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Cracks in Concrete

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CRACKS IN CONCRETE

1. "Some Considerations of the Cracking or Fracture of Concrete", F. A. Blakey. Civil Engineering and Public Works Review Vol. 52, No. 615, pp. 1000-1003. September 1957.

One of the disadvantages of concrete construction is the tendency of the concrete to crack when its shrinkage is restrained. It is basic to any study of this cracking to be able to define the condition of stress and strain under which it will occur, a problem in some ways analogous to the examination of criteria for yield or flow of metals. However, concrete exhibits a rather complex rheological behavior and its basic properties are time-dependent, so that it becomes necessary to examine not only the stress and strain conditions which will bring about cracking but also the effect of time through the rate and duration of stress and strain.

Present knowledge of the conditions governing fracture of concrete has been summarized. It appears that failure is related to the volumetric strain in the concrete and the shear strain energy absorbed by it. This conclusion is drawn only from short term tests and it remains to be seen whether or not it should be modified for long term loading conditions, although the small amount of evidence which exists on strength of concrete under long term loading suggests that the criteria will be independent of time.

By an idealization of the problem and simple method of analysis it may be possible to predict which origin of failure is most likely when the properties of the materials are known.

No account has previously been taken of the heterogeniety of concrete and no experimental work is known in which the stress distribution between the different phases in the concrete has been measured. Although the analysis which has been made here is very simplified it gives a qualitative indication of the results which should follow from certain properties of paste and aggregate. These results can be tested by observation and the validity of the orignal assumptions assessed.

2. "Width of Cracks in Reinforced Concrete", Concrete Construction Vol. 3, No. 3, p 21, March 1958.

In designing a reinforced concrete structure, the engineer takes into account the fact that cracks will eventually develop in the structure. These cracks expose the reinforcing bars to the atmosphere with consequent corrosion which can weaken the entire structure. Recent evidence uncovered at the National Bureau of Standards, however, indicates that these cracks are narrower near the surface of the bar to corrosion that G. Mathey

of the Bureau's structural engineering laboratory, are expected to be of value to the structural design engineer in making better use of existing design data, with consequent savings in materials.

Since there was indirect evidence that this assumption wasn't entirely true, the Bureau undertook a more detailed study of the variation of width of cracks.

The crack width measurements were made on tensils bond specimens designed to simulate a portion of the tensile zone of a reinforced concrete beam between two successive cracks. Each specimen was essentially a prism of concrete 8 in. long with a reinforcing bar embedded along the longitudinal axis. A tensile force was applied to the ends of the bar. The extension of the embedded portion of the bar, the over-all extension of the concrete prism at points 3/8 in. from the surface of the bar, and the over-all change in length of the exterior surface of the prism were determined.

Since the length of the exterior surface of concrete remained substantially constant during the test, the over-all extension of the embedded bar was taken as the width of crack measured at the surface of concrete. The difference between the extension of the embedded bar and that of the concrete adjacent to the bar was assumed to give the width of crack at the surface of the bar.

3. "Prestressed Concrete Pavements" F. N. Shaston, Constructional Review 1953, 26 (5), 19-24, Building Science Vol 27, No. 1, p. 16, January 1954. Highway Research Abstracts, April, 1954.

Tensile stresses caused by temperatures and moisture variations are the primary cause of transverse cracking in pavements slabs. The use of transverse joints at close spacings is the common method of controlling such cracking, but these joints increase the cost of construction and maintenance. It has been demonstrated that it is possible to reduce or eliminate tensile stressed due to factors other than applied loading by the use of prestressing. This paper discusses briefly the effecrs of subgrade friction and temperature gradients across the thickness of a pavement slab and shows how to determine the amount of prestress required to counteract the described and details of completed prestressed pavements are given. Finally the more-important advantages to be gained by the use of prestressing are discussed.

4. "Crack Formation Due to Shrinkage of Reinforced Concrete", Sven T. A. Odman, Reprint 11, Swedish Cement and Concrete Research Institute at the Royal Institute of Technology, 1961.

The process of deformation in the course of drying of a reinforced concrete prism is described in the introduction which is followed by a theoretical study of this problem.

The difference between the strains of non-reinforced and reinforced concrete is regarded as a fictitious tensile strain of the concrete, and is assumed to be proportional to the ratio of reinforcement and to the compressive strain of the reinforcement. Owing to the introduction of the concept of "effective bond force" in any arbitrary cross-section of the prism, the relative slip between steel and concrete can also be expressed by function of the compressive strain of the reinforcement. Finally, the actual tensile stress in the concrete on a level with the center of gravity of the reinforcement is supposed to be proportional to the corresponding tensile stress in the concrete deduced from the theory of elasticity.

These assumptions have served as a basis in the deduction of formula for the steel stress, the concrete stress, the crack spacing, and the crack width, all of them being functions of the shrinkage of the same non-reinforced concrete prism.

5. "Soniscope Applied to Maintenance of Concrete Structures" Siegfried M. Brauning, Highway Research Board Proceedings, Vol. 33, pp. 210-216, 1954.

The soniscope is an electronic device for the nondestructive testing of materials. The instrument measures the time delay of a shock wave sent through the material, from which the velocity of propagation of sound waves can be counted. This velocity represents a measure of the quality of the materials.

Testing techniques for various types of structures are discussed. Tests on prestressed-concrete beams loaded to failure shown close correlation of soniscope readings with the behavior of the beam. The influence of reinforcing steel is shown by tests on a reinforced bridge pier. The detection of cracks and deterioration in concrete are both demonstrated by tests of several bridge members. A graphical presentation of soniscope results on a bridge pier is then discussed.

The results of these indicate that the soniscope can be a valuable supplement to visual inspection.

6. "Crack Control in Reinforced Concrete" Engineering Outlook at the University of Illinois, Vol. 4, No. 6, June 1963.

Most existing concrete structures have cracks in them. Sometimes these cracks extend to the reinforcing materials, exposing it to the elements so that it corredes. Although this is often not a cause for great alarm, it is not impossible that by this process the structure could become weakened, or even collapse. Crack control thus plays an important part in reinforced concrete design.

Kesler and his staff in the University of Illinois Department of Theoretical and Applied Mechanics recently conducted an investigation into this problem. The study dealt with the crack control characteristics of a deformed wire grid reinforcement material. Two different types of experiments were performed in determining these characteristics-bond behavior experiments and slab tests.

Because a reinforcing material that bonds well to the concrete will result in smaller crack widths, the researchers reached the conclusions that bond behavior is directly related to crack control. Testing machines were used to pull the reinforcement material out of concrete cylinders, and the bond strengths for various types of reinforcements were determined. Deformed wire displayed significantly greater bond strength than plain wire.

Slab tests were also made by supporting 5- by 24- by 76-in. concrete slabs on a 72-in span and placing loads 12 in. from either support. Some of the slabs were reinforced with the deformed wire and others with plain wire. Results showed the crack widths in slabs reinforced with the deformed fabric were smaller. In some cases, crack widths in deformed wire slabs were over twice as small as widths in similar plain wire slabs.

These preliminary experiments point out the excellent crack control qualities of a deformed wire reinforcement material. Current studies are aimed at finding the reasons for crack formation, finding how large cracks can be before they are considered critical, and refining the various methods of crack control.

7. "X-Rays for Study of Internal Structure and Microcracking of Concrete" Floyd O. Slate and Stanley Olsefski, Journal American Concrete Institute, No. 1, pp. 575-588, May 1963.

Use of X-radiography for studying the internal structure of concrete is described and discussed. Thin slices of concrete are sawed out of a mass and irradiated. Radiographs provide a permanent record for further study. Microscopic examination of stained specimens is used as a companion method and as a check.

Both methods revealed cracks formed during drying (and possible carbonation) almost exclusively at the interfaces between aggregate and mortar, predominately on larger aggregates. These cracks were observed in concrete not subjected to any prior loading. In concrete subjected to large compression strains, bond cracking at the interfaces was observed to be greatly increased, with additional cracks through mortar briding between bond cracks. Internal segragation of unhardened concrete is also observable (on the hardened concrete) by this technique.

The X-ray technique described is a powerful new tool for study of the internal structure, and changes in the internal structure of concrete.

This paper is chiefly concerned with new experimental techniques. Systematic accounts of extensive findings made with these techniques have been presented in the Journal by others at Cornell University.

8. "Repairing Cracked Concrete Road Slabs" Roads and Road Construction Vol. 43, No. 505, p 13, Jan. 1965.

A new and rapid method of insetting a rubber joint to repair cracks and prevent further cracking in concrete roads has been developed by the Road Research Laboratory in conjunction with construction companies. The method was first tried out experimentally on the concrete section of the M.1 and M.10 after irregular cracking had appeared on the surface. The cracks were several miles long, longitudinal with the road and irregular in contour. It was important that the filling be flush with the road surface and absorb any movement at the crack to avoid further cracking and spalling. The method was successful on the experimental length of about 300 yd, so about 5 mi of the cracks were repaired this past autumn.

The rubber is an extruded wedge-shaped meoprene sponge, 1 or 1½ in. deep and 3/8 in. thick at the base tapering to ½ in. at the top and keyed along the length. It is softened and lightened by having holes longitudinally through its length; through these holes are run one or two lengths of malleable wire of suitable gage.

The crack is broken out to a depth and width of 1 to 1½ in. and 6 to 9 in. respectively. The preformed rubber strip is laid along the line of the crack; the wire core enables the strip to take up and retain the irregular contour of the crack. The excavated area on either side of the rubber strip is then filled with an apoxy-resin mortar which retains a bond with the strip by virtue of its keyed wedge shape.

9. "The Extensibility and Microcracking of the In-Situ Concrete in Composite Prestressed Concrete Beams", R. H. Evans and F. K. Kong Structural Engineer, Vol. 42, No. 6, pp 181-189, June 1964.

Detailed microscopic investigations were made of the extensibility and microcracking of the in-situ concrete in composite beams with present prestressed concretes members and in-situ reinforced concrete members. The experimental work included the use of mirror extensometer gages (sensititity = 0.5×10^{-6} strain approximately) to indicate the onset of cracking, and the location and examination of the cracks with microscope of 100X.

Observations were made on the dimensions and spacings of the first microscopic cracks, the development of microscopic cracks into visible cracks and the influence of microscopic cracks on concrete strength. It was found that the extensibility of the in-situ concrete was 107 x 10^{-6} on the average, much lower than values of 300 x 10^{-6} and 400x 10^{-6} reported by other investigators.

"Extensibility" is defined as the maximum tensile strain that can occur before cracking takes place. Cracks narrower than about 1/5000 in. are referred to a microscopic cracks; those wider than about 1/2000 in. are referred to as visible cracks.

10. "The Effect of Coarse Aggregate on the Mode of Failure of Concrete in Compression and Flexure" R. Jones and M. F. Kaplan, Magazine of Concrete Research (Cement and Concrete Assoc.,) Vol. 9, No. 26, pp. 89-94, August 1957.

Experiments have been made to determine the flexural and compressive strengths of concretes containing the thirteen different coarse aggregates. In the compression tests, observations were made by an ultrasonic pulse technique to detect the onset of cracking prior to failure.

The main results are as follows:

Concretes containing smooth gravels began to crack at lower compressive strengths than did concretes containing coarser-textured aggregates. The compressive strengths did not show such appreciable differences.

Concretes which best resisted pre-cracking in compression also gave highest flexural strengths. The relation between the flexural strength of the concrete and the stress at which cracks first occured in compression was independent of the type of coarse aggregate; no such unique relation existed between flexural strength and ultimate compressive strength.

Tentative conclusions are drawn on the mode of failure of the concrete as follows:

Pre-Cracking in a cube when tested in compression probably arises from local breakdown in the adhesion between the coarse aggregate and the cement. The average compressive stress at which the first cracks occur is determined by those properties of the aggregate which influence the aggregate after precracking has occurred. Thus the compressive strength of concrete is usually greater than the compressive strength of its comparable mortar.

11. "Cracking Resistance of Hydraulic Cements", Technical News Bulletin Vol. 39, No. 9, pp. 128-29, September 1955. Highway Research Abstracts November 1955.

The cracking resistance and shrinkage rates of a number of hydraulic cements have been under study at the bureau as part of a general investigation of the properties of cements and concretes. Results so far indicate that cements with high shrinkage rates after hardening tend to crack and craze sooner than cements with lower shrinkage rates. Included in the study were 180 samples of portland cements from all areas of the United States, seven portland blast-furnace slag cements, two portland-pozzolan cements, and five portland cements from other countries.

Two types of specimens, prismatic and annular, were prepared from water-cement mixtures of each sample.

Each cement sample was mixed with water, and a prismatic and an annular specimen were formed from the mixture. The specimens were covered to prevent mositure loss and cured at 73 F. and 95 percent humidity. Under these conditions some drying took place. The length of the prism was measured when removed from the mold, and length of the prism was measured for changes, recorded periodically up to an age of 28 days.

The specimens were supported in a simple metal rack and arranged to so that the length of the prisms could be measured continuously with dial gages. A line of conducting paint around each annular specimen was connected to an electronic detecting device that turned off an electric clock when the specimen broke because of its restrained drying shrinkage. To eliminate the need for an operator on a 24-hour basis to ready the length changes of the specimens, an automatic camera was set up to photograph the equipment with its dial gages and clocks once an hour. The pictorial records indicated the length attained by each prism when the corresponding annular specimen broke.

12. "Recent Trends in Concrete Road Construction", W. H. Glanville, and F. N. Sparks. Road Research Laboratory, Department of Scientific and Industrial Research. Reprinted from "The Indian Concrete Journal" January 1953. Highway Research Abstracts, January 1954.

The most-recent development in the design of concrete roads in Great Britain has been the use of prestressed concrete. It is to be expected that a residual compressive stress in the concrete would enable a large reduction to make in the number of joints and might be well eliminate cracking. The reduced number of joints would result in a smoother flow of the construction operations leading to better riding quality and,

together with the reduction or elimination of cracks, would result in a longer life and lower maintenance costs.

Several prestressed-concrete roads have already been constructed in England, the longest slab being 404 ft. long. It is usual to provide a prestress in the longitudinal direction of about 250 lb. per sq., the transverse prestress being very small or zero. The indications are that some transverse prestress is desirable in order to prevent the development of longitudinal cracks.

A problem still remaining to be solved concerns the special types of expansion joints required at the ends of very long slabs, arising from the relatively large movements which have to be accommodated. Also, with certain methods of prestressing, it is necessary to leave a gap of 4 to 5 ft. between adjacent slabs, which must subsequently be filled in a manner which will maintain the prestress along the length of the road. A third problem concern the spacing of the prestressing cables which should be as far apart as possible without producing variable stresses across the section. Work on this problem is proceeding at the Road Research Laboratory and in the field.

There are two main disadvantages in the use of prestressed concrete in road construction. First, all underground services must be installed at the sides of the road and not beneath it. If it became necessary to dig a trench across the prestressed concrete road the prestress would be lost in the vicinity of the trench and would be difficult to reapply. Second, the problem associated with the use of this technique on vertical curves has not been solved and great difficulty might be experienced in maintaining the prestressing tendons in their correct position in the slabs.

The indications are that the cost of constructing prestressed-concrete roads are about the same as that for ordinary reinforced-concrete roads. Cost of the steel is similar in the two cases, since althoug the unit cost of the high tensile steel used in prestressing is much higher than the cost of the mild steel used as mesh reinforcement, the quantity used is considerably less. The costs of placing the two types of reinforcement are about the same, and the cost of stressing the high tensile steel is largely balanced by the use of a cheaper base, a thinner slab, and fewer joints.

Further developments may be expected in the use of prestressed concrete for roads, and it would appear to be particularly suitable for road construction on very-poor ground, such as peat.

13. "Deterioration of Concrete Due to Alkali Reaction", Concrete and Constructional Engineering, Vol. 55, No. 4, pp. 181-82. April 1960.

Observations of the deterioration of concrete structures have led to the discovery during the last decade that this is sometimes caused by a chemical reaction between the alkalis present in cement and soluble silica which is present in certain aggregates. Most British aggregates are inert but some European and American aggregates are not. A committee appointed in Denmark in 1953 to study the problem has issued 2 interim reports (Committee on Alkali Reactions in Concrete-Progress Reports N.1(1956) "Disintegration of Field Concrete", by F. M. Idorn; and L. I (1957) "Investigation of the Effect of Some Pozzolans on Alkali Reactions in Concrete," by A. H. M. Andreasen and K. E. Hauland Christensen. Copenhagen: The Danish National Institute of Building Research.

14. "Symposium on Sawn Joints in Concrete Pavement: California Division of Highways Experience Report" D. B. Evans, Southwest Builder and Contractor, Vol. 121, No. 19, pp 36-7, 40, May 8, 1953.

Late in 1952, the California Divisons of Highways began sawing the weakend plane constraction joint in concrete pavement and to date nearly 260,000 lin, ft. of these joints have been sawed. This report is summarized the experiences developed in the sawing of these joints.

Projects constructed so far have been largely on an experimental nature and while some conclusions are apparent, no definite sawing procedure has been decided upon as yet. Joints constructed are generally satisfactory and appear to be superior to the ribbon-type weakened plane joint constructed in the past. The cut joint is at present, however, a more-expensive joint, and under certain conditions numerious cracks have appeared in the pavement as a result of their use.

The excessive cost and many uncontrolled cracks are characteristics of any new operation with its untrained operators and inspectors and unproven equipment. Additional experience should result in lowered costs and better control.

15. "Recent Experimental Studies of the Shrinkage of Cement and Concrete", R. L. Hermite and J. J. Grieu. Inst. Tech. Bat. Trav. Publ.,-Ann., 1955, 5(52-53) 491-514. Building Science Abstracts, Vol. 25, No. 5, pp 134-135, May 1952.

This report is a continuation of that published in Dec. 1949. Annales, No. 5, and is the result of 5 yr. of work on the volume changes of cements and concretes. The work is continuing. Tests were made on specimens 31.6 by 31.6 m by 100 mn. at a temperature of 18 to 20 C. and in humidity cabinets at 35, 50 and 75 percent relative humidity and in water. Two cements conforming to the AFNOR standards were principally used; the results of the standard tests on these are given. A ring test for shrinkage cracking, and a dilatometer for measuring volume changes during the first period of setting, are described and illustrated. A number of graphs of loss of weight by evaporation and of shrinkage against the logarythm of time are given, with experimental data and the calculated theoretical curves. The swelling when stored in a large excess of water was also studied. An expotential law for a rate of loss of water from a specimen in air is deduced, of the same type as that of Fourrier for rate of loss of heat from a soiid. The shrinkage of cement if found to be a function of the amount of water evaporated and of coefficient which depends on the state of hydration of the cement, which coefficient varies with time. Applications to concrete, the effects of additions of calcium chloride and of protective membranes of a point sprayed on the surface to reduce evaporation and thereby to control surfaces cracking, are also discussed.

16. "A Field Study of Methods of Preventing Reflection Cracks in Bituminous Resurfacing of Concrete Pavements", M. M. Davis, Ontario Joint Highway Research Programs, Univ. of Toronto, and Ontario Dept. of Highways Reports No. 12, 1960, 37p.

It becomes general practice in the years since World War II to resurface old concrete pavements, whose conditions is not longer satisfactory because of scaling, cracking, roughness, inadequate width, or slipperiness, with bituminous concrete. Unless there is serious lack of structural strength, this bituminous surfacing (with widening where required) usually constitutes a perfectly satisfactory rehabilitation.

However, one problem remains with this resurfacing. Within a few years most of the cracks and joints in the concrete pavement have broken through the bituminous resurfacing. No completely satisfactory method has been found for treating these cracks. Furthermore, particularly where traffic is heavy, the repair of cracks isn't only hazardous, but also a nuisance to traffic.

Therefore, highway engineers have been searching for some method of preventing the cracking of the bituminous resurfacing. Experiments and trail sections in the United States indicate that the placing of steel reinforcing in the bituminous resurfacing can definitely mitigate the problem of crack reflection.

The Ontario Department of Highways decided to install a test section of reinforced bituminous resurfacing to determine its feasibility under the climatic and service conditions existing in this Province. The University of Toronto, through the Ontario Joint Highway Research Program was asked to make the detailed study of this experimental project.

This report outlines the theory of behavior, describes the test site and initial condition of the road, and outlines the construction techniques, problems, and recommendations. The effectiveness of the treatment will not be known for a period of years. Annual performance surveys will be conducted and will be reported later.

17. "Behavior in Flexure of Reinforced Lightweight-Aggregate (LYTAG) Concrete Beams" R. H. Evans and C. O. Orangun, Civil Engineering and Public Works Review, Vol. 59, No. 694, pp 597-601.

Results of tests carried out on 28 sintered pulverized fuel ash (LYTAG) concrete beams are reported. A study is made of the behavior of LYTAG concrete beams with particular reference to ultimate load, deflection and visible cracking characteristics in Flexure. Load factors are very satisfactory and flexural cracks at a steel stress of 30,000 psi would not exceed 110 x 10^{-3} in. - a width regarded as permissible for conventional gravel concrete beams.

18. "Revere Resurfacing Project: An Experiment in Control of Reflection Cracking in Bituminous Surfaces over Concrete", Alexander J. Bone and L. W. Crump, Joint Highway Res. Proj. MIT and Mass. Department of Public Works, Research Report No. 8, Cambridge, June 1954.

The Revere Resurfacing Project was built in the fall of 1952 to test experimental techniques of controlling reflection cracking in bituminous resurfacings. After 14 months of service, including one complete annual climatic cycle, several developments have taken place which lead to tentative conclusions.

Of the special joint treatments applied, the use of wire mesh to reinforce the resurfacing over the joint offer the most promise for controlling reflection cracking. However, the width of the mesh should be to the edge of the mesh. Cement grout filler was effective in reducing movement as some joints, but not at others. The soil-mix placed in certain joints was effective in reducing movement and cracking. Neither the building paper placed on the concrete nor the leveling of joints with bituminous mix had any significant influence on cracking. Both the 11-gage plates and the chain-link fence became springy and caused failures of the resurfacing by repeated flexing. The 26-gage plates are more satisfactory.

More cracking has developed in the northbound roadway where the resurfacing is 2½ inches thick than in the southbound roadway where it is 3 inches thick.

The section paved with rubber-asphalt mix has cracked less than either of the other two sections. The section paved with catalytically blown asphalt-blend mix has cracked more than the one paved with regular Massachusetts Type I mix.

Longitudinal cracking occured mostly over the edge of the concrete slab next to the median strip.

Since asphalt pavements change character with age, these results must be considered as tentative only. Subsequent developments may lead to modifications.

19. "Spacing and Embedment Depth of Wires in Prestressed Units", Highways and Bridges and Engineering Works, Vol. 30, No. 1458, p 11, July 11, 1962.

The spacing of wires for prestressed units is necessarily governed by the depth of embedment and that depends not only on the diameter of the wire and the quality of the concret but also on the prestress and on the size and shape of the indentions, said Mr. Louis Garay, his paper in Prestressed Concrete.

If the anchorage length is proportionally to the cross-sectional dimensions, stirrups can be avoided even when wires are placed close, together. This length is limited by the maximum permissible slip, about 0.8 mn with the wires examined.

The quality of concrete and the wire surface should be chosen with due consideration of the need for economy as well as of the safety of the structure. For instance, an excessive identation giving a very short transmission length may require an unnecessary depth of embedment as well as produce undesirable stresses in the end of the beam.

The ends of beams are most likely to crack when the prestress is released. Some days after casting cracks become visible, so that faulty units can be rejected. Slip of wire can result in an unstable condition even after a long time; therefore bond must be checked by quality control tests. The need for such a test illustrates an essential difference between prestressed and ordinary reinforced concrete structures.

Mr. Garay put forward a new method of calculating the stresses in the ends of prestressed concrete beams which make possible the evaluation of the effect of variation in anchorage length.

20. "Statistical Aspects of Fracture in Concrete: I. An Analysis of Flexural Failure of Portland Cement Mortar from the Standpoint of Stochastic Theory" Motoo Hori, Journal of the Physical Society of Japan, Vol 14, No. 10, pp 1444-52, 1959. Journal of the American Ceramic Society (Ceramic Abstracts) Vol 43, No. 5 pp 107, May 1960.

An application of the theory of stochastic processes to the static fracture of nonhomogeneous brittle materials such as portland cement concrete, is presented. Numerous flexural failure tests on standard mortar specimens made in accordance with JIS were made under constant load and under uniformly increasing loads, and the results are analyzed statistically from the standpoint of stochastic theory. It is concluded that the scatter observed in the breaking time or the static strength of concrete appears to be a result of inherent characteristics of the material itself associated with a Markoff process as a kind of rate process.

21. "Flexural Cracking Propagation in Two-Way Concrete Slave Reinforced With High Strength Welded Wire Fabric", Edward C. Nawy. Dept of Civil Eng., Rutgers, the State University, Nov. 1963. pp 31.

A detailed investigation is reported on the flexural cracking behavior of two-way concrete slabs reinforced with cold-drawn plain high-strength welded wire fabric. Large-scale square slab panels were used. They were either simple supported or clamped and were centrally loaded.

Crack width propagation was observed with illuminated miscropes at close space intervals on the amjor cracks. Strain in the wire reinforcement was electronically recorded in the vicinity of locations where the crack widths were observed. Compressive strain in the concrete and deflections at critical locations were also measured.

The size and spacing of wire were to the extremes in the different specimens to observe their effect on the cracking behavior. A cracking equation in the form of a power function was developed for crack control in two-way slabs.

22. "The Performance During the First Five Years of the Experimental Concrete Road at Oxton, Nottinghamshire" John Allister Loe, Proceedings, Institution of Civil Engineers (England) Vol. 4, No. 1, Pt. 2, Paper No. 5970, pp 137-166. February 1955.

The paper gives an account of the structural performance of the experimental concrete road at Oxton, Nottinghamshire (in Great Britain) during the first 5 years after being opened to traffic in February 1948;it also includes information on the horizontal movements occurring at some of the joints during this period.

Interim conclusions and observations on the performance of the road after 5 years use by traffic show that the plain concrete slabs of 6-in thickness and less have not given satisfactory performance, but the plain concrete slabs of 7- and 8-inch slabs contain some cracking. The reinforced slabs of 3- and 4-inch thickness contain a large number of hair cracks and joints and corner cracking. The satisfactory condition despite a large number of hair cracks in many of the slabs, and the reinforced concrete slabs of 7- and 8-inch thickness are in a satisfactory condition only a few hair cracks.

The use of a cement stabilized sand base of up to 6 inches thick has had no apparent effect on the performance of plain and reinforced concrete slabs 3,4,5 and 6 inches thick. Most of the transverse cracks originated from the longitudinal joint. The maount of cracking is greatest in the bays adjacent to the expansion joints. Measurements made on selected joints showed that greater permanent openning occurred in dummy contraction joints spaced 15 feet apart than in butt contraction joints spaced 30 feet apart.

23. "Symposium on Sawn Joints in Concrete Pavement: California Division of Highways Experience Report" D. B. Evans, Southwest Builder and Contractor, Vol 121, No. 19, pp 36-37-40, May 8, 1953.

Late in 1952, the California Division of Highways began sawing the weakened plane constraction joint in concrete pavement and to date nearly 260,000 lin, ft. of these joints have been sawed. This report is summarized in the experience developed in the sawing of these joints.

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The excessive cost and many uncontrolled cracks are characteristic of any new operation with its untrained operators and inspectors and unproven equipment. Additional experience should result in lowered costs and better control.

24. "The Effect of Random Distribution of Glass Fiber in Concrete Mixes, I. O. Oladapo, Civil Engineering and Public Works Review Vol. 58, No. 678, pp 97098, Jan 1963.

The addition of glass fiber to concrete causes an increase in its modulus of rupture; the effect is more pronounced particularly in yourg concrete. This could be a useful way of preventing early cracking in young concrete but it is doubtful if glass fiber will have any appreciable effect on mature concrete; it might be desirable, however to investigate load-deflection characteristics before drawing any general conclusions.

25. "Flexure of A Road Surfacing, Its Relation to Fatigue Cracking, and Factors Determining Its Severity", G. L. Kehlen, Highway Research Board Bulletin 321, pp 26-39, 1962.

This paper describes some aspects of theoretical and experimental work carried out in South Africa, over the past four years, in a study of "chicken net" cracking of a road surface, and of the flexure induced in it by wheel loads.

The accuracies of common measures of the severity of flexure are discussed. Of These, radius of curvature has been adopted for general testing. Results of field observations which reveal a distinct relation between curvature and degree of cracking of a surfacing are presented, a radius of about 125ft. being critical in the case of one road studied.

A field study is described which revealed that Elastic Theory is applicable to a limited extent in regard to the deflection and curvature of a road under its normal traffic.

A number of factors which affect the severity of the flexure developed beneath a wheel load are discussed. Curvatures are practically independent of the nature of the materials below a depth of about 15 in. and depend mainly on the materials of the base and subbase. Curvatures are affected considerably by the tire pressures of the vehicle inducing them, but little by the wheel load.

Existing design methods do not appear to take adequate account of flexure cracking, and the likely form of possible additional design consideration is discussed.

26. "The Behavior of a Continuously Reinforced Concrete Road at Dundee", K. M. Brook and P. J. Pullar-Strecker. Roads and Road Construction, Vol. 40, No. 478, pp 290-295, Oct. 1962.

This report gives the results of three crack surveys which were made on an asphalt-surfaced continuously reinforced concrete base, laid at Dundee in 1957. The 8-in. base is 3,896 ft long, with no expansion or contraction joints, and it is beleived to be the longest of its kind in Great Britain. The reinforcement weighing 10.76 lb/yd^2, was continued through each construction joint where, in addition, tie-bars were provided. The traffic intensity on the road is classified as "heavy".

The first and second crack surveys were made on the concrete in August 1957 and October 1957, the second being carried out just before the road was surfaced with asphalt. The third survey, made on the asphalt surfacing, was carried out in March, 1961.

27. "Testing of Concrete by Ultrasonic-Pulse Technique" R. Jones, Highway Research Board Proceedings Vol. 32, pp. 258-276, 1953.

A description is given of the apparatus for making high-prevision measurements of the velocity of an ultrasonic pulse in concrete. The use of this velocity (the longitudinal-wave velocity) as a criterion of quality is discussed with reference to such conventional criteria as the modulus of rupture, compressive strength, density of the concrete. The effect of a large number of variables has been studied and it was found that the longitudinal-wave velocity could be used to measure changes in the quality of the concrete, except when the aggregate-to-cement ratio was varied. For this reason the longitudinal-wave velocity cannot be used as a general criterion of concrete quality.

The technique can be applied directly to the concrete in structural members and can be used to detect any weakness due to deterioration or poor compaction. Where test specimens of the structural concrete are available, a calibration curve can be obtained from which the equivalent strength of the concrete can be inferred. Examples of such tests are given.

Laboratory applications of the technique have been the study of crack formation in concrete (1) under load, (2) subjected to frost action, and (3) when inversion takes place in high-alumina cement. An interesting result showed that concrete cubes in compression develope initial cracks with plan s parallel to the direction of application of the load at about 30 percent of the ultimate load.

28. "Composite Partially-Prestressed Concrete Slabs. Strength Under Repeated and Static Loading", P. W. Abeles, Engineering 1954, 178 (4628), 464-8. Road Abstracts Vol. 22, No. 4, p 57, April 1955.

Results are given of fatigue test made on 3 slabs of partially-prestressed concrete. The first two slabs were subjected to static loading until cracks had occurred and then to a million repetitions of loading corresponding to 50 psi. compression and 550 psi. in nominal tensile strength in the tensile fibers of the slab. The second slab was subjected to a further 2 million repetitions each with a successively higher load. The third slab, in which metallurical Sealithor cement was used, was subjected to alternate cycles of fatigue testing and static loading at higher stresses. It is concluded that, provided that the partially-prestressed slabs fulfill certain strength requirements and the upper range of loading does not exceed a value corresponding to a tensile stress of 650 psi, (1) The occurrence of cracking under fatigue loading is avaied. (2) Fatigue loading does not affect adversely the commencement of cracking at a subsequent static loading. (3) When cracks have developed, no noticeable permanent deformation remains afer a million repetitions of loading. (4) The ultimate failure resistance in a static loading is not affected by a previous fatigue loading of millions of repetitions applied in a cracked state.

29. "Prestressed Concrete in Highway Bridges and Pavements" Curzon Dobell, Highway Research Board Proceedings, Vol. 32, pp. 188-208, 1953.

Brief historical review. Advantages; reduction in critical materials; reduced ratio DL/ll, particularly for long spans; elimination of cracks. Pretensioned wires or strands for precast members. Post-tensioned multiple parallel wire cables systems. Post-tensioned bars and cables. Continuous multispan bridges. Principle of prestressing with reference to importance of high steel and concrete stresses. Analysis of critical loading stages. Magnitude and frequency of vibration for thin, prestressed slabs. Recommend steel and concrete stresses. Factors of Safety; Special consideration: importance of end anchorage, bond of reinforcing, and end block stresses, etc. Choice of most economical prestressing system. Comparative cost with structural steel a d reinforced concrete. Need to adapt prestressing methods to suit standard American construction procedures and equipment. Material and labor costs for different systems of prestressing. Review experimental prestressed pavements. Suggest method to produce continuous prestressed pavement without joints for infinite lengths. Definitions and notations. Design criteria. Need to overcome domination of patents system; establishment of consulting engineers in prestressed concrete design for major structures; need for simplified methods of prestressing for smaller structures.

30. "Method of Studying Formation of Cracks in a Material Subjected to Stress", R. Jones, British Journal of Applied Physics, Vol. 3, pp. 229-232, July 1952. Highway Research Abstracts, March 1953.

A method is described to determine the onset of cracking in specimens of concrete subjected to tension or compression in mechanical testing machines. While the loads were being applied, measurements were made at innervals of the velocities of ultrasonic pulses passing through the test-piece in the axial or transverse directions. In compression, the valocity of the ultrasonic pulses in the direction of loading remained constant while the load was increased to failure, but in the transverse direction a fall in the velocity started at only a fraction of the ultimate load and the velocity then decreased with increase of load. This indicated that cracking occurred internally parallel to the direction of loading. The load at which it started depended on the strength of the concrete and the uniformity of the stress distribution. In tension, fracture was preceded by only a very small, and often insignificant, amount of cracking which occurred at right angles to the direction of loading.

31. The Extensibility and Microcracking of the In-Situ Concrete in Composite Prestressed Concrete Beams. R. H. Evans and F. K. Kong. Structural Engineer (11 Upper Belgrave St., London, S.W. I, England) Vol. 42, No. 6 pp. 181-189 June 1964.

Detailed microscopic investigations were made of the extensibility and microcracking of the in-situ concrete in composite beams with precast prestressed concrete members and in-situ reinforced concrete members. The experimental work included the use of mirror extensometer gages (sensitivity = 0.5×10^{-6} strain approximately) to indicate the onset of cracking, and the location and examination of the cracks with a microscope of 100X.

Observations were made on the dimensions and spacings of the first microscopic cracks, the development of microscopic cracks into visible cracks and the influence of miscroscopic cracks on concrete srrength. It was found that the extensibility of the in-situ concrete was 107×10^{-6} on the average much lower than values of 300×10^{-6} and 400×10^{-6} reported by other investigators.

"Extensibility" is defined as the maximum tensile strain that can occur before cracking takes place. Cracks narrower than about 1/5000 in. are referred to as visible cracks.