Laboratory Studies of Progressive Bond Failure In Continuously-Reinforced Concrete Slabs

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This paper reports the results of research initiated to determine a method of measuring bond failure, to evaluate the effect of repetitive vertical loads in producing progressive bond failure from crack to crack in continuously-reinforced concrete pavements, and to determine the magnitude and distribution of bond stresses in the vicinity of cracks.

To evaluate bond stresses near cracks and to study their change under repetitive loads, a plastic gage was developed to determine minute movements of the steel bar with respect to the concrete. These movements change the rate of compressed air flow through the gage, and linear movements are determined by measuring the rate of air flow. An attempt was made to relate these differential movements to bond stress by assuming that these differential movements, divided by the distance between plastic gages, were strains in the steel.

Pull-out tests on 9-in. concrete cubes were used in arriving at a satisfactory size and configuration for the plastic gage.

Conclusions reached are as follows:

1. The plastic gage used in conjunction with an air flow meter provides a simple and practical means of determining the differential movement of steel bars with respect to concrete without destroying any of the deformation on the bars.
2. Bond stress at points within a region of slip may greatly exceed the average bond stress over this region.
3. Heavy repetitive vertical loads increased the magnitude of slip in regions adjacent to cracks, but bond stresses were not increased in the same proportion.
4. Seven million repetitions of heavy wheel loads resulted in slip of less than 0.002 in. at a distance of 6 in. from a crack; 12 in. from a crack the slip was zero.
5. When cracks are spaced more than 2 ft apart, the possibility of 9,000-lb truck wheel loads producing progressive bond failue in continuously-reinforced pavements on medium plastic subgrades is practically nonexistent.

• SINCE 1955 Purdue University has been engaged in laboratory research on continuously-reinforced concrete slabs. Nineteen concrete slabs 7 or 8 in. thick have been poured in forms in the laboratory and then placed onto special rubber mat subgrades. Longitudinal tensile forces were applied to the slabs to simulate temperature decreases. Vertical static loads were then applied by jacks to simulate vehicle wheel loads. The results of these experiments have been reported by Gutzwiller and Waling (1, 2).

With financial support by the National Science Foundation, this laboratory research has been extended to include studies of progressive bond failure in concrete slabs under dynamic loads. This paper is a report of the first work completed in this phase of the research.

PURPOSE AND SCOPE OF RESEARCH

The possibility of a bond failure progressing from crack to crack has occurred to many who are interested in the field of continuously reinforced pavements. A report of the American Concrete Institute in 1959 stressed the need for research on bond behavior at cracks (3). The problems involved in such research include the detection of bond failure without removing an appreciable portion of the bonding surface of the steel from contact with the concrete, and the isolation of the many variables affecting stresses in the slab so that their effects might be evaluated separately.

This phase of the research project had a two-fold purpose:

1. To develop a method of detecting bond failure without destroying the deformations on the bars.
2. To apply such a method to laboratory models of continuously reinforced concrete slabs to determine if repetitive vertical loads cause bond failure to progress along the reinforcing bars.

The controlled variables included in the experiments were percentage of longitudinal reinforcement, position of reinforcement, subgrade modulus, longitudinal load on the slab, and magnitude and position of a simulated wheel load. The principal dependent variable measures was the longitudinal movement of the reinforcement relative to the concrete adjacent to the bars. Concrete surface crack widths were also obtained for most specimens. A limited number of measurements of steel strains and vertical deflections of the slab were recorded.

DEVELOPMENT OF GAGE TO MEASURE SLIP

To implement this research, it was necessary first to seek a means of detecting breakage of bond between reinforcing bars and the concrete without appreciably reducing the bonding area of the bars. After several attempts to create devices for detecting

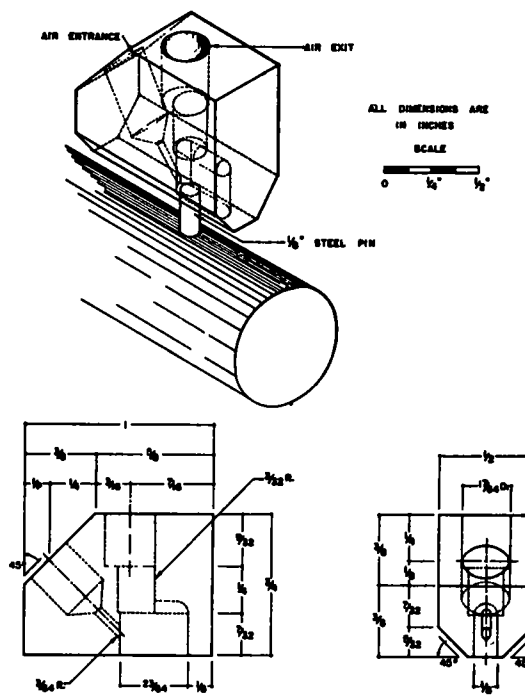

Figure 1. Plastic gage.

such breakage, a plastic gage was developed, which when coupled with an air flow meter provides an accurate measure of the longitudinal movement of the bar with respect to the concrete. In this paper this type of movement is referred to as "slip." Although no attempt is made to define the amount of slip required for bond failure, the plastic gages were used to measure slip along a bar in the vicinity of a transverse crack. The point at which the slip became zero was determined from a plot of the slip values recorded at the gages located along a bar.

The size and positioning of the plastic gage is shown in Figure 1. The gage was 1 in. long and made of $\frac{1}{2}$-in. plexiglass. A $\frac{1}{4}$-in. O. D. polyethylene tubing was cemented into the "air entrance" and "air exit" chambers, and the far end of the "air entrance" tubing was connected to Column Type Precisionaire instruments (manufactured by the Sheffield Corporation of Dayton, Ohio). The Column Type Precisionaire instruments, hereafter referred to as the "column gages," are a type of air flow meter and were used to measure the amount of air flowing through the plastic gages.

The plastic gage was positioned along the longitudinal ridge, two of which are present on any reinforcing bar, so that the air entrance hole was plugged by a $\frac{1}{8}$-in. stainless steel pin that had previously been set into a $\frac{1}{8}$-in. hole drilled into the longitudinal ridge of the bar. The groove in the bottom of the plastic gage into which the stainless steel pin fitted was machined with a $\frac{1}{8}$-in. end mill to obtain a snug yet workable fit. The tubing from the air exit hole of the gage extended to the exterior of the concrete to provide a path for the flow of air as the pin was moved with respect to the plastic gage.

When installed on the bars and cast in concrete, the plastic gage was held in a fixed position by the concrete; therefore, the column gages registered the movement of the steel with respect to the concrete as the steel strained on being stressed. At a crack the steel is strained and this strain gradually decreases as the force in the steel is transferred to the concrete by bond.

In calibration a metal guide was used to prevent lateral movement of the plastic gage. Longitudinal movement of the gage relative to the steel pin was produced through a pusher block machined to slide in the same groove of the metal guide as that used by the plastic gage. The pusher block was activated by pressure from a screw that itself was fitted in a second housing that could be fastened to the reinforcing bar, as shown in Figure 2. Longitudinal movement was measured with a dial gage with 0.0001-in. graduations. A typical calibration curve indicating the spread of points obtained in the calibration process is shown in Figure 3.

The plastic gage was used only to detect movement of the pin in one direction from its "home" position, the "home" position being defined as that at which the steel pin plugged the air entrance hole. Movement of the steel pin away from the air entrance

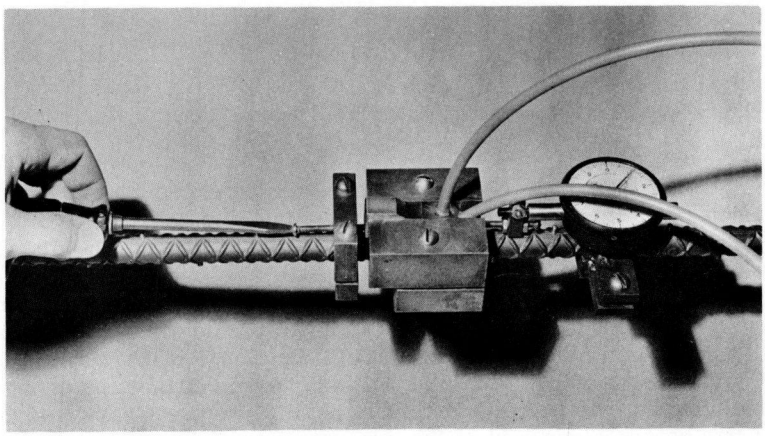

Figure 2. Calibration of plastic gage.

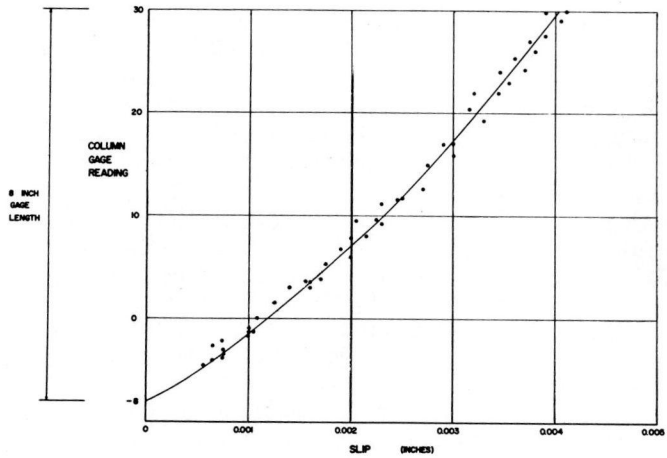

Figure 3. Calibration curve for gage 28, slab 7.

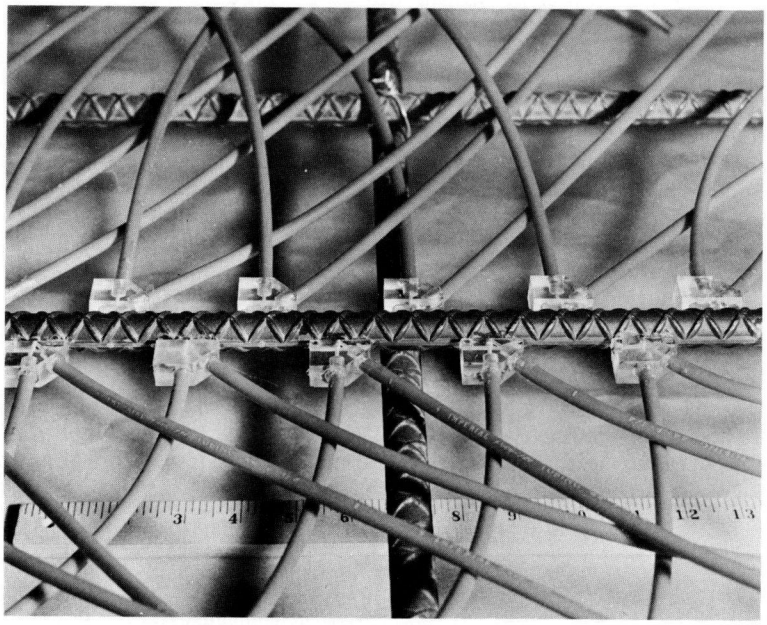

Figure 4. Plastic gages glued in position on reinforcing bars.

hole to allow air to flow through the gage is hereafter referred to as movement in the positive direction, with movement in the opposite direction being referred to as that in the negative direction. It is therefore apparent that the gage must be installed with consideration to the direction of positive movement.

After calibration, the plastic gages were cemented to the reinforcing bars with Duco cement. Long steel guide plates and tape were used to hold the gages in alignment and in their "home" position for 24 hr. Additional thin coatings of Duco cement were then added to seal any small openings along the milled groove between the under side of the gage and the reinforcing bar to exclude cement paste. Figure 4 shows several gages cemented to a bar before placement of the concrete.

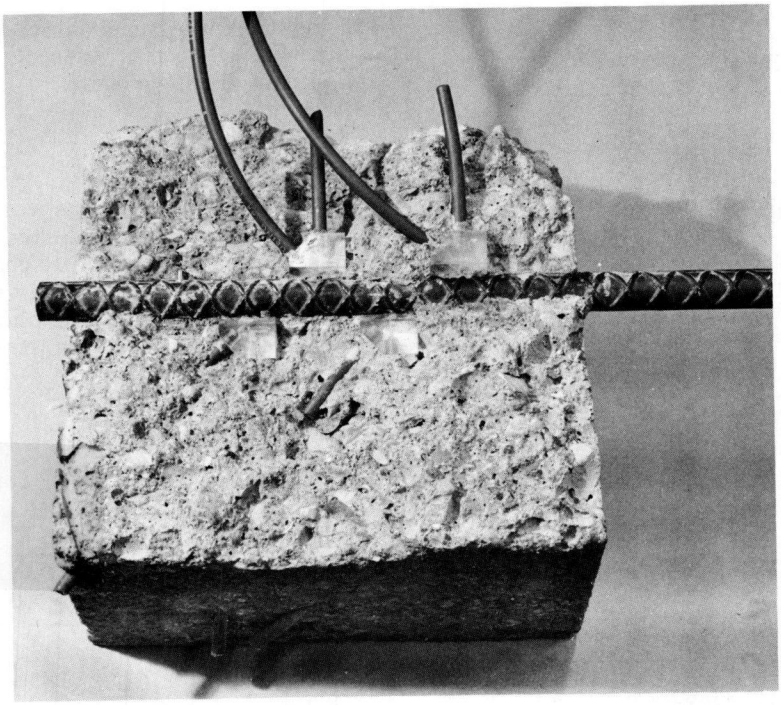

Figure 5. Plastic gages in pull-out specimen after a test.

In the development of the plastic gage numerous simple pull-out experiments were conducted on reinforcing bars fitted with plastic gages and cast in 9-in. concrete cubes. The gages, which were in contact with the bar only along its longitudinal ridge, did not appear to produce planes of weakness in the concrete. In fact it was very difficult to split a specimen along a satisfactory plane to obtain the picture for Figure 5.

The column gages used in this research had pressure regulators and 8-in. graduated vertical columns in which the rate of air flow was indicated by the position of a float. By experience it was found that with the pressure regulators set to 20 psi, movement of the plastic gage along the reinforcing bar from 0.003 to 0.004 in. from its "home" position caused the float to travel the 8-in. calibrated length of the column. Sensitivity decreased as the air pressure was lowered.

DESCRIPTION OF EXPERIMENTAL SLABS

Size and Number

Experiments were performed on eight slabs in this phase of the research. Due to limitations in space beneath the loading frame, the slabs were limited to 3 ft by 12 ft by 8 in.

Materials

Steel. — As shown in Figure 6, each slab was reinforced longitudinally with 0.54 percent steel, provided by five equally spaced No. 5 deformed billet steel reinforcing bars conforming to ASTM A 15-58T and having diamond pattern deformations conforming to ASTM A 305-56T. Properties of this steel are given in Table 1. The longitudinal steel was placed at mid-depth of all slabs except slabs 5 and 7, in which cases it was placed ¾ in. below mid-depth.

Concrete. — The concrete was obtained from a local ready-mix company and was to meet the following requirements:

TABLE 1

PROPERTIES OF REINFORCING STEEL

Property	Steel
Yield strength (psi)	73,000
Ultimate strength (psi)	120,200
Modulus of Elasticity (psi)	29×10^6
Percent elongation over 8-in. gage length	12.0
Percent reduction of area	48.7

28-day ultimate compressive strength	4,000 psi
Maximum size aggregate	1½ in.
Slump	2-4 in.
Entrained air	3-6 percent

Three 6- by 6- by 16-in. beams and six 6- by 12-in. cylinders were cast for flexural and compressive strength tests. Slabs 1 and 2 were initially considered as pilot experiments, and it was decided to use concrete with a higher slump in these tests. Results of tests on the concrete are shown in Table 2.

TABLE 2

PROPERTIES OF CONCRETE FOR SLABS[a]

Slab No.	Date of Pour	Slump (in.)	Avg. Cylinder Strength (psi)	Avg. Modulus of Rupture (psi)	$E \times 10^{-6}$ (psi)
1	9/23/60	7	3,060	400	3.30
2	11/15/60	8	3,320	423	3.50
3	12/23/60	4½	2,830	433	2.76
4	1/27/61	1½	4,285	527	4.00
5	2/27/61	4½	3,490	394	3.40
6	3/24/61	4	4,000	576	3.78
7	4/21/61	2	4,490	494	4.00
8	5/12/61	4½	4,710	669	4.54

[a]All cylinder and beam tests made 28 days after pour.

Forms for Experimental Slabs

The forms consisted of two plywood carts, each 6 ft long, resting on truck casters. The two carts were assembled end-to-end with side and end boards in place to provide a clear space of 3 ft by 12 ft by 8 in. Holes were drilled in the side and end boards of the form to receive the tranverse and longitudinal bars.

Because the object of these experiments was to determine the slip pattern in the vicinity of a crack, a weakened plane was created at midlength of the slab to cause the slab to crack initially at that position. This was done by threading four rows of 12-gage wire through vertically aligned holes in the side boards of the form and tightening them to produce five approximately equal spaces between the longitudinal steel and the bottom of the form. Another four rows of the wire were similarly placed between the steel and the top of the form.

Other Preparations for Casting

Short lengths of deformed bars were installed at each end of the slab, as shown in Figure 6, to provide adequate strength in fittings for applying longitudinal forces. Threaded adapters were welded to the ends of all bars. Similar adapters had been used in static tests previously reported (2).

The transverse steel bars indicated in Figure 6 were of the same size and grade as the longitudinal steel. These bars not only supported the longitudinal steel, but were used also to tide together the side boards of the forms. Later, hanger bars were attached to these bars to support the slab while it was lowered to the subgrade.

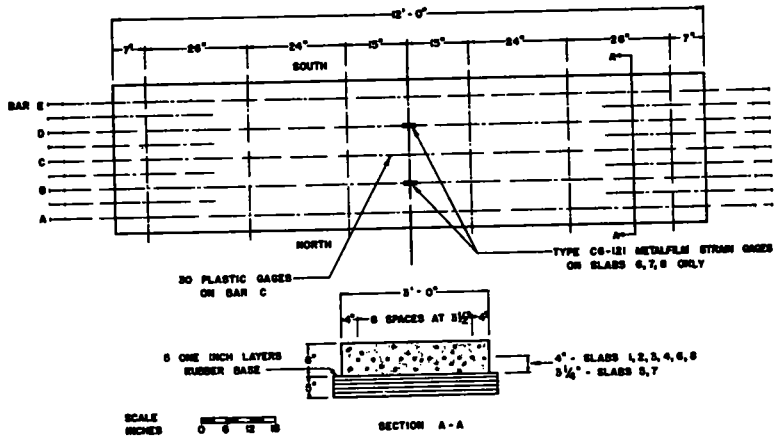

Figure 6. General plan for slabs.

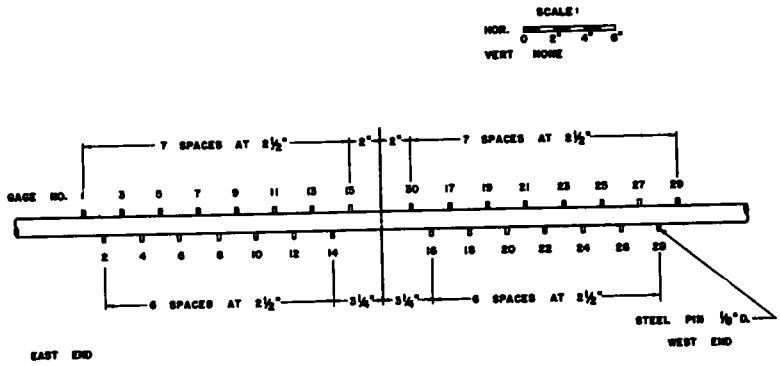

Figure 7. Bar C.

Plastic gages were arranged in a staggered pattern on two sides of bar C (see Figs. 6 and 7). The midpoint of the bar was placed at the location of the prepared weakened plane in the slab. Steel plugs were also embedded in the surface of the wet concrete at 10-in. intervals on lines 7 in. from the longitudinal edges of the slab. Other gage plugs were cemented to the side of the slab at the elevation of the longitudinal steel after the slab was poured. A 10-in. Whittemore strain gage was used to make surface strain and crack width measurements on all slabs except slab 1.

Deflections of the last four slabs were recorded by means of eight dial indicators with 0.001-in. graduations suspended from a framework. The stem of each gage rested against a piece of sheet metal that had been cemented to the surface of the concrete 1 in. from the edge of the slab.

As shown in Figure 6, electric resistance strain gages were bonded to bars B and D at midlength of the last three slabs tested. These gages were waterproofed with an asphalt coating.

Placing and Curing the Concrete

All slabs were cast inside the laboratory. The truck-mounted concrete mixer was driven inside the building in cold or inclement weather. The date of pour of the slabs is given in Table 2.

To avoid the possibility of disturbing the arrangement of the plastic gages, bar C was removed from the form while concrete was placed up to the level of the other longitudinal bars. Then bar C was lowered into the form with the rows of plastic gages in a horizontal plane. The air exit tubes were then passed through holes that had been drilled in the sides of the form, and the four rows of wire were placed above the steel at midlength point to complete the provision for the initial crack.

After bar C was in position, the pouring of the slab was completed using an internal vibrator to insure filling all spaces around the reinforcement, the gages, and next to the form. After striking off and before initial set had taken place, plugs for the Whittemore strain gage were embedded in the top surface of the slab.

Approximately 2 to 3 hr later a coating of Kurez curing compound was poured on the surface of the slab and left to dry. Within 24 hr, the slab surface was given a second coating of the compound, followed by a third coating approximately 24 hr later. Cylinders and beams from the same pour were also cured by painting with three coats of curing compound, and were tested 28 days after casting.

Elastic Subgrade

To reduce the variables in the experiments with the slabs, a rubber mat subgrade capable of providing an average subgrade modulus, or load to deflection ratio, of 140 to 145 psi per in. of deflection was used. This mat consisted of a number of 41- by 33- by 1-in. pads of rubber specially prepared by the Firestone Industrial Products Company, Noblesville, Ind., to simulate a soil having medium plasticity. This material had the same composition as that used in the static load tests previously conducted (2). Five layers of mats stacked in brick fashion were used under all slabs. The subgrade modulus was obtained by plate-bearing tests. A plate of 30-in. diameter was used for these tests.

Positioning Slabs for Loading

After the side and end pieces of the forms were removed, it was possible to roll each slab in turn into position beneath the loading frame. The slab was then transferred from the base of the form to the rubber mat subgrade. Eyebolt hangers were hooked onto the projecting ends of the transverse bars in the slab, and the threaded upper ends of the hangers were engaged by nuts and washers to a longitudinal timber beam supported by blocks on each side of the slab. The nuts at the upper end of the hangers were tightened a uniform number of revolutions to raise the slab free of the form and keep it suspended while the form was removed. The rubber mat subgrade was then laid in brick fashion on the concrete floor beneath the slab, and the slab was lowered onto the subgrade by loosening all of the nuts evenly. A single piece of wrapping paper was placed between the slab and the top of the subgrade to reduce the friction between the rubber and slab.

LOADING OF SLABS

Longitudinal Loading

Tensile stresses, simulating a temperature drop, were induced into the slab by applying longitudinal loads to the reinforcing bars projecting from the ends of the slab. The four additional lengths of reinforcing bars spaced between the five longitudinal steel bars at the ends of the slab aided in distributing the force to the concrete as well as in reducing the possibility of fatigue failures in the connections at the ends of the bars. The threaded adapters, which were made from 1⅜-in. steel rods, were threaded on one end for a nut and were drilled at the other end so that the reinforcing rods might be inserted and welded to them.

A set of two I-beams was then placed transverse to the slab at each end with the projecting reinforcing bars passing between them. Plates and then nuts with washers were fitted onto the adapters with the plates flush against the flanges of the I-beams. Hydraulic jacks were then aligned with pipe columns on each side of the slab, with one end of the pipe column pressing against the set of I-beams at the west end of the slab while the

hydraulic jack piston pressed against a small bearing beam that transferred the jack load to the set of I-beams at the east end of the slab. When compressive loads were applied to the columns through the hydraulic jacks, this same force was transferred through the I-beams to the reinforcing rods protruding from the ends of the slab.

The hydraulic jacks were calibrated before each experiment in a compression testing machine. Each day during loading of a slab the jacks were observed to determine if there had been any loss in load. When such losses reached 2 kips, the jack loads were adjusted back to the original settings. Such adjustments were generally necessary only four or five times during the three-week duration of each experiment.

Repetitive Vertical Loading Arrangements

Amsler hydraulic jacks were used with a hydraulic pulsator to produce sine-wave loadings at two load points on the slab. The two sine-wave loadings were 180° out of phase and thus simulated the transfer of the wheel load from one load point to the other, as would occur as a truck wheel passed over the crack at midlength of the slab.

For all slabs, except Nos. 7 and 8, the center of load point E (east) was 9 in. to the east of the midlength of the slab; while the center of load point W (west) was 9 in. to the west of the midlength line. These load points were centered transversely on the slab. Figure 8 shows jacks at these two load points. In this figure the west load point is to the right of the crack ①, which is at midlength. For slabs 7 and 8 the east load point was centered over the midlength line and this load location is hereafter referred to as EE; in a similar manner the west load point was centered $4\frac{1}{2}$ ft to the west of the midlength line as shown in Figure 9, and this load position is referred to as WW. As would be expected, there was an increase in deflection at midlength of the slab during a loading cycle when the loads were shifted from E and W to EE and WW.

The vertical loads from the jacks were transferred to the slabs through a tier of circular steel plates of increasing size, the largest of which was 18 in. in diameter. A 1-in. circular rubber mat 18 in. in diameter was placed between the plates and the surface of the slab.

Three Amsler jacks were used to obtain the out-of-phase sine-wave loadings at the two load points. The larger jack, shown over the east or left load point in Figure 10,

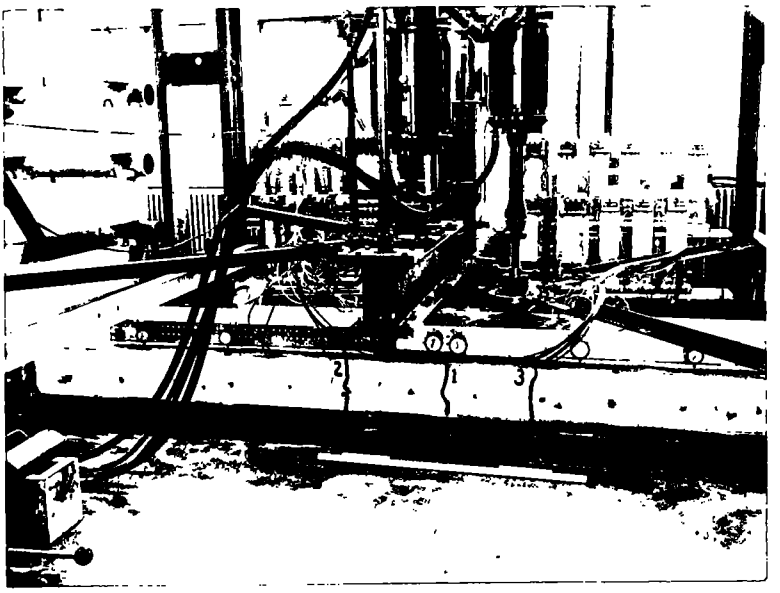

Figure 8. Crack pattern for slab 5.

was connected to the dynamometer shown by the window at the right. The dynamometer supplied a constant force to this jack. The reaction for this jack, as well as for the other two, was provided by a heavy steel beam supported by girders connected to columns. The jack over the west load point (see Fig. 10) was connected to the Amsler pulsator shown at the left. The pulsator was operated at 250 cycles per min to produce a sine-wave loading between some minimum and some maximum value. In general this minimum was 1 kip and the maximum was 9 kips. This type of loading is referred to as 9K-1K. Some slabs were loaded with a vertical loading of 17K-1K. The dynamometer

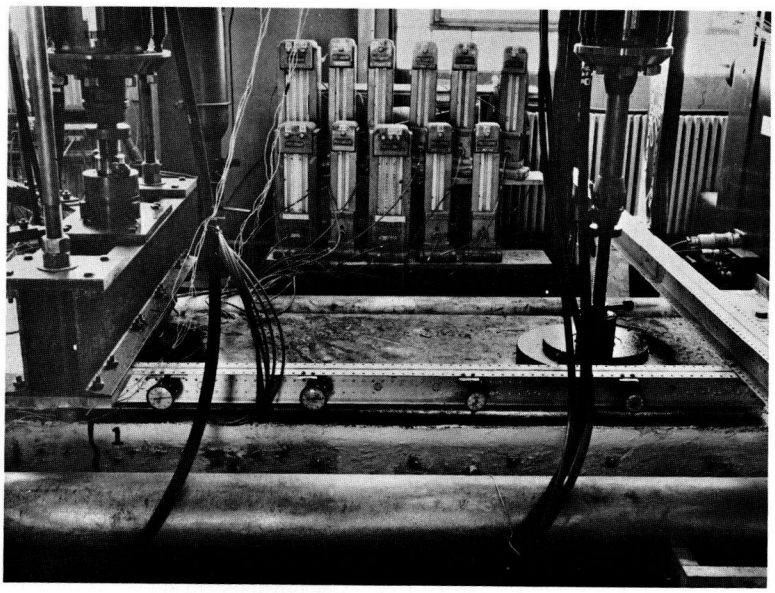

Figure 9. Crack pattern for slab 8.

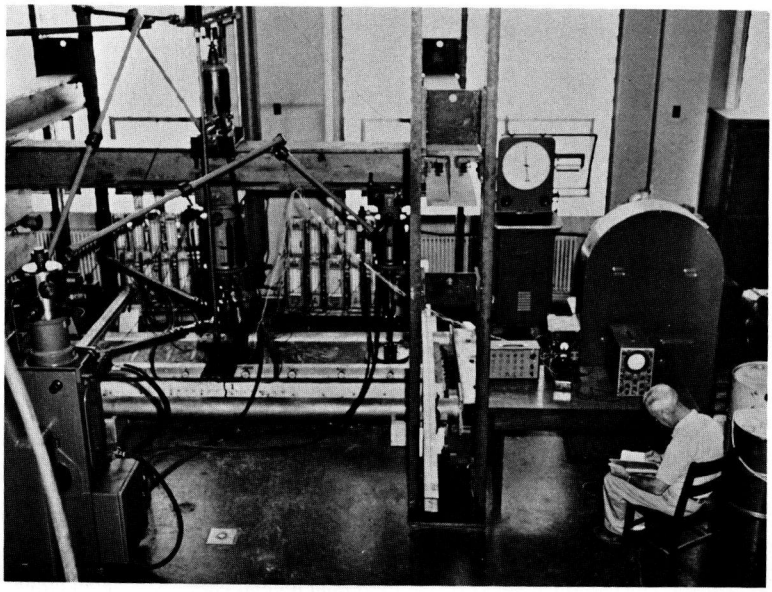

Figure 10. General view of longitudinal and vertical loading arrangement, slab 8.

loading for the large jack was 10 kips for the 9K-1K type of loading, and 18 kips for the 17K-1K loading.

The third jack, also connected to the pulsator, was placed directly over the larger jack which was connected to the dynamometer and was coupled to the larger jack by a loading bracket. Therefore, when the pulsator was on a pressure stroke, the constant force in the larger jack was in part nullified by the force in the third jack; so the load delivered to the slab at the east load point was the dynamometer load minus the pulsator force at this instant. At this same instant, the jack over the west load point was applying a load equal to the pulsator force to the pavement at the west load point. The sum of the loads applied to the pavement at the two load points always remained a constant, but during each cycle the loading arrangement allowed the load at the east load point to become a minimum whereas that at the west load point was a maximum, and vice versa. The loading therefore simulated the passage of a wheel load across the crack from one load point to the other.

TEST PROCEDURE AND RESULTS

The eight slabs differed somewhat in the quality of the concrete, as can be seen in Table 2. The only difference in the steel arrangement was that in slabs 5 and 7 the longitudinal steel was lowered so that it was ¾ in. below mid-depth. The subgrade modulus was maintained constant at 140 to 145 lb per cu in. for all experiments.

The longitudinal load was varied for the first slab to observe its effect on slip. For the second slab this load was maintained at 70 kips. For all other slabs it was maintained at 50 kips.

In general, all slabs received approximately 7,000,000 repetitions of vertical load. This number of loads was considered to be at least equal to the number of truck wheel loads greater than 8 kips which may be expected over a 3-ft longitudinal strip of a heavily travelled highway lane in 24 yr.

The repetitive vertical load was varied from 9K-1K to 17K-1K for the first slab, and then was maintained at 17K-1K for the second and third slabs. The fourth slab was loaded the first 3,500,000 cycles with a 9K-1K loading, and thereafter with a 17K-1K loading. Slabs 5, 6, 7, and 8 were loaded with a 9K-1K loading. This loading was placed at load points E and W for all slabs except slabs 7 and 8 for which it was placed at points EE and WW.

Loading Procedure

In the loading of slabs, the longitudinal force was applied first. This force generally produced a small crack across the weakened plane at midlength of the slab. After approximately one hour the static load was applied at the E or EE load point through the jack attached to the dynamometer. As shown in Table 3, this load often produced other cracks in the specimen. Within 15 to 30 min the pulsator was turned on and adjusted to deliver a load to the two jacks attached to it, such load varying sinusoidally from a maximum of 9 kips to a minimum of 1 kip for a 9K-1K loading, or from a maximum of 17 kips to a minimum of 1 kip for a 17K-1K loading. the minimum load of 1 kip was maintained to keep positive pressure on the jacks at all times, and therefore prevent their lifting off the slab and shifting position between load cycles. All repetitive loads were applied at the rate of 250 times a min.

Slip readings were made on the column gages at intervals that made for satisfactory plotting of the slip against the logarithm of the number of loading cycles. Generally about twenty sets of slip measurements were taken during the 7,000,000 cycles of vertical loading. The crack width, vertical deflection, and steel strain measurements were taken at less frequent intervals.

Progressive Slip

Although each slab cracked in a somewhat different pattern from the others, the data obtained from the plastic gages mounted on bar C had common characteristics for all slabs. Figure 11 shows the small amount of additional slip which might be attributed

to numerous repetitions of vertical loading. Data for the slip for all gages in the eight slabs are omitted from this paper but are available elsewhere (4).

TABLE 3

CRACK WIDTH AND SLIP DATA FOR SLABS

Slab	Loading Conditions			No of Cracks	Mid-Length Crack Width (in)		Distance to Zero Slip (in)	
	Long	Vert	Cycles of Vert Load		Sides	Top	E	W
1	50K	0	0	1	No data		9	7
	50K	10K	0	1			10	10
	70K	9K-1K	6,184,000	6			7	7
	70K	0		6			7	7
2	70K	0	0	2	0 0142	No data	7	14
	70K	18K	0	4	0 0261		7	14
	70K	17K-1K	6,729,000	8	0 0275		9	11
	70K	0		8	0 0274		9	11
3	50K	0	0	3	0 0097	-0 0006[a]	11	9
	50K	18K	0	5	0 0156	-0 0027	9	9
	50K	17K-1K	7,290,000	5	0 0148/0 0150	-0 0035/-0 0040[b]	9	9
	50K	0		5	------	-0 0021	9	9
4	50K	0	0	1	0 0077	-0 0009	8	5
	50K	10K	0	2	0 0109	-0 0023	9	7
	50K	9K-1K	7,925,000	2	0 0160	-0 0032/-0 0040	11	10
	50K	0		2	0 0142	-0 0014	11	10
5	50K	0	0	None	0	0	0	0
	50K	10K	0	2	0 0112	+0 0002	10	12
	50K	9K-1K	7,206,600	3	0 0136	-0 0015	10	9
	50K	0		3	0 0138	+0 0012	10	9
6	50K	0	0	1[c]	0	0	0	0
	50K	10K	0	2	0 0101	-0 0004	7	12
	50K	9K-1K	7,072,000	3	0 0103/0 0109	-0 0019/-0 0024	6	12
	50K	0		3	0 0150	-0 0016	6	12
7	50K	0	0	1	0 0084	0 0007	10	9
	50K	10K	0	2	0 0135	0 0006	12	9
	50K	9K-1K	7,504,600	4	0 0154/0 0159	0 0148/0 0155	10	9
	50K	0		4	0 0154	0 0105	10	9
8	50K	0	0	1	0 0144	-0 0019	7	11
	50K	10K	0	1	0 0163	-0 0038	7	11
	50K	9K-1K	7,573,800	1	0 0168	-0 0001/+0 0006	7	11
	50K	0		1	0 0122	-0 0006	7	11

[a]Negative crack width refers to decrease from initial (no loads) reading between gage plugs set on 10-in centers
[b]Observed minimum/maximum readings
[c]This crack not at midlength

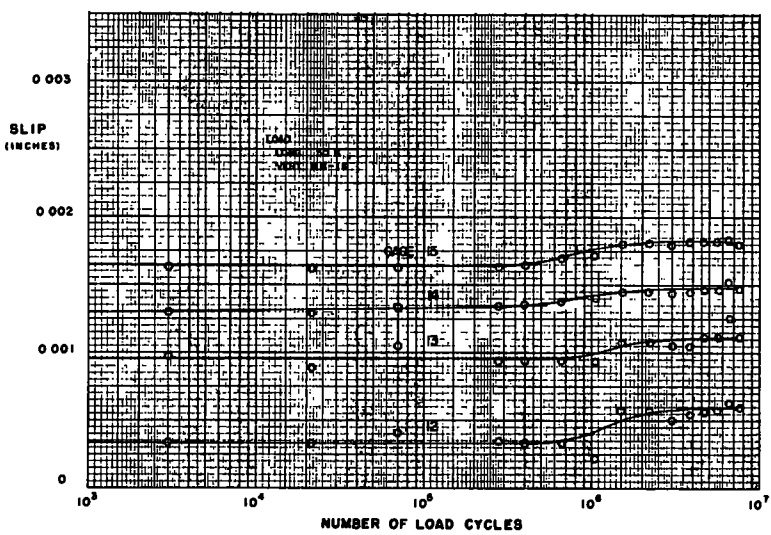

Figure 11. Slip vs number of load cycles, slab 8.

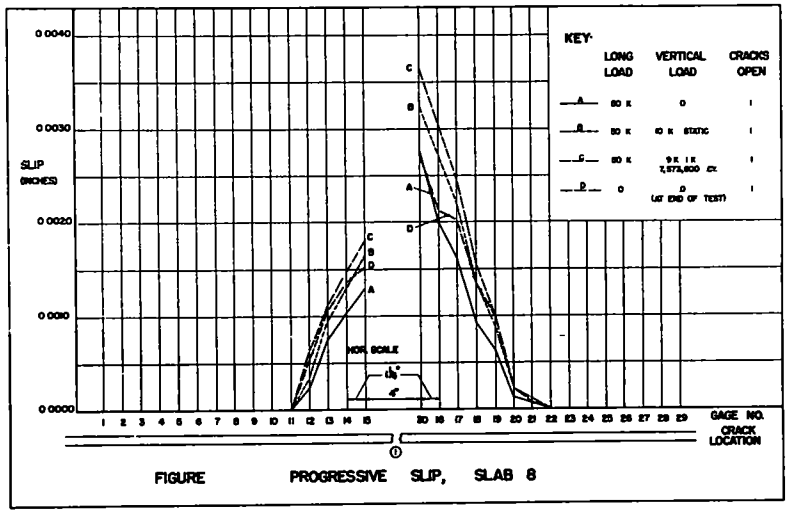

Figure 12. Progressive slip, slab 8.

A comparison of curves A and C in Figure 12 reveals more clearly the progressive movement of the steel with respect to the concrete. The crack ① occurred at the weakened plane in this slab and was therefore approximate 2 in. from gages 15 and 30. From the nature of the curves it is apparent that the crack was nearer gage 30 than gage 15. It is also apparent that with only the longitudinal force the maximum observed slip was the nature of about 0.0027 in. (at gage 30), and that gages beyond Nos. 11 and 22 recorded 0 slip. After 7,573,800 cycles of 9K-1K loading the maximum slip had increased to about 0.0037 in. at gage 30, and the values for slip were still recorded as 0 at gages 11 and 22.

Figure 12 is typical of the information obtained from experiments with the other slabs. Because the plastic gage functions only in a positive direction, any crack occuring between gages 1 to 15 or between gages 30 to 29 causes some slip in the negative direction for certain gages and therefore they become useless.

TABLE 4

MAXIMUM EXTENSION OF SLIP AWAY FROM CRACKS

Slab	Max. Distance from Crack (in.)		
	0.002-in. Slip	0.001-in. Slip.	0 Slip
1	5	7½	9½
2	6½	10	14
3	5½	7	11
4	4	6½	11
5	4½	6	12
6	5	8½	12
7	5½	8½	12
8	5½	7	11

Tables 3 and 4 reveal some points of interest in regard to the point of zero slip. Table 3 clearly shows that the point of zero slip remained practically constant once the midlength crack occurred. In Table 3 the decreases in this initially recorded distance to zero slip are attributed to later cracks which caused some plastic gages to function in a negative direction and therefore subsequently provide useless data. However, many of the cracks given in Table 3 were outside the middle 5 ft of slab and had no effect on the gage readings. Throughout the experiments it was the desire that the slabs crack only at the midlength weakened plane but this was only obtained in the case of slab 8. Table 4 was compiled using only data from gages unaffected by negative slip. Slab 2, which was loaded longitudinally with 70 kips, exhibited some slip along bar C as far away as 14 in. from a crack. For all the other slabs that were loaded with a 50-kip longitudinal force the point of zero slip was within 12 in. of the crack; i.e., with a

50-kip longitudinal force on an 8- by 36-in. cross-section of slab, 7,000,000 repetitions of vertical loads as large as 17 kips did not produce any slip at points over 1 ft from the cracks.

The point of zero slip did not change when the repetitive vertical loading was increased from 9K-1K to 17K-1K. Also, the slabs with the longitudinal steel ¾ in. below mid-depth gave results very similar to those obtained from slabs with this same amount of steel at mid-depth.

Deflections and Crack Widths

The deflection data observed in these experiments were solely for the purpose of evaluating the severity of the vertical loading system. These data led to a decision to load slabs 7 and 8 at points EE and WW rather than at points E and W as used in the previous slabs. This change was made to be certain of some upward and downward movement of the slab at the midlength point. Deflection as well as crack width data observed for slab 8 are shown in Figure 13.

Although information on crack widths was obtained for all cracks in all slabs with the exception of slab 1, these data are not presented in this paper but are available elsewhere (4). The crack width data for the crack at midlength, called crack ① in all slabs, are given in Table 3. Some crack-width values for top surface cracks recorded in this table are shown as negative and therefore need explaining. Crack-width values recorded in this table are the difference in readings observed on Whittemore gages set on plugs placed at 10-in. intervals on the slab. The base for these readings was the initial no-load condition of the slab. Once a crack occurred, some spalling and change in slab configuration took place; hence the data reflect that the plugs were closer together (horizontally) than they were before the experiment began. The crack widths measured at the elevation of the steel on the side of the slabs are therefore considered more meaningful.

Steel Stresses

The electric resistance strain gages placed on bars B and D of slabs 6, 7, and 8 were a supplementary part of the instrumentation, and data from these gages were

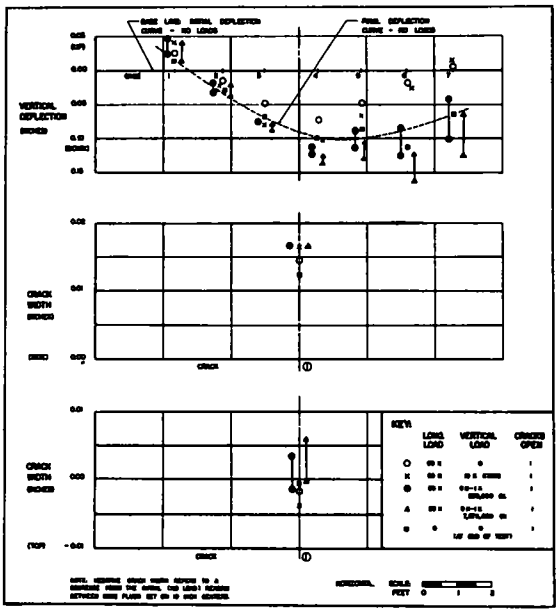

Figure 13. Vertical deflections and crack widths, slab 8.

erratic and therefore of doubtful value. For this reason the data are not reproduced in this paper. The gages did reveal that practically 90 percent of the longitudinal force applied at the ends of the slab was present at the midlength point, and that the steel was stressed to about 50,000 psi under the 9-kip vertical and 50-kip longitudinal loads. The strains caused by the varying vertical loads were not more than a few percent of the strain caused by the longitudinal load.

SUMMARY OF CONCLUSIONS

As a result of these experiments on short lengths of slabs resting on subgrades with a constant subgrade modulus of 140 to 145 lb per cu in. and subjected to constant longitudinal forces, the following statements can be made:

1. The plastic gage used in conjunction with the Sheffield Column Type Precisionaire instrument provides a simple and practical means of determining the differential movement of steel reinforcing bars with respect to concrete. The plastic gages can be used on alternate sides of the bars and thus provide slip data at intervals as close as $1\frac{1}{4}$ in. without any apparent detrimental effects on the quality of the concrete.
2. These experiments provide evidence that beyond 12 in. from a crack there is no slip between the reinforcing bar and the concrete in slabs subjected to temperature drops which are equivalent to not more than the 50-kip longitudinal force used in these experiments. This length of bar along which some slip occurs remains practically constant from the instant the crack is formed, regardless of the number of repetitions of a heavy vertical load; that is, there is very little, if any, progressive slip due to vertical loads.
3. Once a crack has formed, repetitive vertical loads of as much as 17 kips cause larger slip values throughout the length of bar along which slip first occurs. However, slip values are in general less than 0.002 in. at points 6 in. or more from the crack even after 7,000,000 repetitions of this vertical load.
4. There is practically no possibility of large truck wheel loads causing slip to progress from crack to crack in a continuously reinforced pavement since cracks generally occur in such pavements at intervals much greater than 2 ft. Consequently, the possibility of a progressive bond failure due to such wheel loads is quite remote when about 0.5 percent steel is placed near the middepth of the slab.

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