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FIRST YEAR PERFORMANCE REPORT
ON CONTINUOUSLY REINFORCED
CONCRETE PAVEMENTS IN PENNSYLVANIA

by

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INTRODUCTION

When the Romans of the early Christian era extended their routes of communication into the lands of the conquered barbarians, concrete as then used was an established road building material. People still travel these roads that once bore toga clad Roman soldiers in horse drawn chariots, on their way northward to battle against many of our less civilized ancestors. Bridges, retaining walls and pavements along the famous Appian Way give existing evidence of the extensive use of concrete by the ancient highway engineer.

Much better concrete is available to the engineer of today. The development of Portland Cement gave him a uniform product of known quality. Modern batching equipment assures uniform mixtures with controlled water content, and various cement additives are available to regulate the final density and curing processes.

More concrete is used in construction work than all other materials combined, yet the average engineer probably knows less about it than any of the others. He finds it difficult to understand the complicated chemical reactions that must occur before the separate ingredients become a usable solid. Also, some of the physical conditions which influence its continuing strength and durability are often not fully understood.

He may leave the pursuit of greater knowledge in these matters to the chemists, physicists and others who can devote their full time to this aspect of the study, but he must never forget some of the following fundamental facts about concrete that have been known for several hundred years.
1. **Concrete requires time to gain strength.**

   Fresh concrete is a semi-liquid mixture which must be retained within forms and protected from extreme changes in temperature and strain until it solidifies and develops strength. During this interval, all reinforcement within the plastic mass must be rigidly supported to prevent any movement that could interfere with, or destroy the existing bond between the weak concrete and steel reinforcement.

2. **Concrete shrinks as it hardens.**

   When the water content of fresh concrete is reduced by evaporation, absorption or other means, the volume of the concrete is also reduced. Friction and other restraints cause stresses throughout the shrinking concrete. If these stresses exceed the tensile strength of the concrete, cracks will form and relieve part of them. While this cracking is more prevalent during the early curing process, it may occur as long as water is present.

3. **Concrete is sensitive to temperature changes.**

   Most materials, including concrete, decrease or increase in volume in direct relationship with changes in their temperature.

   An unrestrained concrete beam 10 ft. long will increase approximately .072 in. in length if its temperature is raised from 0°F. to 100°F. However, if the ends of this beam are restrained and not allowed to lengthen, compressive forces will develop. Since the ultimate compressive strength of concrete is high, no damage is likely to occur. Most concrete beams 10 ft. long will withstand a compressive strain of at least 0.20 in. without failing.

   A reversal of this temperature change has quite a different effect.
If the ends of a 10 ft. long beam are restrained when the temperature is 100°F, failure of the concrete is apt to occur long before 0°F is reached, because of the relatively low tensile strength of concrete.

These three basic characteristics are common to all Portland Cement concrete. The addition of reinforcing materials may influence or possibly control their effects, but it must be remembered that these inherent tendencies are always present in concrete structures, regardless of their size, configuration or reinforcement.

Transverse cracks that form in continuously reinforced concrete pavements are caused by these same reactions. The longitudinal reinforcement will affect the stress distribution throughout the pavement when bond with the concrete develops, and hence will exert a limited influence on the cracking, but the principal forces which cause cracks to form originate in the concrete.

Since practically full restraint exists near each end of the pavement, any tensile strain that develops at these cracks must be carried by the reinforcing steel in the immediate vicinity of the crack. As a result, the reinforcing steel spanning each crack must either contain the strain within its elastic limit by loosing bond with the surrounding concrete, or yield in tension.

It is not intended that the rather complex subject of crack development be covered in these few general statements. As this report continues with the presentation of results obtained from the research on two separate continuously reinforced pavements, it is hoped that the purpose of these introductory remarks will become more obvious.
GENERAL DESCRIPTION

In 1957, at the thirty-sixth annual meeting of the Highway Research Board, a report was presented describing the construction, instrumentation and early behavior of a continuously reinforced concrete pavement on U. S. Route 111 near York, Pa.

This pavement was approximately two miles long and consisted of four 12 ft. wide lanes with a 20 ft. wide median strip separating the North-bound and South-bound dual lanes.

A concrete thickness of 9 in. on a 6 in. thick granular insulation course was the construction design followed throughout the project.

A longitudinal reinforcement for each lane consisted of twenty #5 hard-grade, deformed steel bars with a nominal diameter of 5/8 in. These bars, comprising a .5% cross-section area of the pavement, had been fabricated into mats 16 ft. long with seven #3 deformed bars to provide transverse reinforcement.

The mats were placed at the vertical center of the pavement on a 4-1/2 in. thick spreader run of concrete. Several mats were installed, allowing an end overlap of 1 ft. with adjacent mats to maintain reinforcement continuity. Then the paving equipment was backed up and the strike-off run of concrete was placed.

Midway between the ends of the pavement, in the outside North-bound traffic lane, special gages were installed to facilitate the measurement of temperature and longitudinal strain in the vicinity of a transverse pavement crack that would develop at an artificially induced plane of weakness. (Fig. 1)
Brass plugs were installed on each side of the plane of weakness near the edge of the pavement, to allow the measurement of crack opening with a 10 in Whittemore gage.

Resistance wire temperature gages were placed at selected locations in the pavement and in the insulation course to indicate the local temperature and also to permit a study of the effects of vertical temperature gradation.

Bakelite SR-4 strain gages were attached to the surface of six of the longitudinal reinforcing bars comprising a mat. These gages were located at the preformed crack and at distances 2 ft and 4 ft to each side of the crack.

In order to provide a smooth surface for attaching the strain gages, the deformations on each bar were removed for a distance of 2 in. at every gage location. This reduced the nominal diameter of the bar from 5/8 in. to 9/16 in. and resulted in a 20% reduction of cross-section area in each gaged bar or a 6% reduction in the total steel across the crack.

The electrical leads from gages within the pavement were carried underground through a metal conduit to a terminal box at the edge of the highway right-of-way.

The pavement was placed at the instrumented panel at 1:10 P.M. on October 10, 1956.

Gage readings taken immediately after the surface finishing operation provided a basis for all subsequent measurements.

During the first 10 days after the pavement was placed, gage readings were taken every few hours throughout the day and night to determine the initial
behavior of the panel.

For the next 12 months, readings were taken over a 24 hour period each 30 days.

In May and June of 1957 another continuously reinforced concrete pavement was constructed on U.S. Route 22, near Hamburg, Pa.

The design and construction of this pavement was essentially the same as the pavement at York, Pa., except in vertical dimensions and types of reinforcement. Pavement thicknesses of 7, 8 and 9 inches were poured with insulation courses of both 3 and 6 inches under each different pavement thickness. Also, a 9 inc. thick section 1000 ft. long was poured, using welded wire mesh as reinforcement instead of the deformed bars common to the major portion of the pavement.

The steel reinforcement throughout the entire project was held constant at 0.5% of the cross-section area of the pavement.

An instrumented panel, similar to the one on the York Project, was installed in the 7, 8 and 9 in. pavements containing bar mats, and in the 9 in. pavement that was reinforced with wire mesh. The insulation course at each of these panels was 6 in. thick.

In addition to the four instrumented panels, the Hamburg pavement provided an opportunity to extend the scope of the research and include several other measurements in the observations.

An effort was made to provide sufficient instrumentation to allow a complete study of the cracking that occurs in a continuously reinforced concrete highway.
Plugs were installed at 100 ft. intervals in the outside North-bound lane to permit the measurement of relative longitudinal movement of the pavement.

Monuments were placed at the ends and quarter points in all four lanes to measure the absolute longitudinal movement especially that occurring at the bridge-type expansion joints at the extreme ends of the pavement.

Devices were installed at selected sections of the pavement to induce cracking, and reinforcement end-laps were marked to determine their influence on the crack pattern of the finished pavement.

Special plugs were installed near cracks to measure the longitudinal and transverse warping caused by uneven temperature distributions and surface loading.

Continuous recordings of strains and temperatures were taken at the panel in the 8 in. thick pavement, from the time the concrete was poured until a crack developed 36 hours later.

Provisions were made to allow continuous recording of the strains imposed by traffic upon the steel and concrete of the completed pavement.
PAVEMENT BEHAVIOR

By October of this year, the pavement at York had been under observation for a full year. The highway had remained closed to the public while some of the bridges were being completed, and very little traffic had passed over the instrumented panel.

The behavior of the pavement during the first few days after pouring provided very interesting information. Definite trends were evident, and individual gage response fitted well into the expected pattern. However, the most significant feature of the early behavior did not become apparent for several months, and may best be reviewed after a presentation of the strain history throughout the entire first year of the pavement life.

Thirty days after the pavement was poured, the effects of colder weather started to become noticable in the pavement. (Fig. 2) With decreasing temperature, the instigated crack opened wider and tension strains increased in the reinforcing bars spanning the crack. Strains in the steel 2 ft. away from the crack indicated a slight compression.

By the end of the second month, when the air temperature was 52°F, the crack was open to a width of 15,000 micro-inches and the gaged bars across the crack were beginning to yield in tension at 2,800 micro-in/in strain. The gages on the bars at each side of the crack were indicating a change from compression to tension.

During January of 1957, when the pavement was 3 months old, measurements were made when the temperature was 22°F. The crack width had increased to 23,000 micro-inches and the gaged bars at the crack were strained to 3,600 micro-in/in in tension or beyond the yield point. Tension strains in the gaged bars away from the crack had reached only 150 micro-in/in.
This was the lowest temperature at which readings were made on the gages, but temperature records at a nearby airport indicate that a low of 20°F was recorded during this month. Considering the previous ratio of change in strain with change in temperature, it is probable that at this extreme low in temperature, the strains in the bars at the crack reached 4,000 micro-in/in and the crack opened to 27,000 micro-inches.

For the next three months the temperature was in the warming phase of its yearly cycle. The crack opening and steel strain at the crack reversed their direction and approached the condition that existed shortly after the pavement was poured. Gages located on the bars at each side of the crack, where the strains had previously remained in the low elastic range of the steel, began to indicate significant compression.

Throughout the late Spring and Summer, measurements were made when the temperature was between 70°F and 80°F, although it was known that in the time interval between the periodic measurements, the temperature fluctuated within a range of 40°F.

During this time, while the crack width remained about 8,000 micro-inches, the gaged bars at the crack yielded in compression until they retained only 100 micro-in/in of tensile strains. These same bars, at a distance of 2 ft. away from the crack, were then yielding in compression with a strain of 3,300 micro-in/in.

In order to explain the development of this unusual strain pattern it was necessary to understand the behavior of the pavement when the instigated crack occurred.

The pavement was poured at the instrumented panel when the temperature was 60°F and the crack was formed at the induced plane of weakness 40 hours
later when the temperature had dropped to 25°F. During the following 3 days, the temperature fluctuated through a range of 30°F and the measured crack width corresponded in proportion to these temperature changes.

In this test panel, relatively large differential movements occurred between the concrete and steel within 40 hours after the pavement was poured.

Although the reinforcing steel was strain sensitive to the changing temperature, there seemed to be very little relationship between the amplitude of the strain in the bars and the width of the crack opening. This apparent independent action of the steel and the concrete continued for two weeks after the pavement was poured, but when the seasonal cooling cycle started a reasonable ratio could be established between temperature, crack width and steel strain at the crack.

Figures 3 and 4 show the phenomena which occurred during the development of the crack along the induced plane of weakness. Since the instigated crack was the first crack to form in a center section of the pavement, free end influence did not exist. Therefore points A and A1 may be considered as being in areas of complete restraint. Due to shrinkage and finally to temperature, relatively high tensile forces developed at B and B1 in the concrete, and a crack formed in the plane of weakness at X. The developing bond along the reinforcing bar C did not have sufficient strength to transfer these forces from the concrete into the bar. As a result all of the adhesive bond in the vicinity of the crack was destroyed.

Constant temperature cycling during the first few days of pavement life prevented the reoccurrence of adhesive bond, and a purely mechanical bond was developed at the extreme limits of differential movement between the concrete and the deformations on the reinforcing bar. (Figure 4)
As the concrete developed additional strength, the relatively free independent movement between the concrete and the reinforcing bar was confined within the limited range of movement established when the concrete was weak. Strains measured in the bar at X1 and X2 indicated that the loss of bond extended to these points, but that the range of free differential movement diminished as the distance from the crack became greater.

This mechanical bond action could be compared with a bolt that fits loosely into a threaded hole. It has adequate strength for transferring forces in either tension or compression, but allows a short range of free movement during a reversal of the loading.

When lower temperatures and continuing shrinkage opened the crack beyond the range of free movement, the strain was transferred into the reinforcing bar. Crack width and strain in the bar at X increased in proportion with the decrease in temperature throughout the progressive cooling cycle, but gages located at X1 and X2 on the bar indicated only mild tension strain.

Since the coefficient of expansion in steel and concrete are practically the same, all of the temperature induced strain in the bar and concrete were mobilized at the crack to produce sufficient tension to cause yielding at X.

With the approach of Spring the temperature began to rise. The strain direction reversed and the tension strain at X was gradually relieved.

Earlier yielding had increased the length of the reinforcing bar at X and therefore compressive straining occurred at this point before the crack was closed. Since friction was the only restraint to movement within the established free movement area of the mechanical bond, this strain was carried
along the bar to some points beyond X1 and X2, into the area of true bond.

As the higher temperatures of Summer continued to increase the compression stresses in the pavement, "creep" in the concrete allowed additional strain to be imposed upon the bar. Compression strains at X1 and X2 were increased to the yield point while the bar at X was yielded in compression and returned very near to its original length.

After one year of pavement life and the beginning of the cooling phase of the temperature cycle, all measurements show a definite reversal in direction of straining and are returning to condition of tension.

It will be very interesting to determine the effect of heavy traffic loads and repeated temperature cycling during the next year.

The pavement at Hamburg was constructed in the late Spring and early Summer; at a time when the temperature was in a seasonal warming phase.

Cracks at all instrumented panels formed within 40 hours after the concrete was poured.

During the first 10 days of the pavement life, measured strains at the induced cracks were low in amplitude and rather erratic. There was some similarity to the early behavior of the pavement at York, although the temperature at the Hamburg project was more stable and wide crack openings did not occur.

A strip-chart recorder was used at the panel in the 8 in. thick pavement to obtain a continuous amplitude-time history of the formation of a crack. Pavement temperature, strain in the reinforcement at the crack, and longitudinal strain in the concrete adjacent to the crack were recorded
simultaneously over a 12 hour period, beginning 24 hours after the pavement was poured.

During this recorded period, the crack formed and opened to a width of 5600 micro-inches. The strain in the reinforcing bar increased 196 micro-in/in, while the temperature in the pavement decreased from 95°F to 88°F. Strain in the concrete adjacent to the crack changed from 50 micro-in/in compression to 22 micro-in/in tension.

Examination of the chart records revealed that all of the strains in the steel and concrete occurred gradually. There was no sudden increase in strain that would indicate the dynamic rupture of the concrete when the pavement cracked.

This was considered as further evidence that early cracking is primarily the result of shrinkage in the concrete. The new concrete, being unable to withstand the tension strains developed by shrinkage, permitted a crack to form at the induced plane of weakness. This crack formed with a minimum of tension in the fresh concrete and continued to open slowly without a direct transfer of strain to the reinforcement.

Throughout the Summer months, all strains in the pavement continued to increase in compression. Crack openings remained small, and in some instances completely closed in a measurable compressed condition.

By early October of 1957, all of the compression strains had decreased in amplitude and were beginning the seasonal change to a condition of tension.

In order to determine the possible influence of the end laps of the reinforcing bar-mats on the development of a later crack pattern, a section
of the pavement was marked at each lap of the mats. Forty mats with 12 in. overlap were included in this test section.

After 4 months, with a normal crack pattern existing in the test section, there were no cracks found in the immediate area where the steel had overlapped.

Artificial planes of weakness were installed at several points along the pavement. These included the insertion of transverse asphalt strips at the center of the pavement and covering sections of the reinforcing bars with rubber tape to eliminate effective bonding.

The asphalt strips reduced the cross-section area of the pavement 6% and the rubber tape eliminated bond on each longitudinal bar for a distance of 8 inches.

These induced planes of weakness were installed at 32 positions in the pavement. A normal crack pattern developed in the area where they existed, but only one crack formed along a plane of induced weakness.

This lone crack could be attributed to chance.

Additional information will be available from the several other phases of the testing at Hamburg after a complete cycle of seasonal temperature has had its effect.
CONCLUSION

At this time, it is impossible to give complete details and explanations of the extensive information obtained during the current investigation of continuously reinforced pavements in Pennsylvania. Yet, in view of the wide interest and accelerated research involving pavements of this type, it is considered important that these findings be made available to others who may contemplate similar research projects.

With this objective, a brief summary of observations, noticeable trends and conclusions is presented. Subsequent reports, elaborating on individual aspects of the research program, will be made available as the work at Lehigh University continues and as additional data are collected and reduced.

1. A 12 in. overlap of adjacent reinforcing bar mats was sufficient to maintain continuity of the steel throughout the length of the pavement.

2. Longitudinal continuity of the steel is very necessary. Complete local failure of the pavement will occur at places where it is not maintained.

3. The first cracks to appear in the pavement were the result of shrinkage. This tended to set the pattern for future cracking and probably will remain influential throughout the life of the pavement.

Shrinkage cracks formed in the new pavement even after rising temperature had forced the longitudinal reinforcing bars into a state of compression.

4. At extremely low temperatures crack widths up to 1/32 in. may be expected. Limited infiltration of silt and water does not appear to result in damage, and the cracks close tightly during the warm season.
Crack widths of 1/16 in. or more should be looked upon with suspicion. They should not occur in a pavement of proper design.

5. When crack openings exceeded .020 in., tension yielding probably had occurred in all of the deformed steel bars spanning the crack.

When these cracks were forced to close, the steel yielded in compression. This action caused a loss of bond along the bar. The amount could be determined when the crack width, steel strain and steel characteristics were known. It is possible that this bond loss increases with the yearly cycle of strain until the steel is capable of responding within its elastic limit.

It should be pointed out that yielding which may occur at normal cracks is well within the working capabilities of the steel reinforcement. (Figure 5). The steel which was used in the pavement at York yielded at a strain of 2,700 micro in/in, yet a strain of 98,000 micro in/in would have been required to cause failure.

6. The season of the year in which a pavement is constructed has a tremendous influence upon its early behavior.

Tension strains during cold weather have an obvious effect upon existing cracks and may cause several new cracks to form, but the more subtle effects of warm weather compression are equally important in a new pavement.

Concrete will creep under prolonged strain, and if this creep is excessive it may not be fully recovered when the direction of the straining is reversed.
Compressive strains measured in both pavements described in this report remained very high throughout the Summer of 1957. Some of the creep which has occurred will probably influence the cold weather behavior and result in a slight increase in crack width or the formation of new cracks.

7. The induced cracks at test panels were formed approximately 40 hours after the construction of the pavement, while normal cracking in the remainder of the pavement did not start until the sixth or seventh day.

A more representative crack at the test panel would have resulted if the metal crack instigator had been omitted and the crack had been induced by transverse sawing after the pavement had developed more strength.

8. Temperature is by far the most damaging influence to which continuously reinforced pavements are subjected.

There is some evidence to indicate that pavement "growth" is not confined to the extreme ends of a continuously reinforced pavement, but occurs throughout its entire length when hot weather causes the concrete and steel to expand.

Only a limited amount of the pavement end is moved by cold weather contraction. Since this is visibly evident in the crack pattern, it is probably the basis for the belief that all "growth" occurs within this area.

Non-recoverable "creep" occurs in the concrete when high compressive forces develop during very hot weather. Yearly infiltration of foreign
matter and dislocation of sand particles in the cracks may cause additional "creep". This will continue until sufficient loss of bond with the reinforcement permits the pavement to expand and contract within the elastic range of the concrete and steel.

The free ends of the pavement will be subjected only to forces equal to the yield strength of the reinforcing steel when the pavement is in a state of tension, but the forces of compression may be of much greater magnitude.

There is some evidence to indicate that the first few annual temperature cycles may stabilize the pavement straining within the elastic range of the steel and the recoverable creep range of the concrete. Subsequent annual cycling may cause additional yielding, but only to the extent that the infiltration of silt into the transverse cracks prevents their complete closure.

The experiences with continuously reinforced concrete pavements in Pennsylvania have been encouraging.

Much remains to be learned before an ultimate design can be specified, but it is believed that design based on currently available knowledge could produce highways of superior riding qualities and greater durability.
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