outer and inner portions of the slabs by mixes are: Mix "C", outer edge - 0.19 in., inner edge - 0.16 in.; mix "B", outer edge - 0.13 in., inner edge, 0.08 in. However, 50 percent of the joints treated with mix "C" had not settled and 62.5 percent had settled one-eighth inch or less. This is to be compared to 41 percent with a settlement of an eighth-inch or less.

/b - This includes treated slabs which had failed because of faulty treatment resulting from equipment failure.

Crack Survey

Detailed crack surveys of this two-mile section of U.S. 30 were made in 1942 (prior to treatment), in May, 1943 (six months after treatment), and in October, 1944 (two years after treatment). Each survey consisted of stationing all cracks and plotting their position with respect to joints on plan sheets of the two-mile section. The results of each survey have been analyzed to determine the number of new cracks occurring during the various periods following treatment and to determine their positions relative to joints. The crack survey data have been divided into the following:

1. Distribution of cracks on cut and fill (Table 6).
2. Cracks on the 6-in. sand section (Fig. 23).
3. Distribution of all cracks by years (Figs. 24 and 25).
4. Distribution of cracks on the forward and rear slabs by years (Figs. 26 and 27).
5. Distribution of all cracks within 13 feet of the joints (Figs. 28, 29, and 30).
6. Distribution of new cracks - those occurring in two years only (Figs. 31 to 34).

Each of the above has been further divided into treated and untreated joints so that the effect of treatment on cracking can be studied.

In order to study the possibility of the cracking in cuts exceeding the cracking in fills a table was prepared in which these two variables are compared. Study of Table 6 shows that there are 134 slabs in cut areas and 143 in fill areas, and that by 1944 the "cut" slabs had 343 cracks and the "fill" slabs had 354 cracks. This small difference of the cracking in the cut and fill areas shows that cut or fill sections had little or nothing to do with the cracking in this particular area. This can be explained because of the similarity of engineering properties of the soils of both cut and fill areas.

On the 6-in. sand-treatment section all of the cracks in the 40-ft. slabs occurred in the middle third of the slabs. Figure 23 shows the distribution of cracks in the slabs in the 6-in. sand section. There are only two cracks less than 13 ft. either side of a joint in fifty-nine, 40-ft. slabs of this section. Further, it was found that after seven years, 42 percent of the slabs had no cracks and 47 percent contained only one crack. Since this section receives the same traffic and rainfall, is of the same pavement design, and was constructed approximately at the same time as the two-mile section under observation, it is believed that the cracking distribution on this section can be taken as typical of a pavement placed on a firm, well-drained support. Assuming this to be the case, cracks occurring less than 13 ft. either side of a joint can be considered as the result of slab movement caused by pumping action and that cracks occurring in the middle third of a 40-ft. slab are the result of other causes.

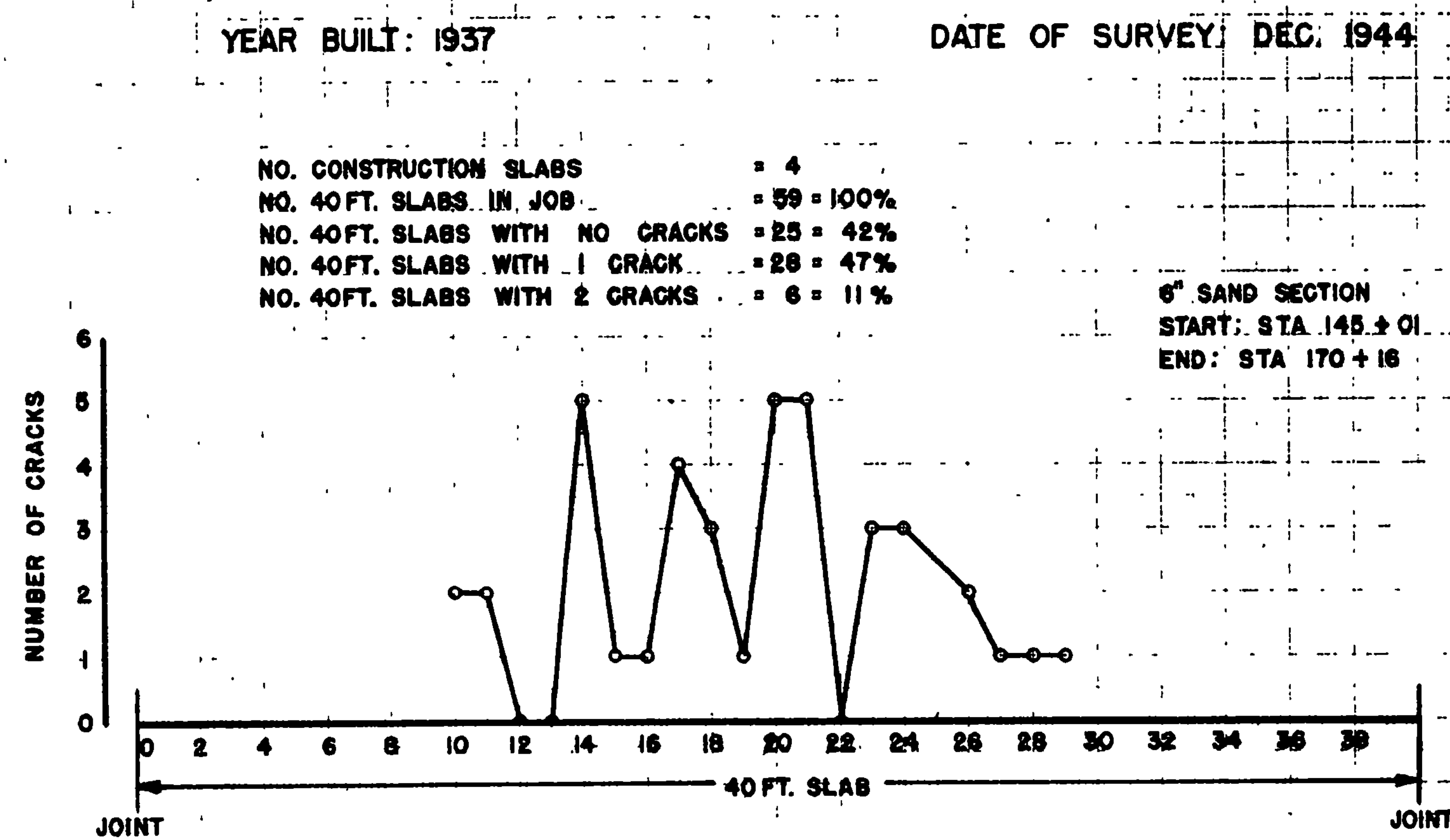


FIGURE 23. DISTRIBUTION OF CRACKS IN 59 SLABS IN 6 INCH SAND SECTION

Figures 24 and 25 show the distribution of all cracks (both forward and rear slabs combined) with respect to any joint for both treated and untreated joints for the 1942 and 1944 surveys. Both curves show a decided drop in the number of cracks at 13 ft. in the distribution curves. It is interesting to note, by comparing the two curves in each figure, that the cracking less than 13 ft. from the joint was considerably more in 1944 than in 1942 and that cracking past 13 ft. from the joints remained fairly constant during the same two-year period. This observation confirms the statement that cracking up to 13 ft. from the joint must be directly influenced by slab movement initiated by pumping action, and that cracks past 13 ft. either side of the joint are not caused by any movement at the joint.

Additiomal study of Figs. 24 and 25 shows that the distribution of cracking less than 13 ft. in 1944 is bi-modal,/c having a mode between 5 and 6 ft. and one at 10 ft. This perhaps shows that once a slab cracks about 10 ft. from the joint, a new and smaller slab, lighter in weight and able to move more freely, is formed. This, in turn, begins to break up usually at a point 5 or 6 ft. from the joint.

Since the curves shown in Figs. 24 and 25 are bi-modal, a second distribution was plotted in which cracking is divided into cracks occurring in forward and rear slab areas. This distribution is contained in Figs. 26 and 27. Study of Figs. 26 and 27 shows considerable difference in the cracking of the rear and forward slabs and that in 1942 cracking less than 15 ft. ahead of the joint was more severe than cracking less than 13 ft. to the rear of the joint. However, by 1944 cracking in the rear slabs had developed considerably in proportion to cracking on the forward slabs. The 1944 curve of the forward slab distribution of cracks contains modes at 6 and 10 ft. as compared to 5 and 10 ft. on the rear slabs. However, cracking at 5 ft. in the rear slabs was more severe than cracking at 5 ft. in the forward slabs in the 1944 survey; also, that cracking at 10 ft. on the forward slabs was more severe than at 10 ft. on the rear slabs in 1944.

In 1942, at the time the pavement was five years old, there were 466 cracks on 277 slabs (1.68 cracks per full slab). This is divided into 218 cracks on 277 rear slabs (0.78 per half slab) and 248 cracks on 277 forward slabs (0.89) per half slab - up to 20 ft. to the rear of a joint. By 1943, six months after treatment of 50 slabs, there was a total of 496 cracks (or 30 new ones) on the 277 slabs. Of the 30 new cracks, four occurred on the rear slabs of mix "C" joints; two on forward slabs of mix "A" joints; three on forward slabs of mix "B" joints; one on a forward slab of a mix "C" joint; and the remainder on untreated slabs.

By 1944, two years after treatment, there was a total of 697 cracks in 277 slabs (2.4 per slab) or a total of 231 new cracks in two years. This can be divided imto 326 cracks on 277 rear slabs (1.18 per half slab) and 371 cracks on forward slabs (1.34 per half slab). The above data, stated differently, show that at the time the pavement was five years old, there were 233 cracks per mile, and that by the end of the next two years (1944) this had increased to 348 cracks per mile, which is

/c - The mode is that value of a distribution that occurs most frequently. A bi-modal distribution is one in which two sets of values occur as prominent peaks on a distribution curve.

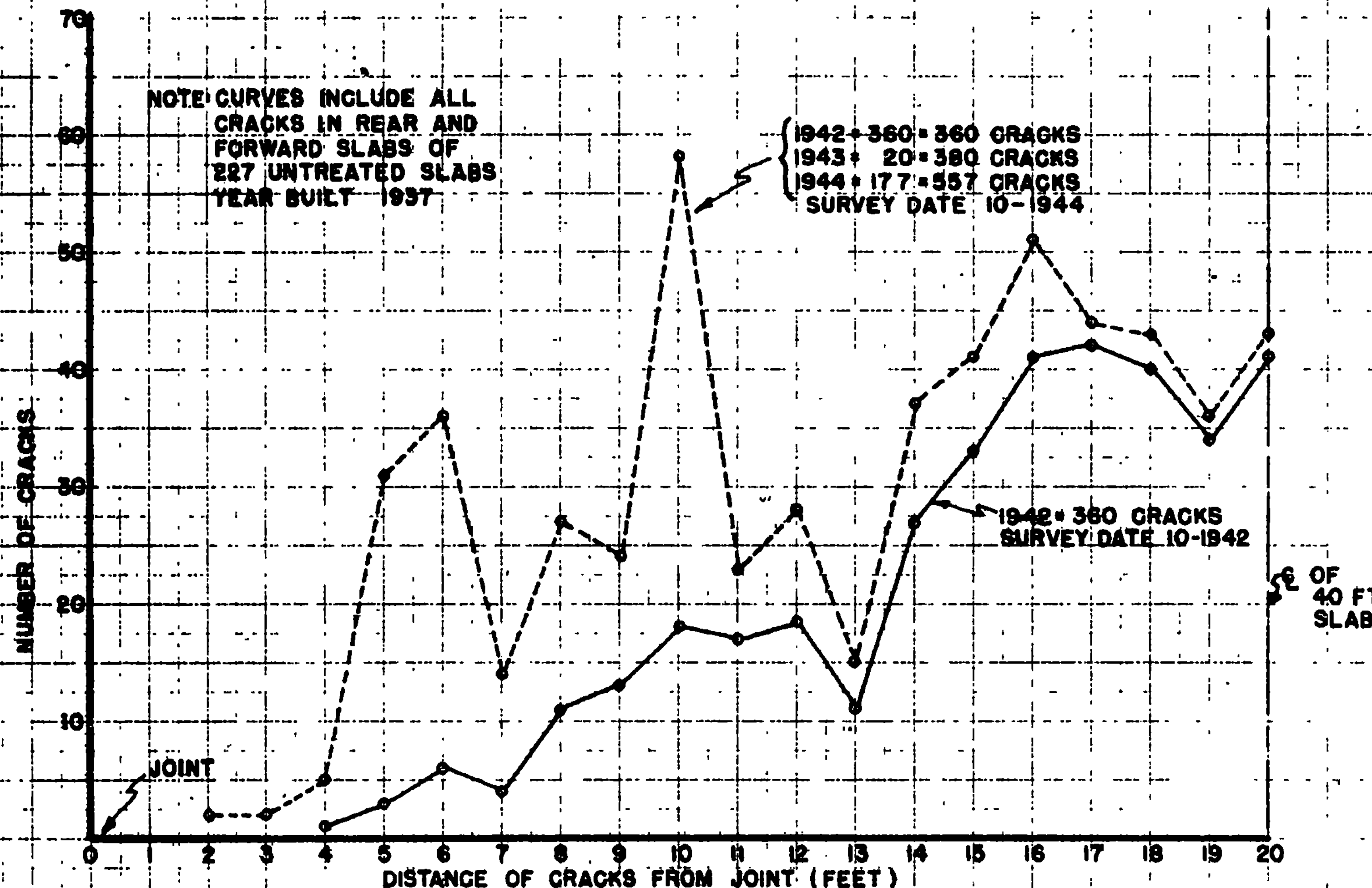


FIGURE 24. DISTRIBUTION OF CRACKS IN UNTREATED SLABS 1942–1944

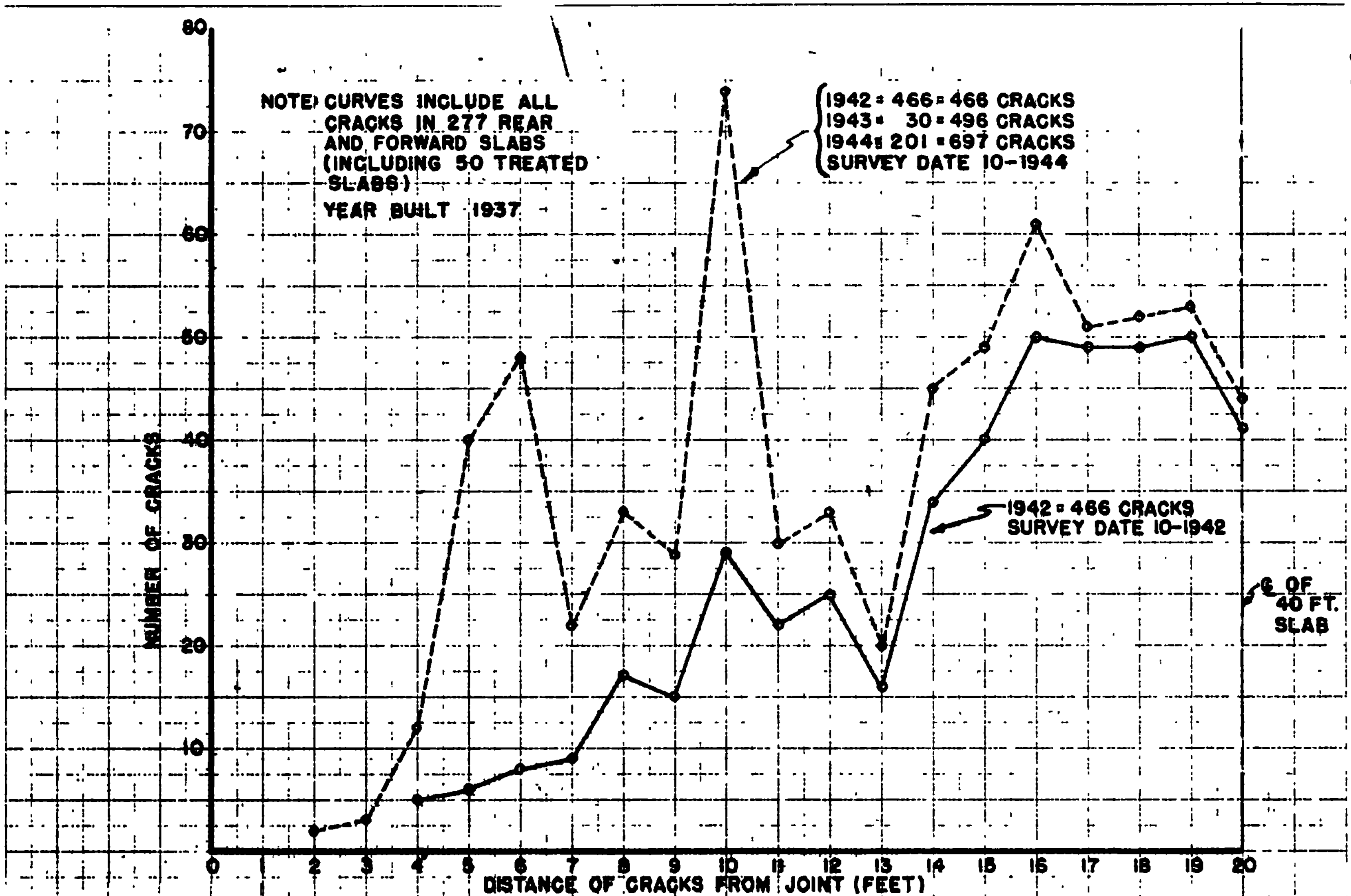


FIGURE 25. DISTRIBUTION OF CRACKS IN ALL SLABS 1942 – 1944

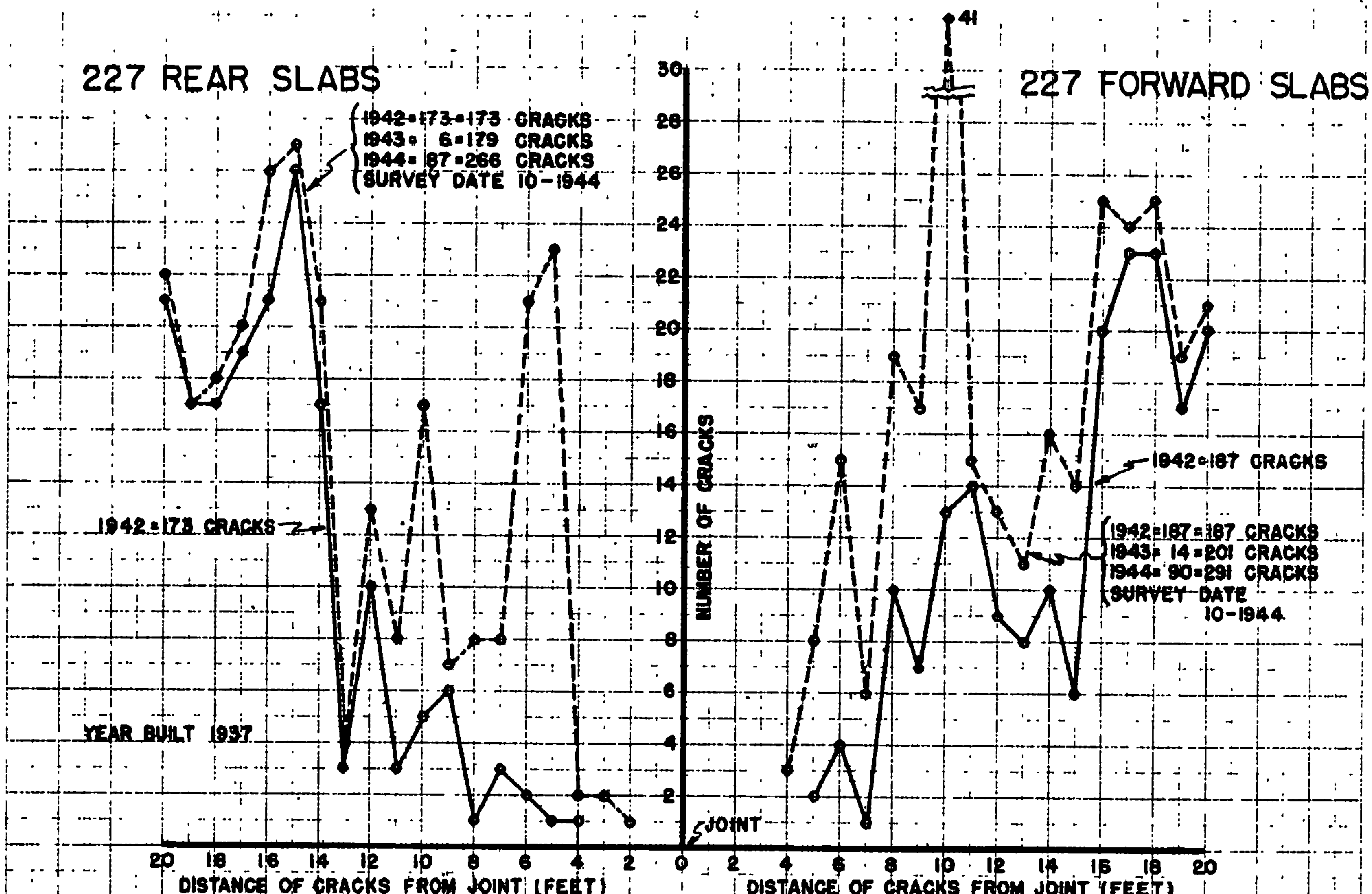


FIGURE 26. DISTRIBUTION OF CRACKS IN UNTREATED SLABS 1942-1944

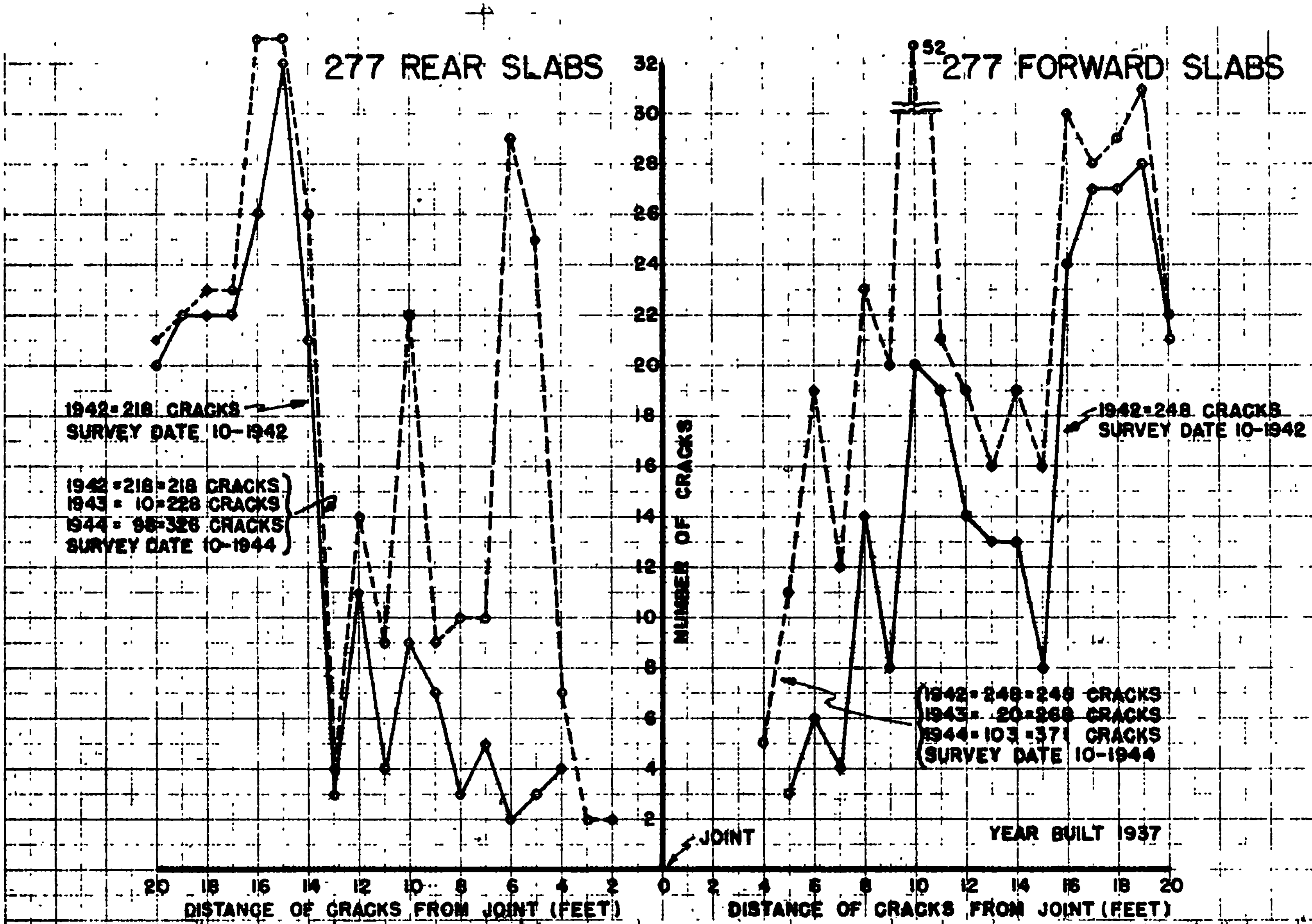


FIGURE 27. DISTRIBUTION OF CRACKS IN ALL SLABS 1942 – 1944

an increase of 49.3 percent during the two-year period. Further, the number of new cracks occurring in the forward slabs was nearly equal to the number of new cracks occurring in rear slabs (of the entire 277 treated and untreated sections). However, study of Fig. 27 shows a remarkable difference between the position of new cracks in forward and rear slabs with respect to the joints.

Figures 28, 29, and 30 are distribution curves of cracks less than 13 ft. from the joints of untreated slabs, treated slabs, and individual mixes for each of the three surveys. Further study of Figs. 28, 29 and 30 illustrate the effect of mud jacking on cracking. Assuming that all cracks less than 13 ft. either side of a joint are caused by pumping action, these data show that treatment by mud jacking has decreased considerably the expected number of cracks on both rear and forward slabs. Study of Fig. 28 shows that in 1942 there were 35 cracks in 227 untreated rear slabs and that by 1944 there were 114 cracks which is an increase of 226 per cent during the two-year period. This can be compared to the data contained in Fig. 29 which shows that in 1942 there were 17 cracks in 50 rear slabs, that were later treated, and that by 1944 there were 29 cracks, which is an increase of only 70.5 per cent. In other words, the expected cracking in untreated rear slabs should have been a 226 percent increase but treatment reduced this to a 70.5 percent increase. A similar study of forward slabs shows that the expected cracking was reduced from a 117 percent normal two-year increase to an increase of 51.5 percent for the treated slabs.

The distribution of new cracks, those occurring during the two-year period only, less than 13 ft. from the joints for each class of pavement is contained in the series of curves, Figs. 31 to 34. Study of Fig. 31 shows that the new cracking of untreated slabs during the two-year period was nearly equally divided between rear and forward slabs with rear slabs receiving 79 and forward slabs 80 new cracks. The curve shows that the distribution of cracks about the joint varies considerably between rear and forward slabs. Cracking was excessive between five and six ft. to the rear of the joints and excessive at 10 ft. ahead of the joint. These data, representing cracking of untreated slabs, can be compared with the data contained in Fig. 33 which is a distribution of cracking in the 50 treated slabs. This curve shows that cracking of the forward slabs remained fairly constant - that is, the distribution curve does not contain a mode. However, the distribution of cracking on the rear slabs shows that cracking was quite severe at six feet from the joint, which is the modal point of the distribution. The difference in cracking of rear and forward slabs of treated joints is significant because 47 of the 50 joints treated were treated on the forward slabs only. This can be attributed to the fact that, at the time of treatment, the rear slabs of treated joints had not settled and did not require treatment as did the forward slabs.

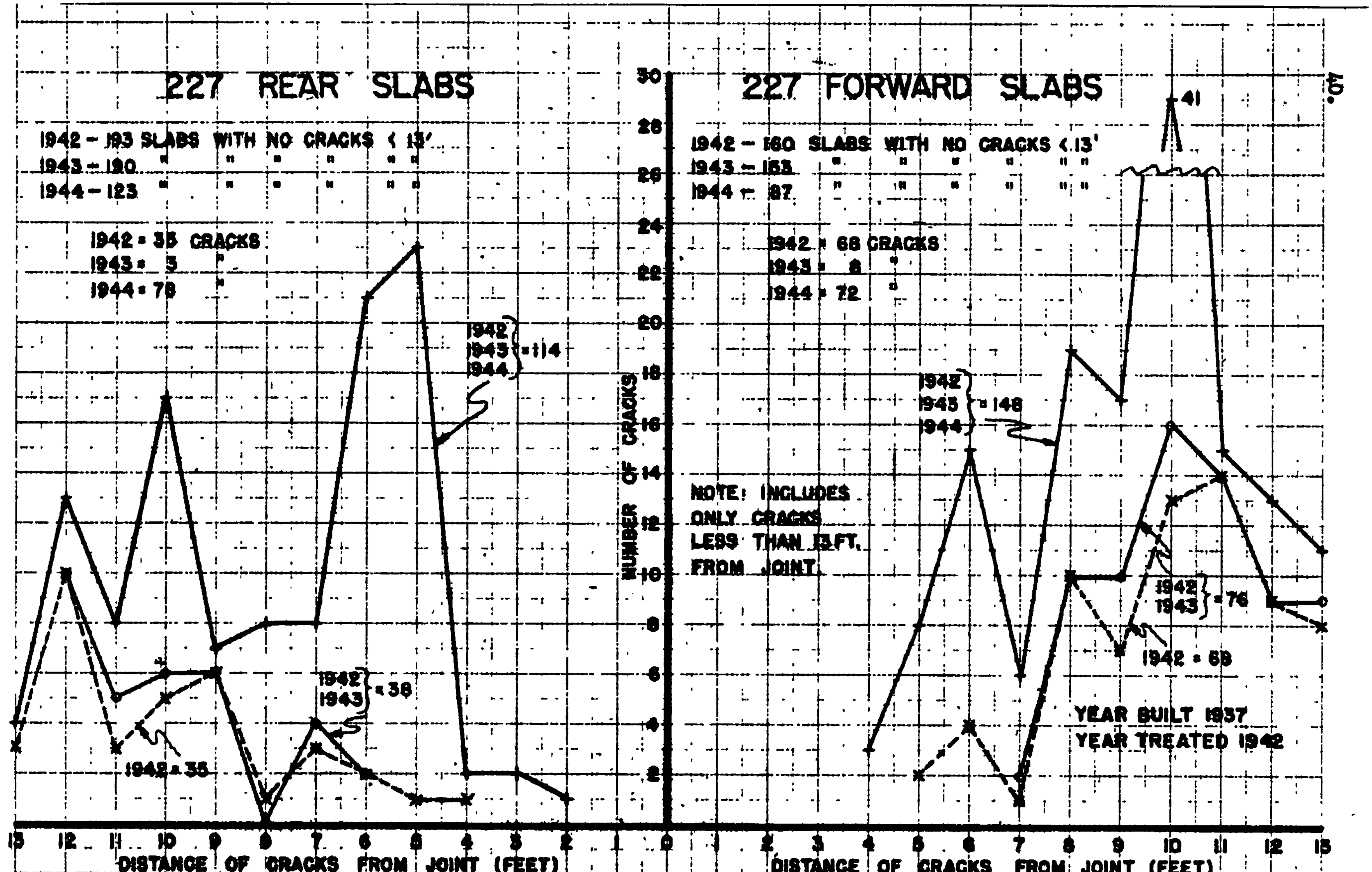


FIGURE 28. DISTRIBUTION OF CRACKS LESS THAN 13 FEET FROM THE END JOINTS OF THE 227 UNTREATED SLABS

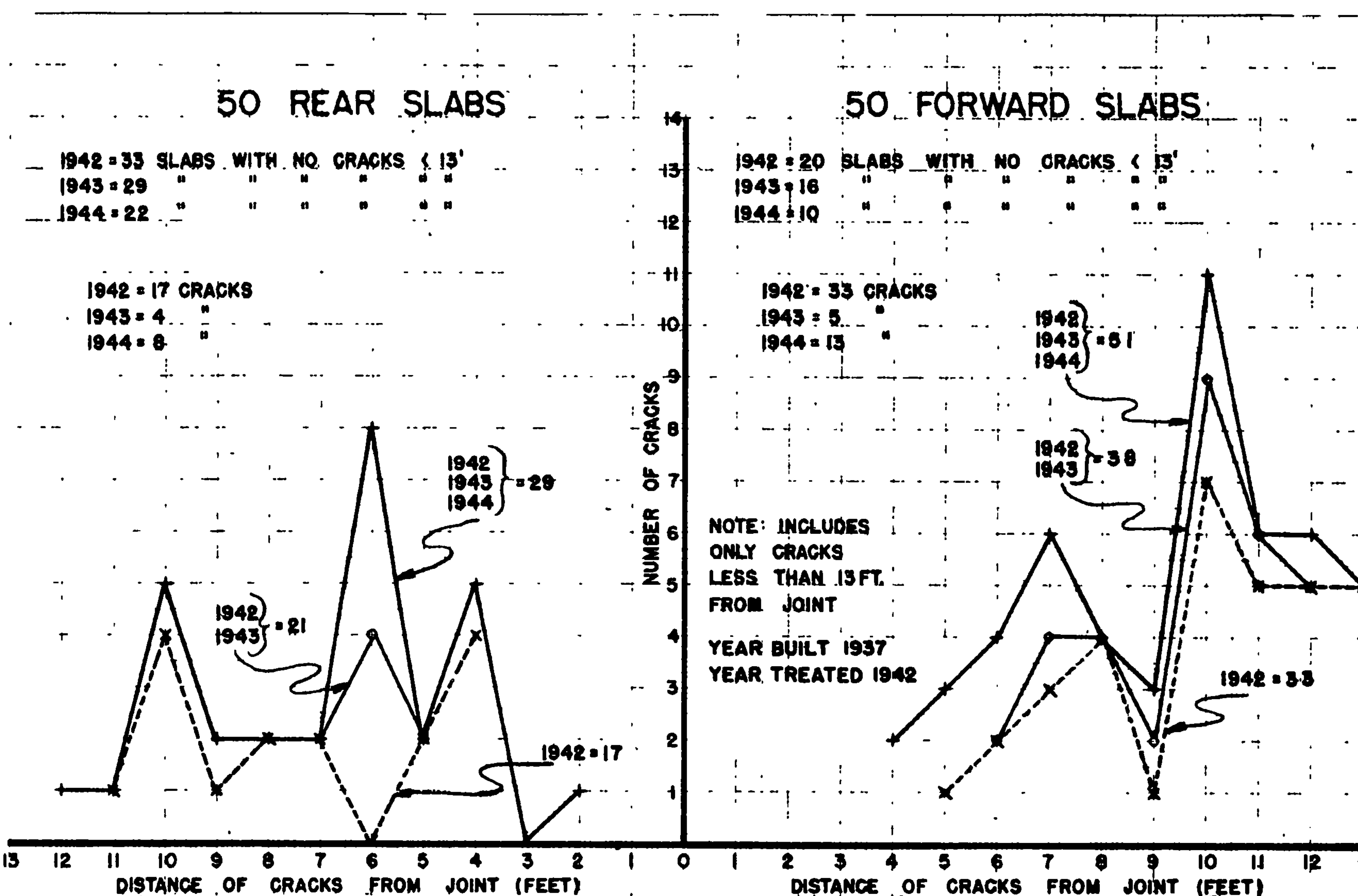


FIGURE 29. DISTRIBUTION OF CRACKS LESS THAN 13 FEET FROM EITHER END OF 50 TREATED SLABS

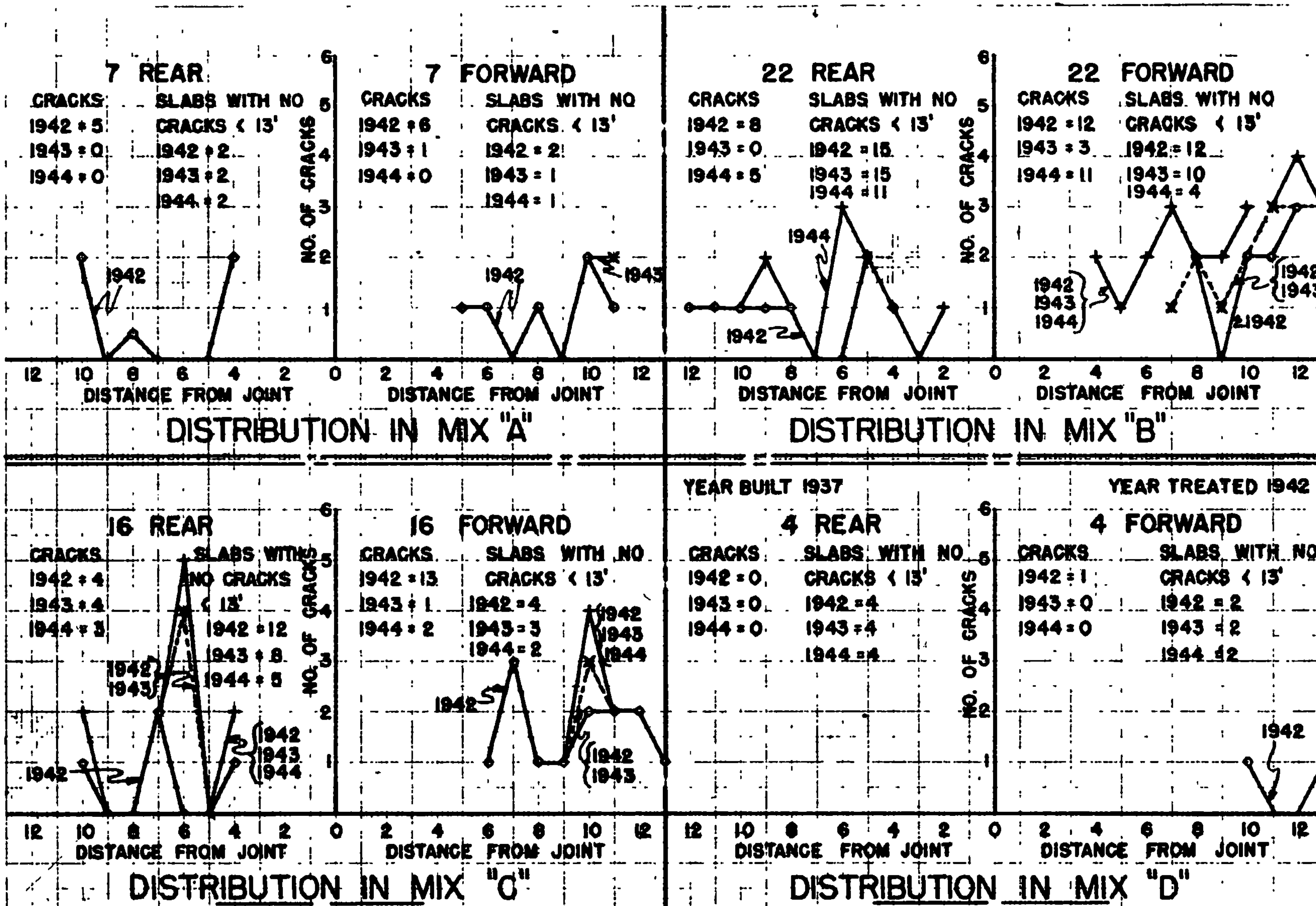


FIGURE 30. DISTRIBUTION OF CRACKS LESS THAN 13 FEET FROM THE JOINT BY MIXES

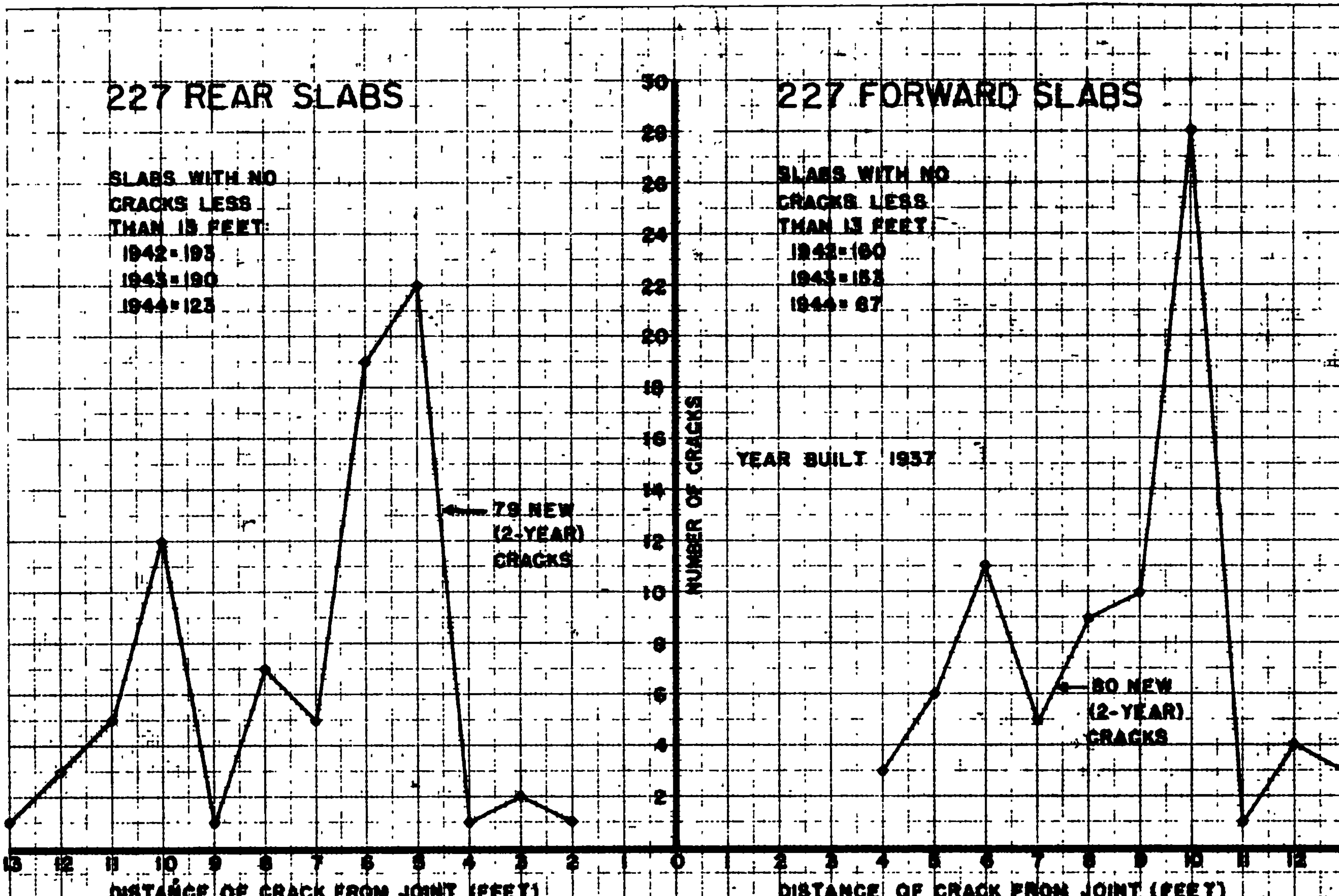


FIGURE 37 DISTRIBUTION OF NEW CRACKS OCCURRING IN TWO YEARS - 227 UNTREATED SLABS

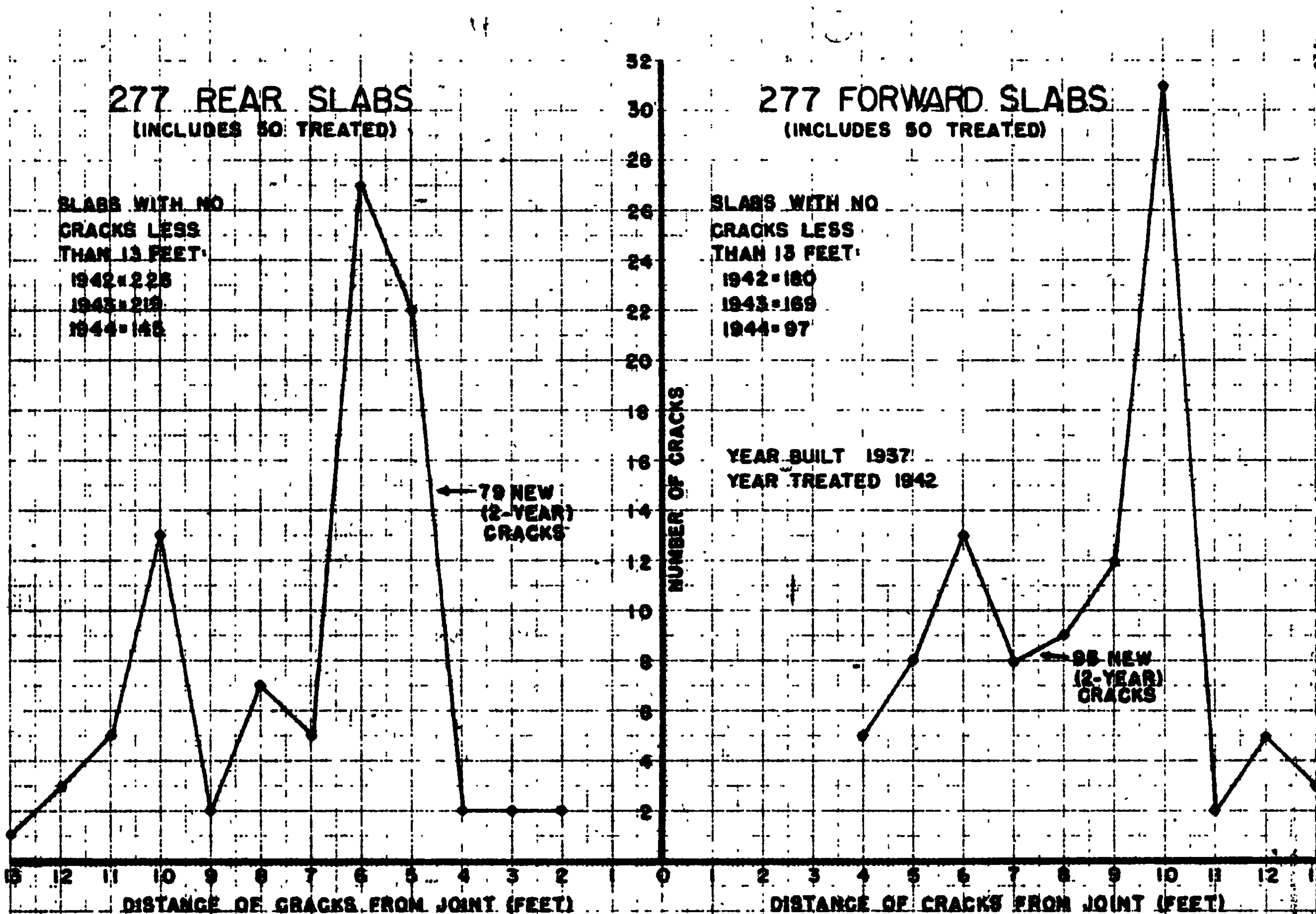


FIGURE 32. DISTRIBUTION OF NEW CRACKS OCCURRING IN TWO YEARS - TWO MILE SECTION

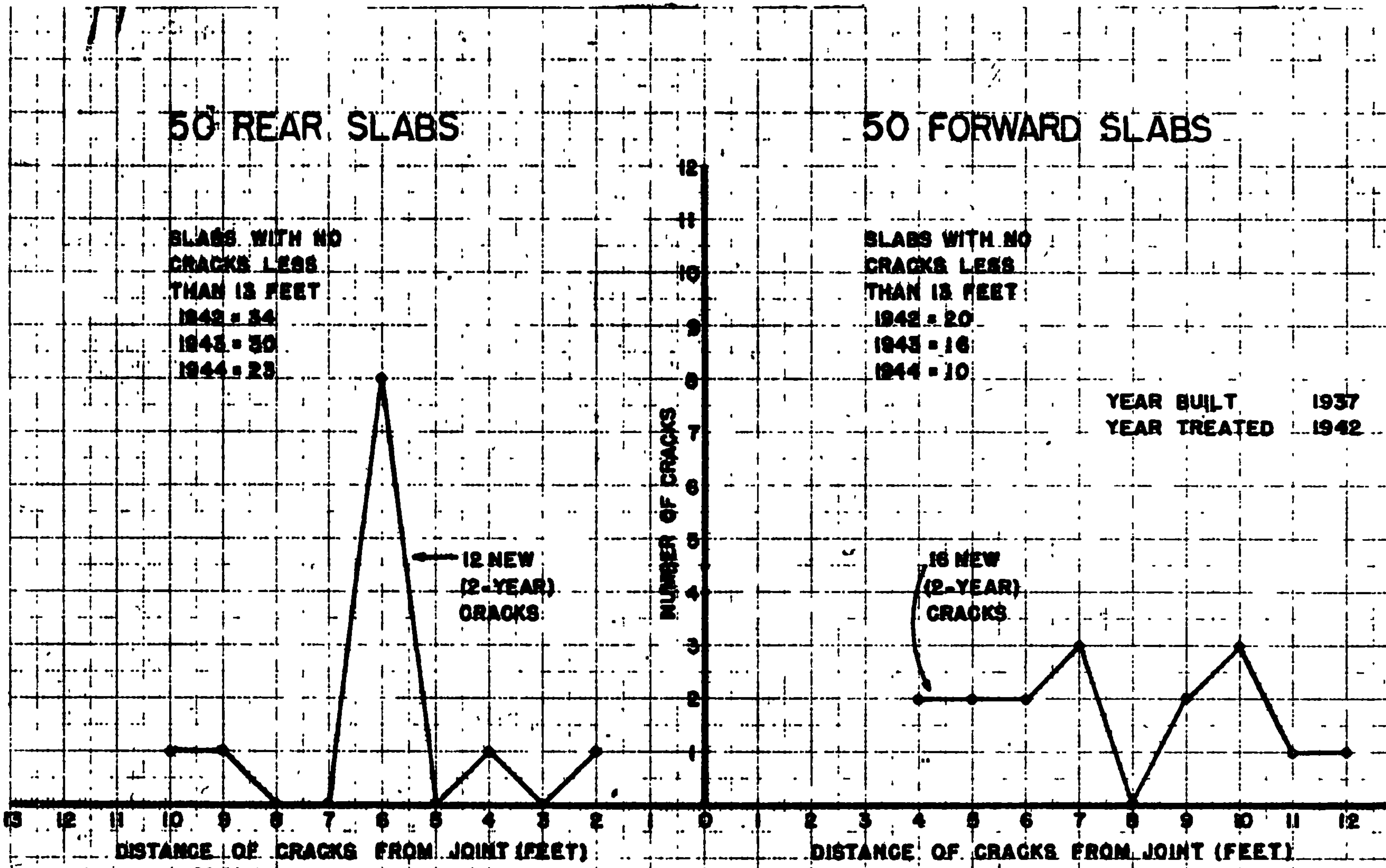


FIGURE 23. DISTRIBUTION OF NEW CRACKS OCCURRING IN TWO YEARS - 50 TREATED SLABS

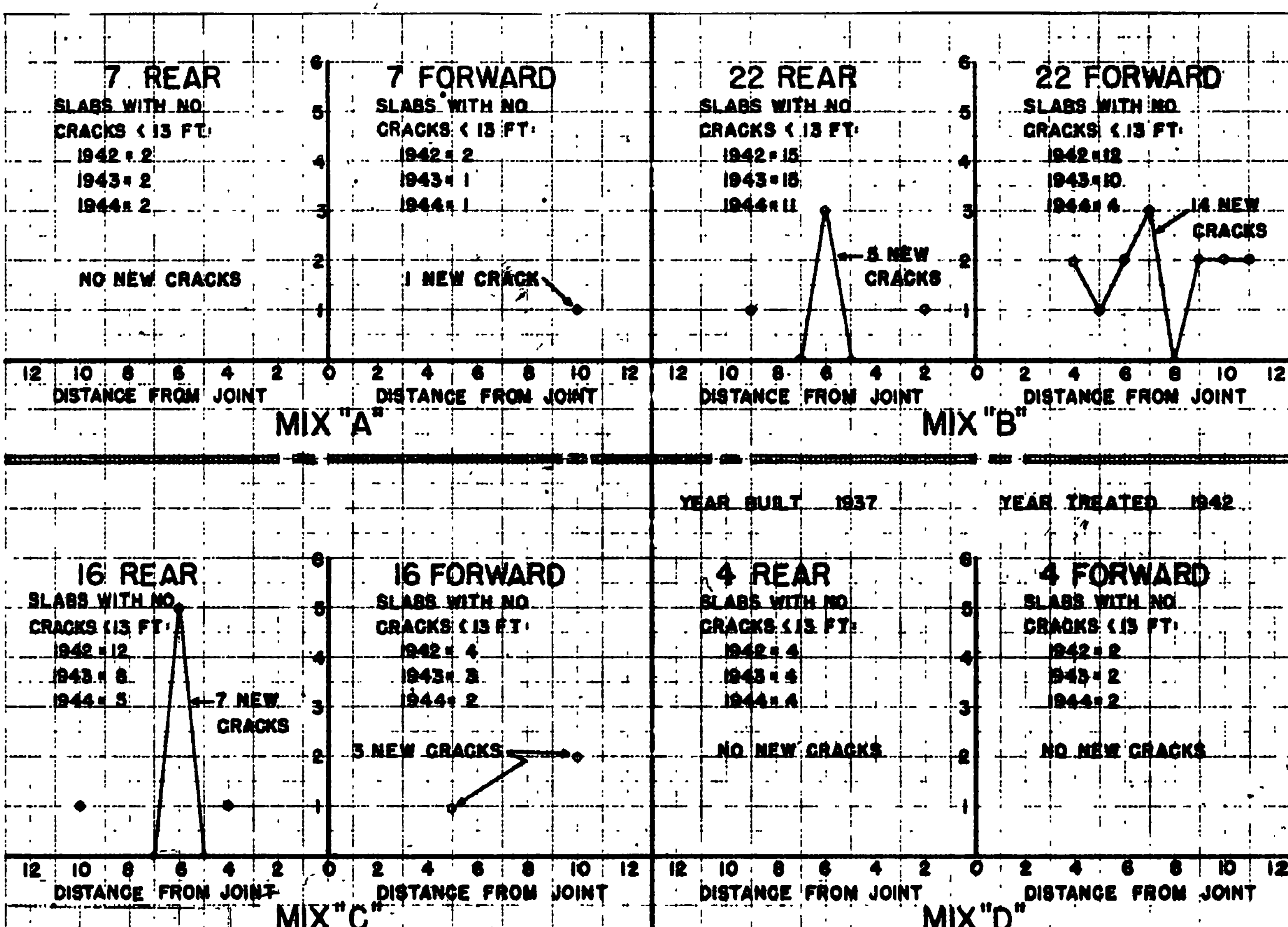


FIGURE 34. DISTRIBUTION OF NEW CRACKS (TWO YEARS) BY MIXES

REMOVAL OF FAILED SLABS

On November 27, 1944, portions of three slabs that had failed and settled considerably were removed and replaced with sand and given a limestone surface. Each of the failed slabs had been patched; some containing two patches. Two of the slabs had been treated by mud-jacking (mix B) and one was of the untreated section. The two treated slabs that failed were located in a cut section where the grade was such that drainage was exceptionally poor. Both were rated P-3 (severely pumping) at the time of treatment. A description of each joint and the condition during each performance survey are contained in the Appendix (Record of mud-jacked joints that were patched). Figures 35 and 36 were taken at the time of removal of these slabs. Figure 37(A) is a photo of a sample of mud-jack mix taken from beneath the slab at Sta. 694+86. The mix under this slab was laminated and strings of bituminous material were found in the mix. This is perhaps because of the fact that mixing and treating were done during cold weather and that the hot bituminous material chilled and became stringy when it came in contact with the cold mixing water. Figure 38 contains a series of sketches showing the condition of the subgrade at each location at the time the slabs were removed.

Examination of the mix under the slab at Sta. 695+26 showed the mix to be somewhat disintegrated (cracked) but that it was fairly uniformly mixed and not plastic. The area in which the mix was found seemed to be somewhat drier than the rest of the subgrade. A band of mud about two feet wide was found under the joints and cracks. It appeared that the broken slab sections were rocking on or being supported by the drier area in which mud-jack mix was found. This was true in the other treated section which was removed. A similar muddy condition was found under the untreated slab. The subgrade was dry under the inner portions of the slab and extremely wet under the cracks and at the joint and edge.

The drains in all three cases had clogged from the bottom of the slab to the tile. The stone particles were completely coated with silt and clay pumped from beneath the subgrade. Figure 39 shows the condition of the stone in some of the drains.

A sample of the mix under the slab at Sta. 695+26 was compared to a sample that had been exposed for two years in a ditch on the Deep River hill and found to be similar in all details. Both were hard, non-plastic, uniformly mixed, somewhat porous, and relatively dry.

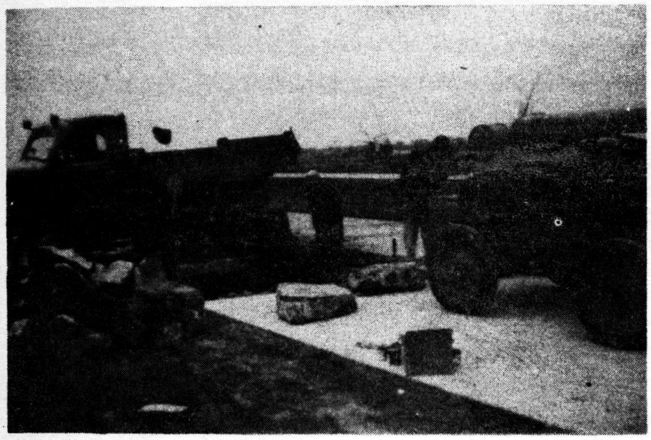


FIGURE 35. REMOVING A SLAB THAT HAD FAILED DUE TO PUMPING.

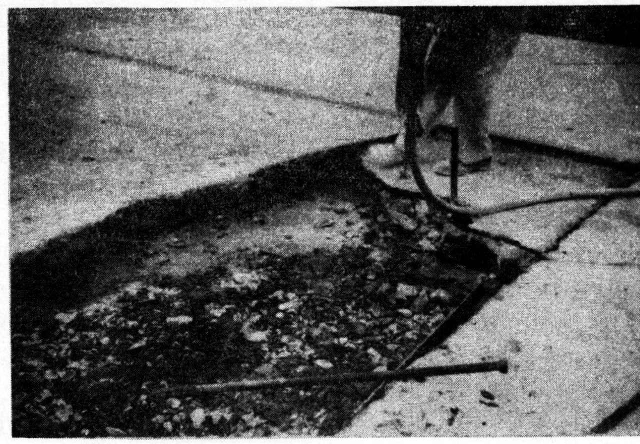
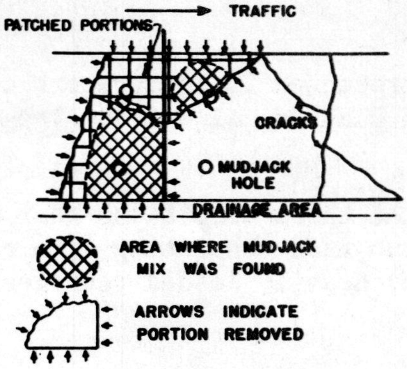


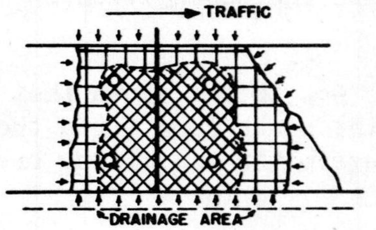
FIGURE 36. AN ILLUSTRATION OF THE ZONE OF MUD FOLLOWING THE CRACK.

FIGURE 37. PHOTOGRAPHS OF THREE SAMPLES OF MUD-JACK MIX. THE SAMPLES IN PICTURES A AND B WERE TAKEN FROM BENEATH THE PAVEMENT OF TWO TREATED SLABS, AFTER TWO YEARS OF SERVICE. THE SAMPLE IN PICTURE C WAS EXPOSED TO WEATHERING FOR TWO YEARS IN THE DITCH LINE. COMPARE THE TEXTURE OF SAMPLE A WITH THAT OF SAMPLES B AND C. STATION 694+86 WAS TREATED WITH MIX B DURING COLD WEATHER AND THE CHILLING OF THE BITUMINOUS MATERIAL RESULTED IN A NON-UNIFORM MIX. NOTE THE LAMINATIONS IN SOME OF THE SAMPLES IN PICTURE A.



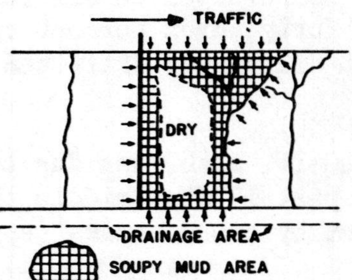
MIX "B" STATION 694+86

The mix under the slab varied in thickness and texture. The thickness varied from 0 to 2"; the thickest being farthest from the holes and the maximum under the holes. No trace of the mix was found in the inner rear portion of the section. The mix was laminated. Mud was found under the parts adjacent to the mix. The stone in the drain had clogged to the tile.



MIX "B" STATION 695+26

The mix under the rear slab had disintegrated and only a slight trace was found. The mix under the forward slab was also disintegrated but there was more present. The thickness varied from 0 to ½". The mix had cored to 3" under the holes. An area of soupy mud was found around the crack areas. The drain (stone) was clogged to the tile.



UNTREATED STATION 662+46

This slab was not treated. A zone of soupy mud was found directly under the cracks and the joint. The remainder of the subgrade-pavement contact area was fairly dry. The drain at this joint had also clogged to the tile.

FIGURE 38. SKETCH OF SLAB AREAS FOR REPLACEMENT.

FIGURE 39. COMPARISON BETWEEN CLEAN STONE AND STONE COATED WITH MUD SLURRY FROM A PUMPING JOINT. THIS STONE WAS REMOVED FROM A DRAIN THAT HAD CLOGGED.

SUMMARY OF RESULTS

The following statements summarize the data presented in this report concerning the performance of U.S. No. 30 from Valparaiso to U.S. No. 41 and the two-mile section under observation:

1. This work confirms previous studies in that three conditions must be satisfied in order to have pumping. These are: (a) A subgrade consisting of a relatively plastic and impervious clay or silty-clay soil; (b) Heavily loaded vehicles; and (c) free water.

2. Once pumping starts the rate of progression increases, with severe pavement cracking and settlement resulting.

3. Each performance survey conducted on U.S. No. 30 has shown that all of the experimental subgrade treatments constructed on the south lane (with the exception of the water-saturated section) have been successful in minimizing or preventing pumping.

4. Pumping does not occur in natural sand areas or in the sections constructed on 6 in. of sand. Forty-two percent of the slabs constructed on six in. of sand contained no cracks after seven years of service and forty-seven percent contained only one crack. All slabs on the two-mile section on silty clay drift had cracked by the end of seven years.

5. Cracking within 13 ft. of a joint, in a 40-ft. slab, was due to slab movement initiated by pumping action and that cracks past 13 ft. (middle third of slab) were not caused by any movement at the joint but by other causes (applies to untreated slabs only).

6. The destruction of 40-ft. slabs by cracking initiated by pumping at joints on U.S. No. 30 appears to follow a definite pattern: the forward slabs pump and appear to break off first, usually 10 ft. from the joint and then six ft. from the joint; the rear slabs follow by breaking off usually at five feet from the joint which is followed by a break at 10 ft. (applies to untreated slabs only).

7. Between the fifth and seventh year of this pavement's life cracking less than 13 ft. from the joint increased 154 percent while cracking past 13 ft. (or in the middle third) increased only 10 percent (applies to untreated slabs only). (See Fig. 28.)

8. During the two-year period (fifth and seventh year) cracking less than 13 ft. to the rear of untreated joints increased 226 percent, and cracking on the forward slabs increased 117 percent. During the same period, cracking within 13 ft. to the rear of treated joints increased only 70.5 percent and on forward slabs only 51 percent.

9. Treatment by mud jacking reduced the expected increase in two-year cracks (fifth to seventh year) within 13 ft. from joints from an increase of 154 per cent to an increase of 58 percent. (See Fig. 28)

10. Each mud-jack mix was effective in reducing cracking. Only one new crack occurred in 7 slabs treated with mix "A"; none occurred on 4 slabs treated with mix "D"; and 10 new cracks occurred on 16 slabs treated with mix "C".

11. During the two years following treatment, mud jacking has been successful in reducing the average settlement of slabs at pumping joints. The average settlement of the outer edge of treated slabs two years after treatment was found to be 0.093 inches as compared to 0.194 inches for untreated slabs.

12. During the two years following treatment 48 percent of the treated slabs had not settled as compared to 26 percent not settling for untreated slabs. Sixty-eight percent of the treated joints had settled less than one-eighth inch as compared to 53 percent of the untreated slabs.

13. Mixes "A" and "D" were the most effective in reducing both cracking and settlement. Of mixes "B" and "C", slabs treated with mix "B" settled less than slabs treated with mix "C".

14. It was found that the amount of material pumped from beneath a slab due to pumping action is appreciable, as indicated by an average of 8.7 cu. ft. of material per joint which was pumped beneath the slabs.

15. When bituminous material is used in mud jacking, the operation should be done during periods of warm weather to avoid chilling of the bituminous material in the mix.

16. Observations extraneous to the data contained indicate that periodic maintenance of mud-jacked joints by pouring of the cracks and joints and by keeping the drilled holes filled will prolong the effective life of treatment.

17. These data show that since cracking, settling, and pumping on rear slabs increases rapidly following the failure of forward slabs, they should also be treated by mud jacking which, if done during the initial stages, would consist of a void-filling operation while that of the forward would be a raising operation.

18. The limited data contained in this report regarding mud-jacking procedures prevent recommendation for operational procedures; however, by way of observation the following are pertinent:

(a) The work should be under the care of an experienced operator or one competent to judge when a slab has been properly treated, since mistakes will perhaps prove detrimental rather than beneficial.

(b) Each slab should be handled as an individual case rather than following a standard procedure of operation.

(c) Traffic should be kept off of treated slabs for at least 24 hours following treatment.

(d) In areas where surface drainage is exceptionally poor, the slab should be given some form of supplemental drainage that should receive periodic maintenance.

19. The results of this survey show that mud jacking can prolong the life of a pavement being destroyed by pumping action, and the above results show a need for further research in which other materials should be used and in which various operational procedures are investigated.

REFERENCES

1. "Performance Survey on a Portion of U.S. 30, Four-Lane Divided Pavement in Lake and Porter Counties", Unpublished Report No. 4 on Concrete Performance Survey, Project C-36-35, by T. E. Shelburne, Research Engineer, Joint Highway Research Project, Purdue University.

2. Woods, K. B. and Shelburne, T. E. - "Pumping of Rigid Pavements in Indiana", Proc., 23rd Annual Meeting, Highway Research Board, 1943.

3. Wartime Road Problems No. 4, page 9, Highway Research Board, Washington, D. C. (See page 133 of this publication).

APPENDIX

RECORD OF MUD-JACKED JOINTS THAT WERE PATCHED (FIELD NOTES)

Mix A. One joint out of seven had been patched and was rated P-4 (pumping very severely) after two years' service.

Sta. 721+66

10/21/42 - During the mud-jacking operations at this joint the hose broke and operations ceased for the day, and were resumed on October 27.

10/27/42 - The RC-3 mix was very stiff due to cold weather and more water had to be added to make the mix workable. Total mix applied - 11¼ cu. ft.

5/ 6/43 - Performance Survey
Rated the joint as P-2 (moderately pumping). Pumping was observed along the edge of the pavement and along the joint. One new crack had developed in the forward slab. The French drain was plugged.

10/12/44 - Performance Survey
Rated the joint as P-4. Pumping very severe. Even though the joint had been patched with a bituminous patch, the joint was pumping and the slabs had settled an additional amount.

Mix B. Three joints out of 22 had been patched, two of which were rated P-4 and one rated OK after two years' service.

Sta. 717+26

10/28/42 - Treated by mud-jacking. The subgrade was dry and there was no soupy mud under the pavement. The pavement could not be raised by pumping material into two holes so it was necessary to use three holes along the joint. A gasket leak developed in the pressure chamber which was sufficient to prevent complete mud-jacking. The mix applied on 10/28/42 was 4½ cu. ft. (Road oil mix).

5/ 6/43 - Performance Survey
The joint was rated as P-2. No new cracks were found in either slab but two rear slab cracks were pumping P-1 and P-2. The mud-jack holes were full.

10/12/44 - Performance Survey
The joint was rated OK since pumping was not observed. One new crack was observed in the forward slab and one corner break in the rear slab.

Sta. 695+26

11/ 2/42 - Mud-jack operations. The treatment at this joint was somewhat complex. A small amount of mix was added to each hole to raise both slabs to grade. Each slab had settled and two holes were drilled in each slab. The forward slab required 12 cu. ft. to raise; the rear slab four cu. ft. or a total of 16 cu. ft. of Road Oil mix. The joint was then drained with French drain consisting of No. 8 stone. However, the drain had insufficient outlet as the pavement section was in a cut area.

5/ 6/43 - Performance Survey
This survey showed three of the mud-jack holes half full and one empty. The joint was rated P-1 and the first crack in the rear slab (nearest the joint) was rated P-2 and was spalled severely. One new crack (corner break on inner side of forward slab) had developed.

10/12/44 - Performance Survey
This survey showed the joint to be a complete failure. Even though the joint had been patched (area between cracks), the inner section of the slabs had settled 1-3/4 inches since patching. The joint was rated as P-4 because pumping was severe. Two new cracks had developed in the forward slab.

11/27/44 - Slab removed for replacement.

Sta. 694+86

11/ 2/44 - Mud-jack operations. This joint required using four mud-jack holes (two on the forward slab and two on the rear slab) to raise to grade. The forward slab required 12 cu.ft. and the rear slab four cu.ft. The pavement (rear slab) was cracked during mud-jacking operations (corner break). The pavement was in a cut area and the joint was drained using a French drain (#8) stone. The outlet was insufficient for successful drainage.

5/ 6/43 - Performance Survey
The joint was rated as P-1. One new crack had developed (corner crack on inner part of slab) on the forward slab. The crack nearest the joint on the rear slab was rated P-1. One mud-jack hole was empty.

10/12/44 - Performance Survey
The joint was rated as P-4 because the inner part of both slabs had been patched between the corner cracks and pumping was severe. The rear slab section had settled one inch (to the top of the patch). The actual settlement was over four inches.