New Developments in Concrete Pavement Design

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According to the program I am supposed to talk on new developments in concrete pavement design. I shall tell you briefly of some new design features which we have adopted in Illinois and then devote most of my time to a discussion of our experimental continuously-reinforced concrete pavement.

The trend in Illinois during the last 15 years, as elsewhere, has been toward heavier and stronger pavements to meet the requirements of increasing heavy-transport traffic. For more than 10 years before 1934, the standard design for rural pavements was a plain concrete pavement having a 9-6-9 cross section. This was successively changed during the next four years to 9-6½-9, 9-7-9, and 9-9-7-9-9. Until 1928 no expansion joints were used, and during the following four years expansion joints were installed at 800- to 1000-foot intervals. From 1933 to 1938 expansion joints were placed every 90 feet, with two contraction joints between expansion joints, making the joint spacing 30 feet.

Beginning in 1938, the joint spacing was increased to 50 feet, contraction joints were eliminated, and the pavements were reinforced with 55-pound wire fabric. This design had to be discontinued during World War II because of the shortage of steel, and the limited mileage built during that period was plain concrete, uniformly 10 inches thick, with expansion joints at 120 feet and dummy contraction joints at 20 feet.

The tremendous increase in heavy-transport traffic, during and following the war, and the concurrent increase in pavement pumping and other pavement damage led Illinois, in 1946, to adopt its present design. This consists of a 9- or 10-inch uniform cross-section, depending upon the anticipated volume of heavy truck traffic, reinforced with 78-pound wire fabric, with contraction joints every 100 feet. The joints are provided with 1-inch round dowels, 18 inches long, at 13½-inch centers.

No expansion joints are used. If the soil has pumping characteristics, a 6-inch granular subbase is provided.

GRANULAR SUBBASES

Granular subbases, expressly for the elimination of pumping, have been used in Illinois since 1947, with eminent success. There are the two customary schools of thought with respect to grading of the granular material, and the standard specifications permit both dense-graded and open-graded material. So far as is known, both types have been successful in preventing pumping, but there is a somewhat greater preference for the dense-graded material.

Pavements of this design have not been in service long enough for ultimate service to be predicted, but their present performance is excellent. Pumping is practically non-existent, no serious faulting has occurred at joints, very few cracks have developed in the 100-foot slabs between contraction joints, and the wire fabric reinforcement appears to have been effective in holding tightly closed such transverse cracks as have formed.

AIR-ENTRAINED CONCRETE

Another recent development has been the use of air-entrained concrete for pavements. The value of entrained air in providing protection against the damaging effects of chloride salts used for ice removal was first forcefully demonstrated in Illinois by an experimental pavement built on Archer Avenue in Chicago in 1941.

This pavement, about 1½ miles long, consists of two 20-foot separated roadways. The south roadway was built with air-entraining cement and the north roadway with untreated cement from the same mill. Both have received heavy applications of chloride salts, and the beneficial effect of the entrained air became definitely apparent after the second winter. After four years, the north roadway had become so seriously damaged that it was necessary to resurface it with bituminous concrete. The south roadway is still in excellent condition after eight years of service.

As a result of this experience, the use of air-entraining cement was made a requirement, in 1943, for all concrete pavements built in Chicago by the Illinois Division of Highways or under its general supervision. In 1945, the same requirement was extended to apply to all municipalities in Illinois. The use of air-entrained concrete for all pavements and structures built under the supervision of the Illinois Division of Highways was made a definite requirement in 1948. Air-entrainment may be obtained by either the use of air-entraining cement or by the use of non-air-entraining cement and an air-entraining agent added at the mixer. The air content is required to be within the range of three to five percent.

The pavements so far constructed with air-entrained concrete have shown excellent resistance to damage by chloride salts, with the possible exception of one instance of late fall construction where extremely early winter conditions required the application of salt to a pavement a month or less after its construction. Though engineers have expressed various opinions as to the reason for the surface defects observed in this particular case, it is nevertheless indicated that even air-entrained concrete should be permitted to attain a reasonable age and strength before it is exposed to chloride salts.

The use of air-entrained concrete in pavement has introduced some problems in the field. When it was first used, the finishers complained that it was harder to finish than non-air-entrained concrete. They were using the technique which they had developed for non-air-entrained concrete, and it just would not work. They soon found that if they began their finishing operations earlier, they experienced no great difficulty.

EARLY-STRENGTH CONCRETE

Another problem which has arisen in the field, and which has been given considerable study in the laboratory, is the problem of obtaining early-strength concrete. It has been the practice over a number of years, where early opening to traffic is desired, to use specially designed mixtures, containing increased amounts of cement, to produce sufficient strength for opening to traffic at three days. It has been found, when air-entraining concrete is used, and particularly when the coarse aggregate is gravel, that the required strength generally cannot be obtained in three days.

Laboratory studies now under way indicate that addition of cement to the regular mixtures, with adjustment of the amount of mixing water to maintain constant slump, does not result in a commensurable increase in strength, when the air content is in the vicinity of four percent, and particularly when the coarse aggregate is gravel. When the coarse aggregate is crushed stone, somewhat better results are obtained from the use of increased amounts of cement. Nevertheless, insofar as the test data available can be judged at this time, it appears to be poor economy to try to obtain increased strength of air-entrained concrete by increasing the amount of cement materially beyond 5.5 bags per cubic yard, at least when the coarse aggregate is gravel. The answer to the question of obtaining early-strength air-entrained concrete probably lies in the use of high-early-strength cement, which has shown both satisfactory strength and good durability in laboratory tests.

Although ample evidence exists of the beneficial effect of air-entrainment in imparting durability to concrete, it is felt that other information available is fragmentary, and that thorough and far-reaching research with respect to the effects of air-entrainment is urgent and will pay great dividends. The Illinois Division of Highways plans to do its share of this work.

CONTINUOUS REINFORCEMENT

I hesitate to refer to continuous reinforcement of concrete pavement as a new development because actually the idea is not new. It was used as early as 1921 in the Columbia Pike experimental pavement near Washington, D. C. This pavement consisted of a series of slabs 200 feet long and one slab 350 feet long, all containing continuous longitudinal reinforcement. In 1925, the Bureau of Public Roads con-

FIGURE 1. Workmen placing and tying longitudinal steel for experimental pavement.

structed a number of experimental slabs two feet wide and 200 feet long, containing various amounts of reinforcing steel.

Most of you are undoubtedly familiar with the experimental continuously-reinforced pavement constructed in 1938 on U.S. 40 by the Indiana State Highway Commission, in cooperation with the Public Roads Administration. This pavement included slabs ranging in length from 50 to 1,320 feet and containing longitudinal steel varying from 0.07 to 1.82 percent of cross-section area.

Another example of this type of construction is the continuously-reinforced slope pavement constructed in 1937 at Lake Mathews Reservoir. This consists of an 8-inch concrete slab 7,575 feet long, varying in width from 100 to 275 feet, reinforced longitudinally with 0.5 percent of steel.

Perhaps the longest continuous reinforced slab in existence is the canal lining in the aqueduct of the Metropolitan Water District of Southern California. The lining is over 60 miles long, varies from 6 to 8 inches in thickness, and also contains 0.5 percent of longitudinal steel.

Interest in this type of construction was revived recently, largely through the efforts of Mr. W. R. Woolley, Materials Engineer, Division 4, Public Roads Administration, through his paper "Continuous Reinforced Concrete Pavements Without Joints," which first appeared in 1946 and was later published in the *Highway Research Board Proceedings* of 1947. The revived interest stems from the realization that joints and open cracks have proved to be the cause of much distress in concrete pavements.

In 1946 the Illinois Division of Highways decided to conduct an investigation of continuously-reinforced concrete pavements; and in 1947, in cooperation with the Public Roads Administration, construction was started on the first of three proposed experimental pavements. Also in 1947, the New Jersey State Highway Department constructed two sections of pavement each approximately one mile long, having uniform thicknesses of eight and ten inches and containing approximately 0.9 and 0.7 percent of longitudinal steel, respectively.

ILLINOIS BUILDS EXPERIMENTAL PAVEMENT

The experimental pavement described in this paper is officially identified as F. A. Route 12, Section 0-2, Fayette County. It is just west of Vandalia on U.S. Route 40, which carries a large volume of traffic. It is estimated from traffic studies that over a 24-hour period the pavement carries 2,100 vehicles consisting of 1,600 passenger cars and 500 commercial vehicles. Construction was started in September, 1947, and completed in May, 1948.

The experimental pavement is 22 feet wide and about 5½ miles long, and is divided into eight test sections, six of which are approximately 3,500 feet long and two about 4,230 feet long. The pavement contains no transverse joints except those separating the test sections and the construction joints at the end of each day's run. The reinforcing steel was carried across each construction joint so that it is continuous

FIGURE 2. Complete assembled continuous reinforcement.

from end to end of each test section. The transverse reinforcing bars extend the full width of the pavement, creating continuous reinforcement in that direction also, and the customary center joint has been omitted. The variables between test sections are thickness of pavement and amount of longitudinal reinforcing steel.

Four of the sections are uniformly seven inches thick, and four have a uniform thickness of eight inches. These thicknesses, chosen somewhat arbitrarily, were thought most likely to give the desired performance within economic limits.

AMOUNT AND DISTRIBUTION OF REINFORCING STEEL

Previous experiments had indicated that 0.5 percent of longitudinal steel may be sufficient for proper performance, although the theoretical amount is about one percent. For this project four percentages of longitudinal steel were used with each thickness of pavement, namely, 0.3, 0.5, 0.7 and one percent. These percentages, it was believed, provided sufficient range to establish the proper amount of reinforcement necessary to induce closely-spaced transverse cracks and to keep them permanently closed under the action of the elements and heavy traffic.

Rail-steel bars meeting the requirements of ASTM Designation A-16 were used for the longitudinal reinforcement; and intermediate-grade, billet-steel bars meeting the requirements of ASTM Designation A-15 were used for transverse reinforcement. All bars met the requirements of ASTM Designation A305 for the deformations of deformed steel bars for concrete reinforcement.

PAVEMENT BUILT ON "PUMPING" SOILS

Since one of the basic arguments for the use of continuous reinforcement is that it will eliminate "pumping," the pavement was constructed directly over the natural soil as graded, without granular replacement or special subgrade treatment of any kind. About 90 percent of the pavement is built over potentially pumping soils.

CONSTRUCTION METHODS

Construction was carried on in the orthodox manner, with only such slight variations as were necessary to fit special features of the work. Conventional paving equipment employed by the contractor consisted of a form grader, a form tamper, a mechanical subgrader, a 34-E dual drum paver, a screw-type mechanical spreader, a finishing machine, and a mechanical longitudinal float. The finishing machine was equipped with a vibrating front screen to improve consolidation of the concrete around the reinforcing steel.

Air-entraining cement was used. The aggregates used were a siliceous sand containing some limestone, and a crushed limestone coarse aggregate. The proportions per bag of cement used for the most part were 215 pounds of sand, 359 pounds of stone, and 5.25 gallons of water, which gave a cement factor of 1.4 barrels per cubic yard. The slump varied from 1¼ to 1½ inches. The average flexural strength of the concrete was 837 pounds per square inch at 14 days.

The longitudinal reinforcing bars were 30 feet long; the transverse bars were 21 feet, nine inches long. These were assembled on the subgrade into a continuous mat supported 3 inches below the surface of the pavement by means of chairs welded to certain of the transverse bars. Longitudinal bars were lapped 30 diameters. Since the paver was operated outside the forms, as required in Illinois, it was possible to lay out the reinforcement a sufficient distance ahead of the paver to prevent delays from this source.

POURING CONCRETE

The concrete was placed in one lift, being deposited through the reinforcement, distributed, and consolidated around the steel by the spreader, and further compacted and finished by the finishing machine,

FIGURE 3. Placing concrete on continuous reinforcement.

which made two passes over the pavement. The vibrators on the finishing machine were operated only during the first pass.

The wood header board, which was installed at the end of each day's run, was removed when paving was resumed, the concrete being poured against the end of the adjacent slab. Header boards were placed not less than five feet from a lap in the steel.

The eight test sections were separated from each other and from the adjacent ten-inch standard pavement by a four-inch expansion joint, poured with an asphalt filler. At five of the joints, the ends of adjacent slabs rest on concrete sills. At three, the subgrade for a distance of ten feet each side of the joint was replaced to a depth of six inches with granular material. The pavement at the remaining two joints was built on the natural subgrade without additional support or subgrade treatment.

REFERENCE MONUMENTS AND REFERENCE PLUGS

For the purpose of studying longitudinal and vertical movements of the pavement, reference monuments were constructed at each end and at intervals of 400 feet from one end to the center of each test section.

FIGURE 4. Measuring horizontal and vertical movements from a reference monument.

The top of each monument is about three inches below the surface of the pavement and is protected by a heavy concrete slab fitted with a locking-type steel cover.

Measurements are made between the monuments and brass reference plugs set in the edge of the pavement approximately 24 inches on either side of the monument, using a specially designed vernier caliper-clinometer which will read to a thousandth of an inch horizontally and a hundredth of an inch vertically.

Near the middle of each test section 36 brass reference plugs were set at ten-inch centers along one edge of the pavement for the purpose of measuring the width of cracks that may develop in that region. The distance between plugs is measured with a ten-inch Whittemore strain gage. A measuring microscope is also used to measure representative cracks.

STRAIN-GAGE PANELS

Electric resistance wire strain gages, commonly called SR-4 gages, were installed on selected longitudinal bars along eight transverse lines, 2½ feet apart, near the middle of Sections 3 and 6, both of which contain 0.7 percent of steel. The arrangement is such that the gages in any one line should indicate reasonably closely the average stress in all the

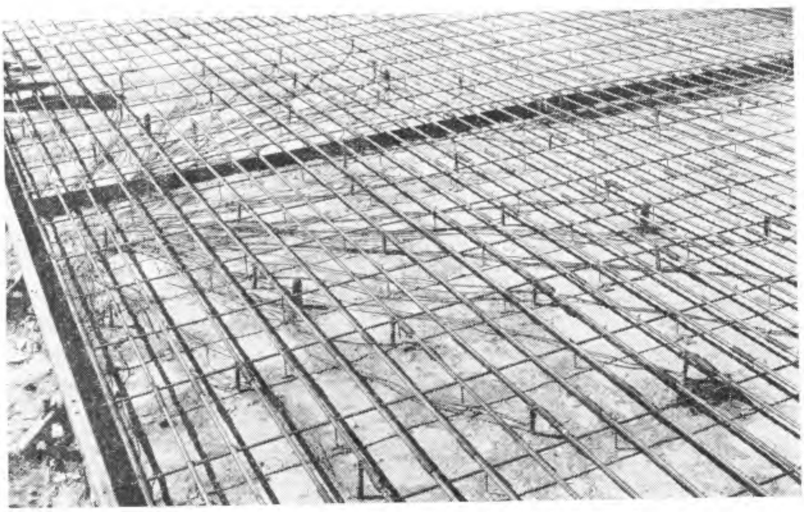

FIGURE 5. A completely wired strain-gage panel for measuring stress in reinforcing steel.

bars at that cross-section. It was anticipated that eventually transverse cracks would develop along one or more lines of gages, and the gages would then indicate total stress at the section, since the steel would receive no assistance from the concrete. But to assure one such crack where early measurements could be made, a depressed contraction joint was installed along one of the lines of gages. The gage circuits were run along the subgrade, through a conduit across the road shoulder and connected to a panel board mounted in a metal cabinet.

The pavement is not old enough to justify definite conclusions; nevertheless, the results obtained so far are interesting and of considerable significance.

Strain readings in the reinforcing steel obtained from the SR-4 strain gages are of special interest because they give the first indication of the forces acting in the pavement and of the performance of the reinforcing steel. Continuous strain readings were taken in the two strain-gage panels during the first two weeks after the concrete was poured. For the first three days, practically all the gages in the re-

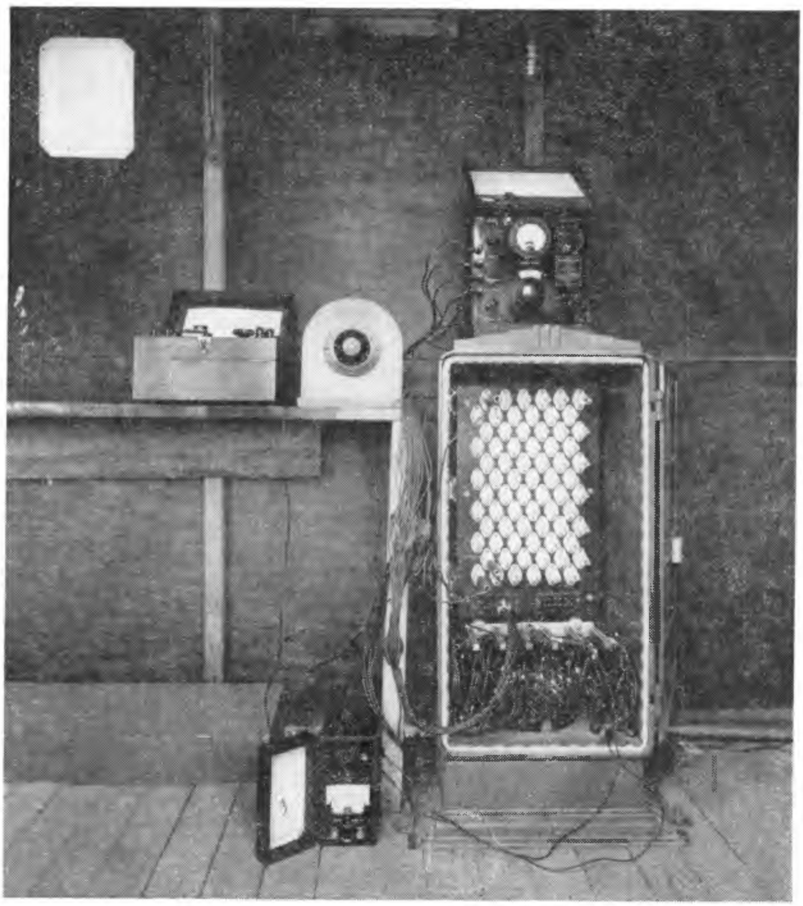

FIGURE 6. Panel board at which strain-gage circuits terminate and some of the instruments used in the investigation.

spective strain-gage panels indicated similar stresses, with maximum daily variations between early morning and midafternoon of from 4500 to 9000 pounds per square inch. Tensile stresses were indicated in the morning when the concrete was contracted, and zero stress, or sometimes a small amount of compressive stress was measured in the afternoon. During this period the transverse crack over the depressed contraction joint was hardly visible except at the edges of the pavement. On the afternoon of the third day the paper used for curing the concrete was removed from both strain-gage panels. The next morning the transverse crack over the depressed contraction joint was plainly visible, and the gages along the joint in each section showed unit stresses of approximately 30,000 pounds per square inch. By midafternoon the crack in each panel was again tightly closed and the stress had fallen to 600 pounds per square inch tension in Section 3 and to about 4,500 pounds per square inch compression in Section 6.

Subsequent readings indicated a comparatively large tensile stress in the morning and a sharp reduction in the afternoon. Much lower stresses have been indicated by the gages placed at points where structural continuity of the concrete still exists.

The maximum average stress which has been measured in the reinforcing steel is 62,400 pounds per square inch. This stress was observed in Section 3 (7-inch pavement with 0.7 percent of steel) when the average slab temperature was 13°F, or about 70°F lower than that for which the zero or "no stress" condition was determined. Since the yield point for the reinforcing steel is about 70,000 pounds per square inch, the observed stress is within the critical range and indicates that less than 0.7 percent of steel probably is inadequate.

Maximum stresses in Section 6 have not been as high as those in Section 3 because Section 6, constructed in April of last year, has been subject to a temperature only 50°F below that at which it was constructed. The maximum stress observed in Section 6 is about 40,000 pounds per square inch.

All the test sections have developed relatively large numbers of transverse cracks, according to theory, but the frequency of cracks is somewhat less than was anticipated and the cracks in all but the sections containing one percent of steel are somewhat wider than is desirable. The most recent crack survey, which was made last December, showed average crack intervals for the various sections ranging from 6.7 to 19.5 feet.

In general, the average crack interval varied inversely with the amount of steel. The crack interval was generally greater for the eight-inch sections than for the seven-inch sections, and at first thought it might be assumed that thickness was an influencing factor. However, three of the four eight-inch sections were built in the spring of 1948 and had not gone through a full winter as had the remainder of the sections. The other eight-inch section was kept covered with curing paper for an unusually long period, which permitted the concrete to develop greater than normal strength before excessive shrinkage stresses occurred. It is believed that these are the real reasons for the fewer cracks in the eight-inch sections.

Measurements were made in July, 1948, to determine the width of 60 representative cracks in each section. The average width ranged from 0.003 to 0.010 inch. In general, the crack width varied inversely as the amount of steel. Here also the results appeared to be influenced by the difference in age of the various sections at the time of measurement and by the fact that Sections 4 and 5 and part of Section 6 had not gone through a winter as had the other sections. Considerable spalling has occurred at the wider cracks in Sections 1 and 4, with 0.3 percent steel, and Section 2, with 0.5 percent steel.

Considerable longitudinal cracking has occurred in the various sections, and there appears to be a definite relationship between the amount of longitudinal cracking and the percentage of longitudinal steel, the extent of cracking varying directly as the percentage of steel. The reason for this is not presently apparent, but it may be that the longitudinal steel, in restraining the longitudinal warping, also exerts some restraint in the transverse direction. It is probable that this relationship will become less pronounced as the pavement becomes older, for it seems reasonable to expect that eventually all sections will become cracked for their full length.

Maximum seasonal variation, from winter to summer, in length of the various sections, which range in length from 3,500 to 4,200 feet, has been about 2¼ inches. Had these sections been uncracked and free to respond fully to the action of thermal expansion and contraction, the seasonal change would have been about 18 inches. The difference between this theoretical value and the actual movement was apparently absorbed by the numerous transverse cracks and by stress deformation and plastic flow of the concrete. Actually, no appreciable movement was observed in the central 2,700 feet of those sections which are 3,500 feet long, or in the central 3,400 feet of those sections which are 4,200 feet long, all the movement being realized near the ends of the sections.

One of the objects of the investigation is to determine whether this design will eliminate pumping; therefore, the occurrence of pumping in any test section should be considered as indicating inadequate performance. Pumping was first observed about October 15, 1948, at a construction joint and several transverse cracks adjacent thereto, in Section 4 (eight-inch pavement with 0.3 percent steel), five months after its construction. The presence of four transverse cracks in eight feet immediately west of the construction joint undoubtedly contributed to the flexibility of the pavement and influenced the pumping. However, the major factors are believed to be poor subgrade and inadequate steel. The subgrade soil at this location is a silty clay of the A-7-4 group.

Last November the entire experimental pavement was surveyed for pumping. Pumping at transverse cracks was observed only in Sections 4 and 5. Neither of the sections had gone through a winter, having been built the previous spring. Pumping was severe only in Section 4, where it was observed at 12 transverse cracks, and where a large number of cracks were stained with soil, indicating incipient, if not actual, pumping. Pumping was unusually prevalent at construction joints, indicating that there may be something about the design of these joints that influences pumping.

It is too early to draw definite conclusions, but present indications suggest that satisfactory performance probably cannot be expected with less than 0.7 percent of steel. Observations will be continued on the experimental pavement as long as they yield information of value. The experience from this experimental pavement will serve to establish more definitely the limits of design for this type of pavement, and this information will be applied in the design of two other experimental pavements which the Illinois Division of Highways now has under consideration. Greater knowledge of SR-4 strain gages and improved installation techniques should make possible a wider application of this valuable tool in the new pavements.