REPORT OF INVESTIGATION OF THE ECONOMIC VALUE OF REINFORCEMENT IN CONCRETE ROADS

C A Hogentogler
Highway Research Board, Washington, D C

INTRODUCTION

Most exceptional is an investigation which develops no need for additional research Generally the aims prompting the original project are accomplished satisfactorily only when this additional research has been completed The value of supplementary experiments was amply illustrated by the Bates Road Tests The first series of tests indicated the efficiency of a slab design somewhat different from any one of those comprising the original project Not, however, until after this new design was subjected to the most severe traffic conditions in a second series of tests was it adopted as standard, not only by Illinois, but, with slight modifications, by more than thirty other states

When experiments employing specimens which can be selected, designed and constructed at the will of the researcher necessitate additional experiment properly to solve the problem, it is apparent that such absence of control of both test conditions and specimens as accompanied the reinforcement survey correspondingly increased the need for supplementary investigations

Not only has it been difficult to find specimens embodying variables desired for study, but for a long time roads allowing direct comparisons of any sort could not be located When finally an adequate number of specimens containing both plain and reinforced sections were selected, a number of confusing factors were found during the inspections Many roads had not been in service a sufficient length of time to develop the relative influence of climate and traffic In others variations from office plans were often made to facilitate construction Some road sections of desired age had not the required design, while those having the required design had not been subjected to either the age or traffic conditions necessary to forecast their efficiency

Another confusing factor was introduced by the adoption of center joint construction Thus, roads having the desired age requirement were reinforced primarily in a transverse direction while the information sought concerned the effects of longitudinal as well as transverse steel

In many cases reinforcement was placed only in such sections as were laid on questionable subgrade, and while inspections indicated that these locations were not always the most unfavorable, yet the difference between these subgrades and those supporting the plain concrete sections was such as would often influence the value of the comparison and sometimes would eliminate it from consideration. Because of these limitations information concerning the most effective design of reinforcement can be furnished only by future research

This report is presented in the briefest possible form and consists of

A Outline of the object, procedure and scope of the investigation,

B An annotated summary of conclusions,

C Digest of conclusions,

D Demonstration of the practical application of results,

E Presentation of data,

F Supplementary reports, and discussion

The data were presented at a conference held at the National Research Council November 4 and 5, 1925 Attending the conference were C C. Ahles, A C Benkelman, H Eltinge Breed, V R. Burton, A T. Goldbeck, G H Henderson, C A Hogentogler, F H Jackson, H J Kirk, I B Mullis, Clifford Older, J T. Pauls, E B. Smith, W D Somervell, P M Tebbs, L W. Teller and H M. Westergaard.

The findings were later reviewed by Messrs A N Johnson, T R Agg, E W James, H E Breed, Clifford Older, A T Goldbeck and S S Steinberg and were approved by the Executive Committee of the Highway Research Board.

The fullest cooperation was offered by every highway organization that had intimate notice of the investigation Advantage, however, could be taken only of that offered by the cities of Boston, Philadelphia, New Orleans, St. Louis, and Jackson (Miss), the counties of Milwaukee (Wis), Cook (Ill), Wayne and St. Clair (Mich), Escambia (Fla), and Allegheny (Pa), the States of Massachusetts, Connecticut, New York, Pennsylvania, Delaware, Maryland, Virginia, North Carolina, Georgia, Mississippi, California, Washington, Idaho, Wisconsin, Iowa, Nebraska, Missouri, Illinois, Michigan, Ohio and West Virginia; representatives of the Portland Cement Association at Boston, Hartford, New York, Philadelphia, Pittsburgh, Columbus, Chicago, Detroit, Kansas City, St. Louis, New Orleans and Atlanta, and the U. S Bureau of Public Roads, Troy, N Y, and Washington, D C

OBJECT, SCOPE AND PROCEDURE

OBJECT OF THE SURVEY

The object of the survey was to determine if the use of steel reinforcement in concrete pavements was economically justified

Solution of this problem by comparison of relative first costs, maintenance costs and life of surface would have been ideal, but this method of procedure was impossible, since

I. Annual maintenance costs were not always an index of relative surface conditions

II No definite method for computing salvage value of pavements has been developed

III. Life of concrete pavements could not be ascertained since only in relatively few instances had they completely disintegrated

Because of these facts it became necessary thoroughly to investigate the behavior of concrete pavements in service and to determine how their conditions were influenced by the various factors The purpose of this report is to aid the engineer's judgment in providing against future failures by furnishing detailed information on

I. The characteristics of plain concrete roads and streets

II The influence of age, traffic, subgrade and aggregate on these characteristics

III The influence of joint spacing, width of road, additional concrete thickness and steel reinforcement on these characteristics

PROCEDURE

Except for difficulty of finding roads in which variables were so reduced as to make comparisons practical, the procedure was simple and consisted of

I. Scrutiny of construction records, office plans, contracts, and tabulation of annual maintenance and construction costs

II Survey of plain and reinforced roads subjected to similar conditions of age, traffic, etc (See Progress Report [1])

III. Survey of roads containing both plain and reinforced sections

IV. Correlation of results of this survey with those of previous surveys and highway researches

[1] Progress Report Economic Value of Steel Reinforcement in Concrete Pavements, by C A. Hogentogler, Proc. Fourth Annual Meeting, Highway Research Board, National Research Council, Washington, D C

SCOPE AND LIMITS

The survey consisted of

I General inspection of 5,500 miles in which was sought only
  A Plain concrete surfaces which had disintegrated
  B Reinforced concrete surfaces which had failed
  C Cracks in reinforced concrete pavements, of such width of opening as indicated broken steel

II Detailed inspection of about 2,000 miles of surfaces distributed through twenty-six states, including thicknesses of from 5 to 10½ inches, ages of from 1 to 13 years, subgrades ranging from stable sands to clay causing 9″ heave, traffic between minimum and maximum limits, and reinforcement ranging from light wire fencing to ⅞″ bar mats

The survey was limited by conditions of existent roads, thicknesses of concrete, types of reinforcement and cross sections employed Specimens for study were made available by reason of

  A Desire on part of some engineers to compare plain and reinforced surfaces
  B Expediency of construction when delivery of reinforcement was delayed
  C Desire for extra precaution when subgrades of questionable supporting value were encountered

PRESENTATION OF DATA

The data consists of

I Sketches of comparable specimen roads showing detailed conditions as regards occurrence and character of cracks and breakage
II Photographs supplementing the above sketches
III Tabulation of crack length and extent of breakage with complete design details
IV Charts showing road conditions in graphic form
V Digest of such parts of highway researches as are pertinent to this investigation
VI Reports of allied investigations furnished by cooperating agencies

SUMMARY OF CONCLUSIONS

1. The amount of cracking and subsequent disintegrating is a function of time; thus, the rate of cracking is a measure of the life of the pavement. Pages 35, 39, 66, 102, 114, and 132

2. The data show that steel reinforcement reduced the rate of cracking and thus increased the life of the pavement. This applies both to concrete pavements and other pavements laid upon a concrete base. Pages 50, 52, 54, 97, 108, 119, and 131

3. Crack reduction is more economically accomplished by the use of steel reinforcement than by additional thickness of concrete. Pages 51, 59, 61, 66, and 67.

4. A greater reduction was afforded by small steel members closely spaced than by larger members wider spaced. Page 58

5. Increasing weight of mesh from 25 to 56 lbs. per 100 sq. ft. considerably reduced cracking. Pages 61, 112, and 114

6. Mesh reinforcement, 25 to 56 lbs. per 100 sq. ft., reduced cracks 35 to 70 per cent in pavements of like thickness. Page 58

7. Mesh reinforcement, 25 to 56 lbs. per 100 sq. ft. and bar mat reinforcement 64 lbs. per 100 sq. ft.—25 per cent longitudinal—reduced cracks more than one additional inch of concrete; but one additional inch of concrete reduced cracks more than bars (42 to 48 lbs. per 100 sq. ft.) placed transversely only. Pages 53, 56, 58, 66, 67, 68, 97, 98, 99, and 106

8. With good crushed stone aggregate, 56 to 90 lbs. per 100 sq. ft. mesh reinforcement, or 170 lbs. per 100 sq. ft. bar reinforcement, 50 per cent each way, caused a reduction in combined transverse and longitudinal cracks equal to that indicated for 2 inches additional center thickness. Pages 61, 67, and 129

9. Mesh reinforcement of 38 lbs. per 100 sq. ft. has been effective for a thin layer of concrete laid as resurfacing upon an old concrete road. Page 82

10. One additional inch of edge thickness reduced corner cracks more than mesh reinforcement 25 to 56 lbs. per 100 sq. ft., or ⅜ to ¾ inch bar reinforcement; but progressive destruction following the appearance of corner cracks was arrested by steel reinforcement. Pages 69, 73, 75, 79, 80, and 110

11. All types of steel reinforcement across cracks tended to hold together fractured slabs. Pages 72, 75, 76, 100, and 133

12. Bar reinforcement across transverse joint, without proper provision for slippage and clearance, resulted in breakage and subsequent expensive repairs. Pages 78 and 81

13. For long slabs, 75 to 100 feet or over, edge bar reinforce-

ment with continuous bond caused corner cracks if the area of steel exceeded ¼ sq. inch. Pages 62, 68, 74, 120, and 123

14. A remarkable agreement was found to exist between results of observations or roads in service and results furnished by a wide range of experimental roads and laboratory tests. Pages 65 and 73

DIGEST OF CONCLUSIONS

Concrete road conditions are dependent primarily on age, subgrade and slab design Evidence has shown that stable, well drained subgrades, increased thickness of concrete and steel reinforcement afforded beneficial effects, and, within limits, the relative value of each of these factors was ascertained The limited scope of the survey, however, prevented striking a proper balance between the costs of these mediums and their relative effects Thus exact definition of the most economic pavement resulting from proper proportioning of expenditures for subgrade, drainage, aggregate, concrete thickness and steel reinforcement must await procurement of additional data

The influence of age, subgrade, drainage, aggregate, concrete thickness and steel reinforcement as shown by this survey is given in the following digest There is included also a statement of the information which should be secured from additional investigation

AGE Cracking increased consistently with age for about five years, after which the rate of cracking was reduced Depending on various conditions, the change in rate of cracking would occur either before or after the five-year period ended Breakage occurred whenever sufficiently heavy wheel loads were applied and was dependent on occurrence of heavy traffic units rather than on age Raveling, unevenness of surface and separation of slabs, naturally, was most marked in the older roads If the type of maintenance employed allowed additional unevenness of surface, breakage then increased with age Results of condition surveys can be interpreted properly only with respect to the age or the particular pavements

SUBGRADE AND DRAINAGE Relatively thin slabs laid on certain natural subgrades of sand and gravel had a minimum number of defects Only on these excellent subgrades was the possibility for reduced slab thickness indicated By direct comparison it was shown that a thin slab (4¾-6¾-4¾ x 16 ft wide) laid on a good sand subgrade could develop practically no cracks or breaks of any kind, while the same thickness laid on adjacent clay might be entirely inadequate (Page 39) All natural sands did not afford this subgrade benefit, nor was there any indication that it could be reproduced by subgrade treatment or subbases From information available it is a risk to design on the assumption that the subgrade may be a substitute for precautionary measures in the slab

Slabs laid on firm subgrade, such as old roadbed and rolled stone base course, might develop cracks before slabs laid on softer bases Hard bases, however, seemed effective against breakage and surface unevenness in the slab, while replacements were common on the softer bases

Evidence did not show that undrained porous subbases were effective against cracking, heaving or breakage There were indications, however, that properly drained gravel bases reduced cracking

The most efficient forms of drainage were not determined It was indicated, however, that properly constructed side drains placed under the pavement edges could be beneficial (Page 40) Any type of drainage is undesirable which, on failure to function, would allow reservoirs of water to collect under the pavement

The present survey indicated that existing roads furnish unlimited opportunities for determining both the effectiveness of various types of drainage and also the benefits afforded by various subgrade treatments and subbases

AGGREGATE Current pavement specifications apparently have allowed the use, on equal terms, of aggregates, some of which showed considerably more cracking and breakage than others Undoubtedly a differential should be developed which would specify the manner of use of various aggregates Before this can be accomplished, however, a survey of existing roads should be made to determine those aggregates which are unsatisfactory and tests by which they can be identified should be developed The present survey indicated that an abundance of comparisons for such a study can be found in many states It is recalled that but little is known of the behavior of crushed stone aggregates under test conditions It will be remembered that in the Milwaukee County Experimental Roads, the Impact Tests at Arlington, the Columbia Pike Experimental Road and in all but one section of the Pittsburg, Calif , Test Road, gravel aggregates were used

CONCRETE THICKNESS Increase of *center thickness* of concrete to a certain limit afforded corresponding reduction in longitudinal cracking and beyond that limit the reduction was negligible A slight reduction in transverse cracking accompanied increased *center thickness* of concrete It was indicated that a wheel load sufficiently heavy to crack transversely a 6-inch thick slab (full width or center joint) could crack also slabs 7, 8 and 9 inches thick, but in slightly less amount The average spacing of transverse cracks in roads of considerable age, in both full width slabs and those constructed with center joint, was about 18 feet when heavy traffic units were accommodated, and from 25 to 40 feet otherwise

It would seem that for concrete roads, when separation of slabs was prevented by binding steel, a basic *center thickness* of six inches has been satisfactory Conditions on interurban, terminal roads and busy trunk lines might be such that additional thickness with reinforcement would be advisable Though cracking may be reduced, both by increasing center thickness and by the use of steel reinforcement, the latter method is more economical

A slab thickness of less than 6 inches would be questionable because of its inability to resist progressive breaking down In addition to the necessity of keeping parts of slabs from separating, a 6-inch center thickness to be satisfactory must also be accompanied by an *edge* of such thickness as will prevent corner breaks A 9-inch *edge* thickness seemed adequate for this purpose. The prevention of corner breaks was accomplished more economically by additional *edge* thickness than by steel reinforcement

If no reinforcement is used to prevent fractured parts of slabs from separating, then concrete thickness necessary to resist corner breaks must be furnished throughout the slab Increase of concrete thickness was more effective against corner breaks than against transverse and longitudinal cracking.

REINFORCEMENT Steel reinforcement in concrete pavements seemed to serve two purposes First it delayed the appearance of visible cracks, and second it held the fractured parts of surfaces together after cracking had occurred

The retardation of cracking seemed to result from a change in the character of the concrete caused by incorporation of reinforcement When plain concrete was subjected, either during the curing period or later, to certain prevalent conditions it failed to acquire its normal strength Under such conditions a considerable difference was noted between the plain and mesh reinforced sections. It was noted that when specimens were cured in air, the contraction in the reinforced, was but 50% of that in the plain specimens [1]

When specimens were subjected to rapid expansion by moisture and quick drying out those reinforced with mesh remained intact while the others disintegrated Also, reinforced specimens showed greater resistance to tensile forces during the early ages than did plain specimens [2]

Mesh reinforced concrete specimens at early ages showed greater resistance to repeated loads than did plain specimens [3]

---

[1] Design of Concrete Roads By L W Teller and J T Pauls Proceedings American Concrete Institute, 1926

[2] Summary of Tension Tests on Concrete Briquettes Reinforced with Steel Fabric H E Breed, Proceedings Fifth Annual Meeting of the Highway Research Board, National Research Council, Part 1

[3] Report on Experiments on Extensibility of Concrete By W K Hatt, Proc. Fifth Annual Meeting, Highway Research Board, National Research Council, Part 1.

Mesh reinforced specimens laid on wet subgrade showed greater resistance to impacts than did plain concrete specimens [1]

Experiments indicating the effect of bar reinforcement under these conditions were not available.

Roads in service indicated that in relatively short slabs (20 to 75 ft) all types of two-way reinforcements were effective against cracking and separation of cracked slabs, and that, weight for weight, small members closely spaced were more effective than larger members spaced further apart The greatest reductions in initial cracking were afforded by reinforcement with the use of good crushed stone aggregate

Reinforcement held fractured surfaces together, resisted breakage, retained smoothness of surface with reduced impacts, reduced raveling at crack edges, prevented escape of the cushion under brick and block surfaces, and promoted smoothness in bituminous tops While different weights of reinforcement would probably be required for different purposes, medium weight meshes (42 to 56 lbs) and bar mats (64 to 85 lbs) seemed to be satisfactory for general conditions

The impracticability of having steel in bond function over considerable lengths (more than 100 feet) was evidenced in both bar and mesh reinforcement by cracks appearing at definite intervals (60 to 100 ft) with clear openings (1/16 to ¼ in) and raveling similar to those in plain concrete This indicated that if the reinforcement had not broken, at least one of its chief benefits had been lost When steel (bars) in sufficient amount was concentrated in the side edges or along the center joint, corner cracks appeared often before the road was opened to traffic When bars, without proper provision for slippage and clearance were carried across transverse joints, breakage, resulting in expensive repairs, occurred, and when longitudinal bars of sufficient weight were distributed across the road section and certain aggregates were employed, transverse cracking in excess of that occurring in adjoining sections of plain concrete of the same thickness was found In some cases, this cracking was further increased by additional transverse bars Theory indicates that several square inches of longitudinal steel would be necessary to supply the tensile resistance to visible cracking afforded by the reduction of the concrete section accompanying the use of ⅜ inch transverse rods

In long slabs of the same thickness, less transverse cracking generally was found in the mesh reinforced than in the plain sections When longitudinal bars were painted and oiled, as in the Illinois design, excessive cracking did not develop

---

[1] Impact Tests of U S Bureau of Public Roads By Earl B Smith and L W Teller See page 124, this report

All available evidence indicates that undesirable subgrade conditions have been overcome more economically by the use of steel reinforcement and adequate concrete thickness than by subbases or subgrade treatment This indication, however, should be verified by additional investigation

Planes of weakness and broken reinforcement now being investigated in North Carolina,[1] combined with suggetsions advanced by A T Goldbeck,[2] offer a wide range of possibilities for control of cracking

Reinforcement, while offering considerable reduction in the number of cracks, cannot be expected to eliminate them on movable subgrades Its use in conjunction with planes of weakness placed close enough to allow slabs to crack and function as flexible surfaces will probably take care of any subgrade condition encountered, affording a smooth top with no unsightly, irregular cracks That reinforced concrete surfaces can be extremely flexible was shown by roads in Michigan, North Carolina and Missouri, which in some instances had subsided 12 to 18 inches in 50 feet In this connection, subgrade studies must furnish information for the proper placing of these dividing planes It would seem that reinforced slabs about fifty feet long with planes of weakness placed where subgrade conditions warrant, afford a rational means for transverse crack control

The longitudinal plane of weakness as substitute for constructed center joint also offers field for experiment Since the success of a relatively thin center depends on how well it is held to its neighbor, and since small members of steel closely spaced hold slabs together better than larger members spaced farther apart, a design of this kind might have considerable merit Michigan furnished examples showing that dowels as ordinarily used did not always prevent separation of slabs at the center joint

While not many center-joint roads of sufficient age were available for study, it would seem that all benefits of reinforcement with regard to raveling of cracks, separation and unevenness of slabs, breakage, and reduction of transverse cracking apply to center-joint roads, with thin centers as much as, if not more than to those of full width slabs In narrow slabs, however, a small amount of steel distributed transversely should give beneficial results during the curing period, but will not reduce the concrete section enough to promote transverse cracking, while steel should be used longitudi-

[1] Report on a Field Experiment on Introduction of Planes of Weakness in Concrete Slabs By W D Somerrell, Proc Fifth Annual Meeting, Highway Research Board, National Research Council, Part 1

[2] Interrelation of Longitudinal Steel and Transverse Cracks in Concrete Roads By A T Goldbeck Public Roads, Vol 6, No 6, August, 1925.

nally in sufficient amount to hold transverse cracks together if they develop

Only by additional experiment can the economy of reinforcement for surfaces laid on excellent sand and gravel subgrades be determined One example of minimum cracking, ten years old, showed by a comparison of 8 miles of plain, with 15 miles of reinforced concrete, that corner breaks and transverse cracks in the latter slightly exceeded those in the former, but that longitudinal cracks were only found in the plain section The average annual maintenance costs for 5 years were $16 00 per mile for the plain sections and $9 00 per mile for the reinforced sections These costs, of course, are so low that increased expenditure for either *additional thickness* or *steel reinforcement* would not be justified Experiment, however, might show that under these exceptional conditions a thick edge section, possibly a 7-5-7 or even a thinner center, reinforced, might have lower first cost and at the same time eliminate the corner breaks found in the present 5-7-5 design. The remarkable resistance shown by the 5-inch mesh reinforced section in the Bates Tests with a gumbo soil certainly indicated that a comparatively thin reinforced center could be economic on exceptionally good subgrades

That more attention was not given to bar reinforcement is due to the fact that comparisons were not available Many miles of bar reinforced roads in New Jersey, New York and Massachusetts were in excellent condition, but absence of adjacent plain concrete roads prevented definite comparisons

Many maintenance costs were secured and in general they were considerably less for the reinforced surfaces than for the plain Since, however, in many cases they reflected the variables of age and thickness as well as reinforcement, they were not included in the report.

The agreement between behavior of roads in service and test results was most gratifying, in that it points out vast possibilities for highway research It seems evident that whether the problem be subgrade, drainage, type of surface or aggregate, a survey of roads in service, supplemented by experiments to fill in the voids, will give a decisive and comparatively quick solution

LEGEND FOR CHARTS

Heavy border lines indicate reinforced sections
Cross-hatching indicates broken or replaced areas

———————————	**Joint.**
	Hair crack.
— — — — — — — — — —	**Tightly closed crack.**
— — — R — — — — — — —	**Raveled crack.**
— — — S R. — — — — — —	**Slightly raveled crack.**
— — — 1/8″ — — — — — —	**Crack open 1/8 inch.**

PRACTICAL APPLICATION OF RESULTS FROM ROAD SURVEYS

When complete information has been secured about the influences of the variables affecting road behavior, it will be possible to estimate the differences in surface conditions which may be expected by varying the design of slab or subgrade A comparison of the relative costs of different types in conjunction with their behavior will furnish an index to the most economic procedure

If a pavement laid under certain conditions has developed undesirable defects, application of data derived from surveys can give an indication of what might have occurred with different aggregates, design of slab, or subgrade conditions Future construction can thus be guided with increasing confidence

Application of information furnished by the investigation of steel reinforcement in concrete roads amply illustrates the possibilities of such procedure The method consists of gradually changing the design from a thick center, full width, plain concrete slab to a thickened edge, reinforced slab with a center joint, and in varying the pavement condition at the various stages in accordance with data derived from the survey

Figures D-1 and D-2 illustrate this method of analysis Section 1-A shows the present condition of a 5-7-5 road, 14 feet wide, 11 years old and laid on questionable subgrade In a length of 600 feet it contains 42% breakage, an estimated 800 feet of longitudinal crack length, and 33 transverse cracks

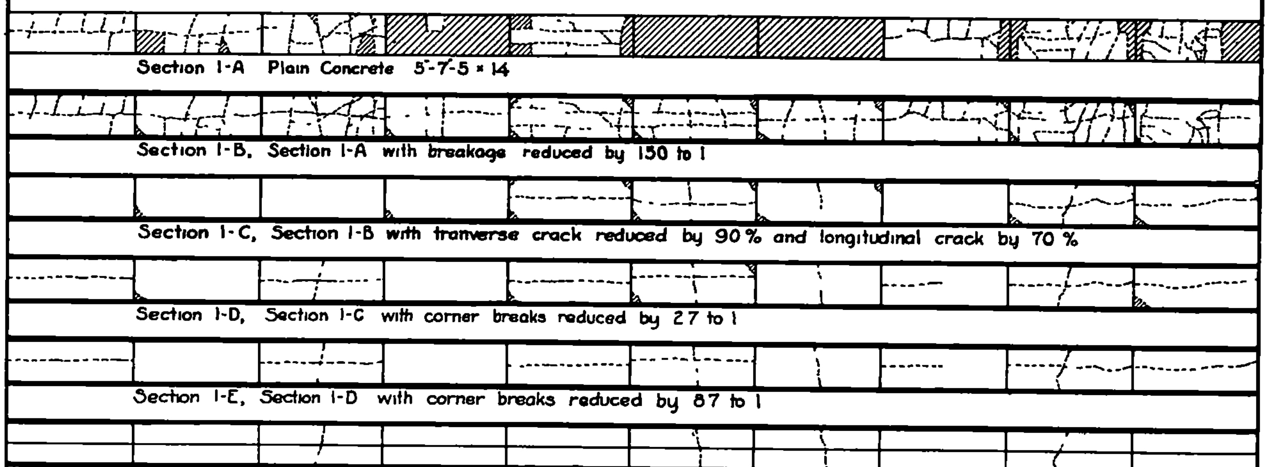
In Section 1-B it is assumed that 42 lb mesh has been added and that the resulting reduction in breakage (150 to 1) would be the same as was shown by comparison of the five-inch plain and mesh reinforced concrete sections in the Bates Road Tests (page 75)

In section 1-C transverse cracking is reduced by 90%, which reduction was shown for 42 lb mesh on the DeKalb Road (page 107), and the longitudinal cracking is reduced by 70% in accordance with the ratio indicated in the general comparisons (page 58)

In section 1-D the section is assumed to have been changed from 5-7-5 to 6-inch uniform thickness With this reduction in center thickness, the transverse cracks are increased 25% in accordance with Figure 40, page 60, and the longitudinal crack length is increased in accordance with Figure 32, page 50 But with change in edge thickness from 5 to 6 inches, corner breaks are reduced by 2 7 to 1 in agreement with roads in service (page 70)

In section 1-E, where the edge thickness is changed from 6 to 7 inches, another reduction in corner breaks (8 7 to 1) is shown in accordance with roads in service (page 70)

LEGEND FOR CHARTS ON PAGE 18



Section No	Cross - Section	Breakage Sq. Yds.	Long Cr Feet	Trans.Crs. No	Cor Brs No	Cost Per Mile - Dollars			
						Concrete	Steel	C Joint	Total
1 A		375	800	33	—	23190			23190
1-B&C	42# mesh	25	240	3	13	23190	1630		24820
1-D	42# mesh	9	400	4	5	21950	1630		23580
1-E	42# mesh	1	400	4	.6	22780	1630		24410
1-F	42# mesh; 6 · 2-0 · 4-0 · 4-6 · 2-0 · 6; 14-0	.1	0	4	6	22780	1630	900	25310

Figure D-1—Transformation from 5″–7″–5″ plain concrete slabs to reinforced 7″–6″–7″ center joint design with assumed corresponding change in condition and cost

Finally the center-joint is added in section 1-F

In this analysis no reduction in corner breaks was assumed for the mesh reinforcement and no reduction in transverse cracks was assumed for the 2-inch increase in edge thickness

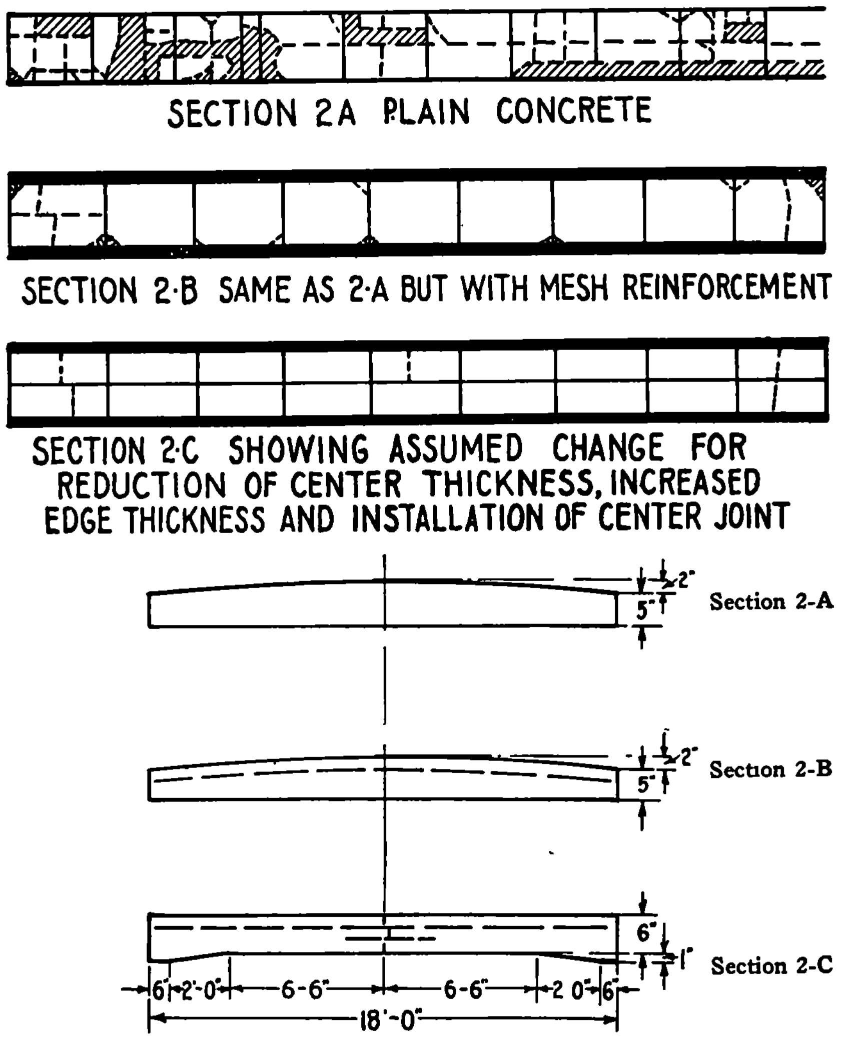


Figure D-2—Transformation from 5"–7"–5" plain concrete slabs to reinforced 7"–6"–7" center joint design with change in condition based only in part on assumptions

A second analysis is shown in Figure D-2, but differs from the first in that the reinforced length has been functioning in the same road with the plain section for 12 years, affording definite comparison Assumption is used only in change from the 5-7-5 to the 7-6-7 section

Section 2-A shows the condition of the plain 5-7-5 section, 18 feet wide

Section 2-B shows the condition of the comparable 5-7-5 slab, 18 feet wide, reinforced with mesh.

Section 2-C shows the condition assumed in accordance with roads in service (page 70), if the design were changed to 7-6-7 slab with center joint, with corresponding increase in crack length for decreased center thickness and corresponding decrease in corner breaks for increased edge thickness

The result from the transformation in Fig D-1, which it will be remembered was based entirely on assumptions, agrees very well with that shown in Fig D-2, which in the main is supported by a road in service This agreement indicates the practicability of the use of the data

In Fig D-1 is given also estimated costs at various stages in the transformation In this estimate the cost of concrete was assumed at $16 00 per cu yd, steel reinforcement at 5 cents per pound, and center-joint at $900 per mile No allowance was made for difference in cost of grading

The difference in costs of $2,120 per mile between sections 1-A and 1-F carries an annual interest (at 5 per cent) of $106 00, $45 00 of which is chargeable to the center joint The reader can judge if the relative conditions of sections 1-A and 1-F warrant this additional interest cost From a replacement standpoint alone the relative first costs of the two sections indicate that if the life of section 1-F is but 8 per cent greater than that of 1-A the change was justified. If the life of section 1-A is 20 years, section 1-F must last 21 6 years to justify its increased cost.

Experiment would determine if the result accomplished by constructed center joint could be secured more economically by the use of a longitudinal plane of weakness, and full width transverse reinforcement

If drainage, subgrade treatment, use of subbases or change of aggregate can effect the same benefits as were shown above through the changed design, and at less increase in cost, then resort to these mediums becomes economically justified However, until additional road surveys have been undertaken and completed, the relative values of aggregates, subgrade treatments and types of drainage can not be determined.

While this demonstration was made primarily to show the possibilities of utilizing survey data, the assumption used seem to be well based

PRESENTATION OF DATA

UNDESIRABLE CHARACTERISTICS OF PLAIN CONCRETE ROADS AND STREETS

Plain concrete surfaces in some instances:

1. **Have developed extensive cracking, excessive surface wear and, in isolated cases, general disintegration, because of a variety of conditions, including faulty aggregate, improper mix, inadequate curing, freezing, etc.**
2. **Have scaled.**
3. **Have developed longitudinal cracks.**
4. **Have developed transverse cracks.**
5. **Have developed raveling along crack edges.**
6. **Have developed unevenness of surface through separation of cracked slabs.**
7. **Have developed corner cracks.**
8. **Have developed broken areas.**

Roads conforming to statements 1 and 2 have been discarded as not being related to this discussion.

Charts 1, 2, 3 and 4, Figure 1, covering some 140 miles of road in six different states, support statements 3, 4, 7 and 8 These roads, some of which are described in Table 1, are given as representative for conditions of thickness, traffic and age encountered

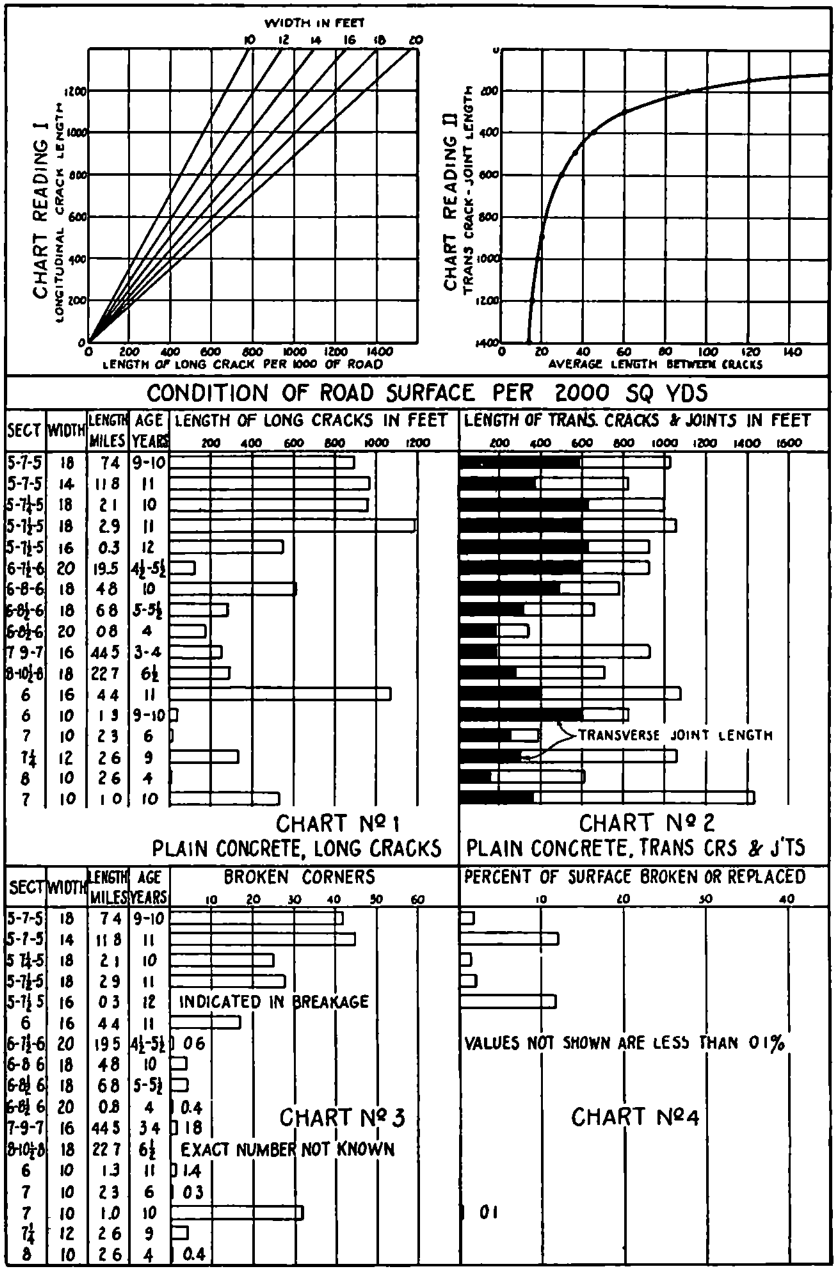
Examples of longitudinal cracking are shown in Figures 2, 3 and 4; transverse cracking, in Figures 5 and 6, raveling, in Figures 7, 8 and 9, separation of slabs, in Figures 10, 11 and 12, corner failures, in Figures 13, 14 and 15, and breakage, in Figures 16, 17 and 18 Representative conditions of the older 5-7-5 surfaces are shown by sketches in Figure 19.

UNDESIRABLE CHARACTERISTICS OF PLAIN CONCRETE ROADS AS INFLUENCED BY AGE, TRAFFIC, SUBGRADE AND AGGREGATE

Longitudinal cracks in some instances:

9. **Were not influenced by traffic.**
10. **Were influenced by subgrade.**

The Bates Road Tests furnished ample support for statement 9 in that the longitudinal crack length in concrete sections, base or surface, plain or reinforced, prior to loading was not appreciably increased by thousands of wheel loadings (2,500 to 12,000 pounds), which comprised both series of traffic tests In Fig 20, which shows crack length for several of the Bates sections before traffic, and



Charts Nº 1 and Nº 2:

SECT	WIDTH	LENGTH MILES	AGE YEARS
5-7-5	18	7 4	9-10
5-7-5	14	11 8	11
5-7½-5	18	2 1	10
5-7½-5	18	2.9	11
5-7½-5	16	0.3	12
6-7½-6	20	19.5	4½-5½
6-8-6	18	4 8	10
6-8½-6	18	6 8	5-5½
6-8½-6	20	0 8	4
7 9-7	16	44 5	3-4
8-10½-8	18	22 7	6½
6	16	4 4	11
6	10	1 3	9-10
7	10	2 3	6
7¼	12	2 6	9
8	10	2 6	4
7	10	1 0	10

Charts Nº 3 and Nº 4:

SECT	WIDTH	LENGTH MILES	AGE YEARS
5-7-5	18	7 4	9-10
5-7-5	14	11 8	11
5 7½-5	18	2 1	10
5-7½-5	18	2 9	11
5-7½ 5	16	0 3	12
6	16	4 4	11
6-7½-6	20	19 5	4½-5½
6-8 6	18	4 8	10
6-8½ 6	18	6 8	5-5½
6-8½ 6	20	0.8	4
7-9-7	16	44 5	3 4
8-10½-8	18	22 7	6½
6	10	1.3	11
7	10	2 3	6
7	10	1.0	10
7¼	12	2 6	9
8	10	2 6	4

Figure 1—Condition of various concrete roads in service
Chart 1. Longitudinal crack length
Chart 2 Transverse crack length
Chart 3. Corner cracks
Chart 4. Breakage

TABLE 1—List of Concrete Surfaces Which Furnished General Information But No Comparisons

Spec No	State	County	Town	Name	Year Cons	Mix	Length	Wdth	Sect	Joint Spac	Reinforcement
1	Pennsylvania	Cumberland	Carlisle	Hanover Ave and Court House and others	1915	1 2 3	1,020	15–23	6	30	None
2	Pennsylvania	Lancaster	Manheim	W Stiegle, Grant and Prussian Sts	15–16	1 2 3	5,053	30–40	6	35	Mesh
3	Pennsylvania	Northhampton	Nazareth	Easton Road	1913		1,502	16	5–7½–5	25–33	None
4	Pennsylvania	Northhampton	Lehigh	Allentown-Easton Road	15–16	1 2 3	31,600	16	6–8–6	39–5	Mesh
5	Pennsylvania	Delaware	Lansdowne	Plumstead Ave	1915	1–2–3	990	24–30	6–8–6	30	Mesh
6	Pennsylvania	Montgomery	Merion	Highland Ave	1913		700	24	6–8–6	25	Mesh
7	Pennsylvania	Philadelphia	Philadelphia	Monument Ave	1914	1–2–3	2,111	18	5–7–5	30	None
8	Pennsylvania	Montgomery	Haverford	Haverford Rd	1913		843	16	5	25	None
9	Pennsylvania	Montgomery	Ardmore	Greenfield Ave	1913		1,419	16	5–7–5	25	None
10	Pennsylvania	Philadelphia	Philadelphia	Oxford Pike	14–15	1 2 3	11,250	18	5–7½–5		None
11	Pennsylvania	Montgomery	Marberth	Wynnewood Ave	1916	1 2 3	1,756	21	5–7–5	36	Mesh
12	Pennsylvania	Montgomery	Ambler	Butler Turnpike	1915	1 2 4	550	18	5–7–5	20	None
13	Pennsylvania	Montgomery	Cynwid	Levering Mill Road	1913	1 2 4	2,100	16	5–7–5	30	None
14	Pennsylvania	Delaware	Media	Providence Road	1916	1 2 4	3,100	18	5–7–5	33	Mesh
15	Pennsylvania	Montgomery	Moreland	Route 198, Sec 4, Hunt Vall Sta to City Line Ave	1913	1 2 4	14,317	16	6		None
16	Pennsylvania	Del & Chester	Phila -Balto	Route 131, Secs 2, 4, 5, 7, 8, 9	1916	1 2 3	115285	16	5–7–5	38 5	Mesh
17	Pennsylvania	Allegheny	Pittsburg	Washington Blvd	1923						Mesh
18	Pennsylvania	Allegheny	Pittsburg	Bankville Road			7,400				Mesh
19	Pennsylvania	Philadelphia	Philadelphia	N E Blvd							Mesh
20	Massachusetts	Bristol	Dartmouth	State Highway	1916	1 1½ 3	6,600	18	5–7–5	30	None
21	Massachusetts	Bristol	Norton	State Highway	1916	1 1½ 3	17,000	18	5–7–5	30	None
22	Massachusetts	Hampden	N Wilbraham	State Highway	1916	1 1½ 3	8,900	18	5–7–5	30	None
23	Massachusetts	Plymouth	Matteposette	State Highway	1916	1 1½ 3	6,100	18	5–7–5	n &n	None
24	Massachusetts	Middlesex	S Chelmsford	State Highway	1915	1 1½ 3	5,200	18	6–8–6	n &n	None
25	Massachusetts	Essex	N Andover	State Highway	1916	1 1½ 3	6,300	18	6–8–6	n &n 75–125	None
26	Massachusetts	Norfolk	Randolf	Randolf-Avon	1915	1 1½ 3	9,500	18	6–8–6	30	None
27	Massachusetts	Worcester	Northridge	State Highway	1915	1 1½ 3	4,300	18	6–8–6	30	None
28	Connecticut	Hartford	Windsor	Windsor Road, Hart Spring	1914	1 2 4	15,486	18	5–7½–5	30	None
29	Connecticut	Hartford	Rocky Hill	Rocky Hill	1915	1 2 4	1,200	18	6–8¼–6	30	Mesh
30	Connecticut	Litchfield	Winsted Torrington	Winsted-Torrington	1917	1 2 4	10,560	16	6–8–6	30	Mesh
31	Connecticut	New London	Groton	Thames St	1916	1 2 4	17,200	16	6–8–6	30–75	Mesh
32	Connecticut	New London	Stonington Mystic	Stonington-Mystic Road	1915	1 2 4	23,760	16–20	6–8¼–6	25	Mesh
33	Connecticut	New Haven	Mildale Chesire	Mildale Chesire	15–16	1 2 4	5,280 21,120	16	6–8–6	30	Mesh Mesh
34	Connecticut	New Haven	Waterbury	Watertown Road	1916	1 2 4	3,500	16	6–8–6	30	Mesh
35	Connecticut	New Haven	Orange	Derby Turnpike	1916	1 2 4	11,980	16	6–8¼–6	40	Mesh
36	Delaware	Georgetown		Street	1912	1 2 3½	1,700	18	6	20	None
37	Maryland	Cecil		Perryville to Principio	1914	1 2 4	17,000	14	5–7–5	30–60	None
38	Maryland	Cecil		Northeast-Bacon-Hill	1914	1 2 4	5,544	14	5–7–5	30–60	None
39	Maryland	Cecil		Bacon Hill-Elkton-Contr	1914	1 2 4	9,293	14	5–7–5		None

TABLE 1—List of Concrete Surfaces Which Furnished General Information But No Comparisons—*Continued*

Spec No	State	County	Town	Name	Year Cons	Mix	Length	Wdth	Sect	Joint Spec	Rein-force-ment
40	Maryland	Anne Arundel		Annapolis to Edgewater Contr	1914	1 2 4	21,806	14–16	5–7–5	30–60	None
41	Maryland	Cecil		Conowingo-Oakwood Contr	1914	1 2 4	8,818	14	5–7–5		None
42	New Jersey			Metuchen-Menlo Park, Route 1, Section 1	1918	1 1½ 3	9,609	18	8 10½–8	52	None
43	New Jersey			Rahway, Route 1, Section 8	1920	1 1½ 3	4,858	29	8–10–8	52	None
44	New Jersey			Menlo Park-Rahway, Route 1, Section 2	1918	1 2 3	18,744	20	8–10½–8		None
45	New Jersey			Robbinsville-Windsor, Route 1, Section 3	1919	1 2 3	13,464	18	8–10½–8	81	None
46	New Jersey			Mavesinlo Riv -Conover Lane, Route 4, Section 1 & 1A	1818 1819	1 1½ 3	20,698	18	6–8½–6	42	None
47	New Jersey			Middletown-Betsy Ross Farm, Route 4, Section 2	1919	1 2 3	15,418	18	6–8½–6	91	None
48	New Jersey			Broadway-Scott Ave , Route 4, Section 3	1920	1 2 3	4,382	20	6–8½–6	100	None
49	New Jersey			Laurelton-Lakewood, Route 4, Section 14	1922	1 2 4	20,710	20	8	75	Bars
50	New Jersey			Central Ave -Lakewood, Route 4, Section 15	1922	1 2 4	13,517	28–50	8	60	Bars
51	New Jersey			Pt Pleasant-Laurelton, Route 4, Section 21	1923	1 1¾ 3½	24,820	20	8	50	Bars
52	New Jersey			Kingston-13 Mile Run, Route 13, Section 1	1918	1 2 3	19,378	18	8–10½–8	57	None
53	New Jersey			Ten Mile Run-Three Mile Run, Route 13, Section 2	1918	1 2 3	11,933	18	8–10½–8	77	None
54	New Jersey			Three Mile Run-New Brunswick, Route 13, Section 3	1919	1 2 3	20,275	18	8–10½–8	64	None
55	New Jersey			Princeton-Kingston, Route 13, Section 4	1920	1 2 3	9,240	18	8–10½–8	100	None
56	New Jersey			Princeton Ave -Trenton							
57	New Jersey			Washington's Crossing							None
58	New Jersey			West Portal-Perryville, Route 9, Section 1 & 2	1921	1 2 4	22,700	20–30	8		Bars
59	New Jersey			Dunellen, Route 9, Section 4	1921	1 2 4	5,597	40–42	8	80	Bars

NOTE —Many miles of center joint roads inspected in New Jersey, New York, Massachusetts, Connecticut, Pennsylvania, and Illinois were not listed

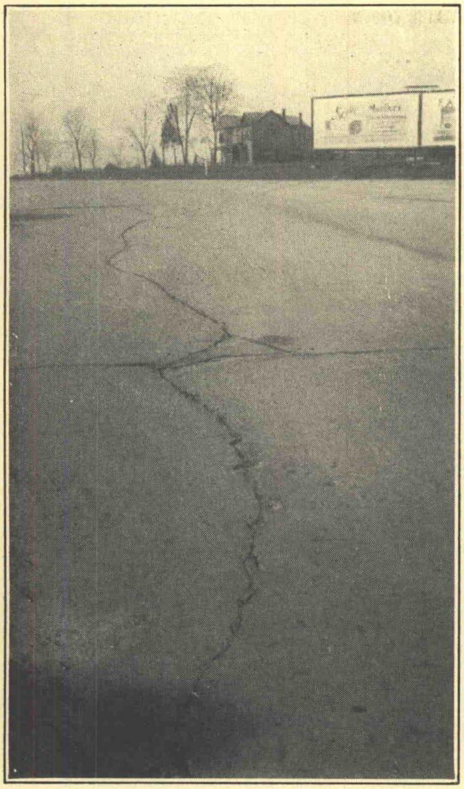


Figure 2—Longitudinal crack in 8-10½-8 section, Road No. 54 between Three Mile Run and New Brunswick, N. J.

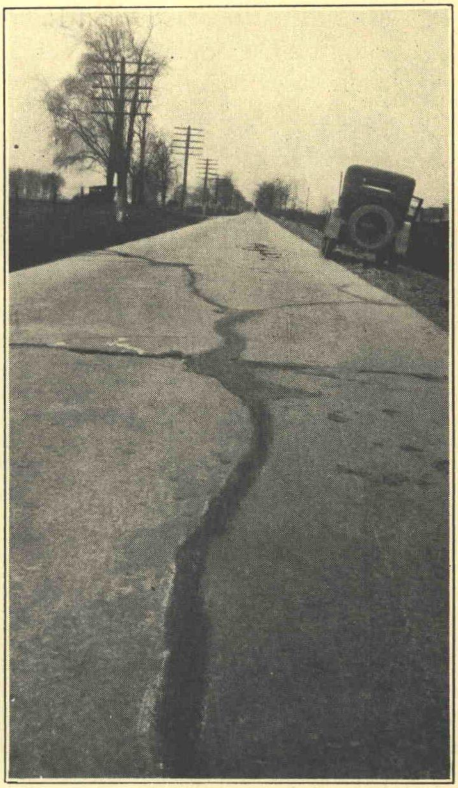


Figure 3—Longitudinal crack in 6-inch section, Road No. 252, Huron Co., Ohio

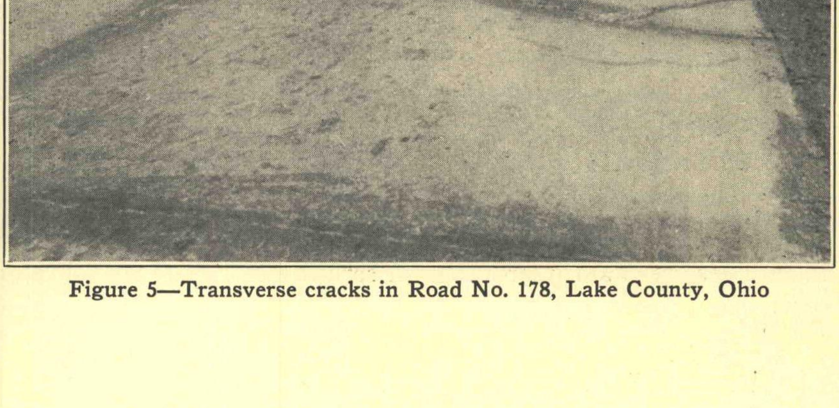


Figure 5—Transverse cracks in Road No. 178, Lake County, Ohio

after the 6,500, 8,000 and 12,000 pound tests, it can be seen that the longitudinal crack length of 2,282 feet which occurred before the traffic tests was increased only 30 feet, or 1.4 per cent, during the load applications.

In isolated cases heavy loads have caused longitudinal cracks both in narrow sections and at the quarter points in wide slabs. Such cracks were the exception when thickness was more than 6″ and indicated breakage of road if overloading was continued. The last road shown in Chart 1, Figure 1 (7 inches thick by 10 feet wide), was one of these exceptions, its condition resulting probably from a combination of traffic and mix or curing troubles. Such a condition is shown in Figure 21.

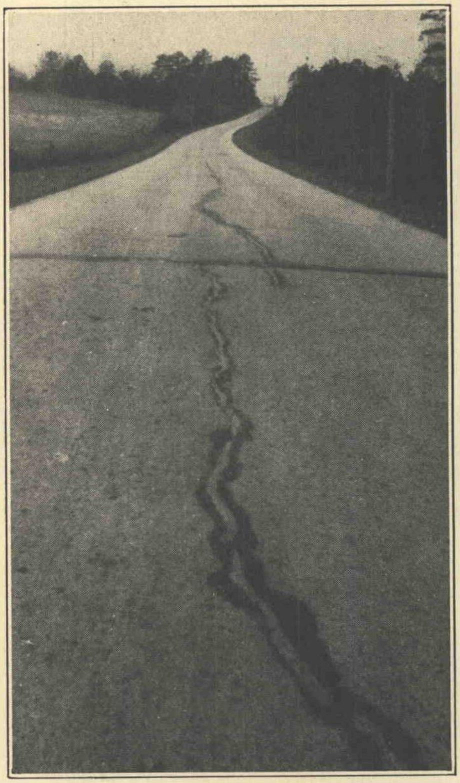


Figure 4—Longitudinal crack in 7-inch section, Road No. 107-A, Georgia

With five inch center thickness both stress measurements (see Harrisburg Test Road Report by L. W. Teller) and roads in service (center joint construction) indicated that cracks of any kind could be caused by traffic.

There was plenty of evidence to warrant statement 10. In some cases, notably in Georgia, longitudinal cracks were found only on fills, while in other states they predominated in cuts. Opportunity was not given for a detailed study of the subgrade conditions influencing this type of cracking.

Transverse cracks.

11. When more than 25 feet apart were generally caused by contraction.

12. When less than 20 feet apart were probably caused by heavy wheel loads.

The development of cracks, both with and without load in the Bates Tests, was most interesting. A scrutiny of Figure 20 indicates that:

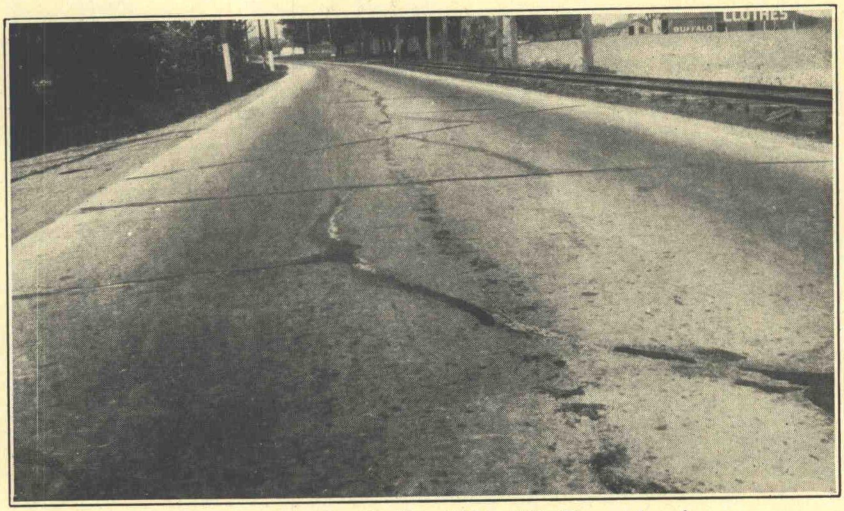


Figure 6—Cracking in Road No. 193, Pennsylvania

A. In full width sections, transverse crack occurring in the absence of and with traffic was slightly reduced by increased slab thickness. The average length of slab prior to traffic was about 34 feet and after both series of loading was about 16 feet.

B. In both full width and also center joint slabs (later with transverse joints spaced 25 feet apart) 6 to 9 inches thick, transverse crack existing prior to traffic tests was not appreciably increased by wheel loads of 6,500 pounds and less.

C. In both full width and center joint slabs a considerable increase in transverse cracking (280 per cent for cracks only) developed when the wheel loading was increased from 6,500 to 8,000 pounds. This increase in transverse cracking was independent of slab thickness occurring at the same time in the 6, 7, 8, and 9 inch sections.

D. In both full width and center joint slabs transverse crack was not appreciably increased by increasing wheel loads from 8,000 to 12,000 pounds.

E. The 6 inch reinforced sections (No. 45 and No. 46 with ⅝ inch bars—6 inches from edges) center joint construction, varied from the plain concrete in that an increase in transverse crack length accompanied increase of wheel load from 8,000 to 12,000 pounds. At the end of the tests these reinforced 6 inch sections had less crack than the 8 inch and slightly more than the 7 inch plain concrete sections.

Figure 7—Raveling of crack 8-10½-8 section, Road No. 44, New Jersey

Figure 8—Raveling of crack 7-9-7 section, Road No. 1, C. H. 164-F, Shelby Co., Ohio

Figure 9—Raveling of crack 6-8-6 section, Road No. 193, Pennsylvania

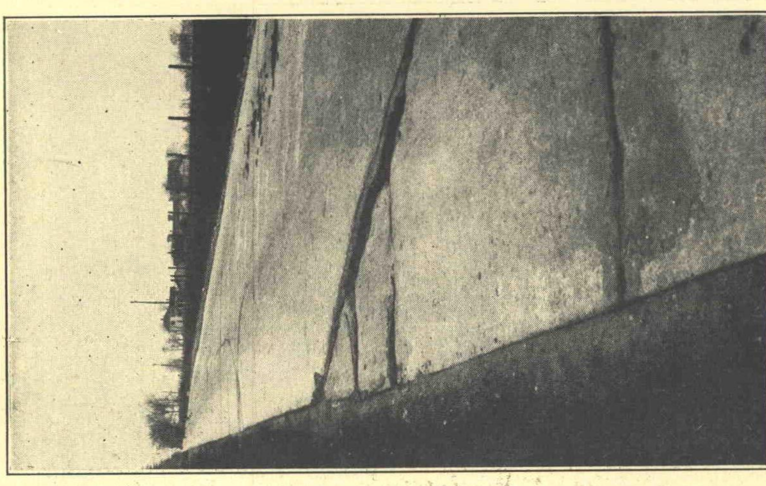


Figure 10—Separation of slabs. Road No. 252, Huron Co., Ohio

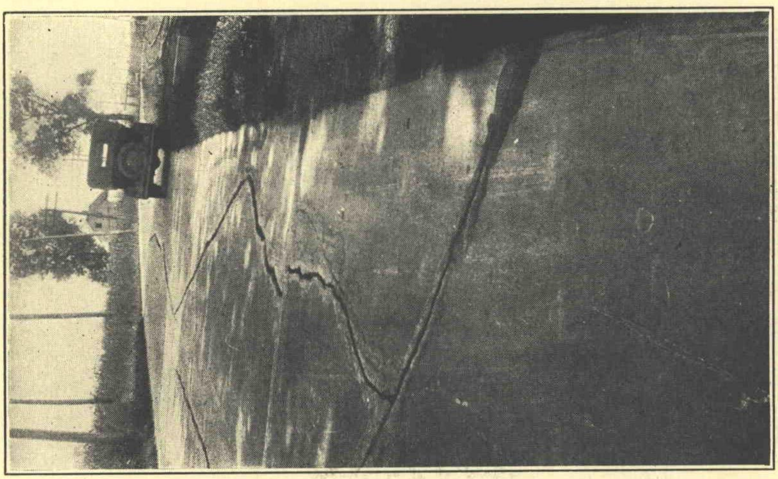


Figure 11—Separation of slabs 7 inch section, St. Clair Co., Michigan

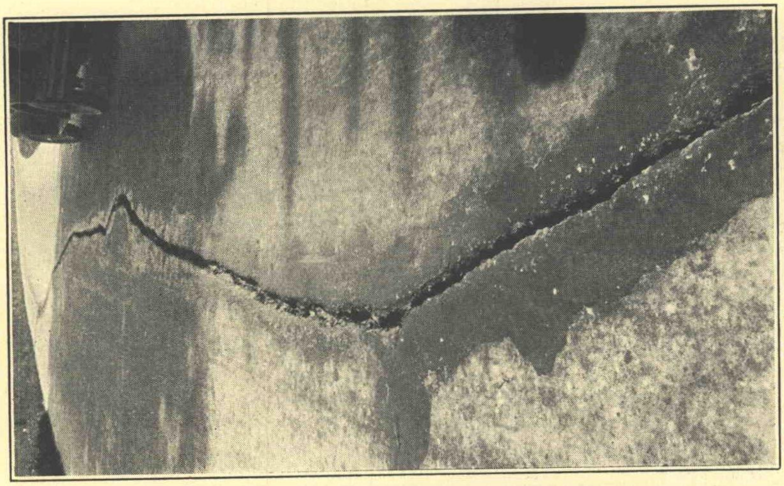


Figure 12—Separation of slabs 7 inch section, St. Clair Co., Michigan

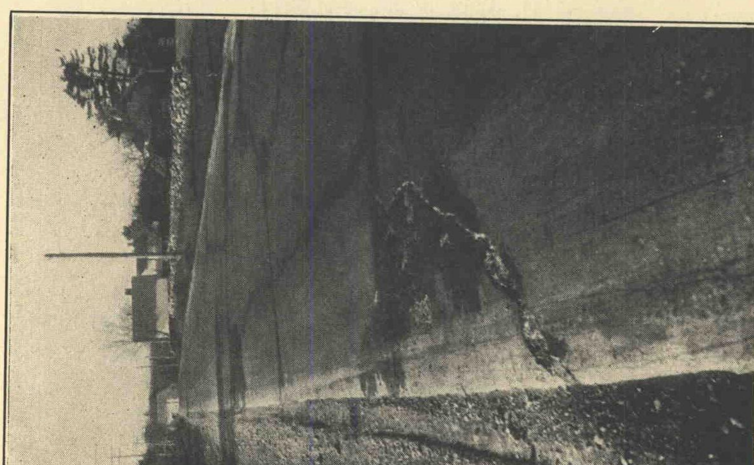


Figure 13—Corner breaks, Road No. 21, Town of Norton, Mass.

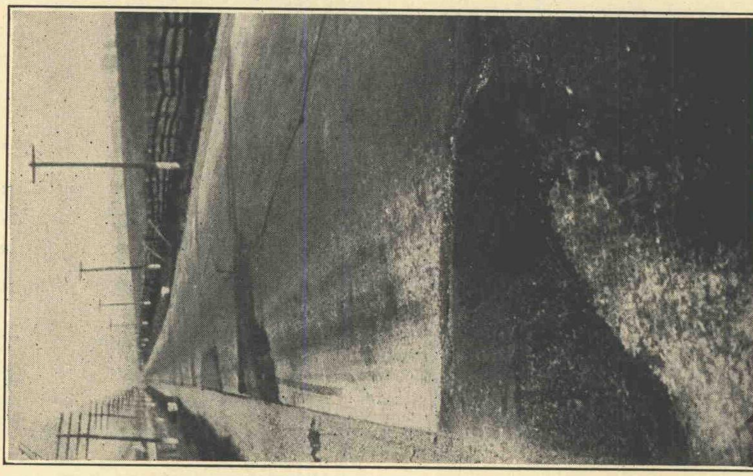


Figure 14—Corner breaks Road No. 37, Perryville to Principio, Md.

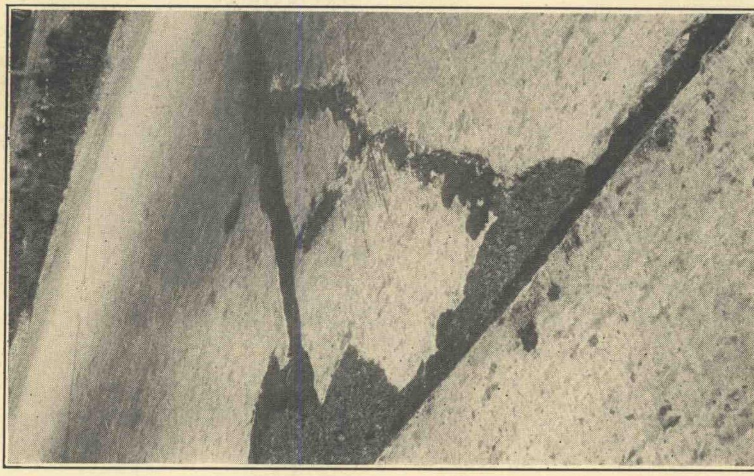


Figure 15—Corner break along center joint, Road No. 101, Conn.

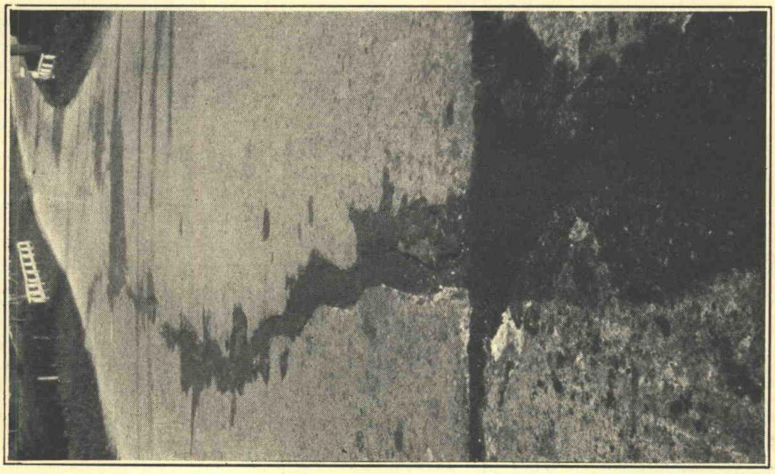


Figure 16—Breakage in Road No. 143, New York

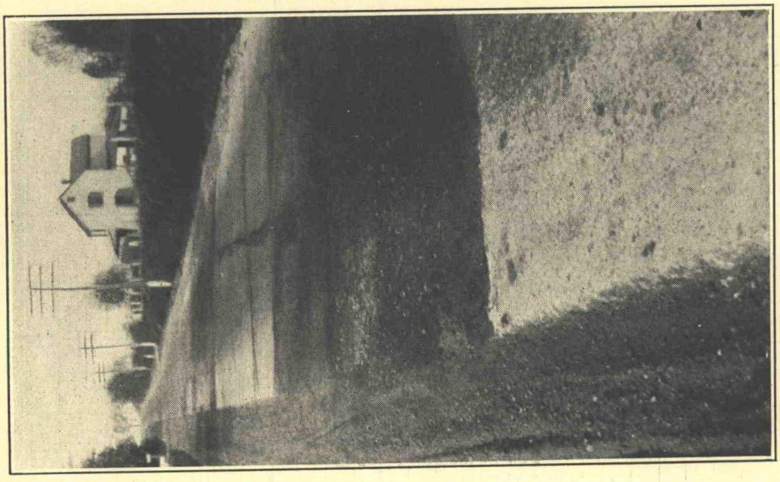


Figure 17—Breakage in Road No. 39, Maryland

Figure 18—Breakage in Road No. 253, Ohio

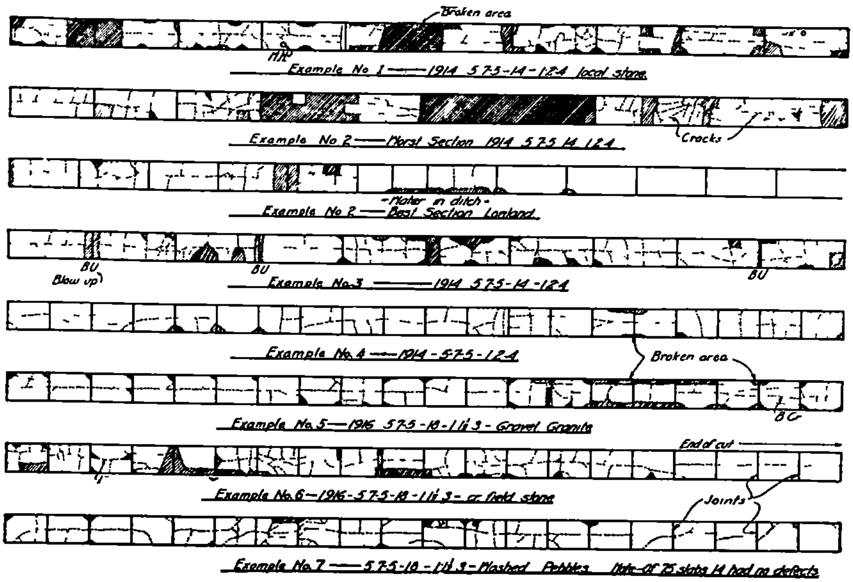


Figure 19—Condition sketches of the older 5-7-5 section roads

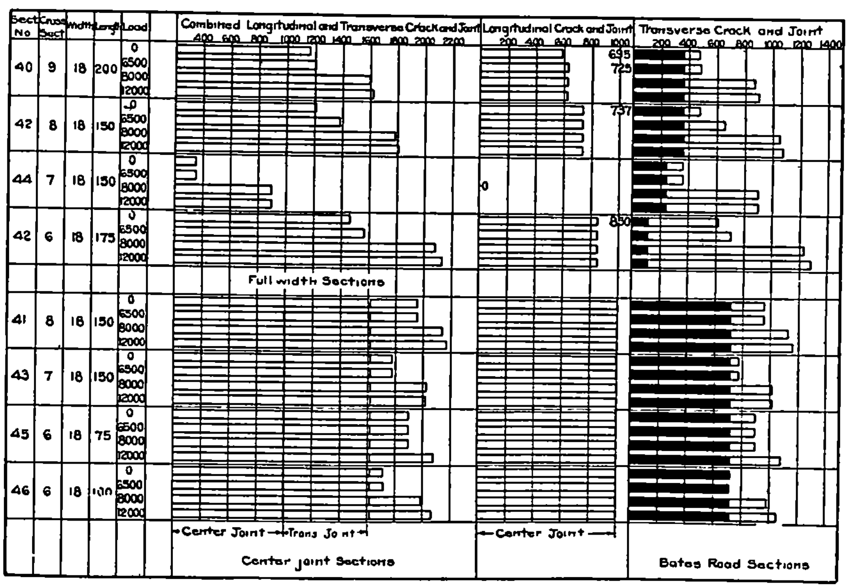


Figure 20—Condition of various Bates Road Sections before test and after the 6500, 8000 and 12,000 pound wheel loadings

F The average slab length of center joint sections No 41 and No 43 (8 and 7 inches thick) at the end of test was about 16 feet This agrees very closely with the Waterbury-Meriden, Conn , road (8 inch thick, center joint and transverse joints 25 to 35 feet), in which the average slab length was 18 3 feet

G The center joint sections with longitudinal edge bars painted and oiled to prevent bond with the concrete were remarkably free from the transverse cracks at the end of the test These slabs were not subjected to the first series of tests during which the other sections developed the transverse cracking

That good subgrade did not prevent traffic cracks was shown by the Gulf Beach Road, laid on excellent sand base, in Escambia County, Florida, and on which heavy loading of short duration broke 30 and 50 foot slabs into 15 and 16 foot lengths

Slab lengths of roads shown in Chart 2, Figure 1, varied from 15 to 22 feet Figure 22 shows excessive transverse cracking in narrow slabs laid on peat bog in Ohio

*Combined length of longitudinal and transverse cracks in slabs more than 10 feet wide*s

13. **By an interrelationship or balancing, under certain conditions, varied more consistently with influencing factors than did either one separately.**
14. **Was influenced greatly by character of aggregate.**
15. **Increased with years of service until a certain age, after which the rate of cracking was considerably reduced.**
16. **When caused by traffic alone constituted a small percentage of total crack and joint length in the road.**
17. **Was influenced by subgrade.**

The balancing or compensating of longitudinal and tranverse cracks was shown in many instances, several examples of which were

A. Greenbay Experimental Road, Cook County, Ill

B Sections of Milwaukee County, Wis , roads

Crack lengths of the Greenbay Road are shown as Spec No 112 and those for the Milwaukee County sections as Nos 280, 281, 282 and 285 in Chart 5, Figure 23 In each group it will be noted that while considerable variation existed in both transverse or longitudinal crack length, their sums agreed fairly well This is illustrated by sketch of the Greenbay Road shown in Fig 24 In section 1 the cracking was primarily transverse, while in section 3 it

Figure 21—Cracking and breakage in narrow road No. 132-T, Ohio

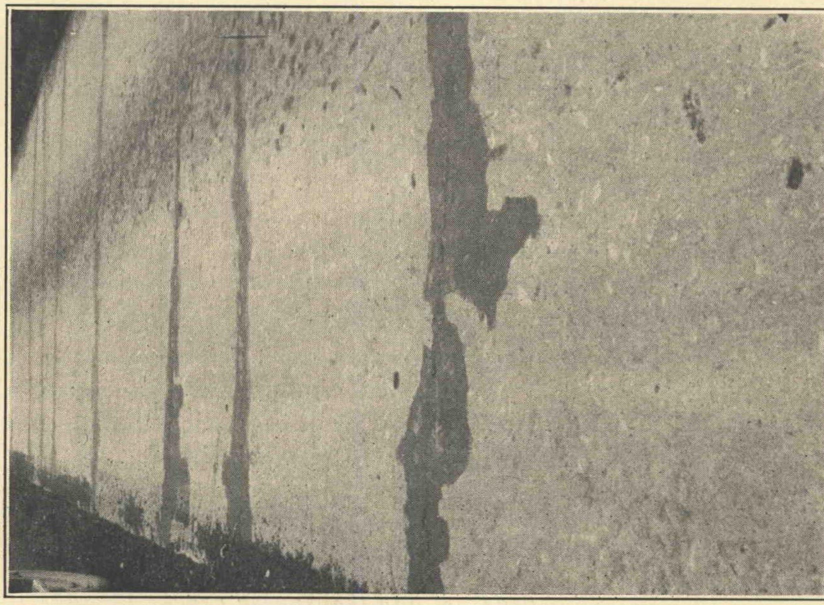


Figure 22—Excessive transverse cracking in narrow slab laid on peat bog subgrade. (Celeryville Road No. 88, Ohio.)

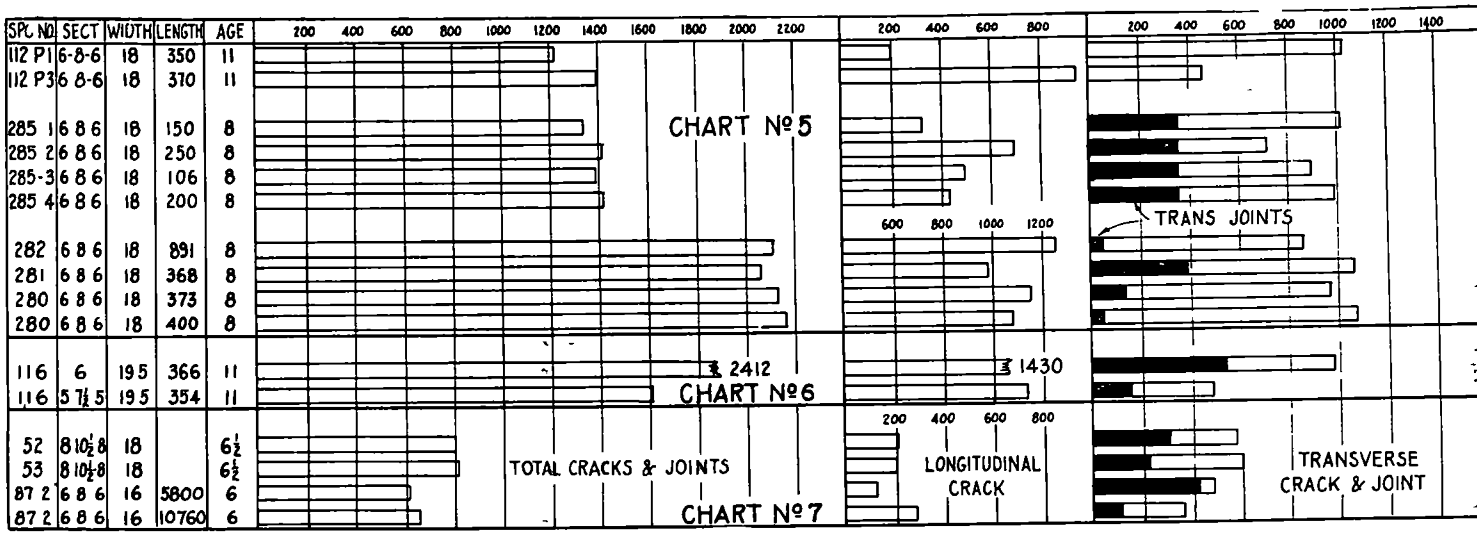


Figure 23—Chart 5. Balancing of transverse and longitudinal cracks in Green Bay Road (No 112) and Milwaukee County, Wis., Roads (280-1-2-5)
Chart 6. Comparative crack length in 6 and 7½ inch centers, North Andover, Mass , Road
Chart 7 Examples in which joint spacing had no appreciable effect on total crack length

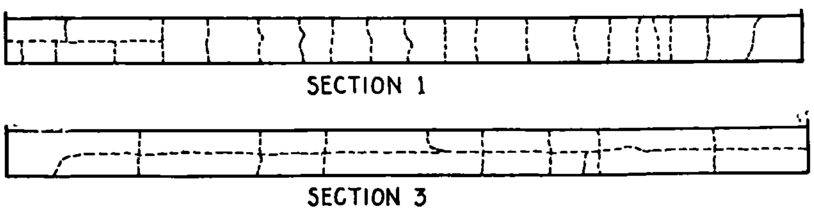


Figure 24—Sketch of portion of Green Bay Road, Cook Co , Ill., showing balancing of transverse and longitudinal cracks

was longitudinal, but, as shown by Chart 5, their totals showed but little variation

As regards statement 14, it has been evident that certain types of gravels develop excessive transverse cracking This is not true of all gravels A number of definite comparisons encountered during the survey substantiate F H Jackson's findings on the National Pike,[1] that sections containing certain types of gravel aggregate developed many more cracks than did those which employed certain types of crushed stone Comparisons affording opportunity for study of various aggregates were found in abundance in almost every state from Massachusetts to Iowa Since such an investigation is a large problem in itself, discussion of aggregates is not given in this report except as concerns reinforcement.

Abundant evidence supports statement 15 Curve 1, Fig 25, shows variation in cracking with age in one road, while Curve 1, Fig 25-A, shows the average crack length of ten different roads in the State of Washington having total length of 50 miles Curves for several hundreds of miles of Washington Roads are given in the accompanying report of E R Hoffman (Fig 95) and for a considerable mileage of 5-7-5 roads in Pennsylvania in supplemental report by P M Tebbs (Fig 89) The age at which rate of cracking changed was variable The consistency between the points and the curves, coupled with the fact that a great number of roads subjected to various conditions were used, warrants the statement that in slabs of the same design, cracking was influenced more by age than by traffic or subgrade Traffic and subgrade were both influencing factors, but were not predominant

Referring again to the Bates sections, Figure 20, it is readily seen that the length of constructed joint, combined with crack existing before traffic, was much greater than that produced by wheel loads This was true despite the fact that but fifteen months elapsed during which cracks could form before the traffic tests This figure indicates also that a wide range of wheel loads could be carried without appreciable change in cracking

That subgrade influenced cracking was evidenced by the minimum number of defects shown by several roads laid on certain natural sands, sands and gravels, and old roadbed of ample width The roads were

A Road in Georgetown, Delaware, 6″x18′—joint spacing 20′—laid on natural sand and gravel subgrade in 1912—no cracks or breaks

[1] Condition of the Ohio Post Road after Ten Years Under Traffic By F H Jackson Public Roads, Vol 6, No 4 June, 1925

B Sections 20 to 28, Coleman DuPont Road, Delaware, 5-7-5x14′ joint spacing about 150′—laid in 1915, on same subgrade as Georgetown Road—exceptionally few transverse or longitudinal cracks—see comparison No 104, Fig 33

C Portion of S Glens Falls-Gansevort Road, N Y , 4¾-6¾-4¾x16′—joint spacing 30′ laid in 1915 on pure sand subgrade—almost entirely free from cracks of any kind An adjacent portion of this road laid in a cut on clay subgrade

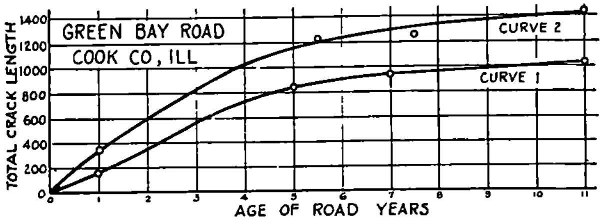


Figure 25—Development of crack Green Bay Road. Curve 1 plain concrete, Curve 2, reinforced concrete

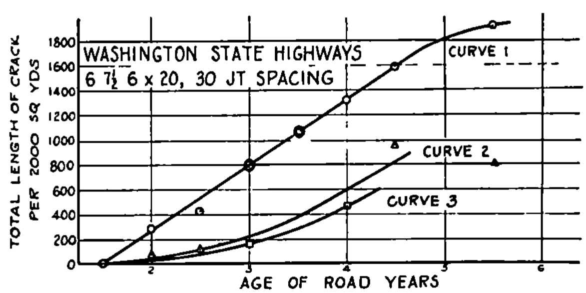


Figure 25-A—Development of crack in Washington State Highways Curve 1 plain concrete, Curves 2 and 3 reinforced sections

had completely broken up and was replaced with bituminous maintenance A sketch showing the condition of another portion of this road laid on clay subgrade is shown in Fig 75, page 96

D. Road in Clinton, Conn —5-7-5x18′—joint spacing 25′, laid in 1912 on old stone roadbed—free from cracks

No other subgrades, natural or artificial, encountered during the survey, afforded such exceptional benefits to relatively thin slabs Nor were these benefits found in all cases of natural sand subgrades

While an attempt to give definte information on subgrade influence will not be made, it was indicated, in some cases, that slabs laid on old roadbed and on rolled stone base cracked before slabs laid on a softer subgrade, but which had uniformity of support Dif-

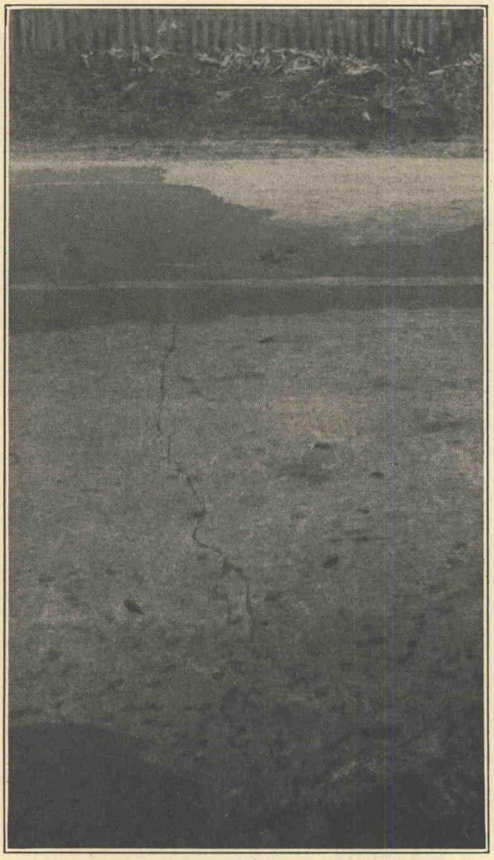


Figure 26—Transverse crack in road No. 60, New Jersey, showing absence of raveling in reinforced slab

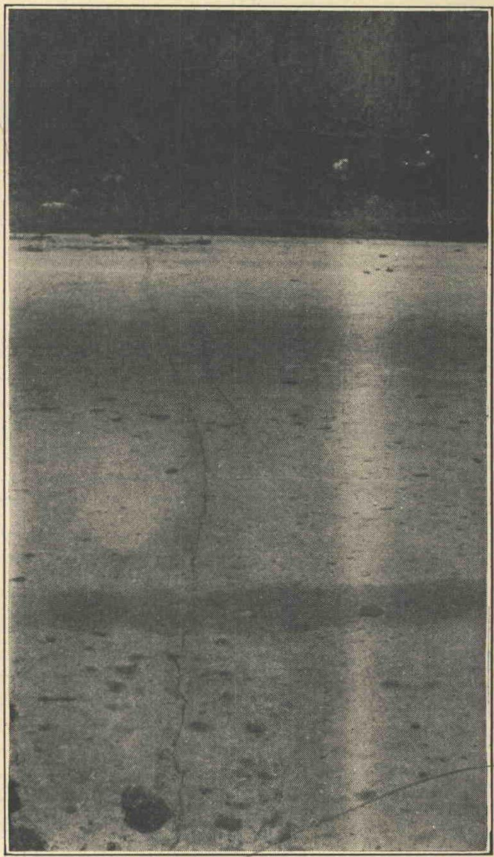


Figure 27—Transverse crack in Road No. 192 Penna., showing absence of raveling in reinforced slab

ference in cracking in cuts and fills also was apparent and this was probably due to difference in drainage. In one instance, in Milwaukee County, Wis., the ratio of crack length in fills and cuts was 2.2 to 1.

A very marked reduction in crack length accompanying the use of broken stone drains (2 feet x 3 feet) placed under the side edges of the pavement was noted between Stations 114 and 120 on the North Andover, Mass., Demonstration Road. Reductions also were reported by V. R. Burton as accompanying drained gravel subbase in Michigan.

Raveling of joint and crack edges:

18. Was caused primarily by a combination of friction and movement between slabs.

19. Was influenced by rubber-tired traffic only when wheel loads caused vertical movement of slabs.

20. Was influenced by properties of concrete.

That raveling was caused primarily by a movement between slabs was evidenced by the fact that when such movement was prevented by reinforcement, raveling was considerably reduced and in many instances completely eliminated. Figures 26 and 27 show this absence of raveling in reinforced slabs.

That raveling was not caused by abrasion from motor vehicle wheels was shown by several factors:

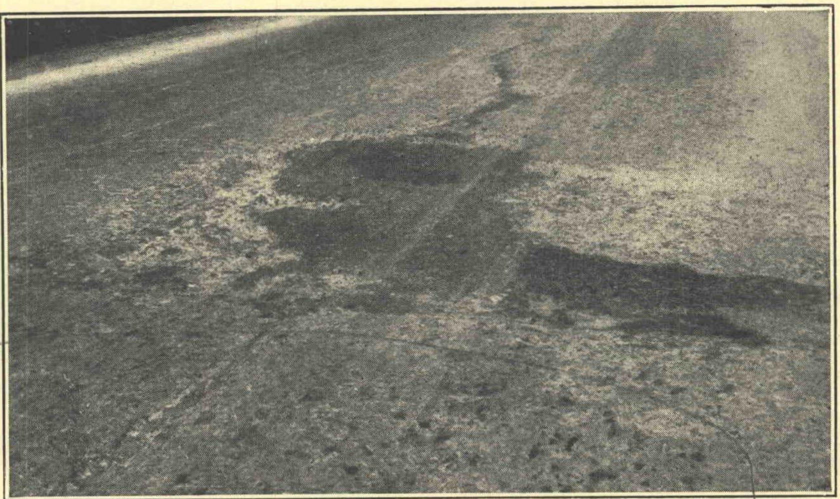


Figure 28—Raveling and scaling along crack and joint, Road No. 187, Pa.

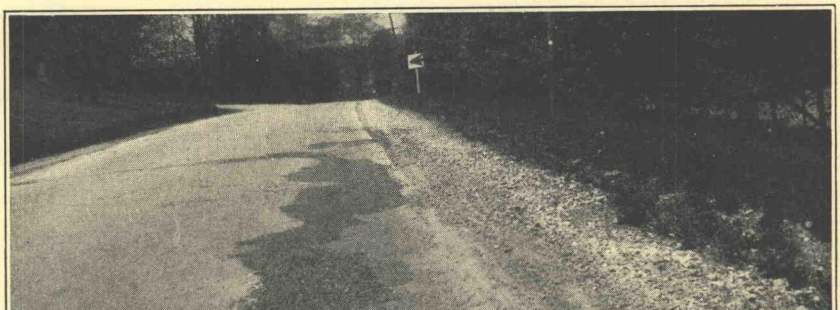


Figure 29—Progressive edge breakage following corner failure. Road 133, N. Y.

A It occurred uniformly across the slab and not only in the wheel tracks

B Abrasion from wheels equipped with chains, as indicated by the tests at Arlington, consisted of fairly smooth wearing down of the aggregate with the grout and was not a breaking out of the aggregate as found ordinarily in roads

Just what properties in concrete influenced raveling were not determined. It was noted, however, that surfaces which had scaled or indicated surface wear, showed increased raveling This type of surface is shown in Figure 28

Unevenness of surface resulting from separation of cracked slabs:

21. Was considerably less on subgrades of high supporting value, such as old roadbed, rolled stone base or natural sands and gravels than on clays and loams.

Corner cracks other than those caused by faulty construction joints:

22. Were caused primarily by wheel loads.

Breakage in plain concrete surfaces other than the shattering and blowups caused by expansion:

23. Was caused primarily by traffic, developing generally from corner breaks.

24. Occurred in less amount on hard subgrades or rolled stone macadam base than on clays.

25. Was not reduced by certain types of undrained stone, slag and gravel subbases.

26. Was increased by any type of maintenance which caused unevenness of surface.

It is believed that no support need be stated for conclusion 23 Figure 29 illustrates progressive edge breakage

The remarkable resistance to breakage shown by 4 inch plain concrete, Bates Road Section, on 6 to 8 inch macadam subbase, demonstrates statement number 24. It is recalled, however, that the first corner cracks in the test occurred in this section

A comparison of the best and worst sections in the Elkton-Bacon Hill Road, Maryland (Example No 2, Figure 19), shows the influence of subgrade on breakage The worst section was in a Susquehanna clay cut, while the best section was on a slight fill In this latter it will be noted that edge breakage occurred at the point where a little water remained in the ditch This condition was typical of practically every edge break in New York State Highways 5546 and 1066 The bottoms of the ditches were 18 to 24 inches below the pavement and well maintained, but adjacent to each sur-

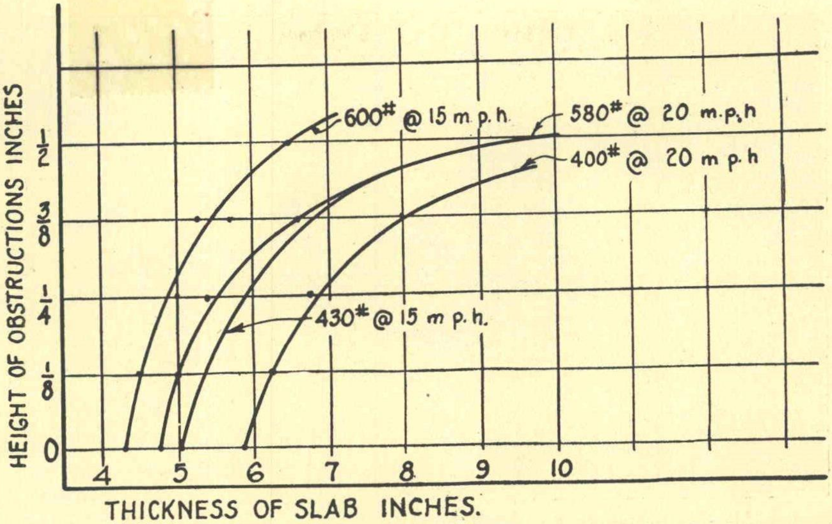


Figure 30—Effect of road roughness on indicated stress in the bottom of the slab

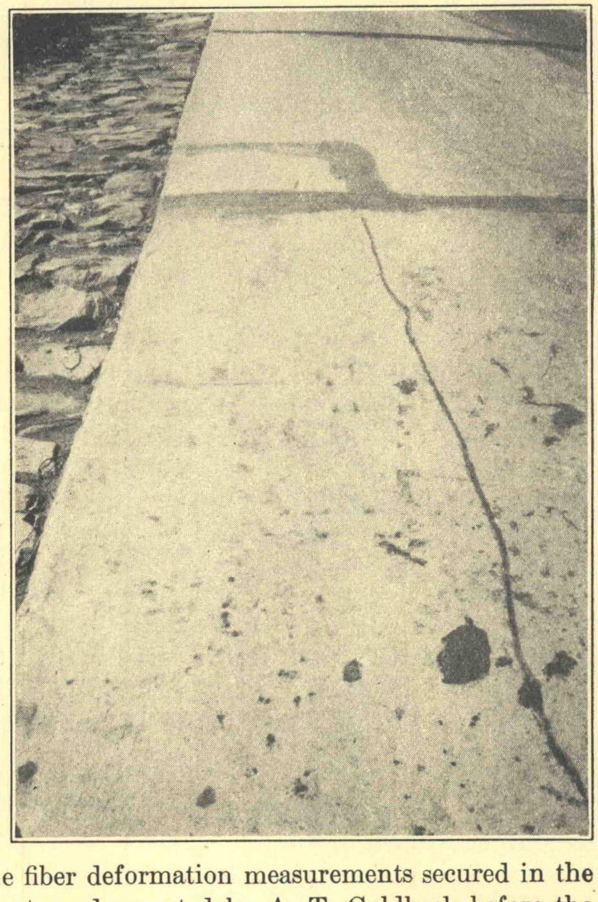


Figure 30-A — Replacement on State Highway Route 131, Penna. This type of repair causes no unevenness or additional impact. The dividing line between the old and new concrete was hardly discernible.

face break the ditches contained either a very slight amount of water or soil in very moist condition.

Unevenness of surface, resulting from either improper maintenance or settlement of slabs, caused increased impacts and thus produced additional breakage. This was shown in numerous cases. If the fiber deformation measurements secured in the Arlington Experiments and reported by A. T. Goldbeck before the

Figure 31—Maintenance on Road No. 108-DeKalb, Sycamore, Ill. Preparation for replacing corner failure with concrete

American Road Builders' Association, 1923, can be taken as a criterion, it is indicated in Figure 30 that a 5,000 pound wheel load, moving at 20 miles per hour, produced about the same stress in a 10 inch slab with ½ inch unevenness as in a 6 inch smooth slab. Or that ¼ inch surface variation a 7 inch slab had the same resistance as a smooth 6 inch slab. Thus any medium which reduced unevenness by ¼ inch added 1 inch effective resistance to the slab. Apparently the type of maintenance shown in Figure 30-A caused no increased impacts. Figure 31 shows preparation for this type of replacement.

Support for statement 25 was somewhat limited.

Sections of New York State Highways 5546, 1216 and 1214 on subbases, showed, in some cases, more breakage than sections laid directly on soil. This coincides with the excessive breakage in Section A—Pittsburgh Test Road (gravel subbase) and the higher deformation measurements shown by sections laid on cinder and gravel subbases, Harrisburg, Pa., Test Road, and reported by L. W. Teller. Table 6 shows relative cracking in sections with and without subbase.

UNDESIRABLE CHARACTERISTICS OF CONCRETE SURFACES AS INFLUENCED BY THICKNESS OF CONCRETE, JOINT SPACING, WIDTH OF PAVEMENT AND REINFORCEMENT.

In drawing the conclusions under this heading there were used in addition to the foregoing roads those described in Table 2. These latter roads contained some 300 definite comparisons of plain and

TABLE 2—List of Roads Which Furnished Comparisons

Spec No	State	County	Town	Name	Year Constr	Mix	Length	Width (feet)	Sect (inches)	Joint Spec (feet)	Reinforcement
100	Connecticut	New Haven	Branford	Boston Post Road thru Branford Hills	1913	1 2 4	4,001	18	5-7-5	25	Mesh
101	Connecticut			Waterbury-Meridan	1918	1.2 4	17,350	18	8	25-35	Bars
102	Connecticut	New Haven	Hamden	Whitney Ave	1914	1 2 4	3,675	20	6	30	Mesh
103	Delaware		Naamans	Phila -Pike	1921	Var	1,159	20	7	290	Bars
104	Delaware	Sussex		Coleman du Pont Road	15-16	1 2 3	126,800	14	5-7-5	60-90	Var
105	Florida	Escambia	Pensacola	S R No 1, Pensacola-Munez Ferry	1923	1 2 3		16	6-8-6	50	None
106	Florida	Escambia	Pensacola	S R No 1, Pensacola-Munez Ferry	1922	1 2 3		16	5½-7½-5	30	Mesh
	Georgia	Fulton	Atlanta	Andrews Ave	14-15	1 2 3	6,000	18	6-8½-6	30	Mesh
107	Georgia	Campbell	Atlanta	Route 174	1922	1 2 4	18,480	18	6	75+	Mesh
107-A	Georgia		La Grange	Route 174	1923	1 2 4	21,120	18	7	75+	None
108	Illinois	DeKalb	DeKalb	DeKalb-Sycamore	1912	1 2 3½	5,500	12	6	50	Var
109	Illinois	Cook	Homewood	Western Ave, Route 29, Section 1	1916	1 2 3½	12,000	18	6-8-6		Bars
110	Illinois	Cook	12th St	Maywood Route No 6	1914	1 2 3½		18	6-8-6	70+	Bars
111	Illinois	Cook	12th St	Hillside Route No 6		1 2 3½		18	6-8-6	Var	Bars
112	Illinois	Cook		Greenbay Road	1914	1 2 3½	3,917	18	6-8-6	100+	Mesh
113	Indiana	La Porte	La Porte	Alexandria St Fox to A	1915	1 2 3	600	20	6-8-6	50	Mesh
						1 1 1½			2-top		
114	Iowa	Cerro Gordo	Clear Lake	Cerro Gordo County Road	1915	1 2 4	5,337	16	4-5½-4	36	Mesh
115	Iowa	Cerro Gordo	Clear Lake	F A I	17-18		33,733	16		E of Day	Bars
116	Massahusetts	Essex	N Andover		1914	Var	26,364	19-6	Var	Var	Mesh
								8-18			
117	Massachusetts		Boston	Beacon St	1916	1 1½ 3	5,700	25	6	40-100	Mesh
118	Massachusetts		Framington	Union Avenue	1922	1 1½ 3	4,200	20		40	Bars
119	Massachusetts		Greenfield	Streets	20-21	1 1½ 3		20	7	100+	Bars & Mesh
120	Maryland	Baltimore	Forest Park	Forest Park Ave	1912		450	26	6-7-6	25-30	Mesh
121	Michigan	St Clair	Marysville	County Highway	1917			16	6-8-6	50	Mesh
	Michigan	St Clair	Marysville	County Highway	1922			18	7	50	None
122	Michigan			F A 68							Bars
123	Michigan			F A 15 & F A 70	23 - 24						Bars
124	Michigan			F A 88							
125	Michigan			F A 70							
125	Michigan			F A 70							
126	Michigan	Kent	E Gr Rapids	Lake Drive	1915		2,450	20	6		Mesh
127	Mississippi		Jackson	President St		1 2 3	4,090	32	6½	30	Mesh
128	Missouri	St Louis	St Louis	Gravois Road	1914	1 1½ 3	5,700	20	6-8-6	25	Mesh
129	Missouri	St Louis	St Louis	Big Bend Road	1921	1 2 3	4,229	36	7-8½-7	30	Mesh
						1 2 4					
130	Missouri	St Louis	St Louis	Forest Park Entrance	1914	1 2 4	400	40	6	35	Mesh
131	Missouri	St Louis	St Louis	Fair Ground Traffic Road	1915	1 2 4	400	33	6	50	Mesh
132	Missouri	St Louis	Kansas City	Raytown Road	1919			18	6-8-6	70+	Mesh
133	New York	Erie	Angola	S H 5546, Evans Center, 18 mi Creek	1915	1 1½ 3	23,654	16	6-8-6	30	Mesh

TABLE 2.—List of Roads Which Furnished Comparisons—*Continued*

Spec No	State	County	Town	Name	Year Constr	Mix	Length	Width	Sect	Joint Spec	Reinforcement
134	New York	Erie	East Aurora	Orchard Park	1916	1 1½ 3	32,974	16	6–8–6	30	Mesh
135	New York	Erie		Cassadago-Jamestown	1915	1 1½ 3	7,704	16	5–7–5	30	Mesh
136	New York	Niagara	Youngstown	Youngstown-Ransomville	1916	1 1½ 3	40,656	16	5–7–5	30	Mesh
137	New York	Niagara	Wilson	Cambria Wilson	1919	1 1½ 3	26,200	16	5–7–5	30	Mesh
138	New York	Niagara	Ransomville	Ransomville-Northridge	1917	1 1½ 3	22,228	16′	5–7–5	30	Mesh
139	New York	Niagara	Gasport	Gasport-McNalls	1915	1 1½ 3	12,302	16′	6–8–6	30	Mesh
140	New York	Niagara	Lockport	Lockport-McNalls		1 1½ 3	24,974	16′	5–7–5	30	Mesh
141	New York	Anondaga	Anondaga	No 1354	1919	1 1½ 3	29,300	14	5–7–5	30	Mesh
142	New York	Anondaga	Minoa	Manlius Center Minoa	1919	1 1½ 3	12,630	14	5–7–5	30	Mesh
143	New York	Saratoga	Glen Falls	S Glen Falls-Gansevoort	1917	1 1½ 3	10,500	16	4½–6½–4½	30	Mesh
144	New York	Cayuga	Port Byron	Port Byron-Montezuma	1917	1 1½ 3	19,853	14	5–7–5	30	Mesh
145	New York	Erie	Alden	No 1214-Genesee St, Part 3	1915	1 1½ 3	31,132	16′	6–8–6	30	Mesh
146	New York	Cayuga	Port Byron	Port Byron Weedsport	1917	1 1½ 3	20,540	14	5–7–5	30	Mesh
148	North Carolina	Orange	Hillsboro	Project No 410	1922	1 1½ 3	12,045	18	6–8–6P 6R	100+	Mesh
149	North Carolina	Gaston	Bessemer City	Project No 632	1923	1 1½ 3	600	18	6–8–6P 6R	100+	Mesh
150	North Carolina	Scotland		Project No 677	1923	1 1½ 3	39,233	18	6-8-6P 6R	100+	Mesh
151	New York	Forsyth	W Salem	Bethania Road	1915	1 2 3	7,927	16	6–8–6	30	Mesh
152a	North Carolina	Pitt	Gritton	Project No 184	1924	1 2 4	37,700	16	6–8–6	100+	None
b	North Carolina	Pitt	Greenville	Project No 186	1924	1 1½ 3	49,044	16	6	100+	Mesh
153a	North Carolina	Guilford	Greensboro	Project No 535	1924	1 2 4	41,050	18′	6	100+	Mesh
b	North Carolina	Guilford	Crowns Summit	Project No 536	1924	1 2 4	22,285	18′	8–7–8	100+	None
154a	North Carolina	Forsyth	W Salem	Project No 741	1923	1 2 4	56,100	18	6–8–6	100+	None
b	North Carolina	Forsyth	W Salem	Project No 742	1923	1 2 4	47 215	18	6	100+	Mesh
155a	North Carolina	Wilkes	Wilkesboro	Project No 782	1923	1 2 4	31,330	16	6	100+	Mesh
b	North Carolina	Wilkes	Wilkesboro	Project No 785	1923	1 2 4	13,290	16	6–8–6	100+	None
156a	North Carolina	Rockingham	Wentworth	Project No 588	1923	1 2 4	42,075	18	6	100+	Mesh
b	North Carolina	Rockingham	Wentworth	Project No 589	1924	1 2 4	48,270	18	6–8–6	100+	
178	Ohio	Lake	Madison	South Ridge Road	1915		28,723	16′	6–7–6	33′-4″	
179	Ohio	Montgomery	Dayton	I C H Section R	1918	1 1½ 3	1,240	16	6–8–6	30	
180	Ohio	Union	Marysville	I C H 191-E	1914	1 1½ 3	2,210	16	6–8–6	60	Mesh
181	North Carolina	Granville	Oxford	Project No 428	1924	1 2 4	15,893	16	6	100+	Mesh
182	North Carolina	Granville	Oxford	Project No 429	1924	1 1½ 3	6,300	16	6–8–6	100+	None
183	North Carolina	Cleveland		Project No 821	1923	1 2 4	8,350	18′	6–8–6	100+	None
184	Pennsylvania	Allegheny		Route 108	1918	1 2 3	16,852	16′	5–7–5	40	Mesh
185	Pennsylvania	Erie		Route 87-1	1918	1 2 3	15,050	18	6–8–6	50	None
186	Pennsylvania	Erie		Route 272-1	1918	1 2 3		18′	5–7–5	40	Mesh
187	Pennsylvania	Westmoreland		Ligonier	1918	1 2 3	5,400	18′	6–8½–6	40	None
188	Pennsylvania	Westmoreland		Youngstown	1918	1 2 3	2,900	18′	5–7½–5	40	Mesh
189	Pennsylvania	Erie		Route 87-2	1919	1 2 3	25,872	18′	6–8–6	50	Mesh

TABLE 2—List of Roads Which Furnished Comparisons—*Continued*

Spec No	State	County	Town	Name	Year Constr	Mix	Length	Width	Sect	Joint Spec	Reinforcement
190	Pennsylvania	Beaver		Route 204-1	1921	1 2 3	5,309	16	6-8-6	40	Mesh
191	Pennsylvania	Beaver		Route 204-2	1918	1 2 3	28,165	18	6-8-6	100+	Mesh
192	Pennsylvania	Beaver		Route 204-3	1921	1 2 3	26,953	18	6-8-6	100+	Mesh
193	Pennsylvania	Erie		Route 87-1-A	1918	1 2 3	7,200	18′	6-8-6	50′	None
194	Pennsylvania	Bradford		Route 287-3	1919	1 2 3		18	6-8-6	30-′80′	None
195	Pennsylvania	Bradford		Route 287-1	1919	1 2 3	31,700	18	6-8-6	30-′80′	Mesh
196	Michigan			F A 36	1919		1,800	18	6 & 7	100+	Mesh
197	West Virginia			West Union	1921	1 1½ 3	420	18′	6-8-6	30	Mesh
198	West Virginia			F A 120	1921	1 1½ 3	2,193	18′	6-8-6	70+	Var
199	West Virginia			State No 3005	1921	1 1½ 3	2,904	18′	6-8-6	33	Var
200	Washington			F A 90 State Project No 537	1922	1 1½ 3	22,950	20	6-7½-6	33	None
200	Washington			F A 90 State Project No 537	1922	1 1½ 3	2,540	20	6-7½-6	33	Bars
201	Washington			State Project No 554	1922	1 1½ 3	33,300	20	6-7½-6	21	None
201	Washington			State Project No 554	1922	1 1½ 3	1,260	20	6-7½-6	21	Bars
202	Washington			F A 34 State Project No 390	1920	1 1½ 3	35,000	20	6-7½-6	30	None
202	Washington			F A 34 State Project No 390	1920	1 1½ 3	450	20	6-7½-6	30	Mesh
203	Washington			F A 44 State Project No 394	1921	1 1½ 3	19,590	20	6-7½-6	30	None
203	Washington			F A 44 State Project No 394	1921	1 1½ 3	1,890	20	6-7½-6	30	Mesh
204	Washington			F A 36 State Project No 385	1921	1 1½ 3	9,580	20	6-7½-6	30	None
204	Washington			F A 36 State Project No 385	1921	1 1½ 3	660	20	6-7½-6	30	Mesh
205	Washington			F A 33 State Project No 384	1921	1 1½ 3	21,390	20	6-7½-6	30	None
205	Washington			F A 33 State Project No 384	1921	1 1½ 3	1,320	20	6-7½-6	30	Mesh
206	Washington			F A 70 State Project No 496	1922	1 1½ 3	8,520	20	6-7½-6	30	Bars
207	Washington			F A 95 State Project No 593	1922	1 1½ 3	11,500	20	6-7½-6	25	None
207	Washington			F A 95 State Project No 593	1922	1 1½ 3	14,050	20	6-7½-6	25	Bars
208	Washington			State Project No 588	1921	1 1½ 3	22,680	20	6-7½-6	30	None
208	Washington			State Project No 588	1921	1 1½ 3	1,260	20	6-7½-6	20	Bars
209	Washington			F A 27 State Project No 376	1920	1 1½ 3	33,270	20	6-7½-6	30	None
209	Washington			F A 27 State Project No 376	1920	1 1½ 3	2,700	20	6-7½-6	30	Bars
210	Washington			State Project No 685	1923	1 1½ 3	26,800	20	9-6½-6	20	None
210	Washington			State Project No 685	1923	1 1½ 3	7,720	20	6-7½-6	20	Bars
212	Washington			State Project No 687	1923	1 1½ 3	26,200	20	6-7½-6	20	None
212	Washington			State Project No 687	1923	1 1½ 3	420	20	6-7½-6	20	Bars
213	Washington			State Project No 688	1923	1 1½ 3	21,700	20	6-7½-6	20	None
213	Washington			State Project No 688	1923	1 1½ 3	2,320	20	6-7½-9	20	Bars
214	Washington			F A State Project No 691	1923	1 1½ 3	22,690	20	9-6½-9	20	None
214	Washington			F A State Project No 691	1923	1 1½ 3	1,960	20	9-6½-9	20	Bars
215	Washington			F A State Project No 692	1923	1 1½ 3	27,870	20	9-6½-9	20	None
215	Washington			F A State Project No 692	1923	1 1½ 3	1,160	20	9-6½-9	20	Bars
216	Washington			F A State Project No 695	1923	1 1½ 3	20,380	20	9-6½-9	20	None
216	Washington			F A State Project No 695	1924	1 1½ 3	1,020	20	9-6½-9	20	Bars
217	Washington			F A 134 State Project No 822	1924	1 1½ 3	23,480	20	9-6½-9	20	None

TABLE 2—List of Roads Which Furnished Comparisons—*Continued*

Spec No	State	County	Town	Name	Year Constr	Mix	Length	Width	Sect	Joint Spec	Reinforcement
217	Washington			State Project No 822	1924	1 1½ 3	2,120	20	9–6½–9	20	Bars
220	Ohio	Darke		I C H 62 Section B & C	1920	1 1½ 3	23,760	16	7–9–7	60-100	None
221	Ohio	Darke		I C H 62 Section A-1	1918	1 1½ 3	13,886	16	6–8–6	120–180	J mat
222	Ohio	Darke		I C H 211 Section O	1915	1 1½ 3	37,752	16	6–8–6	30	None
223	Ohio	Darke		I C H 211 Section F	1920	1 1½ 3	23,288	16	7–9–7	60	None
224	Ohio	Darke		I C H 211 Section E	1916	1 1½ 3	16,262	16	6–8–6	60	Bars
225	Ohio	Montgomery		I C H 65 Section A	1921	1 1½ 3	15,682	16	7–9–7	150–200	None
226	Ohio	Montgomery		I C H 65 Section C	1926	1 1½ 3	17,688	16	6–8–6	50–100	J mat
227	Ohio	Montgomery		I C H 63 Section E	1921	1 1½ 3	13–833	16	7–9–7	80–120	None
228	Ohio	Montgomery		I C H 63 Section E	1921	1 1½ 3	8,606	16	7–9–7	60–100	None
229	Ohio	Montgomery		I C H 63 Section K	1919	1 1½ 3	13,358	16	6–8–6	80–100	Bars
230	Ohio	Montgomery		I C H 27 Section A	1921	1 1½ 3	31,400	16	7–9–7	150–200	None
231	Ohio	Montgomery		I C H 27 Section B	1921	1 1½ 3	8,448	16	7–9–7	180–200	None
232	Ohio	Montgomery		I C H 27 Section B-2	1921	1 1½ 3	1,583	16	7–9–7	180–200	None
233	Ohio	Mercer		I C H 167 Section G	1920	1 1½ 3	29,000	16	7–9–7	80-120	None
234	Ohio	Mercer		I C H 264 Section O-2	1919	1 1½ 3	8,480	16	7–9–7	100-120	None
235	Ohio	Mercer		I C H 264 Section O-1	1920	1 1½ 3	7,920	16	6–8–6	100	Bars
236	Ohio	Erie		I C H 149 Section H	1921	1 1½ 3	4,028	16	7–9–7	120–600	None
237	Ohio	Erie		I C H 149 Section A	1916	1 1½ 3	5,300	16	6–8–6	60–100	Bars
238	Ohio	Erie		I C H 276 Section N	1915	1 1½ 3	6,330	16	6–8–6	30	None
239	Ohio	Erie		I C H 276 Section O-1	1917	1 1½ 3	8,080	16	6–8–6	100	Bars
240	Ohio	Erie		I C H 3, Section L-1	1915	1 1½ 3	18,800	16	5½–7½–5½	30	Bars
241	Ohio	Erie		I C H 3 Section L-2	1915	1 1½ 3	5,330	16	5½–7½–5½	30	Bars
242	Ohio	Erie		I C H 3 Section H	1914	1 1½ 3	13,570	16	6–8–6	30	None
243	Ohio	Erie		I C H 3 Section K-a	1915	1 1½ 3		16	6–8–6		Bars
244	Ohio	Erie		I C H 3 Section K-b	1915	1 1½ 3	22,800	16	6–8–6		Bars
245	Ohio	Erie		I C H 3 Section K-o	1915	1 1½ 3		16	6–8–6		Bars
246	Ohio	Clark		I C H 1 Section M	1921	1 1½ 3	31,300	16	8–10–8	150–200	Bars
247	Ohio	Miami		I C H 27 Section C-1	1921	1 1½ 3	7,938	16	7–9–7	300	
248	Ohio	Miami		I C H 27 Section C-2	1921	1 1½ 3	12,080	16	7–9–7		
249	Ohio	Miami		I C H 63 Section A	1918	1 1½ 3	12,770	16	6–8–6	60–100	Bars
250	Ohio	Miami		I C H 63 Section D	1920	1 1½ 3	18,900	16	6–8–6	100–120	Bars
251	Ohio	Huron		I C H 294 Section R	1916	1 1½ 3	8,237	16	6	50	Mesh
252	Ohio	Huron		I C H 290 Section H	1914	1 1½ 3	13,630	16	6	:120–200	None
253	Ohio	Huron		I C H 289 Section J-1 & 2	1914	1 1½ 2	19,660	16	6	30	None
					1916						
254	Ohio	Huron		I C H 142 Section N	1917	1 1½ 3	1,000	16	5½–6½–5½		Mesh
255	Ohio	Huron		I C H 142 Section M	1917	1 1½ 3	1,000	16	5½–6½–5½		Bars
256	Ohio	Auglaize		I C H 167 Section H	1921	1 1½ 3	15,550	16	7–9–7	500–600	Bars
257	Ohio	Auglaize		I C H 168 No B	1920	1 1½ 3	19,420	17 33	7–9–7	150–210	None
258	Ohio	Auglaize		I C H 168 Section C	1920	1 1½ 3	21,810	17 33	7–9–7	100–120	None

TABLE 2—List of Roads Which Furnished Comparisons—*Continued*

Spec No	State	County	Town	Name	Year Constr	Mix	Length	Width	Sect	Joint Spec	Rein-ment
259	Ohio	Auglaize		I C H 168 Section D	1922	1 1½ 3	8,240	16	7–9–7	200–230	Bars
260	Ohio	Logan		I C H 168 Section G	1919	1 1½ 3	19,480	16	6½–8½–6½	150–225	Bars
261	Ohio	Logan		I C H 168 No F	1919	1 1½ 3	15,860	16	6½–8½–6½	150–210	Bars
262	Ohio	Logan		I C H 168 No E	1919	1 1½ 3	17,000	16	6½–8½–6½	100–200	Bars
263	Ohio	Logan		I C H 130 Section C	1919	1 1½ 3	6,720	16	6½–8½–6½	150-200	Bars
264	Ohio	Logan		I C H 130 Section B	1918	1 1½ 3	14,980	16	6–8–6	150–200	Bars
265	Ohio	Logan		I C H 130 Section A-2	1919	1 1½ 3	8,181	16	6–8–6	140–200	None
266	Ohio	Logan		I C H 130 Section A-1	1918	1 1½ 3	2,640	16	6–8–6	60–100	None
267	Ohio	Median		I C H 97 Section M-1	1916	1 1½ 3	3,960	10	6	30	None
268	Ohio	Medina		I C H 97 Section L-1	1915	1 1½ 3	2,640	10	6	30	None
269	Ohio	Medina		I C H 97 Section L-2	1917	1 1½ 3	6,490	10	6	60	None
270	Ohio	Medina		I C H 32 Section K-1	1921	1 1½ 3	13,460	10	8	150–200	None
271	Ohio	Medina		I C H 32 Section K	1919	1 1½ 3		10		50	None
272	Ohio	Medina		I C H 32 Section H 1-A	1920	1 1½ 3	7,860 (272–273)	10	7	40–100	Bars
273	Ohio	Medina		I C H 32 Section H 1-B	1920	1 1½ 3		10	7	50	
274	Ohio	Portage		I C H 460 Section R	1916	1 1½ 3	13,880	12	7½	60	None
275	Ohio	Portage		I C H 460 Section W	1916	1 1½ 3	14,460	12		60	Bars
276	Ohio	Lake		I C H 34 Section B	1919	1 1½ 3	11,880	10	7	70	None
277	Ohio	Lake		I C H 34 Section A	1916	1 1½ 3	7,970	10	6	70	Bars
278	Ohio	Delaware		Del Section L	1918	1 1½ 3	940	16	6½–8½–6½		Bars
279	Ohio	Delaware		Del Section I	1917	1 1½ 3	915	16	6–8–6		Mesh
280	Wisconsin	Milwaukee		Ryan Road	1917	1 2 3½		18	6–8–6P		Var
281	Wisconsin	Milwaukee		Janesville	1917	1 2 3½		18	6–8–6		Var
282	Wisconsin	Milwaukee		Cedarburg	1917	1 2 3½		18	5–7–5R		Var
283	Wisconsin	Milwaukee		Silver Spring	1917	1 2 3½		18	6–8–6		Var

mesh reinforced sections and more than 100 definite comparisons of plain and bar reinforced concrete sections Utmost care was used in selection of these comparisons, due regard being given to the influencing factors mentioned in the foregoing discussion Many times condition of cut and fill limited the actual lengths compared to 100 feet and in some instances completely eliminated possible comparisons

Longitudinal cracks:

27. Were dependent on thicknesses of less than 8 inches, being reduced as thickness increased, but were not influenced by thicknesses of slabs greater than 8 inches.
28. Varied more consistently with center thickness and average thickness than with section area.
29. Were negligible in slabs 10 feet or less in width when thickness was not less than 6 inches.
30. In the same thickness of concrete were considerably reduced by all types of reinforcement placed primarily perpendicular to the center line of the road. The various types of reinforcement afforded crack reduction as follows:

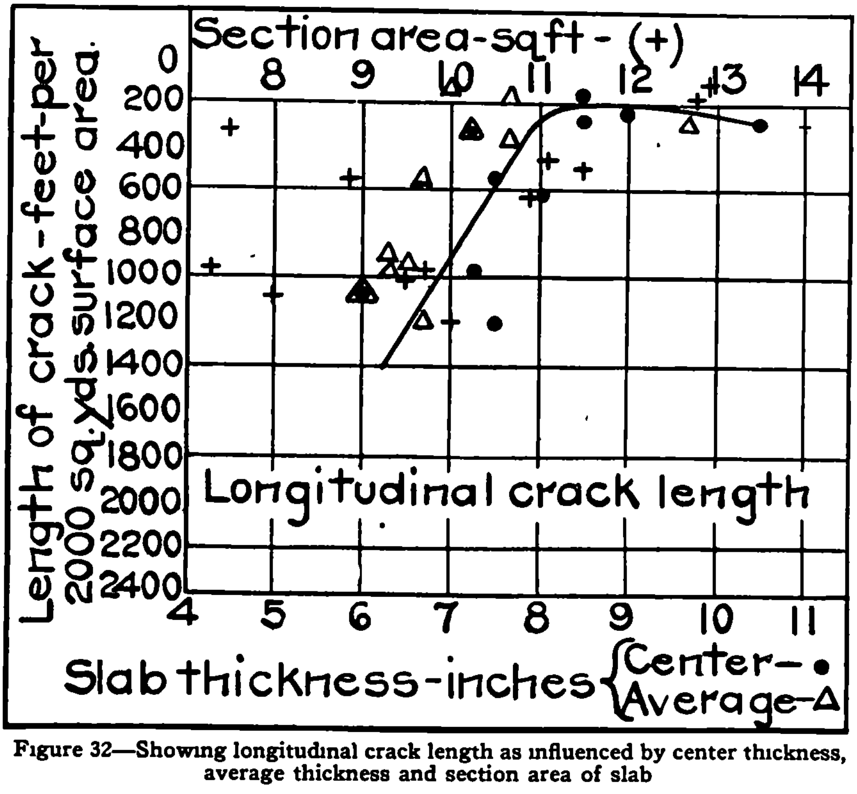


Figure 32—Showing longitudinal crack length as influenced by center thickness, average thickness and section area of slab

A. **Mesh reinforcement 25 to 28 lbs. per 100 sq. feet reduced longitudinal crack more than one additional inch of concrete center thickness.**

B. **Mesh reinforcement 56 to 95 lbs. per 100 sq. feet reduced longitudinal crack more than 2 additional inches of center thickness of concrete.**

C. **With good crushed stone aggregate bar reinforcement 42 lbs. per 100 sq. feet reduced longitudinal crack more than one additional inch of center thickness. This was not true when bars were staggered and placed only in part width of road.**

D. **With certain types of gravel aggregate and joint spacing of 170 feet, bar mat reinforcement 64 lbs. per 100 sq. feet, with 48 lbs. placed transversely, reduced longitudinal crack more than one additional inch of concrete. This was not true for joint spacing of 70 to 90 feet.**

E. **Bar mat reinforcement 170 lbs. per 100 sq. feet, with 85 lbs. placed transversely, reduced longitudinal crack more than 2 additional inches of center thickness.**

Figure 32, showing the longitudinal crack length of the Figure 1 surfaces platted in regard to center thickness, average thickness and cross section area, support statements 27 and 28 Whether or not the 8 inch thickness at which the rate of crack reduction changed, is critical for all roads is not known Also, it is not known if maximum thickness would have the same relative effect when occurring at the edge rather than at the center

Statement 29 was discussed under statement 9 Also Chart 1, Figure 1, plainly indicates the absence of longitudinal cracks in the narrow pavements This indication is supported by inspections of many 9 and 10 feet wide roads in Ohio and hundreds of miles of roads which contained center joint, but which showed no appreciable amount of longitudinal cracking

As support for statements regarding reinforcement there are shown in diagrammatic form

Fig 33 and 33-A Relative conditions of plain and mesh reinforced slabs of like thickness

Fig 34 Relative conditions of plain slabs and mesh reinforced slabs of less thickness.

Fig 35 Relative conditions of plain and bar reinforced roads of like thickness

Fig 36 Relative conditions of plain slabs and bar reinforced slabs of less thickness

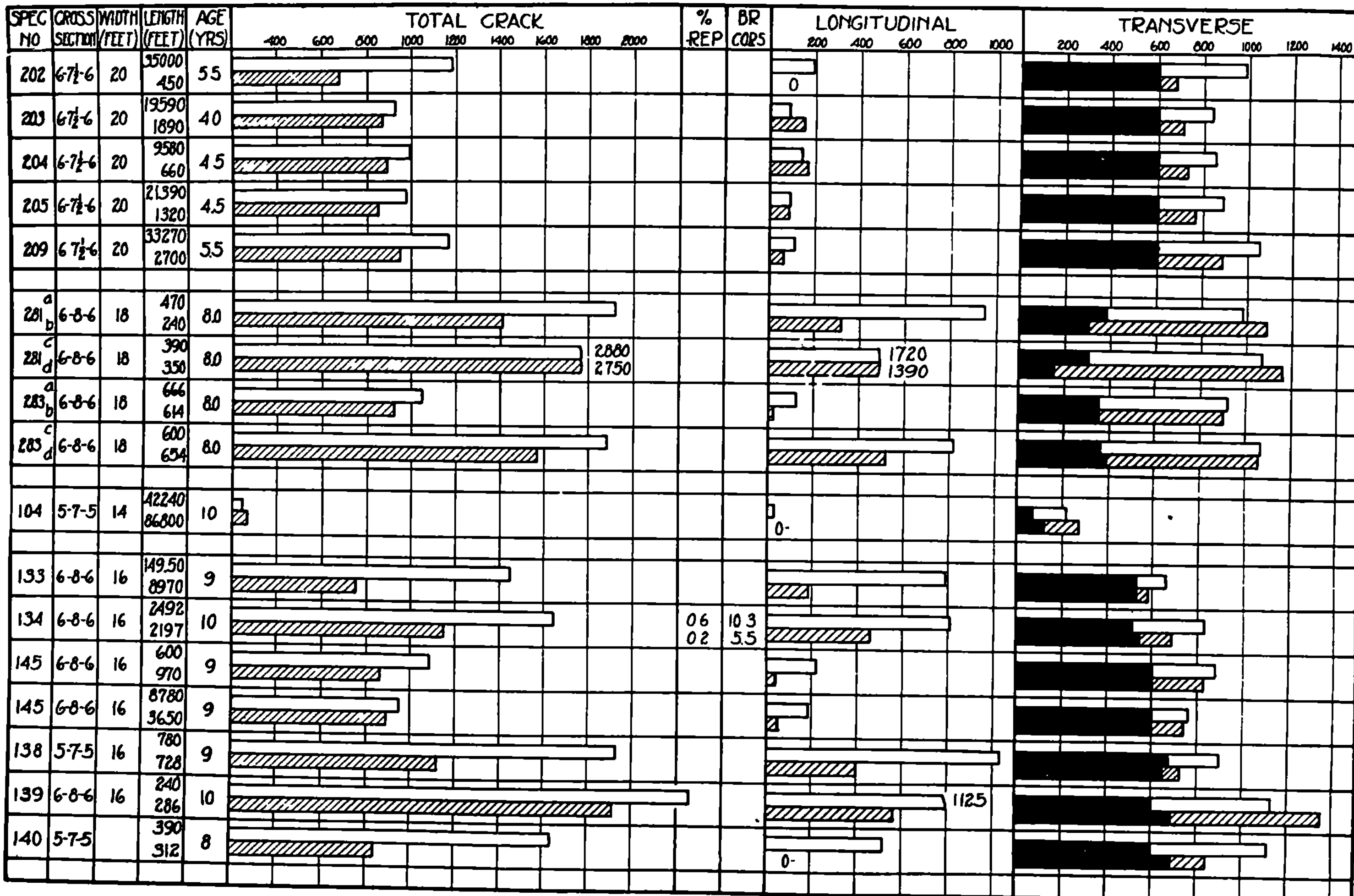


Figure 33—Comparative crack length in plain and mesh reinforced roads of like thickness

NOTE—% REP refers to area repaired or broken Shading shows reinforced sections
BR. CORS. refers to broken corners

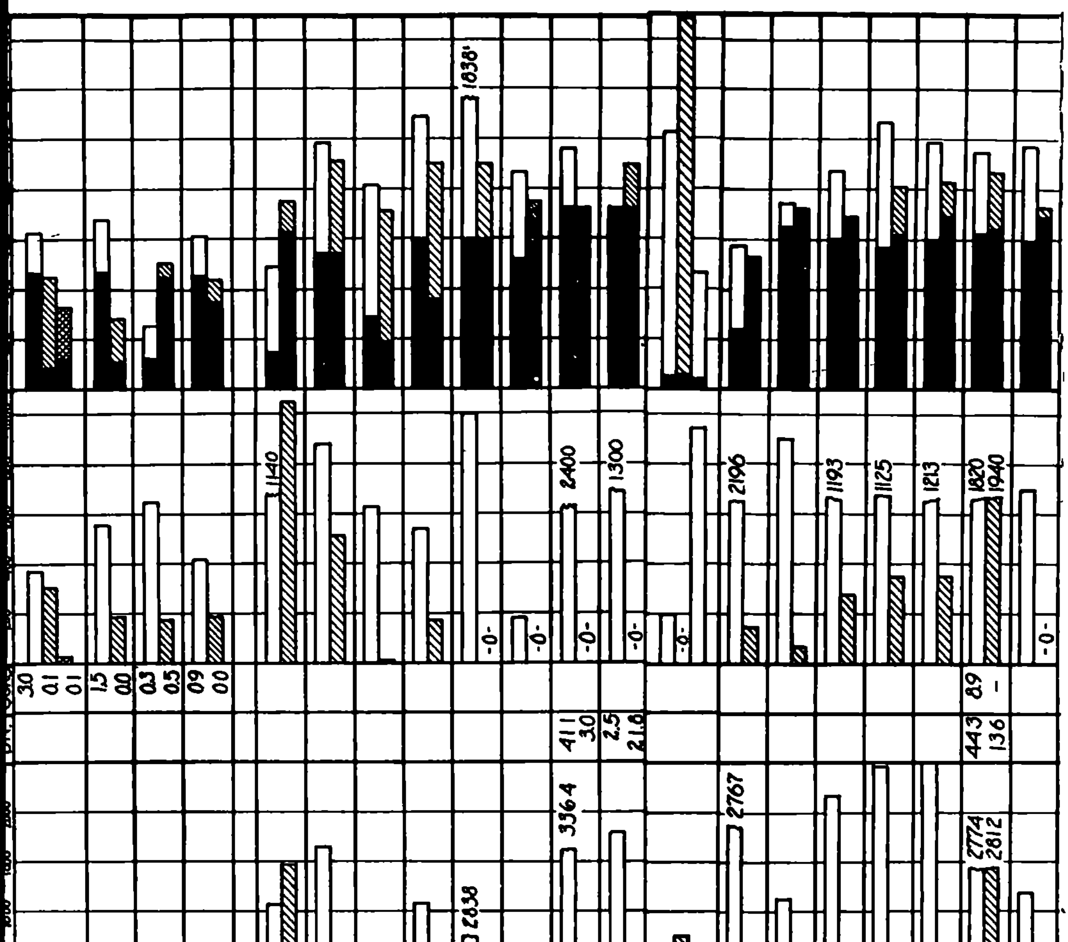


Figure 33-A—Comparative crack length in plain and mesh reinforced roads of like thickness

NOTE—% BR refers to area broken
BR CORS refers to broken corners

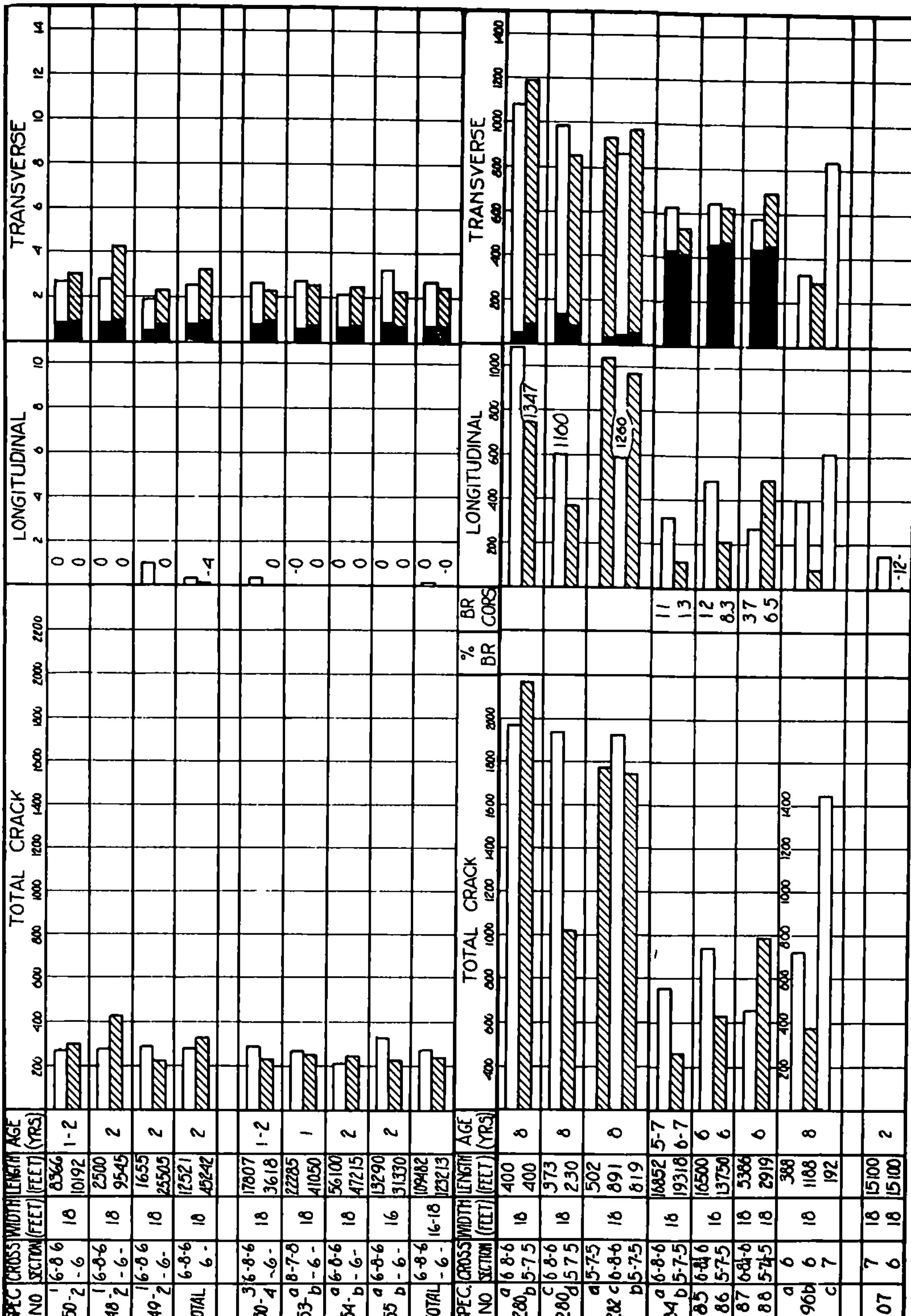


Figure 34—Comparative crack length in plain slabs and mesh reinforced slabs of less thickness

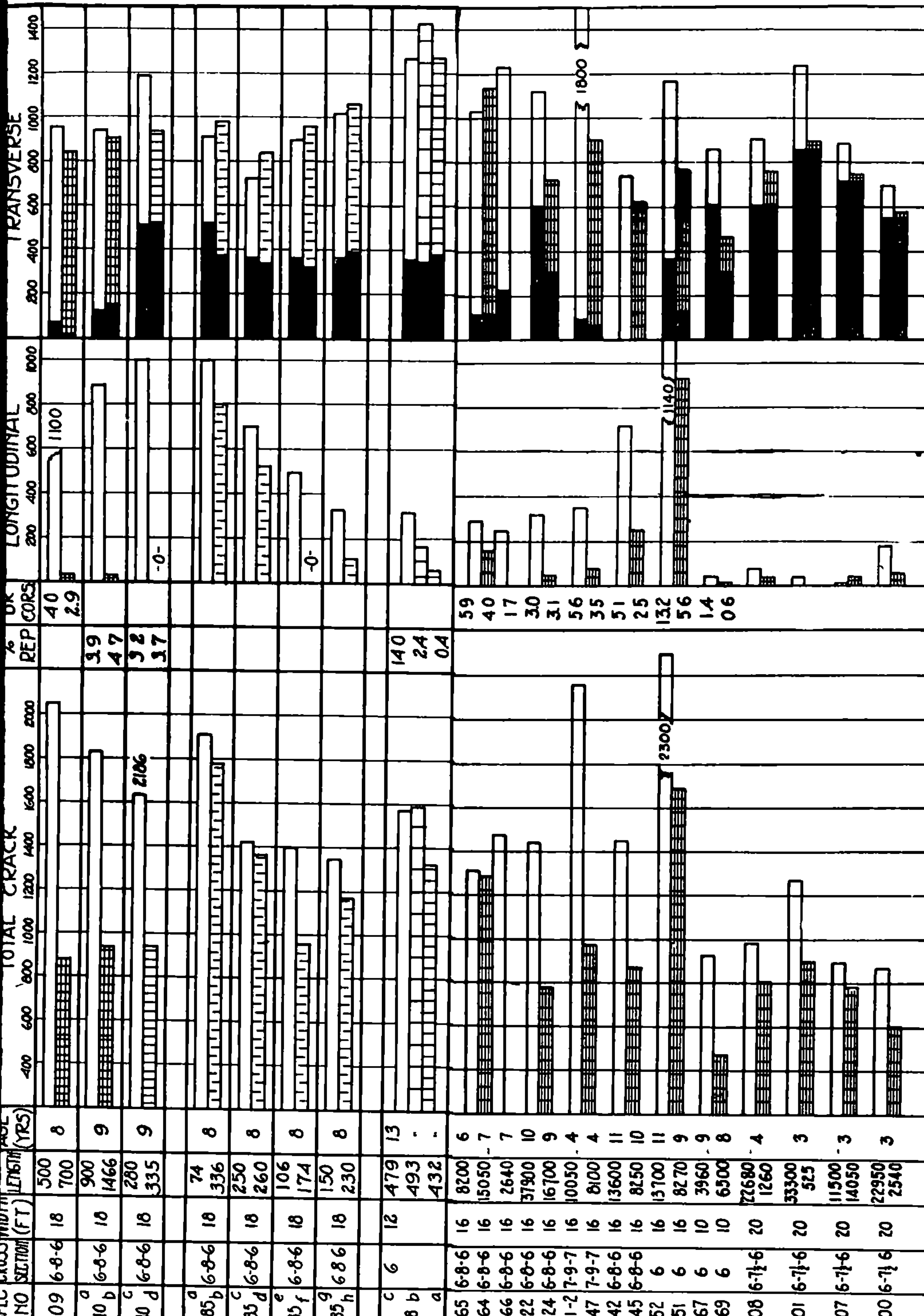


Figure 35—Comparative crack length in plain slabs and bar reinforced slabs of like thickness

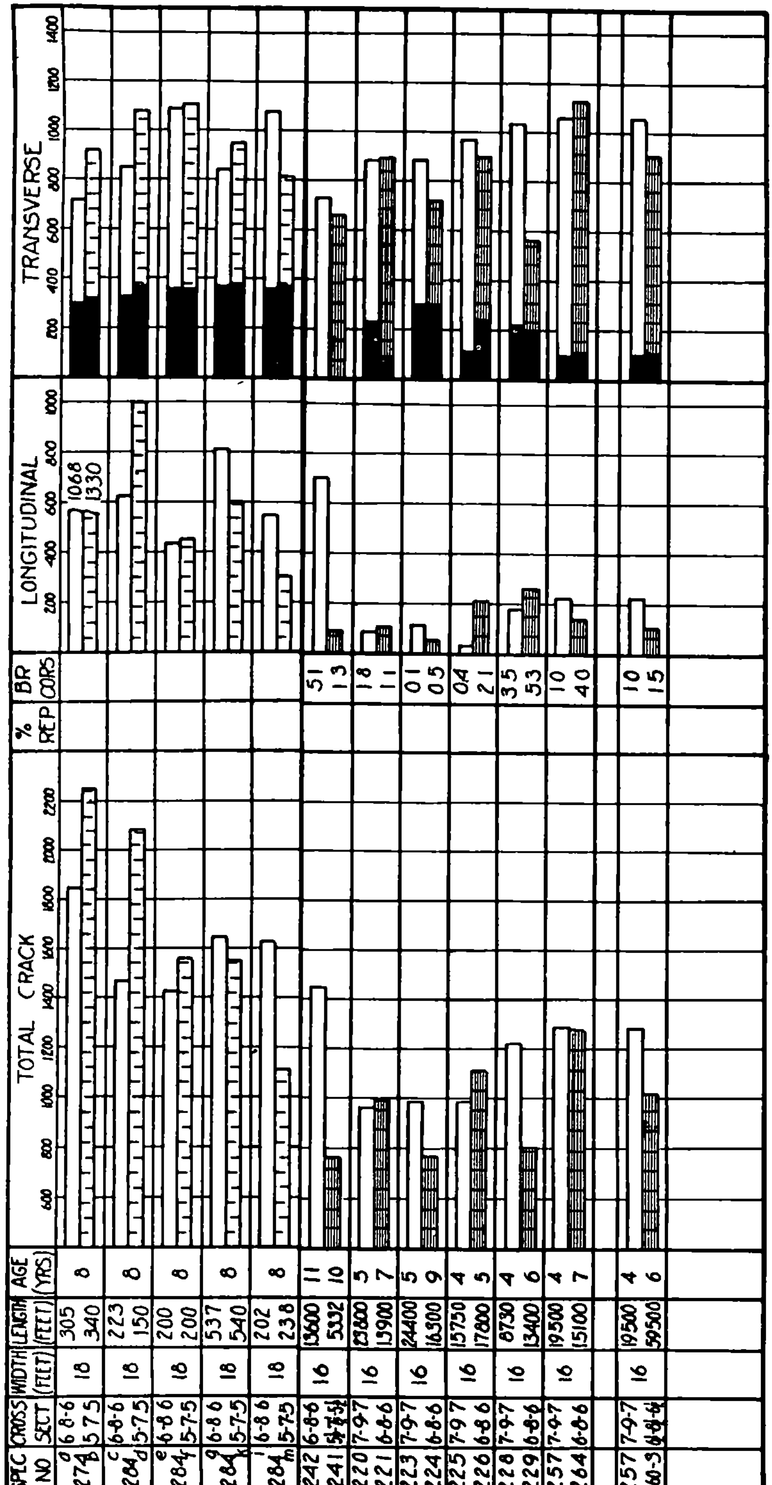


Figure 36—Comparative crack length in plain slabs and bar reinforced slabs of less thickness

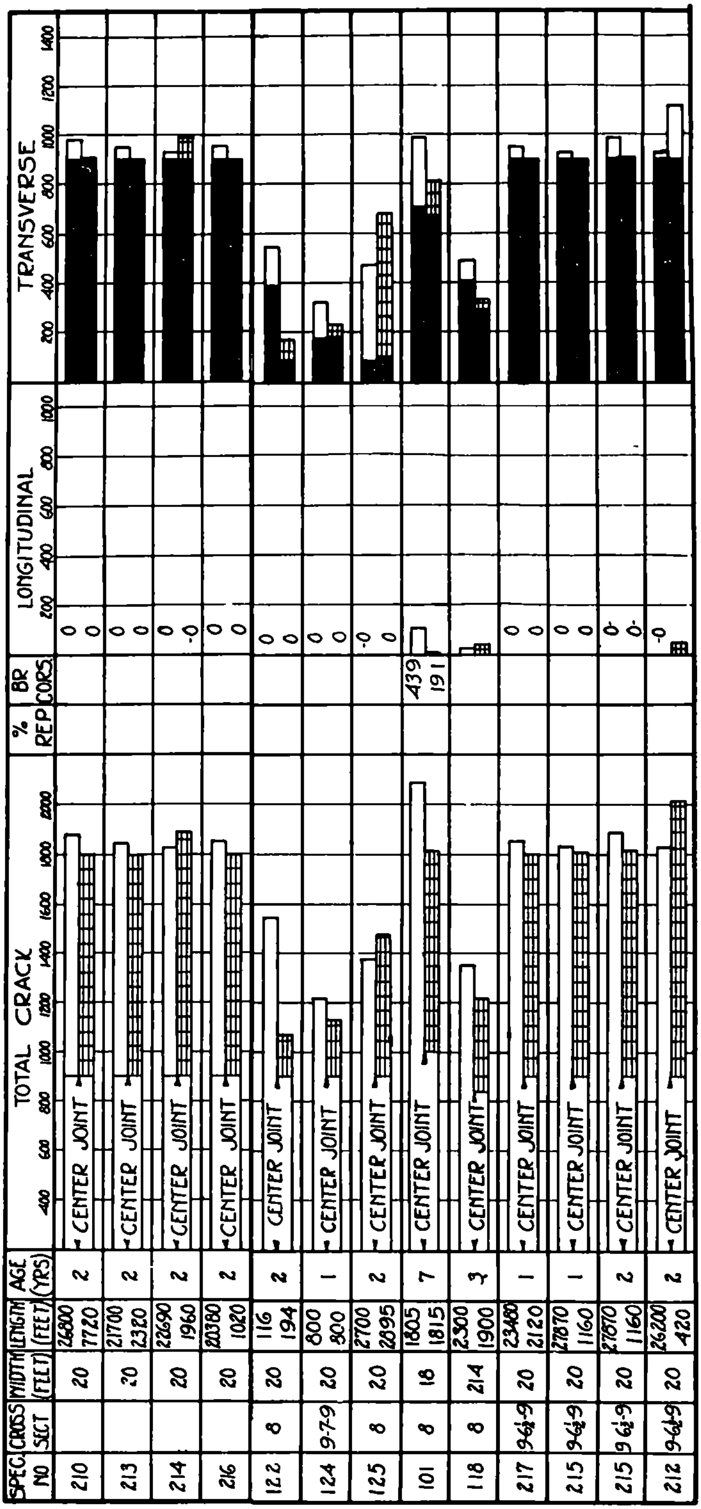


Figure 37—Comparative crack length in plain slabs and bar reinforced slabs of like thickness in center point construction

NOTE —Cross section for Roads 210, 213, 214 and 216 is 9-6½-9

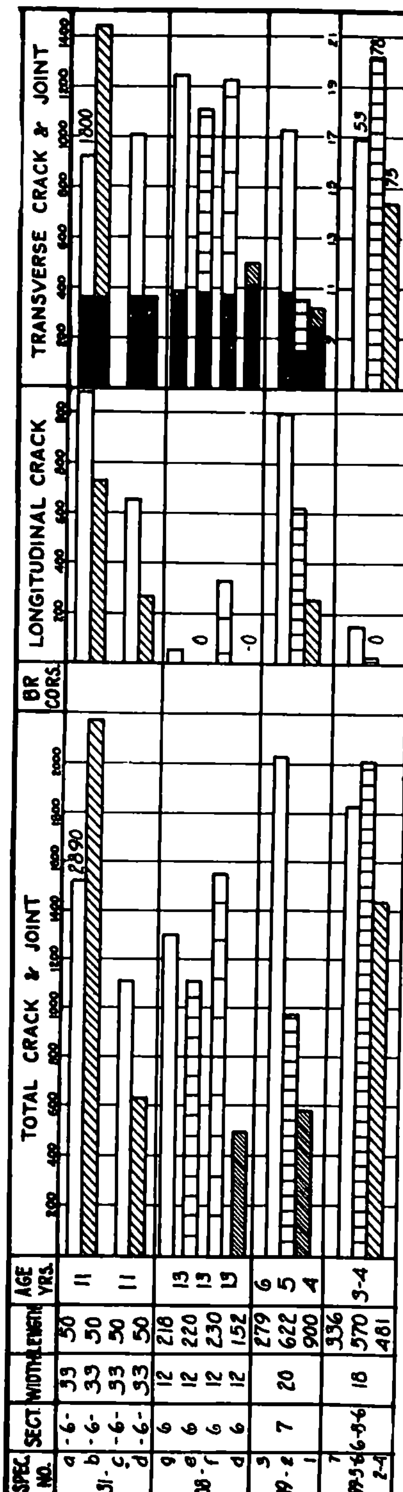


Figure 38—Comparative crack length reduction with variable reinforcement and aggregate

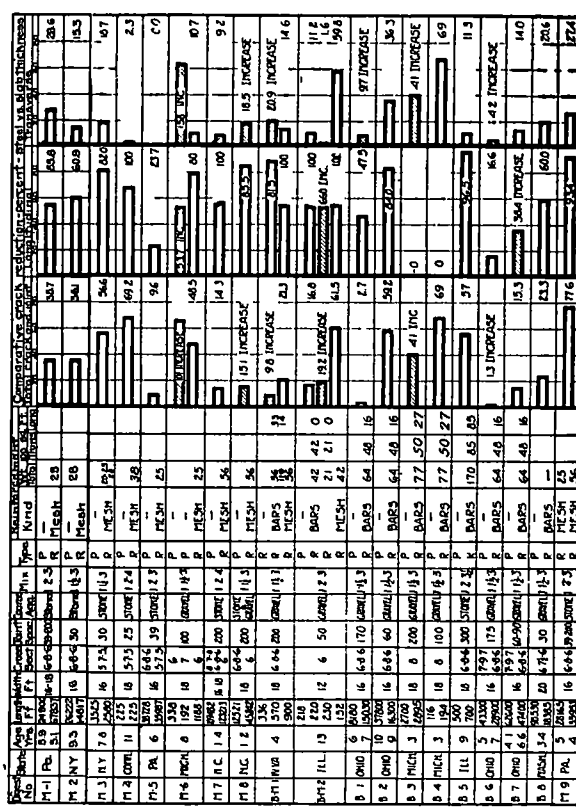


Figure 39—Representative digests showing comparative influence of reinforcement and additional concrete thickness on crack reduction

The specimen number used in the charts identifies the roads in Table 2 The difference in longitudinal crack length between plain and reinforced sections, as shown by these charts, compared with reduction afforded by additional thickness, as shown in Figure 32, gives an indication of the relative effect of each

Transverse cracks:

31. Were reduced slightly by additional thickness of concrete.

32. When produced by traffic were more or less independent of thickness, occurring simultaneously in 6, 7, 8 and 9 inch slabs (both center joint and full width roads), but were slightly reduced in extent as thickness increased.

33. Were influenced by reinforcement as follows:

A. In the same slab thickness were considerably reduced by light mesh reinforcement (25 to 28 lbs. per 100 sq. sq. feet) laid with primary members perpendicular to center line of road.

B. When good crushed stone aggregate was used, were reduced more by mesh reinforcements (56 to 90 lbs. per 100 sq. feet) than by 2 inches additional center thickness of concrete.

C. When good crushed stone aggregate was used, were reduced more by bar mats (170 lbs. per 100 sq. feet with 80 lbs. placed longitudinally) than by 2 inches of additional center thickness of concrete.

D. With certain gravel aggregates and joint spacing exceeding 150 feet, were increased by bar mat reinforcement (with 16 to 70 lbs. per 100 sq. feet placed longitudinally) and in some cases further increased by the addition of transverse rods.

E. With certain gravel aggregates and joint spacing not exceeding 100 feet, were reduced by bar mats (64 lbs. per 100 sq. feet with 16 lbs. placed longitudinally).

Figure 40, showing transverse crack of the roads in Figure 1, platted with regard to slab thickness, supports statement 31 and support for statement 32 was given in discussion of statement 12.

A scrutiny of Figures 33 to 39 verifies statement 33-A.

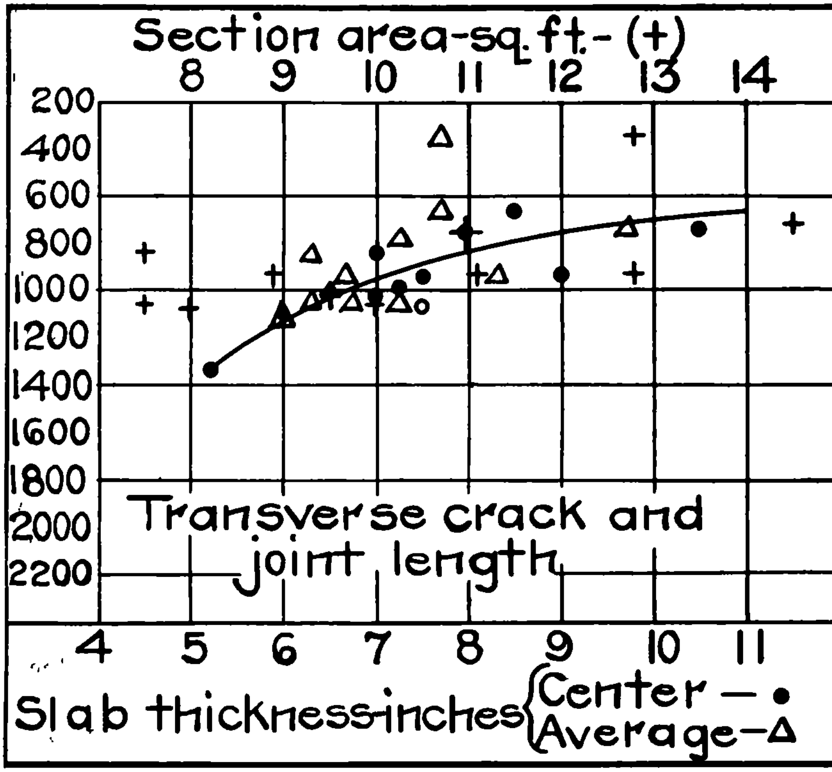


Figure 40—Transverse crack length as influenced by center thickness, average thickness and section area of slab

Statement 33-B is supported by digest M-7, Figure 39, while 33-C is indicated by digest B-5

The increase in transverse cracking with longitudinal bars in bond and certain types of gravel aggregate in long slabs is shown by digests B-1 and B-3 The further increase in transverse cracking accompanying the use of transverse bars in center joint sections under the above conditions is shown by J T Pauls' report on the Columbia Pike Experimental Road (Figure 94, page 129) The sections with 3/8" bars placed transversely have considerably more transverse cracks than those in which only longitudinal bars were used and the section with 1/2" bars has 28 per cent more cracks than those with the 3/8" It is perhaps a coincidence that the increase in steel diameter was 33 per cent It is pertinent to note that all cracks investigated were over the bars This would indicate that the aggregates which develop excessive transverse cracking lack tensile resistance and could be identified by a tension test

Statement 33-E is supported by digests B-2 and B-4, which show that with short slabs and the aggregates referred to above excessive cracking did not develop This fact indicates that transverse cracks of this character were not produced by wheel loads.

Combined length of transverse and longitudinal cracks in roads more than 10 feet wide:

34. Varied more consistently with center thickness of slab than with average thickness or section area, being reduced by additional center thickness of concrete, the rate of reduction decreasing as the center thickness increased.

35. With some aggregates was not influenced by joint spacing, while with certain gravels was increased in long slabs.

36. Was influenced by steel reinforcement as follows:

A. Was considerably reduced by light mesh reinforcement (25 to 28 lbs. per 100 sq. feet) placed with primary members perpendicular to center line of road.

B. Was greatly reduced by increasing weight of mesh from 25 to 56 lbs. per 100 sq. feet.

C. In the vast majority of cases, and when joint spacing did not exceed 60 feet, was reduced more by light mesh reinforcement than would be expected from one additional inch of center thickness.

D. When joint spacing exceeding 150 feet, and when stone aggregates such as used in the Pennsylvania comparisons and those warranting a 1:2:4 mix in North Carolina were employed, was more reduced by mesh reinforcement (56 to 90 lbs. per 100 sq. feet) than would be expected from 2 additional inches of concrete center thickness.

CENTER THICK	SECT	WIDTH	LENGTH	AGE
6	6	16	44	11
7	5 7 5	14-18	13 3	9-11
7¼	5 7¼ 5	12-18	4 7	9-10
7½	5/6-7½-5/6	18 20	227	4½-12
8	6-8-6	18	4 8	10
8½	6-8½-6	18 20	7 6	4-5½
9	7-9-7	16	44 5	3-4
10½	8 10½ 8	18	22 7	6½

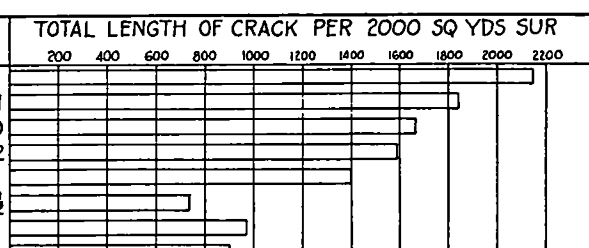


Figure 41—Total crack length of Table 1 surfaces arranged with regard to center thickness

E. When joint spacing exceeded 150 feet, and when certain gravels and such stones as required a 1:1½:3 mix in North Carolina were used, was reduced by mesh reinforcement (72 to 90 lbs. per 100 sq. feet) by an amount which could be expected from 1 inch of center additional thickness. (By inference.)

It is emphasized, however, that with those aggregates which in long slabs developed excessive transverse cracking and very little longitudinal, little or no reduction in crack length could be expected from mesh with its primary members placed to guard against longitudinal cracks In one case of this kind and in the same thickness of concrete, more transverse cracks developed in the reinforced section than in the plain slab adjoining See Figure 25

F. In the same slab thickness, and with relatively short slabs, was reduced by all types of two-way bar reinforcement. This applies to full width slabs as well as those constructed with center joint.

G. Was reduced more by bar-mat reinforcement (48 lbs. trans. and 16 lb. long.) than by one additional inch of center thickness.

H. Was not reduced by bars (42 to 48 lbs.) placed transversely as much as would be expected from one extra inch of concrete. (Wisconsin and Illinois.)

I. With certain gravel aggregates and when joint spacing exceeded 150 feet was more in some cases with bar mats having appreciable weight (33 to 70 lb.) placed longitudinally than that shown by plain concrete of the same thickness.

J. When joint spacing exceeded 150 feet and limestone aggregate was used, was reduced more (57%—see B-5) by a bar-mat reinforcement (170 lbs., 50 per cent each direction), than twice the amount indicated in Figure 44 for 2 inches additional center thickness.

K. In general, was reduced when steel could contract and expand with the concrete (short slabs 20-70 feet); and weight for weight was more reduced by small members closely spaced than by large units spaced further apart; and was increased when steel in bond had to work against the concrete (long slabs—more than 100 feet).

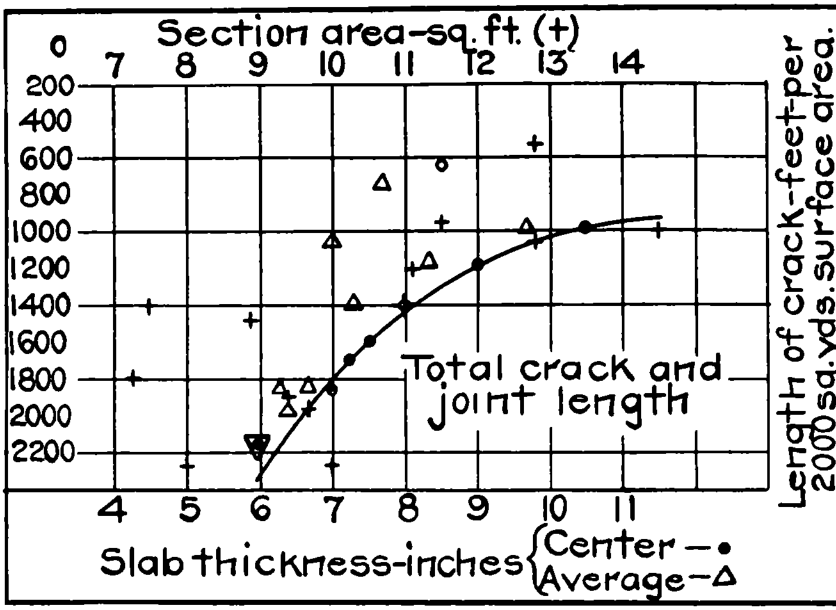


Figure 42—Combined transverse and longitudinal crack as influenced by center thickness, average thickness and section area of slab

L. Was not increased, in long slabs, when the longitudinal edge bars were painted and oiled to prevent bond and thus allowed the concrete to expand and contract independently of the steel as in the Illinois design.

Statement 34 should be supplemented by noting that combined length of longitudinal and transverse crack varied more consistently with center thickness than did either one separately. While neither the longitudinal crack lengths in Chart 1, Figure 1, nor the transverse crack lengths in Chart 2, Figure 1, show a consistent variation with center thickness, their sums shown in Figure 41 indicate a consistent reduction with increase of center thickness.

Reduction of total crack length with increase of center thickness is amply illustrated by the Columbia Pike sections This consistent variation is not shown, however, by either the transverse or longitudinal cracks separately (Figure 94)

That this reduction was more consistent with center thickness than with average thickness or section area is shown in Figure 42 This curve in slightly different form, together with curves of traffic and total crack, Bates section, total crack Columbia Pike sections, and fiber deformation curves, Arlington experiments[1] are shown in Figure 43 All of these curves agree in that reduction in cracking and fiber deformation decreased as slab thickness increased

The consistent variation of total crack length with center thickness as shown by Figure 42, in view of the fact that it represents many different roads subjected to various conditions in different states, warrants the statement that after the age at which rate of change of cracking occurred, center thickness (or possibly maximum thickness) was the controlling factor

To apply the relation (curve 1, Figure 43) to one individual road would be risky but apparently it is representative for average con-

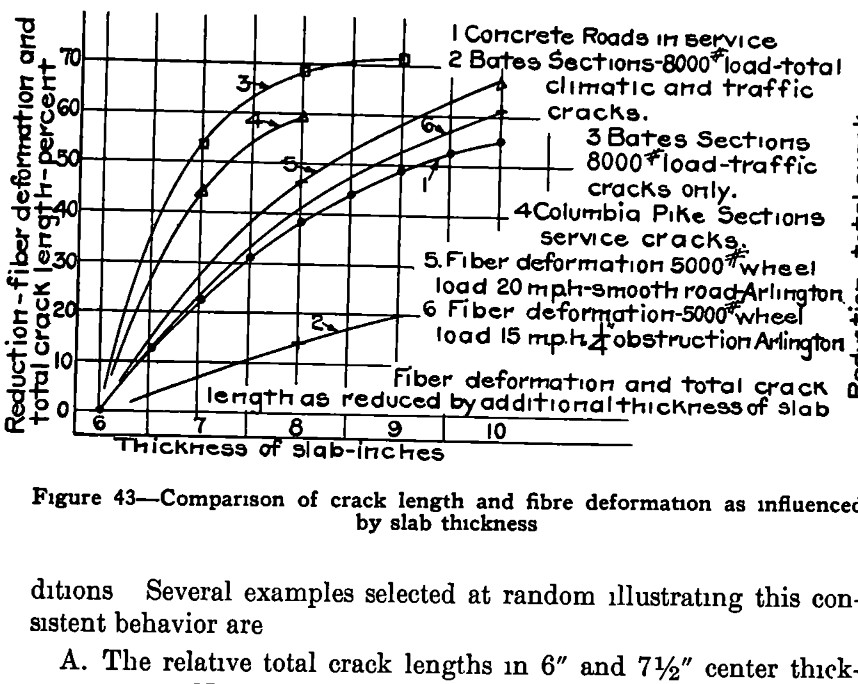


Figure 43—Comparison of crack length and fibre deformation as influenced by slab thickness

ditions Several examples selected at random illustrating this consistent behavior are

A. The relative total crack lengths in 6″ and 7½″ center thickness, North Andover Road (Chart 6, Fig 23) show a variation difference but 6 5 per cent from that indicated by curve 1, Fig 43

B A group of 6-8-6 surfaces (*none of which were used in the development of curve 1*) having age greater than 4 years and length of 27 miles, divided into 25 roads and distributed through 6 different states—showed an average total crack length of *1,436* feet per 2,000 square yards of area Curve 1, Figure 43, indicates that the length should have

[1] Research in Slab Design By A. T Goldbeck, Proc. American Road Builders' Association.

been 1,420 feet The lengths shown by those roads in New York, Ohio and West Virginia agreed very closely while Wisconsin and Illinois were somewhat above and Pennsylvania was considerably below the average.

C Notwithstanding this difference in total crack length between the roads of Pennsylvania and New York it will be seen later that the relative effect of the same type of reinforcement on the 6-8-6 surfaces in the two states varied less than 1 per cent

D The striking agreement between crack length of roads in service and the fiber deformations obtained experimentally.

Feeling that these agreements warrant the use of curve 1, Figure 43, as a general indication of what can be expected from additional concrete thickness as a crack reducer, a further development of it is shown in Figure 44 By changing actual crack-length reduction in Figures 33 to 38 to percentage of reduction and comparing with curve and respective thickness in Figure 44 a general indication of the relative effect of steel reinforcement and additional concrete as crack reducers can be obtained

Roads 280-1-2, Chart 5, Figure 23 (gravel), and 87-2, Chart 7, Figure 23 (crushed stone), were examples in which joint spacing had no appreciable effect on cracking It will be noted in the later case

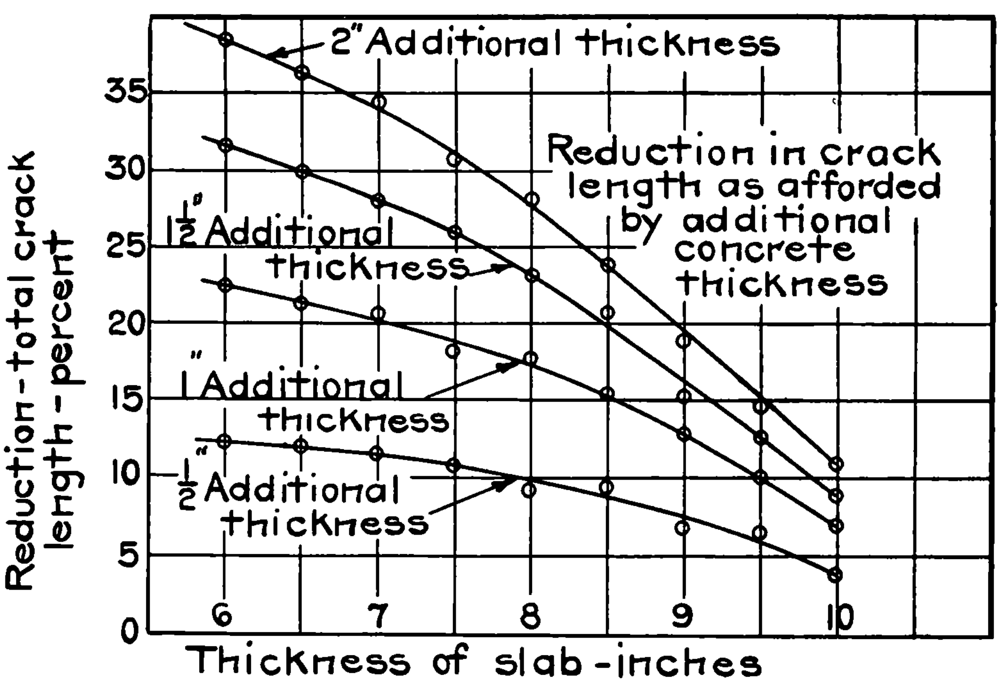
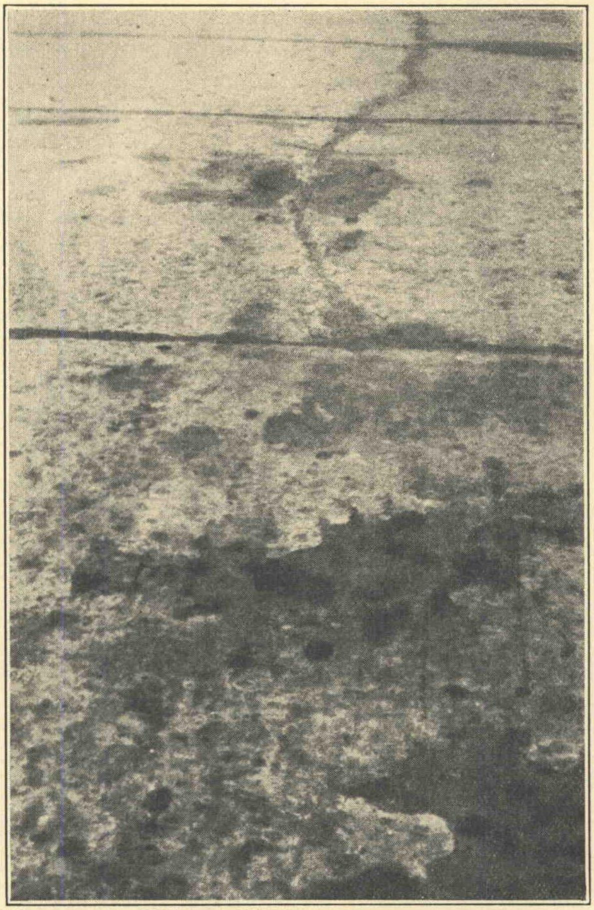


Figure 44—Curves showing crack reduction in percent as influenced by concrete thickness

that while joint spacing in one part of the road was 40 ft. and in another part of the same road was 170 ft., little difference in the total crack and joint length of the two parts was in evidence after 6 years of service.

In one digest in Ohio, covering some 20 miles and with a certain type of gravel aggregate, increases of joint spacing from 70 to 170 feet was accompanied by an increase in cracking of 33 per cent in the plain concrete and 38 per cent in the reinforced sections.



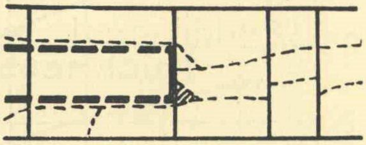


Figure 45—Plain and reinforced sections, Road No. 120, Forest Park, Maryland, showing reinforcement in part width of road only

In considering the value of reinforcement as a crack reducer it is emphasized that of the representative digests of 121 definite comparisons in 40 roads distributed in five different states shown in Figure 39, the steel in more than 100 cases was used because of questionable subgrade, and notwithstanding this fact there were but very few instances in which the reinforced slabs showed as much cracking as their plain concrete neighbors.

Digests number M-1 and M-2 show that for 6-8-6 surfaces, 25 and 28 pound mesh caused a reduction in total crack of 35.7 per cent in New York and 36.1 per cent in Pennsylvania. This is double the reduction which, from curve 1, Figure 44, would be expected from one additional inch of center thickness (17 per cent).

Also the reductions in 5-7-5 surfaces of 56 6 per cent in New York (M-3) 61 5 per cent, (MB-2) in Illinois and 69 2 per cent (M-4) in Connecticut afforded by mesh were more than double those shown by Figure 44 for 1 inch additional concrete thickness (21 per cent) These indications are supported by the direct comparisons which show that the 25 lb mesh (M-5) resulted in 9 6 per cent greater crack length reduction than did one extra inch of concrete thickness, that 38 lb mesh (used only in 12 foot width of road, 18 feet wide—Wisconsin) gave 13 8 per cent greater reduction than 1 extra inch of concrete, that 56 lb mesh (M-9) gave 77 6 per cent greater reduction in 6-8-6 surfaces than 25 lb mesh, which was more than would

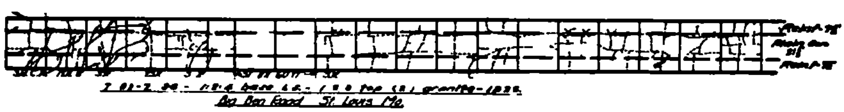


Figure 46—Sketch of Road No. 129, Big Bend Road, St. Louis, Mo., showing effect of placing reinforcement only in sides of road

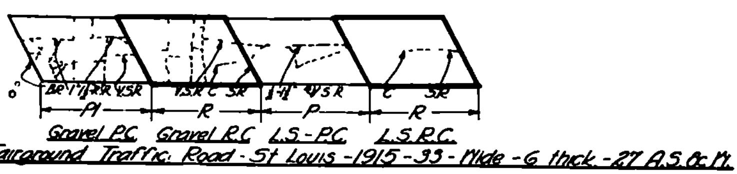


Figure 47—Sketch of Road No. 131, Fair Ground Traffic Road, St. Louis, Mo., showing influence of aggregate on plain and reinforced sections

be expected from 2 inches additional center thickness, that with one type of aggregate (M-7) 72 to 90 lb meshes gave more crack reduction than 2 extra inches of concrete and that with another type of aggregate and in long slabs with no appreciable longitudinal cracking (M-8) 72 to 90 lb meshes gave less benefit than 2 extra inches of concrete center thickness

Crack reduction resulted from full width reinforcement, and still placed uniformly in the major portion of the width (12′ in 16 ft width N. Y , 5546) When mesh was used only in a small portion of the width (10′ in center of 28′, Forest Park, Md , Figure 45, and 7½′ in each side of 36′, Big Bend Road, St Louis, Figure 46), cracks were mainly in the unreinforced portions

North Andover, Mass , Demonstration Road (Figure 80), gravel and granite aggregate, furnished an exception to statement 36-A, in that adding reinforcement to a 5-7½-5 surface did not reduce cracking Also no reduction was afforded by change to 6-8-6 section

Fair Ground Traffic Road, St Louis, 1914, Figure 47, excellently illustrates the difference in crack reduction when the same wire mesh was used with two different aggregates in short slabs. The reduction afforded with the gravel was but 57 per cent of that shown by the limestone. In New York State the reduction with gravel aggregate was but 39 per cent of that secured with limestone (general comparison).

Digest M-7 (North Carolina 1:2:4 mix) and M-8 (North Carolina 1:1½:3 mix) show the difference in crack reduction as influenced by different aggregates in long slabs with mesh reinforcement. If the values from Figure 44 can be taken as a criterion, 43 per cent crack reduction would be expected in the same slab thickness when good crushed aggregate was used and but 24 per cent with the aggregate requiring a 1:1½:3 mix, or a difference of 41 per cent. The reduction of 24 per cent agrees fairly well with the value 21.3 per cent obtained in a direct comparison in West Virginia with similar aggregate and a 56 lb. mesh.

Scrutiny of the various figures support statements 36-F and 36-H.

Support for statement 36-G is found in digests B-6 and B-7, Figure 39. With bar reinforcement 64 lbs. per 100 square feet, 16 of which was longitudinal and with joint spacing not exceeding 100 feet, the total crack length in 6-8-6 surfaces was less than in comparable 7-9-7 plain slabs (B-7). While with 175 foot joints (B-6) a slight increase was noted for the reinforced slabs, it was assumed that this increase could be accounted for by the 40 per cent additional age of the reinforced sections. Figure 48 shows one of the roads used in the Ohio comparisons.

The increased cracking in long slabs with certain gravel aggregates can be seen by comparison of digest B-1 (170′ joint spacing) with B-2 (60′ joint spacing); digest B-3 (200 foot joint spacing) with B-4 (100 foot joint spacing); and digests B-6 and B-7, referred to above.

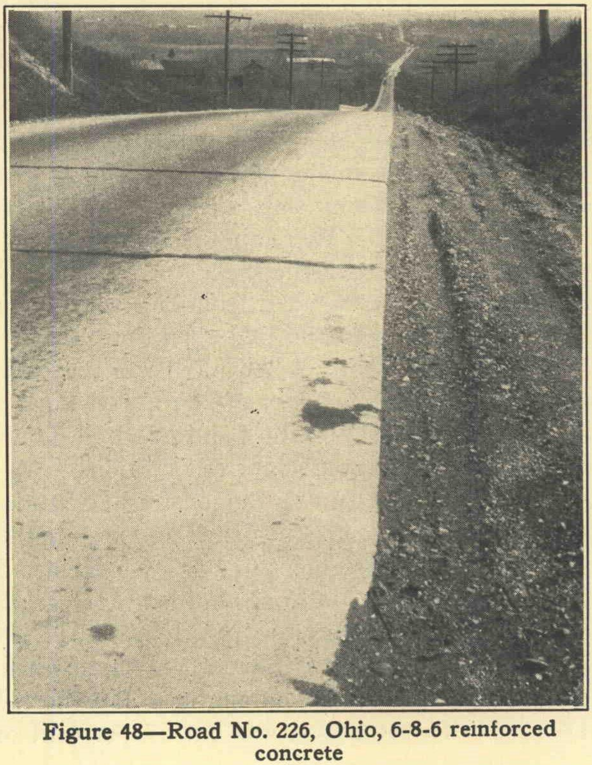


Figure 48—Road No. 226, Ohio, 6-8-6 reinforced concrete

Digest B-5 is an example of long slabs with an aggregate which did not develop excessive cracking

A comprehensive discussion of statement 36-K is given in J T Pauls' report, page 122

Corner cracks other than those caused by faulty transverse joints:

37. Were reduced by increased edge thickness of concrete.

38. Were dependent on center thickness only when interior cracks or joints were not provided with means for transfer of load from one slab to another.

39. In some cases were reduced by increased width of pavement.

40. Were influenced by reinforcement as follows:

A. Were reduced in varying amounts by light mesh reinforcement. This reduction, however, was not as consistent as that afforded by one additional inch of side edge thickness of concrete.

B. Were reduced more by one additional inch of concrete than by ⅜ inch bar mat (64 lbs. per 100 sq. feet).

C. Were reduced more by one-half inch additional thickness of concrete than by ¾ inch edge bars.

D. Were increased by edge bars in bond in long slabs, developing often before the roads were open for traffic.

Increased resistance to corner cracking afforded by additional concrete thickness was evidenced by all information furnished by test,

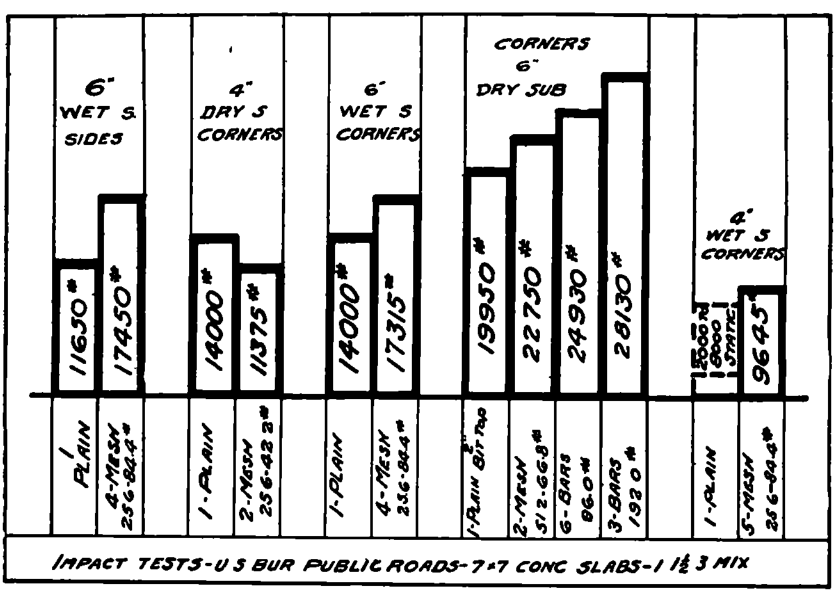


Figure 49—Relative effect of concrete thickness and steel reinforcement on resistance of slab corners to impacts

investigation and survey The effect of additional edge thickness as shown by Chart 3, Figure 1, in which number of broken corners were 35 for 5 inch, 13 for 6 inch and 1 5 for 7 inch edges seemed to be greater than has been indicated by figures available on the resistance of concrete to either static or impact loads

That increased width of road can be effective for reducing side edge corner cracks also is supported by ample evidence

A Studies made by J T Pauls on roads of various widths show that in the wide pavements traffic paths are not so close to the edge as in narrower ones.

B Studies reported by L W Teller (6-inch slab) indicate that fiber deformation caused by a wheel load placed 21 inches from the

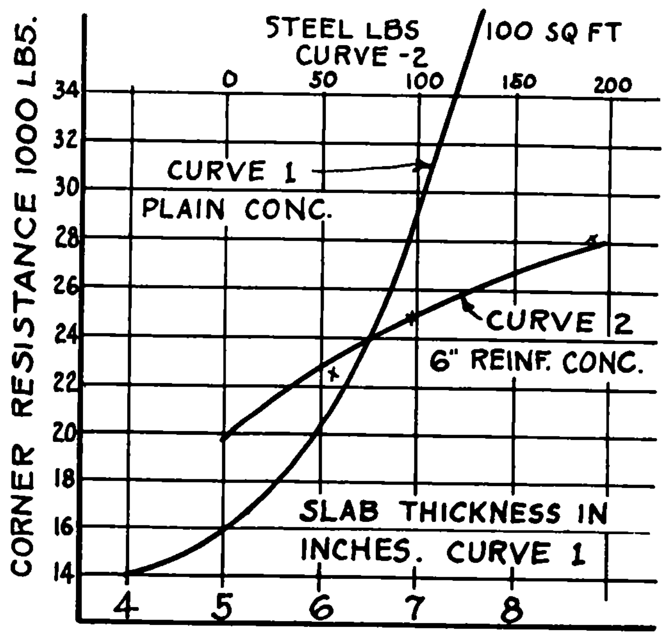


Figure 50—Comparative resistance to corner cracking afforded by reinforcement and additional concrete thickness Impact Tests at Arlington

side edge was but 50 per cent of that caused by the same wheel load when placed but 9 inches from the edge of the pavement

C. Observations during the Bates Tests indicated that wheel loads placed 18 inches from the side edge of an 8 inch slab caused fiber deformation but 75 per cent of that caused by the same load when placed but 6 inches from the edge

That center thickness influences corner cracking when provision has not been made for transfer of load across cracks or joints, is shown by the Waterbury-Meriden, Conn , Road (No 101) In this road, which is 8 inches thick and has center joint without dowels, the ratio of corner breaks were 25 along the center joint to 7 along the side edge. Thus indicating that the traffic paths were closer to the center line than to the side edge of the pavement. This brings out a very pertinent point in connection with the thick edge design.

When cross section is changed from 6-8-6 to 9-6-9, the danger from corner cracks has been shifted from the side edges, which in the wider roads receive but a small percentage of the wheel loads, to the center portions, which receive the maximum traffic. To compensate for the loss of resistance to corner cracking accompanying the the reduction in concrete thickness of 2 inches every effort should be made to secure the most effective transfer of load, not only at center joint and transverse cracks, but at transverse joints as well. When 5 inch centers are contemplated, owing to their exhibited lack of resistance to progressive failure following corner breaks, extraordinary precautions should be taken to effect transfer of load.

While light meshes have given a very considerable reduction in

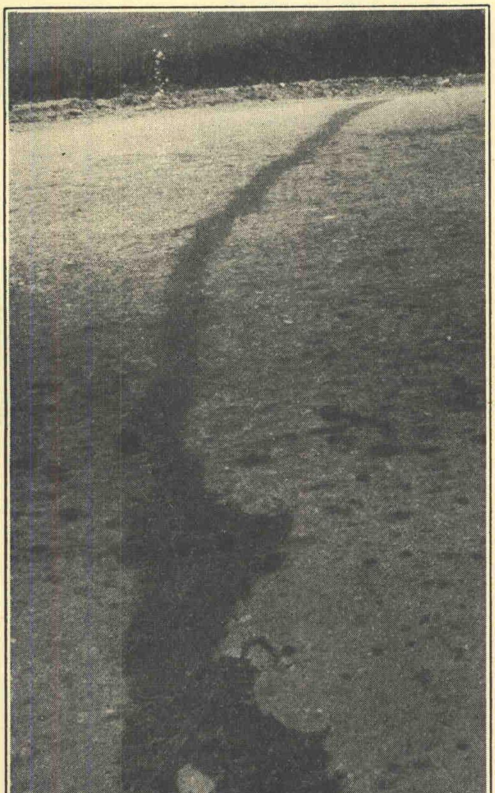


Figure 51—Absence of raveling along transverse crack in reinforced (wire fencing) slab adjoining plain slab shown in Figure 52. Note also absence of longitudinal crack in this slab.

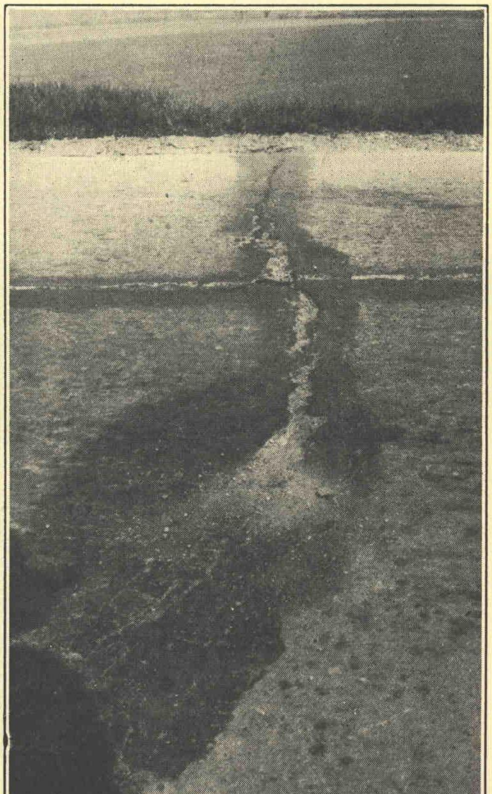


Figure 52—Raveled transverse crack in plain concrete section. Road No. 178, South Ridge, Lake Co., Ohio

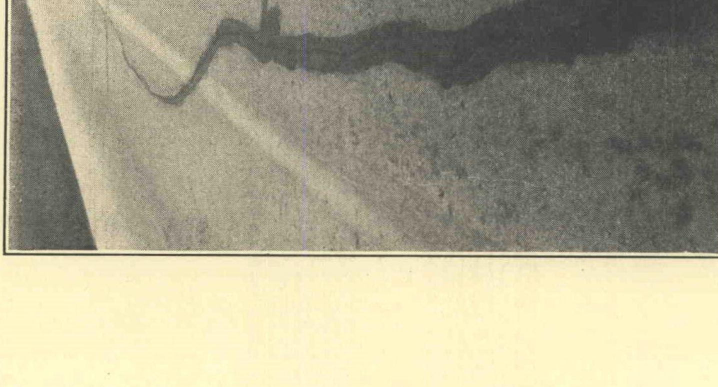


Figure 53—Crack in reinforced concrete road, Milwaukee Co., Wis.

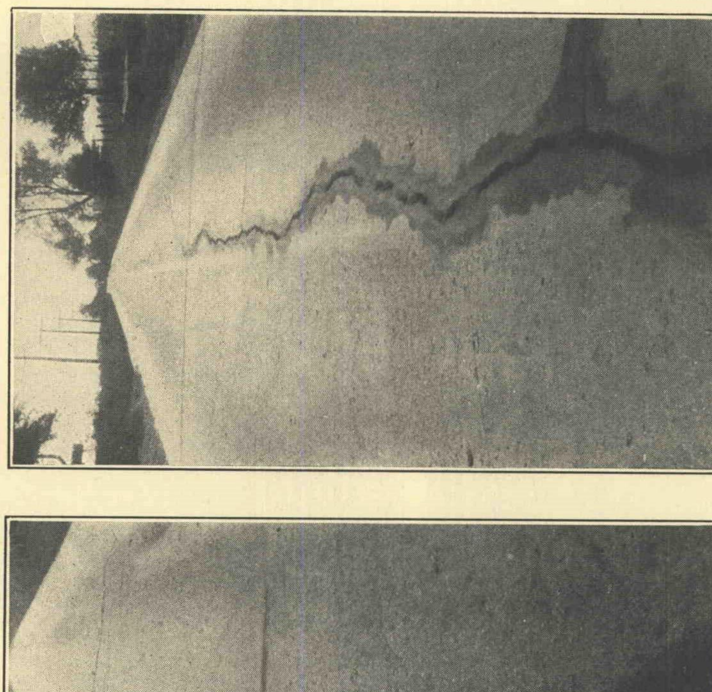


Figure 54—Crack in plain concrete road, Milwaukee Co., Wis.

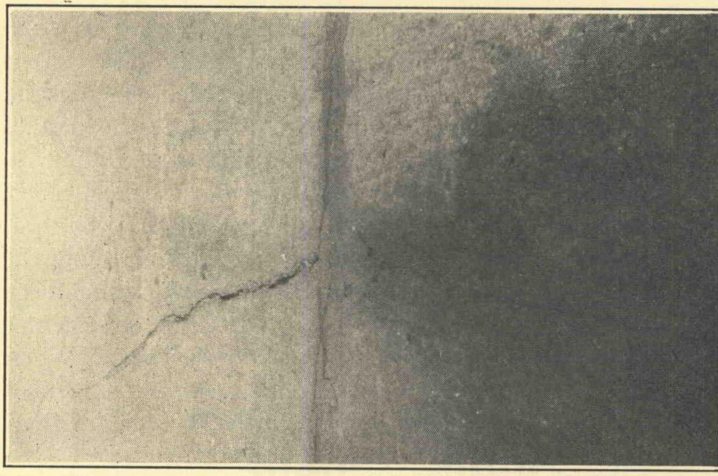


Figure 55—Meeting of closed crack in reinforced slab with open crack in plain slab, Milwaukee Co., Wis.

number of corner cracks evidence indicates that a more consistent reduction was afforded by 1 additional inch of side edge thickness of concrete

Only several comparisons were found on which information on resistance afforded by mesh to corner breaks could be based In six comparisons of 6-8-6 section, 16 feet wide, the corner cracks ranged between 1 to 31 in favor of mesh and 5 to 3 in favor of the plain concrete averaging 17 to 5 in favor of the reinforced sections Three comparisons between 5-7-5 reinforced and 6-7-6 plain yielded a ratio of 8 to 3 in favor of the latter.

In the Coleman duPont road, 5-7-5 by 14′ with excellent subgrade, the corner cracks in the reinforced sections slightly exceeded those in the plain sections

The agreement between these roads and the impact test, at Arlington is striking in that (a) on good subgrade no additional resistance to corner breaks was afforded by the mesh, (b) on other subgrades the beneficial effect was variable, ranging from very little to a very exceptional amount (31 to 1); and that (c) the greatest benefit (31 to 1) was afforded alike by the 25 and 56-pound mesh

These statements are interchangeable with Messrs. Smith and Teller's digest of the behavior of mesh in the Arlington tests (page 124), which results in diagrammatic form are shown in Fig 49

As support for statement 40-B and 40-C, it was evidenced in Ohio that in the same thickness very little reduction in corner cracks was afforded either by ⅜″ edge bar with ⅜″ transverse bars spaced 12 and 15 inches apart, or by ¾″ edge bar with ¾″ traverse bars spaced 30 feet center to center Such reduction as did occur did not equal that afforded by 1 additional inch of concrete in the former nor by ½″ additional edge thickness in the latter case One comparison of 20-mile length showed 5 for the 7-9-7 plain concrete, 6 for the 6½-8½-6½ with ¾″ circumferential bars and 7 corner cracks for the 6-8-6 surface reinforced with the ⅜″ bar mat

While from Figure 49, bar mats used in the Arlington tests seemingly did increase the resistance to corner breaking, Messrs Smith and Teller's report (page 124) states that the concrete in these slabs was of higher resistance, and that, if corrections were made for this factor, no appreciable increase in resistance would be shown over that of the plain specimens This would again bring these test results in agreement with the Ohio roads referred to above The relative effect of concrete thickness and reinforcement as preventives of corner breaks on dry subgrade in the Arlington Tests is shown in Figure 50 Seemingly, reinforcement of 200 lbs per 100 sq feet in a 6-inch slab offered slightly less resistance to corner cracking than was shown by a plain 7-inch slab

A considerable reduction (44 to 19) was afforded in Connecticut by a 7/8" bar mat with units spaced 1'-9" c. to c. longitudinally and 4'-0" c. to c. transversely. Road No. 101.

Corner cracks in long slabs accompanying the use of edge bars in bond were quite common, and this item is discussed in J. T. Pauls' report. That this type of cracking was influenced by joint spacing was shown by one road in Michigan in which, by change in joint spacing from 300 feet to 100 feet, premature corner cracks were reduced from 22 to 2 per mile.

Raveling of crack edges:

41. Was not influenced by slab thickness.

42. Was more reduced by steel reinforcement than by any other factor.

This reduction in raveling is shown by Figures 51 and 52.

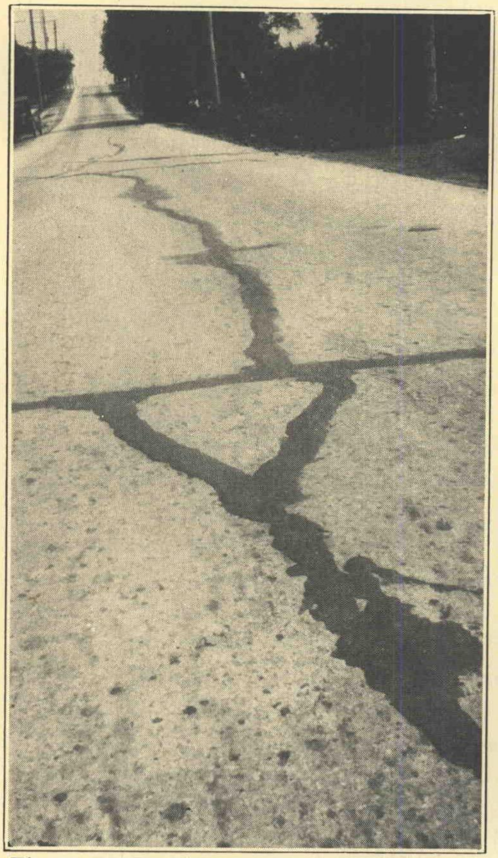


Figure 57—Interior corner break in reinforced slab showing closed cracks, even surface and no need for replacement

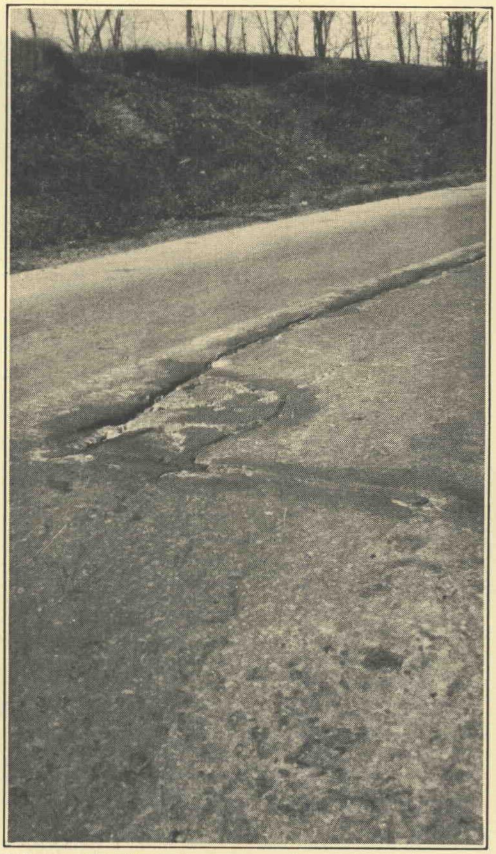


Figure 56—Interior corner break in plain concrete slab showing need for replacement

Separation of fractured slabs and unevenness of surface:

43. Were not influenced by slab thickness.

44. Were considerably reduced by steel reinforcement.

All types of steel tended in the main to hold fractured surfaces together after cracks had formed (see Figures 53 to 57) But to perform this function, steel in sufficient quantity must be placed perpendicular to the crack and should be fairly well distributed The primary members of light meshes placed transversely have been considerably more effective for preventing separation of longitudinal cracks than its secondary members (6 to 10 lbs) have been for preventing raveling in transverse cracks Bars placed only in the sides of the road held the slabs closer together at those locations (sometimes resulting in shattering) than they did in the center of the surface

Under exceptional conditions, failure of steel to prevent opening of a crack has been noted In one instance, when light mesh was used 4 per cent of the longitudinal cracks indicated broken reinforcement

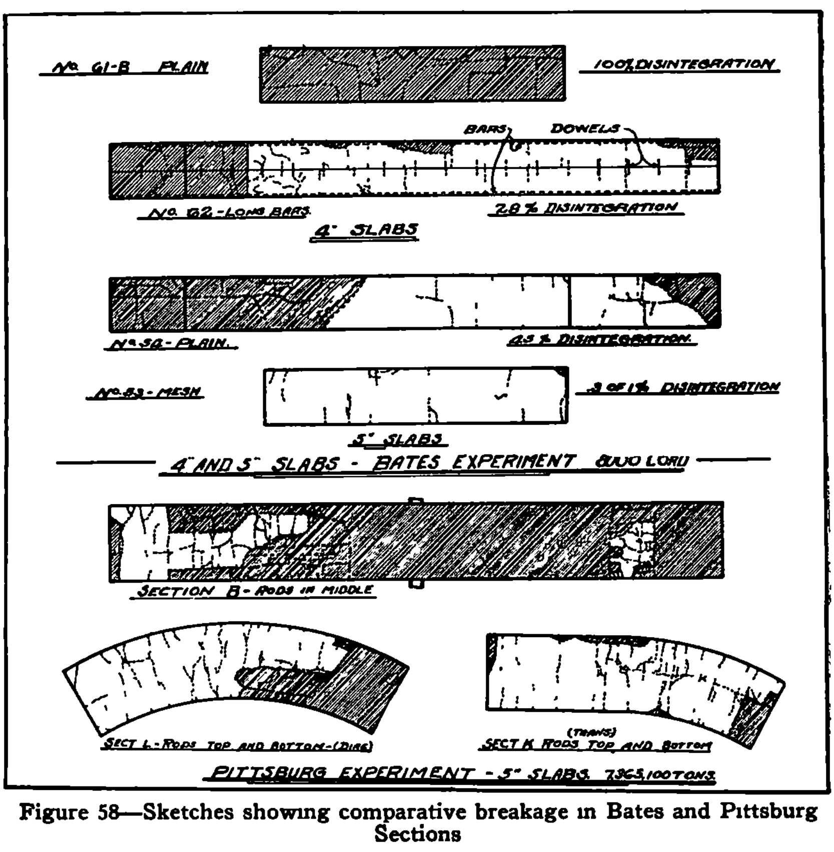


Figure 58—Sketches showing comparative breakage in Bates and Pittsburg Sections

On the Waterbury-Meriden road, Connecticut, where 7/8" bar-mat reinforcement was supposed to have been used, one open diagonal crack, with accompanying side displacement, was found.

In a width of 40 feet in Jackson, Miss, and on a subgrade that, in absence of frost, has caused heaves of from 7 to 9 inches, breaks have been noted in 38-lb meshes when used alone, and also when supplemented by ½" bars.

When cracks are prevented from opening, maximum friction is retained between slab edges for transfer of load This friction transfer is additive to that afforded by the steel itself

This function becomes especially important in concrete bases. Should the top be brick or block, with sand cushion, opening of cracks allows loss of cushion, followed by settlement and breakage in the top and unevenness of this kind promotes increased impacts which precede progressive destruction in the new free edges of the divided base (See Figure 71)

As concerns bituminous tops, if a crack opens in the base, the top separates also, again exposing free base edges to breakage Before this state of deterioration has been reached, however, a slight settlement on one side of the crack in the base may be reflected by unevenness in the top These conditions can be eliminated by preventing the crack from opening, thereby securing transfer of load by means of the steel, by the friction between the broken parts of the base and also by that afforded by keeping the bituminous top intact F A 36, Michigan (page 98, Figure 77), and streets in Jackson, Miss , amply illustrate the above

Smoothness of top afforded by reinforcement has probably been largely responsible for the better conditions shown by surfaces containing steel As indicated by Figure 30, if reinforcement prevents a surface unevenness of ¼", it can add a safety factor against cracking equivalent to that afforded by one inch additional thickness

Breakage and disintegration in concrete surfaces other than shattering and blowups caused by expansion:

45. Were considerably reduced by additional side edge thickness.

46. Were entirely dependent on side edge thickness when center thickness was 6 inches or more and the fractured slabs had not separated.

47. Were dependent on both center and side thickness when former was less than 6 inches.

48. Were considerably reduced by mesh reinforcement and bars placed longitudinally. Bars placed transversely only did not always afford reduction in breakage.

49. Were in some instances caused by bars or dowels carried across expansion joints when no provision was made for slippage or end clearance.

From Chart 4, Fig 1, it can be seen that appreciable breakage was confined to roads having 5-inch edges and, in the main, resulted from progressive breaking down of side edges after corner failures Only under exceptionaly heavy traffic were 6-inch edges badly broken

The difference in behavior between 5 and 6-inch surfaces cannot be too strongly emphasized In a 5-inch thickness, breakage can develop along all joints and open transverse and longitudinal cracks just as readily as from the side edge Even though the latter is sufficient to resist the loads, breakage developing from the center can destroy the slab Sketches of Section I, Pittsburg Test Road, illustrate this action

In 6-inch thicknesses, on the other hand, breakage had progressed mainly from the side edge and, although corners had been broken in the interior of the slab, progressive failure through the center did not develop

That a 6-inch center thickness was most economical in the Pittsburg tests is shown by a digest of L I Hewes' analysis (last column, comparative Pavement Ratings, Pittsburg, Calif),[1] in which, as concerns "comparison of computed cost per mile," the various center thickness ranges as follows 6-inch-1 000, 7-inch-1 053, 8-inch-1 053, and 5-inch-1 525 Stated differently, the total cost for carrying the stipulated traffic was 5 3 per cent greater for the 7 and 8-inch and 52 5 per cent greater for the 5-inch than for the 6-inch centers

The combination of 9-inch edge and 6-inch center, as being proof again breakage under traffic units considerably in excess of present legal standards, has been amply demonstated by

(1) Section J—Pittsburg Test Road
(2) Thick-edge Sections—Bates Test Road

[1] Report of Highway Research at Pittsburg, Calif, 1921-22

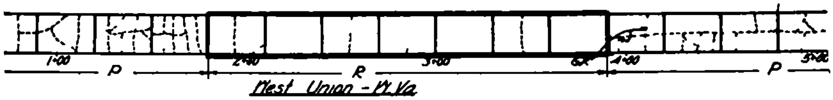
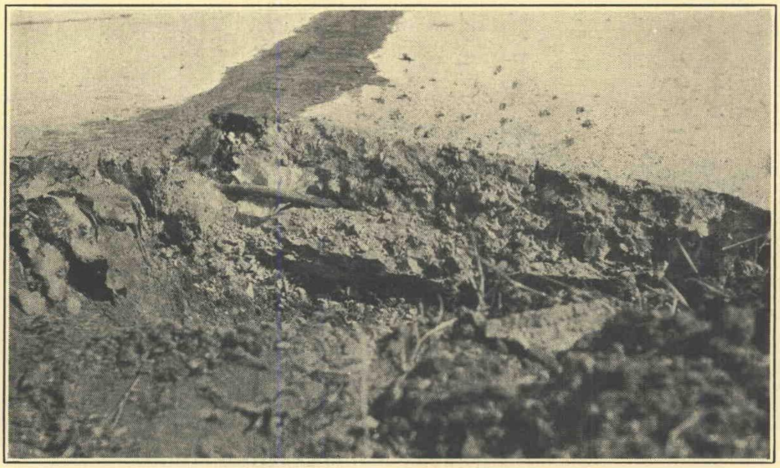
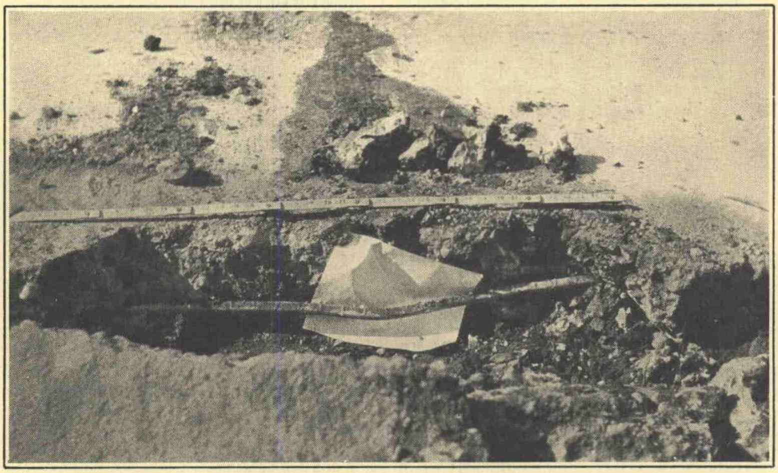


Figure 59—Sketch of Road No 197,[1] Wood Street, West Union, W. Va





Figures 60, 61, 62—Breakage caused by placing bars across expansion joints. Photos by courtesy of Michigan State Highway Commission

And is substantiated by L W Teller's work in fiber deformation measurements on the Harrisburg, Pa , and Cook County, Illinois, roads, which indicated that

(3) Eight-inch edge with 5-inch center showed deformations warranting cracking, and

(4) Nine-inch edge with 7-inch center adequately resisted traffic imposed, but was unbalanced in that the center was more resistant than the edge

Because of the scarcity of reinforced concrete roads showing a considerable amount of breakage, information of this character had to be obtained largely from the various investigations

Unfortunately, in the Pittsburg Tests, absence of plain concrete sections prevented detailed comparisons. It would seem, however, from the results, that bars placed transversely were not an economical means for stopping breakage There was, of course, a beneficial effect, as weight of transverse steel was increased This is shown by Sections K, L, and B (Figure 58), which were reinforced primarily transversely with 145 lbs , 116 lbs . and 42 lbs of bars per 100 sq. ft , and which showed relative breakages of 1 0, 1 9, and 5 5 at one stage of the test

Bars placed longitudinally, however, seemed very effective for retarding breakage The difference in breakage of 100 per cent in Section 61-B, Bates Road, and 28 per cent in Section 62, would indicate that one ¾″ edge bar with center-joint construction was as effective against breakage as the much larger amount of transverse and diagonal rods used at Pittsburg

That this 4-inch section with longitudinal bar was more resistant than the 5-inch plain concrete is shown by Figure 58, since, when breakage in the former was 28 per cent, that in the latter was 45 per cent.

The effectiveness of light mesh was indicated by Section 53, which showed but 0 3 per cent breakage, notwithstanding the fact that the primary members were placed transversely in the road

The Branford, Conn , road (Figure 86) (1914) showed in adjoining lengths 41 1 per cent for the plain and 3 0 per cent for the mesh sections Because of uncertainty as to comparable condition there was discarded in this road a plain section showing 68.3 per cent breakage

In the DeKalb, Ill , road, (12′ wide, 1912) (Figure 85), in one comparison the breaking in the plain sections was 544 square yards (in 2,000 square yards), that in sections with ½″ twisted bars spaced 4′-0″ c to c was 90 square yards, and that in sections with similar bars paced 2′-0″ c to c was 16 square yards Again, because of uncertainty of condition, the 42-lb mesh sections which showed no breakage were discarded from the comparison. On 12th Street, Chicago (Fig. 84), ½″ bars placed transversely only, 12″ c. to c., seemed to afford little if any reduction in breakage.

On Route 108, Pennsylvania, the number of broken corners in the 5-7-5 reinforced portion (25-lb. mesh) slightly exceeded those in the 6-8-6 plain. Replacements, however, have been made only in the latter. In other comparisons in Pennsylva-

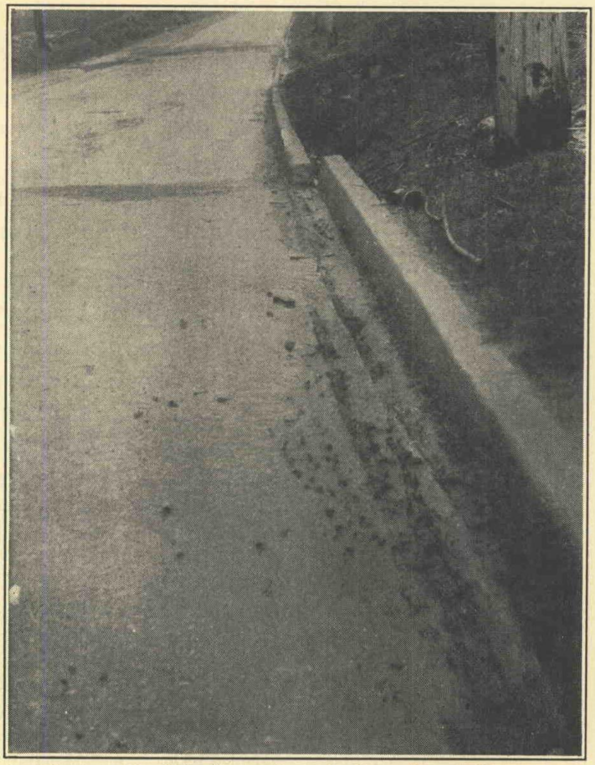


Figure 63—Displacement of slabs, Road No. 61, Freeport, Pa.

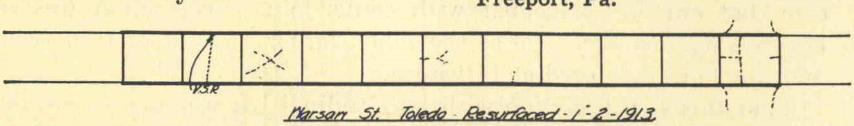


Figure 64—Condition sketch of resurfacing, Warsaw Street, Toledo, Ohio

Figure 64-A—Resurfacing on Boston Post Road

ma the corner replacements in the 5-7-5 reinforced surfaces exceeded those in the plain 6-8-6 surfaces Inability to differentiate between breaks caused by traffic and those caused by expansion and by faulty expansion joints, prohibited any definite conclusions

It has been brought out by the experiments of both W K Hatt and H E Breed that, under certain conditions of curing, plain concrete does not develop its normal strength and also that mesh reinforcement compensated for this deficiency For instance, several of H E Breed's plain specimens, subjected to rapid expansion by moisture and quick drying out, ruptured, while those containing steel remained intact On wet subgrade at Arlington, the plain 4″ sections failed under static load before the impact force could be applied, while the five specimens containing mesh reinforcement remained intact and were broken under impacts One road encountered, which seemed to demonstrate this beneficial effect of light reinforcement, was Wood Street, West Union, W Va (Figure 59), constructed in 1915, and which, from all indications, has had but the very lightest of traffic One part, however, has cracked and broken out to an extent requiring replacement, while an adjacent length of 210 feet, supposed to be reinforced with Buckeye Wire Fencing, contained but very few cracks

There were numerous examples of breakage caused by carrying bars improperly across expansion joints, the well-known instance of which was the Ideal Section of the Lincoln Highway This type of trouble, which is illustrated by Figures 60, 61, and 62 (furnished by the State of Michigan), has been experienced by several of the State Highway Departments In this connection it is plainly evident that all bars placed across expansion joints should have slippage and end clearance amply provided for

Data on proper placement of reinforcement were meager, it would seem, however, that placing of mesh or bars, reinforcing only part of width of road, as used in Milwaukee County experiments, is risky, and under some conditions (in cuts) can result in greater length of crack than would occur in plain slabs

Direct evidence showing whether mesh should be used in the top or bottom of the slab was not available One definite example, Alexandria Street, LaPorte, Indiana (6-8-6-1916), showed the same length and character of crack between A and Fox Streets, where mesh was placed near the top, as between Fox and Indiana Streets, where it was placed near the bottom

Several comparisons in Milwaukee County showed slightly greater crack reduction when mesh was placed near the bottom than was offered when it was placed near the top

In the North Andover, Mass , road, one of the few cases inspected in which no crack reduction was afforded by mesh, it was placed below the center of the slab

The Freeport, Pa, road, subjected to side-hill slips raising one side of the slab only and leaving the center more or less unsupported, was reinforced near the bottom and, although some slabs were displaced several inches vertically and one foot horizontally, (Figure 63) comparatively little cracking was shown

A most interesting example of increased resistance afforded concrete in some cases by the incorporation of mesh, regardless of its placement or weight, was furnished by the Arlington Tests, in that the 6-inch slabs on wet subgrade, with mesh near the top, showed 50 per cent greater resistance to side-edge blows causing tension in the bottom, than the comparable plain concrete specimens (See Fig. 49)

The efficiency of relatively thin layers of reinforced concrete for resurfacing of concrete roads is amply illustrated by the following examples

(a) Gratiot Avenue, Detroit, 1912, surface increased in width (1917) from 16 to 22 feet by means of 4-inch reinforced (gravel) top and 9-inch edges Tightly closed longitudinal crack probably over that in original surface Very few cracks were noted over edge of old pavement

(b) Milwaukee-Janesville Road from Jackson Park southwest ½ mile to Oklahoma Avenue. Frozen, 1912, surface very badly cracked and worn, was resurfaced in 1917 with reinforced concrete varying in thickness from 2 to 4 inches The original width of 18 feet was not increased Notwithstanding excessive cracking in original surface, the road today in general contains not more than one longitudinal and one transverse crack in a slab

(c) Warsaw Street, Toledo One block, frozen during construction in 1913, was immediately resurfaced with reinforced concrete ranging in thickness from 1½ to 2½ inches This block today, both as regards extent and character of cracking, is in much better condition than any other in the street (See sketch, Fig 64)

(d) Boston Post Road, West Haven, Conn Resurfaced with 4 inches and widened with 9 inches of reinforced concrete in 1923. Several very fine cracks were found. (See Fig. 64 -A)

(e) Federal Aid Project 49—Boise, Idaho Resurfaced in 1921 with a 4-inch thickness without transverse joints One blowup and transverse cracks have developed

(f) Syracuse, N. Y. Service test road, constructed (1925) by Bureau of Highways, New York State, under direction of Wm M Acheson, employing various thicknesses and types of reinforcement in resurfacing See page 115, this report

TABLE 3

General condition of slabs, Road No 5546, New York

	1	2	3	4	5	6
	Total No of Slabs	Per cent of Total No			Broken Corners Per 2000 Sq Yds of Surface	Per cent of of Corners Extending More Than 2′ from Edge
		O K	With Hair Cracks Only	Requiring No Maintenance		
P Concrete	499	11 4	6 2	17 6	3 6	55 0
R. Concrete	321	53 8	18 4	72 2	7 0	29 0

TABLE 4 N Y STATE HIGHWAY No 5546

Slab condition of Road No 5546, New York, as influenced by subgrades and reinforcement

Sub-Grade		Type	Total No of Slabs	O K	With Hair Cracks	With 1 Tr Crack Only	With One Long Crack Only	With More Than 1 tr or Long Crack	With open Cracks	With Interior Breakage	Badly Shattered or Replaced
Shale Gr Fill Cut		P	9	66 7	11 1	11 1	11 1		11 1		
		R	45	71 2	2 2	2 2	13 2	11 0			
		P	22	9 1	6 4	6 4	63 4	25 6	40 9		
		R	11	72 7	18 2			9 1			
		P									
		R	8	75 0	12 5		12 5				
Gravel and Loam	C	P									
		R	16	50 0	37 4	6 3	6 3				
	F	P	65	3 1	15 4		51 5	30 0	21 5	3 1	
		R	38	84 1	10 5		2 7	2 7			
	G	P	6	16 6	33 3		50 0				
		R	4	50 0	50 0						
Clay and Loam	C	P	5	40 0		60 0					
		R	7	42 8	28 6	28 6					
	F	P	52	21 1	13 5	1 9	34 5	28 8	40 3	1 9	
		R	18	60 9	37 3	5 8					
	G	P	9	44 4		11 2	44 4				
		R	7	100 0							
Loam	C	P	38	7 8	2 6	2 6	63 2	23 8	47 6		
		R	48	25 0	28 9	14 5	22 9	8 3	10 4		
	F	P	253	9 1	3 5	3 2	50 0	32 1			2 0
		R	115	44 2	17 3	4 3	27 9	6 1	4 3	0 8	
	G	P	40	7 5			42 5	32 5	22 5		17 5
		R	4	25 0	25 0		25 0	25 0			
All Subgrades	C	P	52	21 1	3 8	9 8	48 0	17 3	36 6		
		R	116	47 5	19 8	9 5	17 1	7 8			
	F	P	392	9 7	6 9	2 5	49 0	30 5	30 5	3 1	1 3
		R	182	56 2	17 6	3 3	18 2	4 9	2 7	0 5	
	G	P	55	14 5	3 6	1 8	43 6	23 6	16 4		12 7
		R	23	69 3	17 4		8 7	4 3			
Total		P	499	11 4	6 2	3 2	48 3	28 5	29 4	2 4	2 4
		R	321	53 8	18 4	5 3	16 5	5 9	4 1	0 3	

N Y TABLE 5

Slab condition of Road No 1066, New York, as influenced by cut, fill and grades and reinforcement

		Type	Total No Slabs	O K	Hair Cracks Only	1 Transverse	1 Longitudinal	More than 1 Crack	With Open Cracks	Badly Shattered or Replaced	Corners 2000 Sq Yds Cracked	Corners 2000 Sq Yds Broken	Corners 2000 Sq Yds Total
Clay & Loam A S & W No 20	C	P	24	20 8		12 5	4 2	58 3		4 2	11 3	11 3	22 6
		R	2			50 0	50 0				0	37 5	37 5
	F	P	90	5 6	1 1	4 5	18 8	67 6		3 3	7 5	9 1	16 6
		R	18	11 2		11 2	38 9	38 9			8 3	24 9	33 2
	O	P	3	33 3	33 3	33 3							
		R											
	Total	P	117	9 4	1 7	6 8	15 4	64 0	14 5	2 5	8 9	10 9	19 8
		R	20	10 0	0	15 0	40 0	35 0	5 0	0	3 7	14 8	18 5
Well Rolled A S & W No 28	C	P	52	13 5	1 9	5 8	22 1	57 6			7 2	10 2	17 4
		R	12	66 7		8 3	25 0				0	0	0
	F	P	73	19 2	2 7	16 4	30 1	31 5			0 5	4 1	4 6
		R	41	48 8	4 9	9 7	17 1	19 5			0	0	0
	O	P											
		R											
	Total	P	125	16 8	2 4	12 0	26 4	42 4	22 4		3 3	6 6	9 9
		R	53	52 8	3 8	9 4	18 8	15 1	9 4		0	0	0

* Of which 3 7% are adjacent to bridge abutment

DETAILED STUDY OF TYPICAL ROADS

The behavior of roads in service is illustrated by the following examples

New York State Highway No 5546—Extending from Evans Center to Eighteen Mile Creek, Erie County, 23,654 feet long, 16 feet wide, 6-8-6 section, 1 part cement (Dragon), 1½ parts Niagara River sand, 3 parts No 2 and 3 limestone, joint spaced about 30 feet with ⅜″ creosoted yellow pine filler Is given as a representative specimen because of its age, 10 years, its traffic, heaviest in Western New York, being on the Buffalo-Erie Route, having reinforcement in 19 lengths distributed throughout the road, having 4 types of subgrade and five sections of subbase, both with and without tile drains

The reinforcement, No 28 A S & W, was placed 2 to 3 inches from the top, and covers only the center 12 feet of the road

Concrete was mixed in a Loader & Trostum Drive Foote Batch—16½ cu ft to the batch

Joint filler was held in place by holders set on side forms

Shoulders were of earth and 8′ wide

Road was finished with wooden float, recommended by Wm M Acheson, Div Eng It was cured by wet earth, 2 to 3-inches thick, and was opened to traffic in 15 days

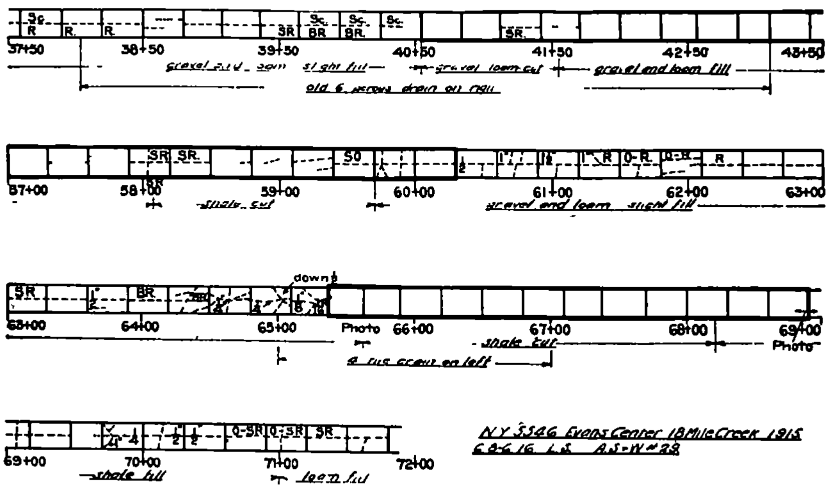


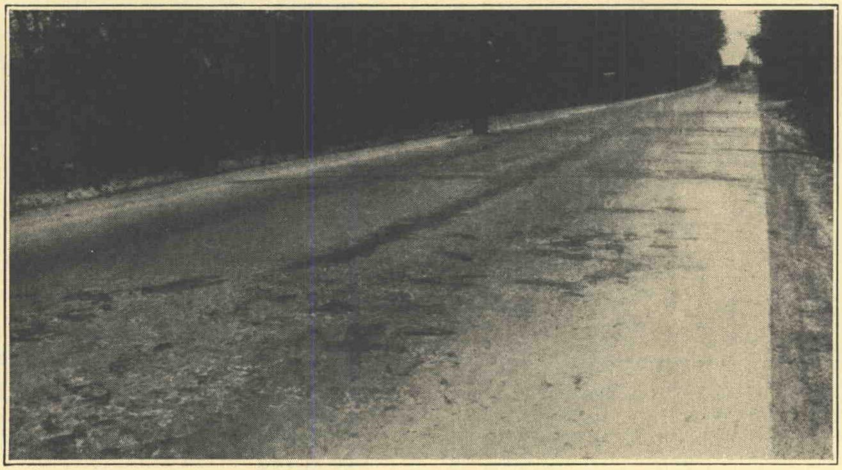
Figure 65—Sketch of Road No. 5546, New York

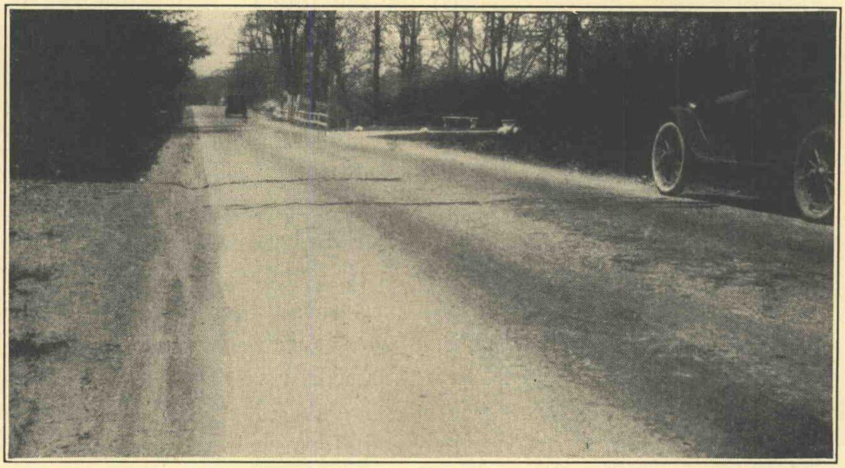
General conditions of the two types of surface is shown in Table 3. Reinforcement was used to take care of supposedly bad subgrade conditions, and, as is evidenced by the much greater number of corner breaks shown in column 5 of Table 3, excellent judgment was used in its placement These breaks did not concern the reinforcement, since the latter extended only to within 2 feet of the side edge Column 6, however, shows effect of reinforcement in stopping the breakage at the 2-foot line With one exception, no corner break penetrated the reinforcement more than 2 feet, the majority of the 29 per cent stopping within 1 foot after steel was encountered The plain corners extended double the above distances

Table 4 shows the condition of the road, as influenced by subgrade and reinforcement This table shows very clearly that, while the plain concrete was considerably influenced by various subgrade conditions, the reinforcement was effective on all types Figure 65 shows a portion of this road in sketch form, while Figures 66, 67, and 68 show relative conditions of slabs at three junctions of plain and concrete sections The condition of the road in diagrammatic form is shown in Figure 75. The five sections laid on subbase course indicated no beneficial effect for this procedure In fact, the only appreciable breakage in the reinforced slabs was in one of these subbase sections at station 166+50

Co-operating in this inspection were H F. Janda, National Research Council, E B Smith, U S Bureau of Public Roads, and E N Scott, New York State Highway Department

Orchard Park, E Aurora Road No 1066—Thickness, aggregate, and age were the same as for Road No 5546 Universal cement,





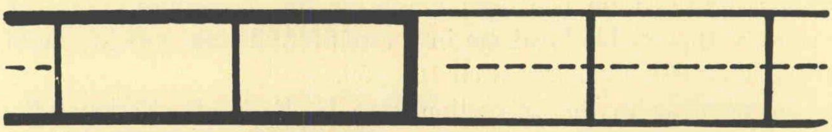


Figure 66—Road No. 5546. Plain and reinforced sections. Station 40+65

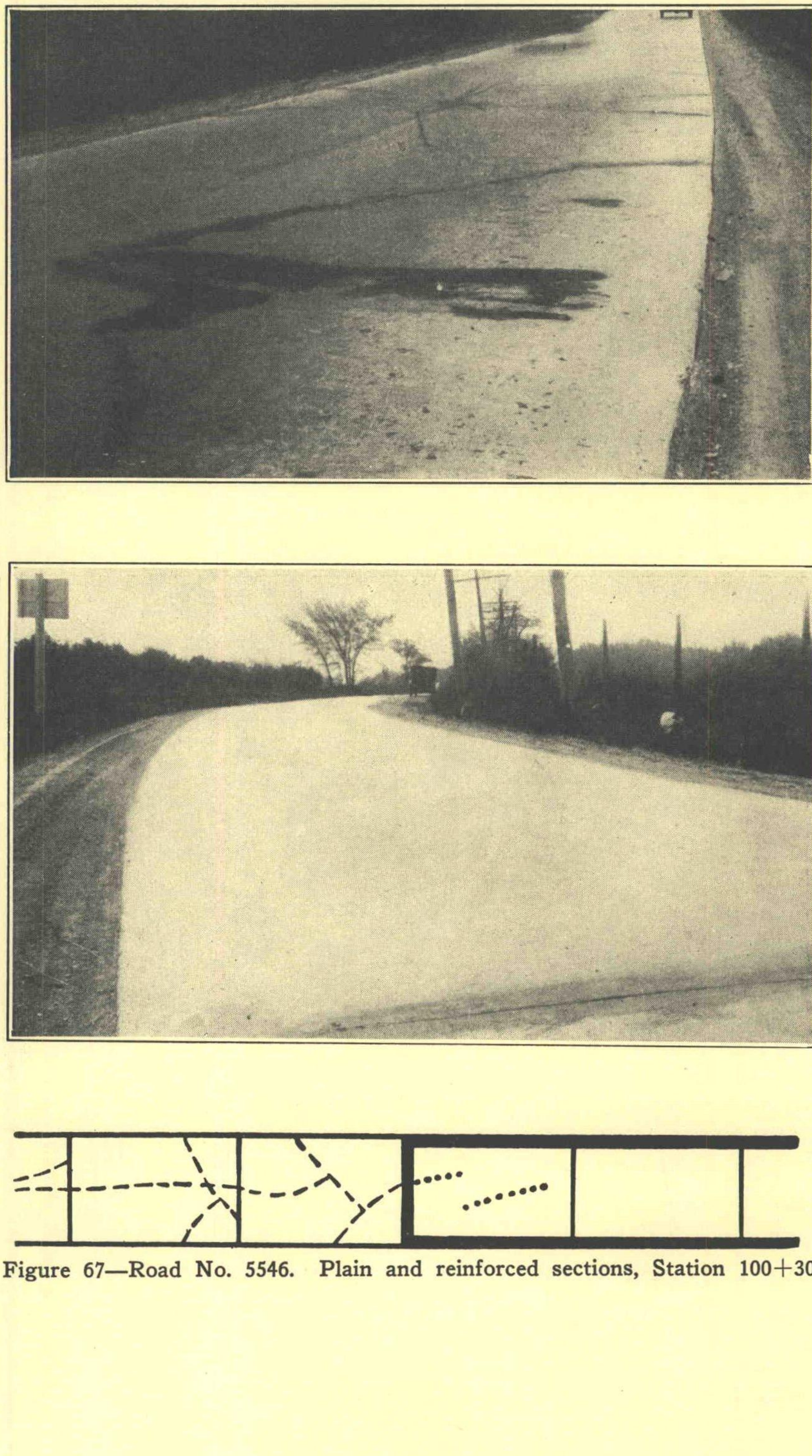
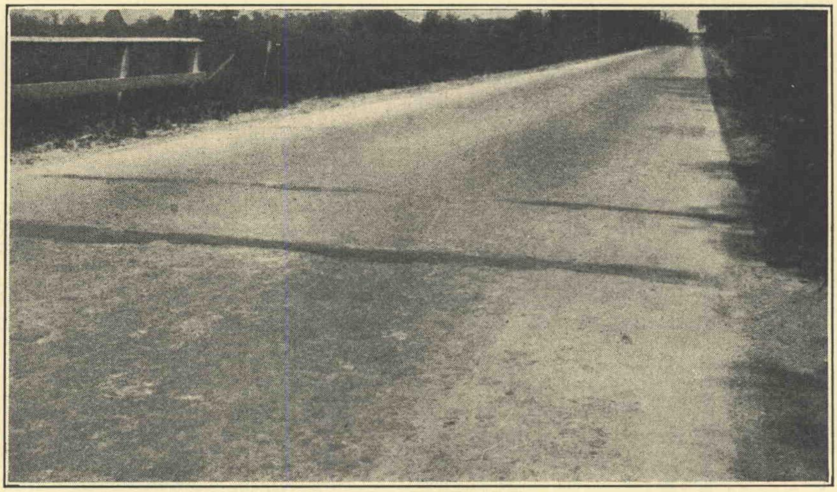
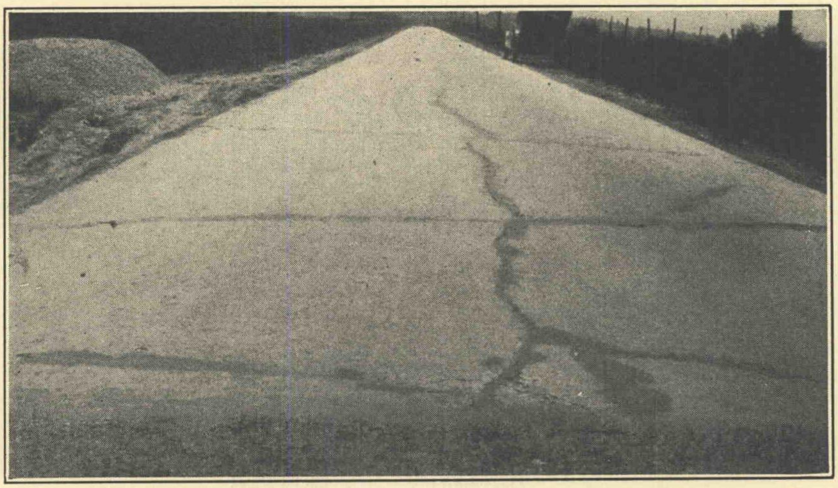


Figure 67—Road No. 5546. Plain and reinforced sections, Station 100+30





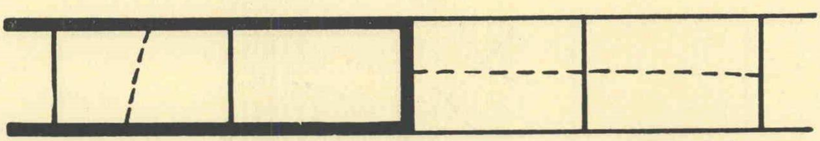


Figure 68—Road No. 5546. Plain and reinforced sections. Station 202+70

TABLE 6 N Y S H No 1416

Condition of Road No 1416, New York, as influenced by subbase and reinforcement

Base Course	Type	Total No of Slabs	Per cent of Total No of Slab: O K.	One Trans Crack	One Long Crack	More Than One Crack	Open Long Cracks	Cors Cr per 2000 Sq Yds. Surface
4" gravel	P	2	50 0	50 0				
	R							
6" gravel	P	19	52 5	26 4	5 3	15 8	21 1	1 9
	R	18	61 0	39 0				
8" gravel	P							
	R	10	80 0	20 0				3 9
10" gravel	P	1		100 0				
	R							
12" gravel	P							
	R	4	25 0	50 0	25 0			
Total for b c Sects	P	22	50 0	31 8	4 5	13 6	18 2	1 7
	R	32	62 5	34 3	0	3 1		1 2
For Sects without b c	P	293	62 4	20 8	12 0	4 8	5 8	0 9
	R	134	74 4	21 6	2 4	1 5		

TABLE 7 N Y S H 1315

Comparison of plain and reinforced section, Road No 1315, New York

Station	Type	Per cent of Total No: Total No Slabs	O K	Hair Cracks Only	One Trans Crack	One Long Crack	More Than One Crack	Open Long Crack
413–82	P	2				100		
	R	2	100					
407–8	P	2					100	
	R	2	100					
348–60	P	2	100					
	R	2	100					
317–90	P	2				100		
	R	2	100					
297–36	P	4				75	25	75
	R	4	75	25				
295–54	P	3				66 7	33 3	100
	R	3	100					
57–20	P	7	14 3			57 2	28 6	28 6
	R	7*	71 3	28 5				
53–20 .	P	8	37 3	25 0		37 3		
	R	8	87 5			12 5		
Total	P	30	16 7	6 7		53 3	20 0	30 0
	R	30	90 0	3 3		3 3	3 3	

* Excluding one slab across culvert which contains two trans cracks

TABLE 8 N Y S H 1315 LENGTH OF CRACK AND JOINT PER 2000 SQ YDS SURFACE *

Type	Joint	Trans Crack	Long Crack	Total Crack	Crack Joint
Plain	600	100	770	870	1470
Reinforced	678		38	38	716

* Based on Table 5—exclusive of hair cracks

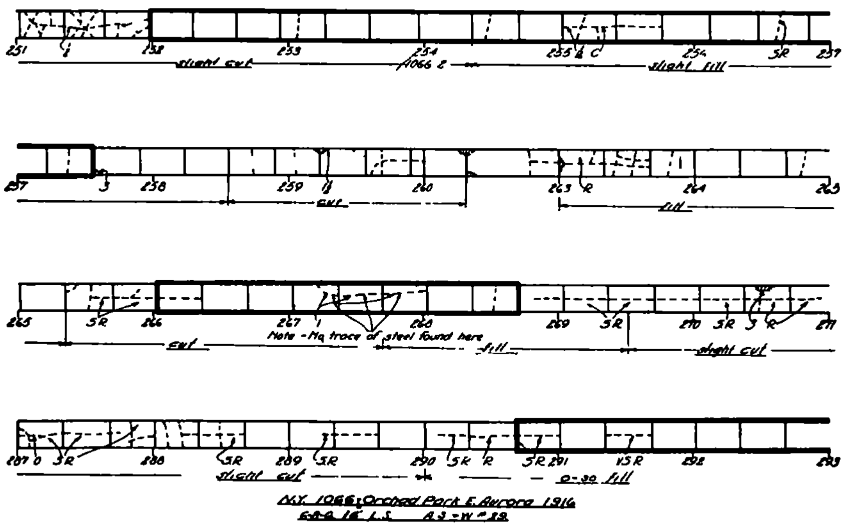


Figure 69—Sketch of Road No 1066, New York

A S & W, No 28, 16 feet wide, used to station 236+30, 15 sections, and A S & W, No 20, 16 feet wide, stations 248 to 307, 15 sections, and A S & W No 28, 16 feet wide, under brick, stations 327 to 348 Inspections were begun at station 179, and included 3 sections with No 28, 5 with No 20, and one with No 28 reinforcement under brick

This road was laid in deeper cuts and on higher fills than No 5546, and in some cases the concrete seemed to be of inferior quality

The general conditions of the road is shown in Table 5, while representative sketches are given in Figure 69 A comparison, ideal because of similarity of surrounding conditions, is shown in Figure 70

This road furnished an excellent example of the beneficial effect of mesh reinforcement in concrete bases Figure 71, showing views looking each direction from station 327+50, amply illustrates the surface benefit derived by holding fractured bases together by means of reinforcement The base course was 4-6-4-inch section with 6 x 12-inch integral curbs, and the top was 4-inch, cement grout-

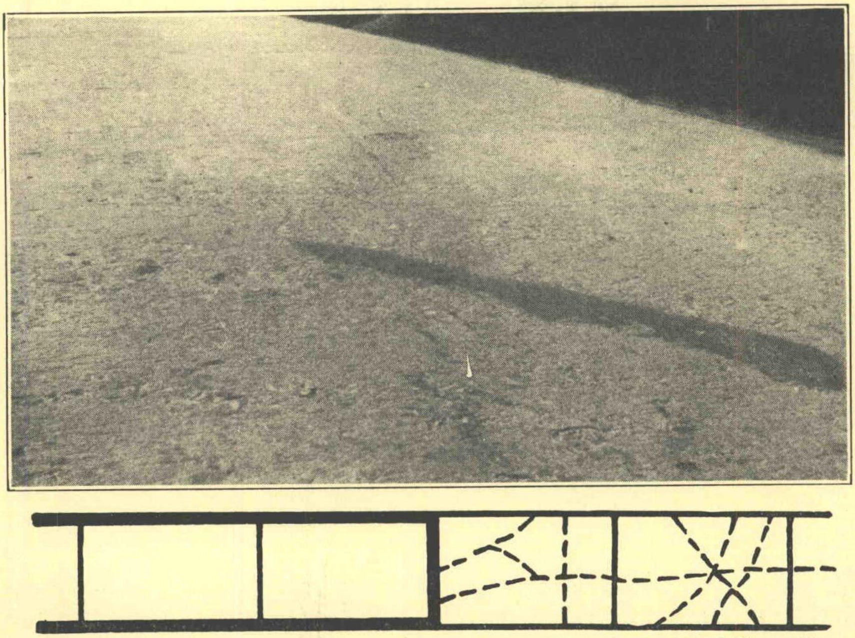


Figure 70—Plain and reinforced sections Station 252+00—Road No. 1066

filled vitrified brick, laid on 1½-inch sand cushion. Reinforcement (28 lbs. per 100 sq. feet) was used between stations 327+50 and 334+58. At the latter station the surface was in excellent condition, showing no apparent difference with change of base. At station 327+50, however, in a 15-foot cut on an 8 per cent grade, the change from plain to reinforced base was clearly marked. In the plain-base section, the grout was broken, bricks were slightly uneven, one corner was broken out, and bricks were shattered in an 18-inch-wide strip, probably over an open longitudinal crack through the center of the base, which allowed the sand cushion to escape.

In the reinforced base section the top was smooth and uniform, with grout intact. One very tight crack, about 50 feet long, extended through the bricks without spalling or disturbance of grout bond.

Co-operation in this inspection was the same as for Road No. 5546.

New York State Highway, No. 1416.—Genesee Street, from town line of Alden, 615+00, to town line of Darien, 926+40 (County Line).

Same design and mix as 5546 and 1066; traffic probably much less, and subgrade better, being gravel and clay in flat country. Quicksand pockets below clay in some locations prompted use of A. S. & W. No. 29, and also gravel subbase.

Inspections were made between stations 796+20 and 926+40 (13,020 feet), in which were 12 lengths of reinforced pavement and 9 lengths of subbase.

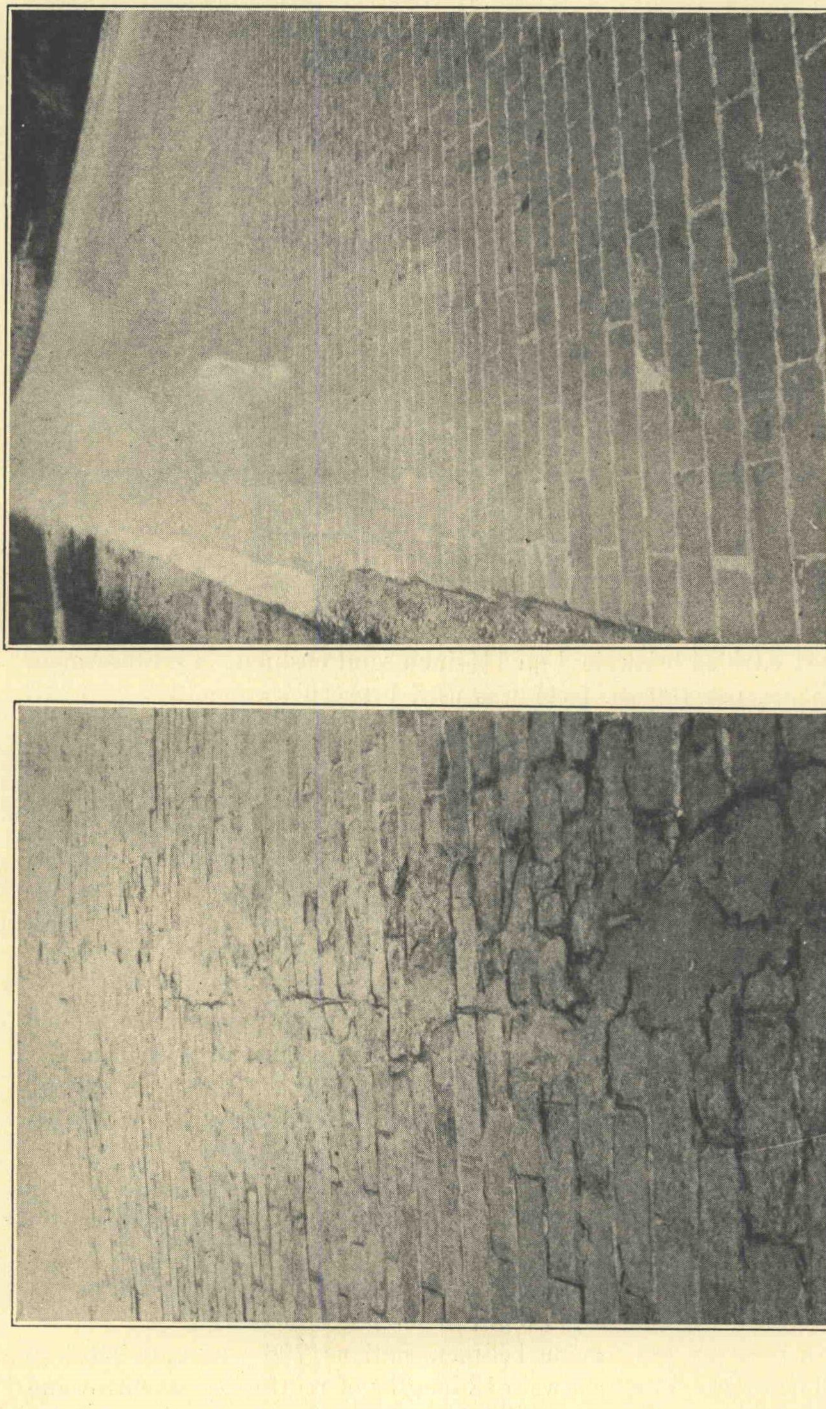


Figure 71—Brick tops on plain and reinforced bases Stations 327+59, Road No. 1066

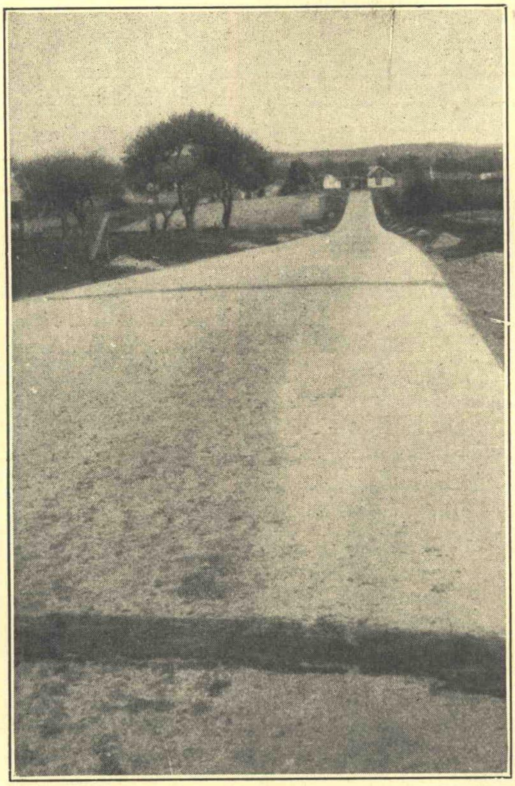


Figure 71-A—General condition of New York State Highway No. 1416

Two slabs contained double layers of reinforcement. One was over a culvert at station 92+65, and contained 2 transverse cracks. The other was O. K., but was between two O. K. single-layer reinforced slabs.

This road was in exceptionally good condition, showing little or no raveling, except the open longitudinals, which were similar to those shown in Road 1066. Figure 71-A shows general condition of this road.

The detailed condition of the part inspected is given in Table 6, which again shows no beneficial effects for the subbase course as used.

E. B. Smith, of U. S. Bureau of Public Roads, co-operated in this inspection.

New York State Highway No. 1315.—Cambria-Wilson (1919) 5-7-5 x 16 feet, 1:1½: 3-Penn-Allen and Edison cements; Niagara River sand and crushed limestone; on clay loam subgrade, rolled with 10-ton roller; reinforced over 17 weak spots with A. S. & W. Style 049 mesh, weighing 25 lbs. per 100 sq. feet, placed 2 inches from top, being but 12 feet wide, and lapped 5 per cent; with Carey elastite and ⅜″ creosoted wood-filled joints, spaced 26 to 30 feet apart.

This road, which apparently received light traffic, was in excellent condition. Comparisons at 8 points of change from plain to reinforced, or vice versa, are given in Tables 7 and 8. Only a small number of slabs were used, as it was felt a larger number would not increase the accuracy or change the result to any considerable extent. For instance, the length of longitudinal unit-crack length of 38 feet, as given in Table 8, compares favorably with the 40.05 feet length in two reinforced sections aggregating 3,784 feet. But two corner breaks were recorded in 4,700 feet, one in plain and one in reinforced sections.

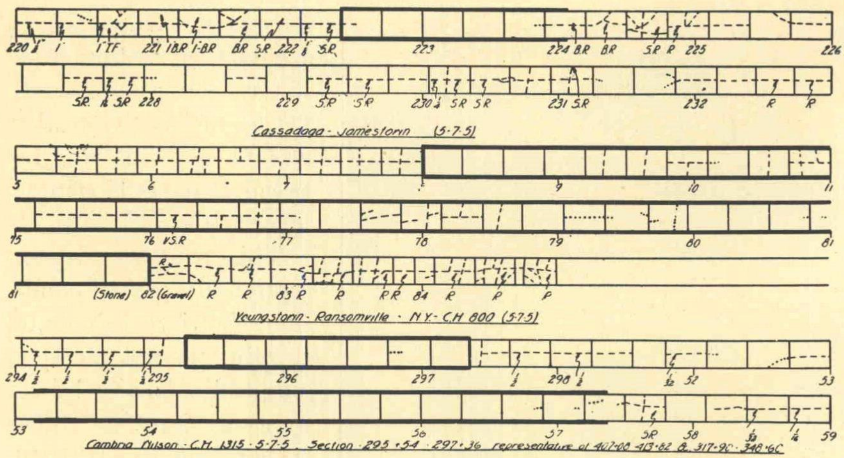


Figure 72—Sketches of New York Roads Nos. 800 and 1315

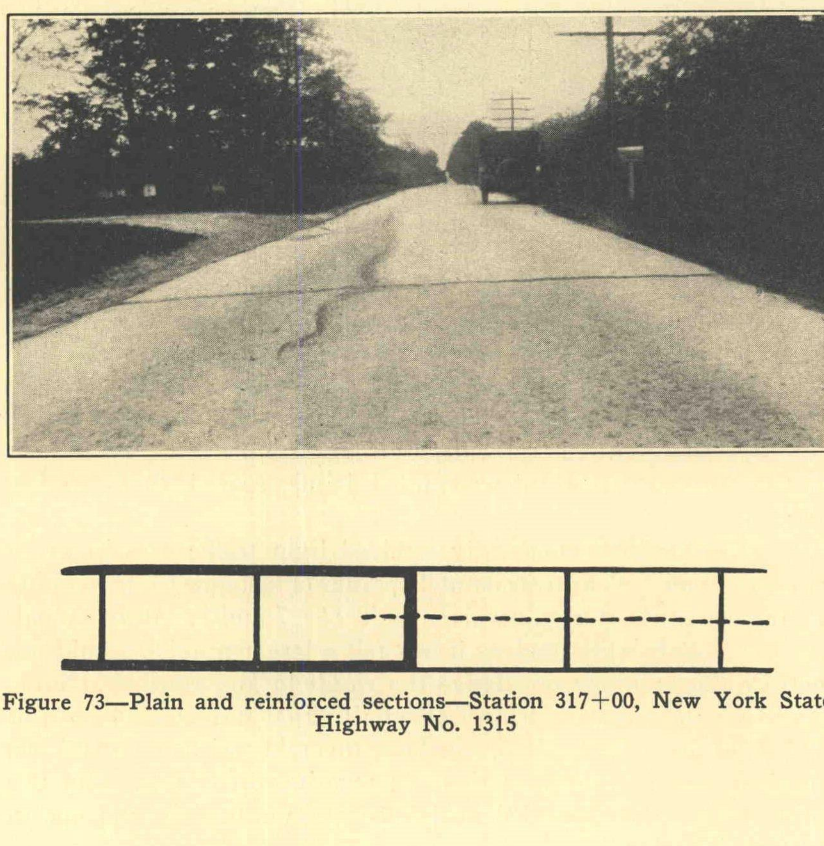
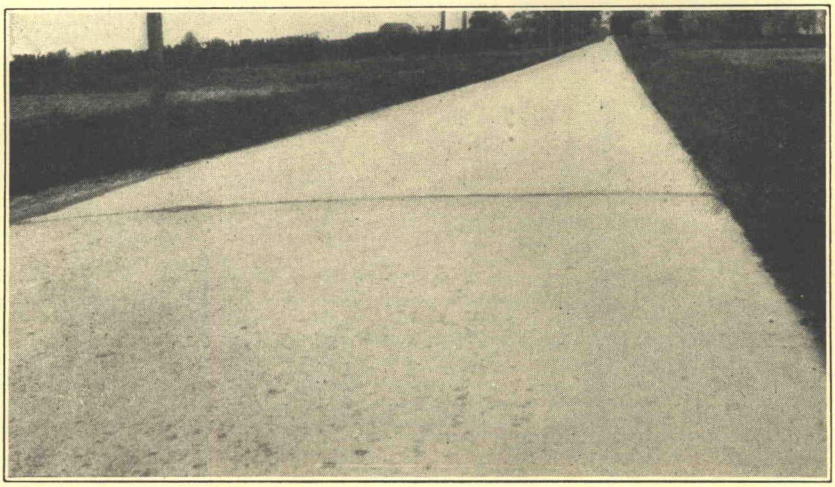


Figure 73—Plain and reinforced sections—Station 317+00, New York State Highway No. 1315



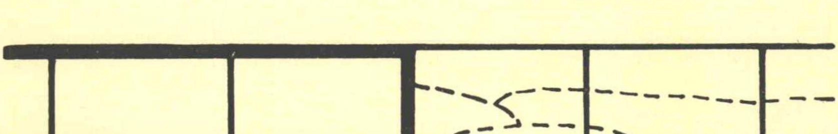


Figure 74—Plain and reinforced sections—New York Road No. 800

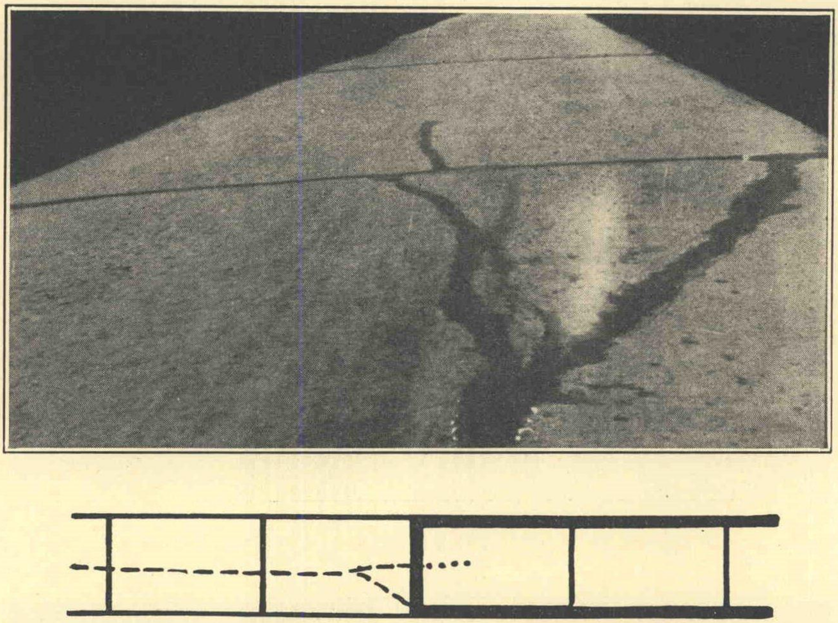
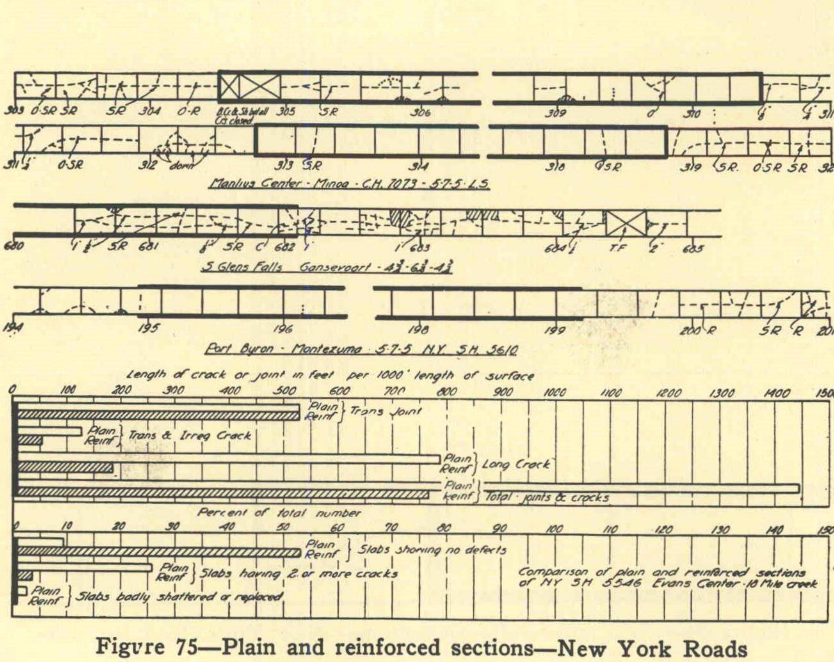


Figure 74-A—Plain and reinforced sections—New York Road No. 799



Figvre 75—Plain and reinforced sections—New York Roads

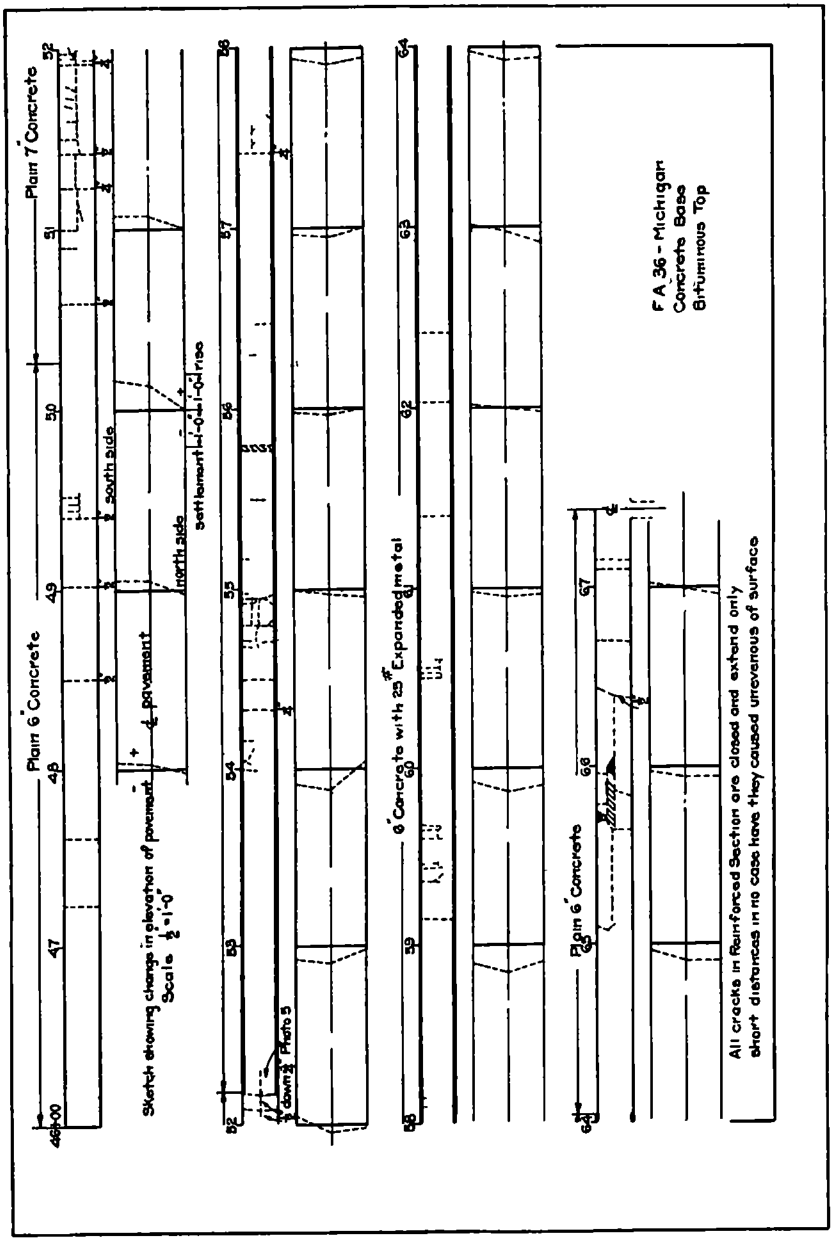
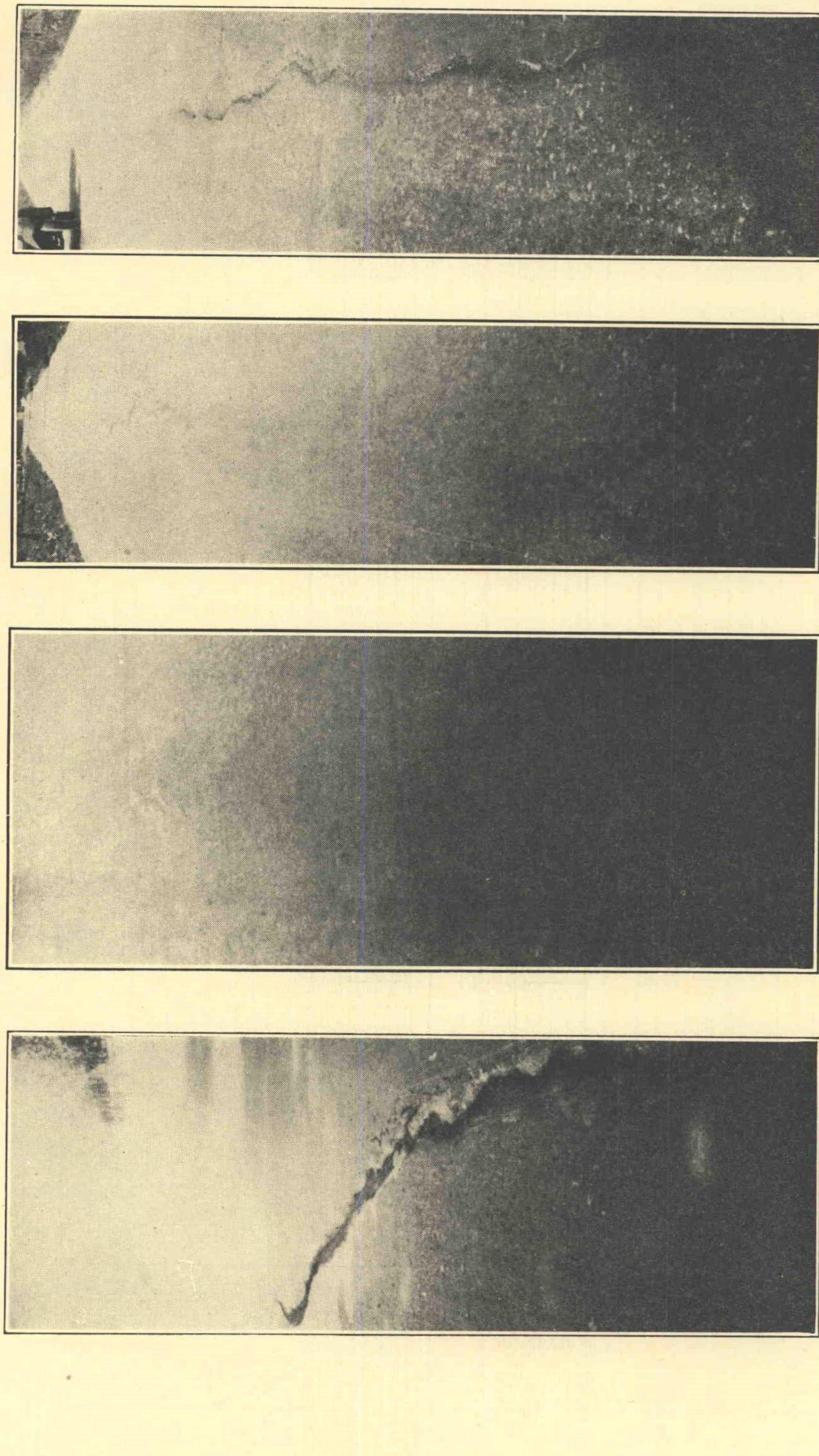


Figure 76—Sketch of comparative sections. F. A. 36, Michigan



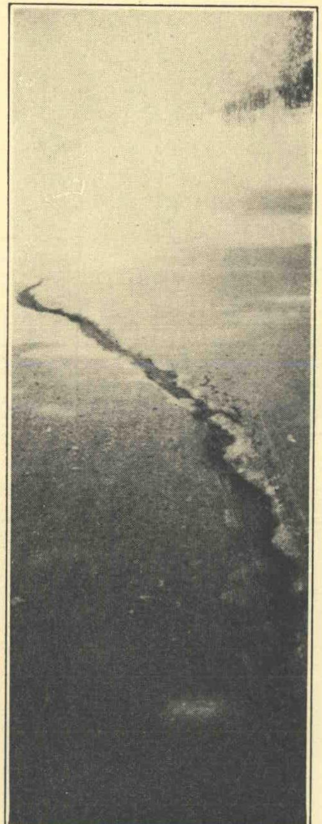
6" plain base

6" reinforced base

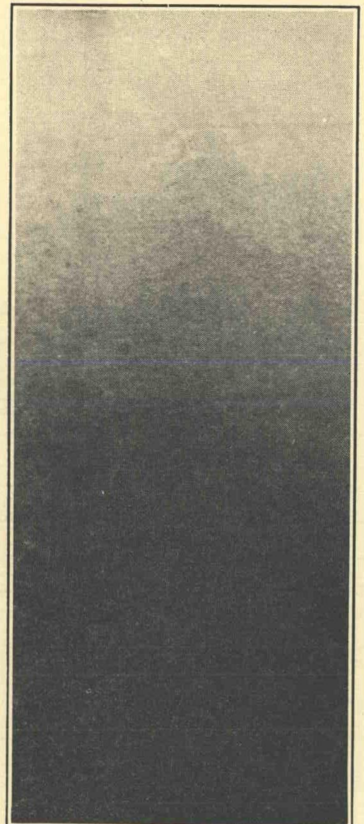
Junction of 6" reinforced (foreground) and 7" plain base

7" plain base

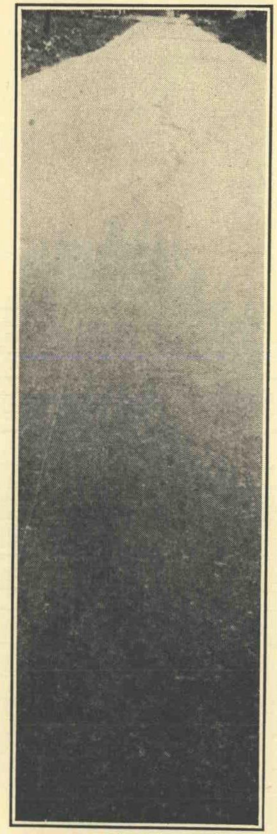
Figure 77—Photos showing relative influence of reinforcement and concrete thickness for concrete base. F. A. 36, Michigan



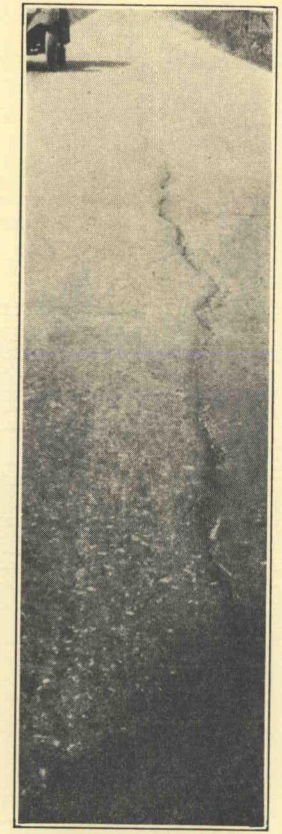
6″ plain base



6″ reinforced base



Junction of 6″ reinforced (foreground) and 7″ plain base



7″ plain base

Figure 77—Photos showing relative influence of reinforcement and concrete thickness for concrete base. F. A. 36, Michigan

Representative comparisons on road 1315 are shown by sketch, Figure 72, and by Figure 73

E B Smith, U S Bureau of Public Roads, co-operated also in this inspection

New York State Highway Cassadaga to Jamestown—5-7-5 16 feet, limestone, 1915 Of eight short fills, four were in good stretches of road and showed few or no defects The other four were in stretches of road considerably cracked on both sides of and extending through three of the fills One of the latter, supposed to be on very poor subgrade, was reinforced and is in excellent condition

The reinforcement (25 lbs A S & W) was 16 feet wide from station 222+40 to 223+70 and 10 feet wide from 223+70 to 224+06 This reinforced fill and a plain one adjacent to it are shown in sketch, Figure 72

H F Janda, National Research Council, co-operated in this inspection

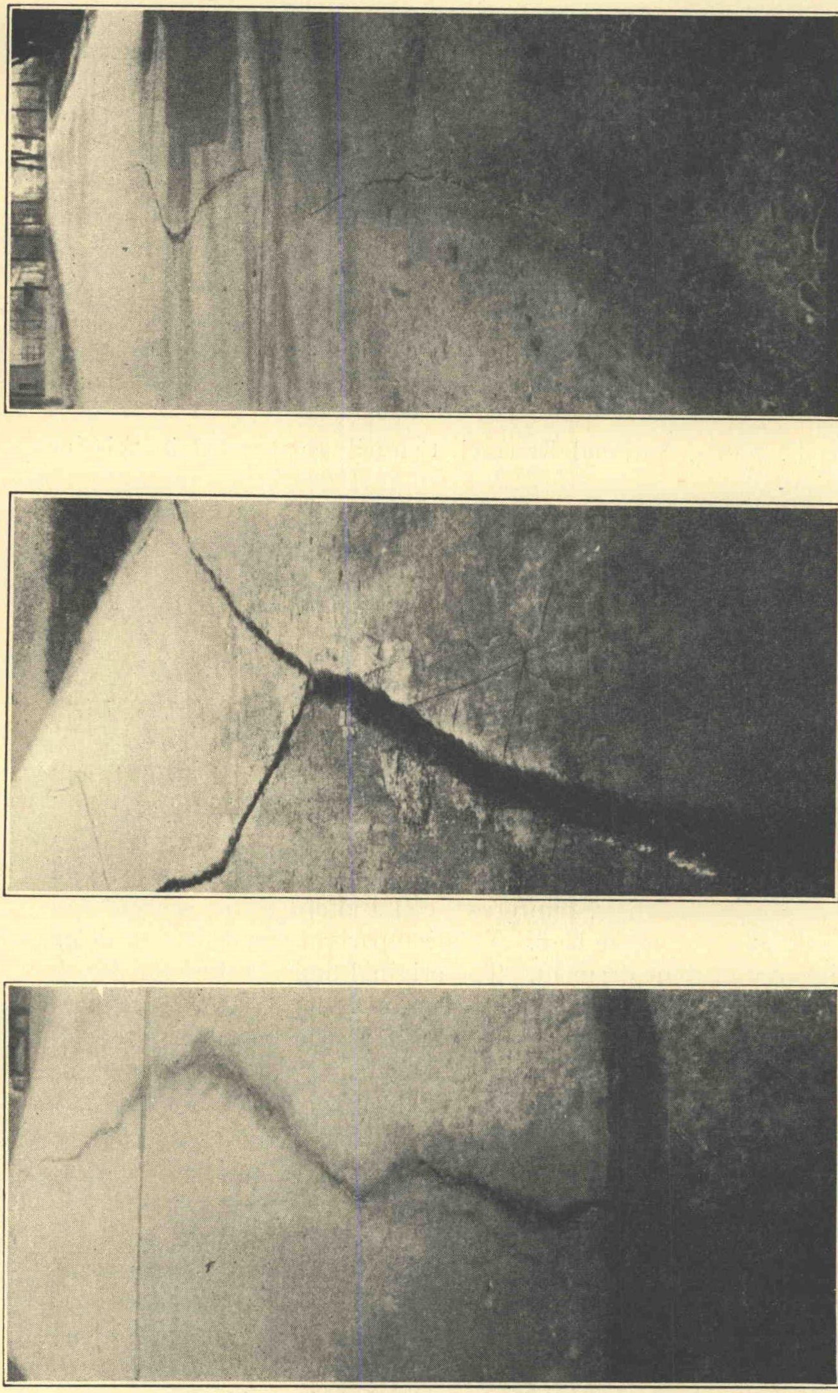
New York County Highway No 800—5-7-5 16 feet, 1916, crushed limestone on clay and loam subgrade, rolled with 10 ton roller

Comparisons between plain and reinforced sections at station 8+00 are shown in sketch, Figure 72, and in Figure 74

Description of other New York roads shown in sketches and plates can be obtained from Table 2, N Y S H Nos 799, 7073, and 5610, being respectively specimen Nos 138, 142, and 144

South Glens Falls-Gansevoort Road Shown in Figure 75 It will be noted that, while cracking was not reduced by reinforcement, breakage apparently was

Michigan State Highway, Federal Aid No 36—Demonstrated that a 6-inch thickness, reinforced, could afford better service than a 7-inch plain concrete base This comparison resulted from delay in delivery of reinforcement The original design called for 6-inch plain concrete base, with 3-inch bituminous top. Because of questionable subgrade, however, one section was to be reinforced with 25-lb expanded metal Failure of this material to arrive on time prompted the use of an additional inch of concrete as a substitute, which resulted in a very definite comparison of the relative merits of 6-inch plain concrete, 7-inch plain concrete, and 6-inch reinforced concrete base These relative conditions are shown in sketch, Figure 76, and in Figure 77 In the sketch is shown, also, the deviation from the original profile to which the surface was subjected during its first year of service The 6-inch base developed a wide longitudinal crack and subsequent breaking down along this crack, which will require repairs or replacement for a length of 50 feet The 7-inch plain base developed a wide longitudinal crack, but resisted further breaking down As can be seen in sketch-



A—Junction of closed reinforced crack (foreground) with open plain concrete crack Milwaukee Co., Wis.

B—7" plain surface, St. Clair Co., Mich.

C—Junction of closed reinforced crack with open plain crack. South Ridge Road, Lake Co., Ohio.

Figure 78—Influence of reinforcement on crack width

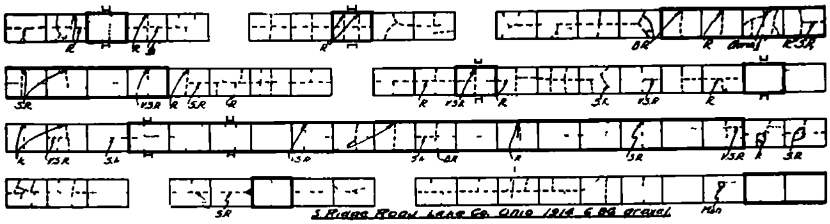


Figure 79—Sketch of comparative sections South Ridge Road, Lake Co, Ohio

at station 52+18, this wide longitudinal crack was tightly closed at the junction with the 6-inch reinforced base, and completely disappeared 15 feet farther on Not only was there considerably less cracking in the latter, but all cracks were tightly closed, and resulted in no unevenness of surface

Inspection of about 100 miles of roads in St Clair County, Michigan, indicated that formation of cracks, such as shown as B in Figure 78, was prevented by 28-lb mesh reinforcement

The difference in width of cracks in plain and reinforced slabs in Milwaukee County, Wis, is shown in A, Figure 78, the slab in the foreground being the one reinforced The difference in crack width in Lake County, Ohio, is shown in C, Figure 78, the reinforced slab again being in the foreground

South Ridge Road, Lake County, Ohio Reported by H D Cummings 1915 As can be seen from Figure 78, the difference in character of crack in adjoining plain and reinforced sections is pronounced Wire fencing was used over questionable subgrades Sketches of this road are shown in Figure 79

North Andover, Mass Road Shown in Figure 80 Similar to F A 36, Michigan, breakage was found in the plain 6-inch

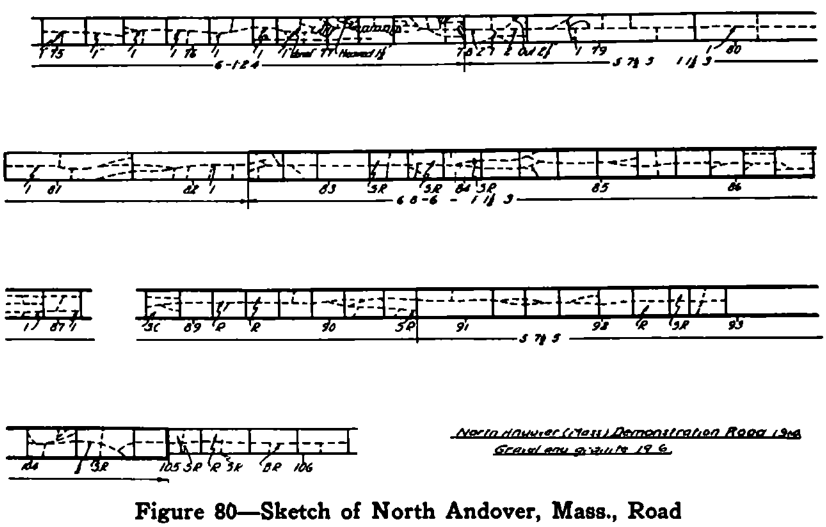


Figure 80—Sketch of North Andover, Mass., Road

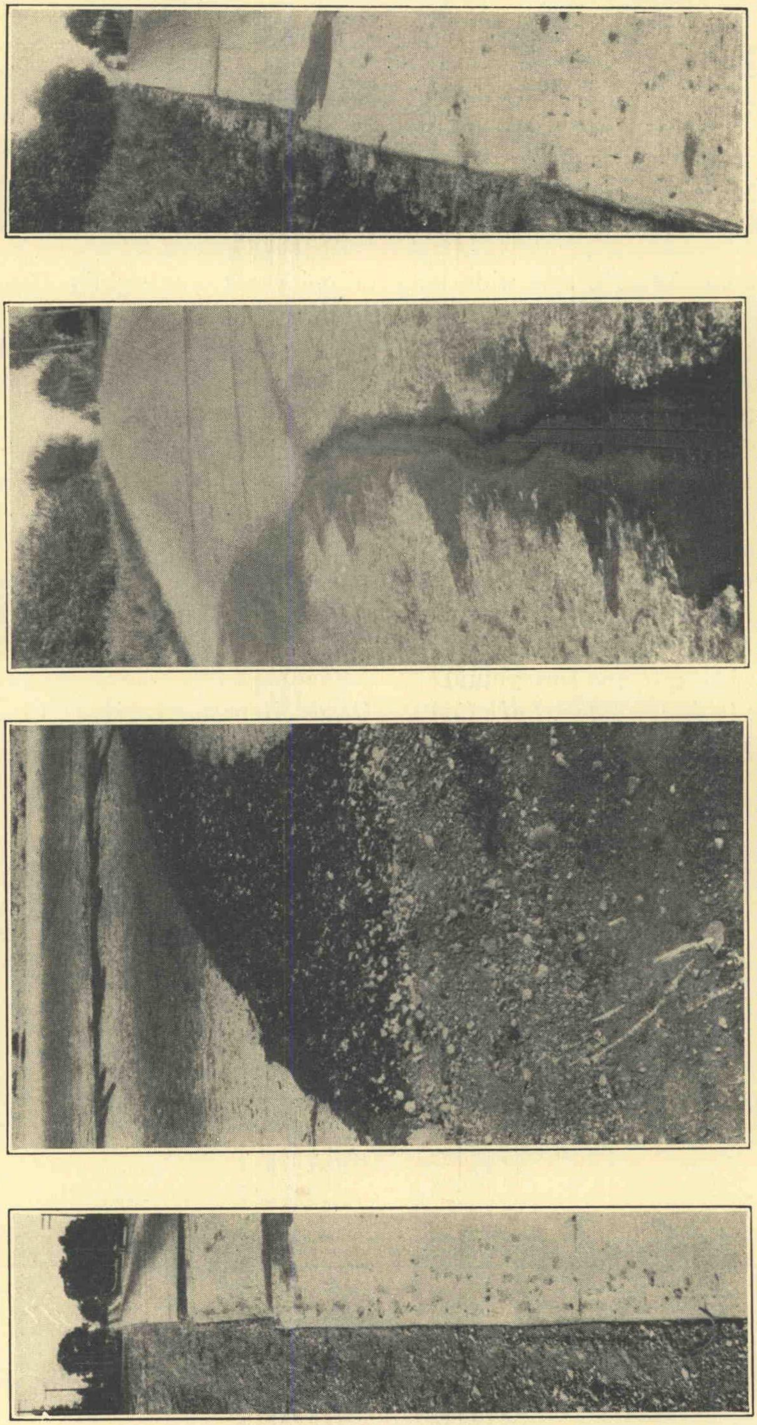


Figure 81—Open cracks in plain concrete slabs with side edge displacement

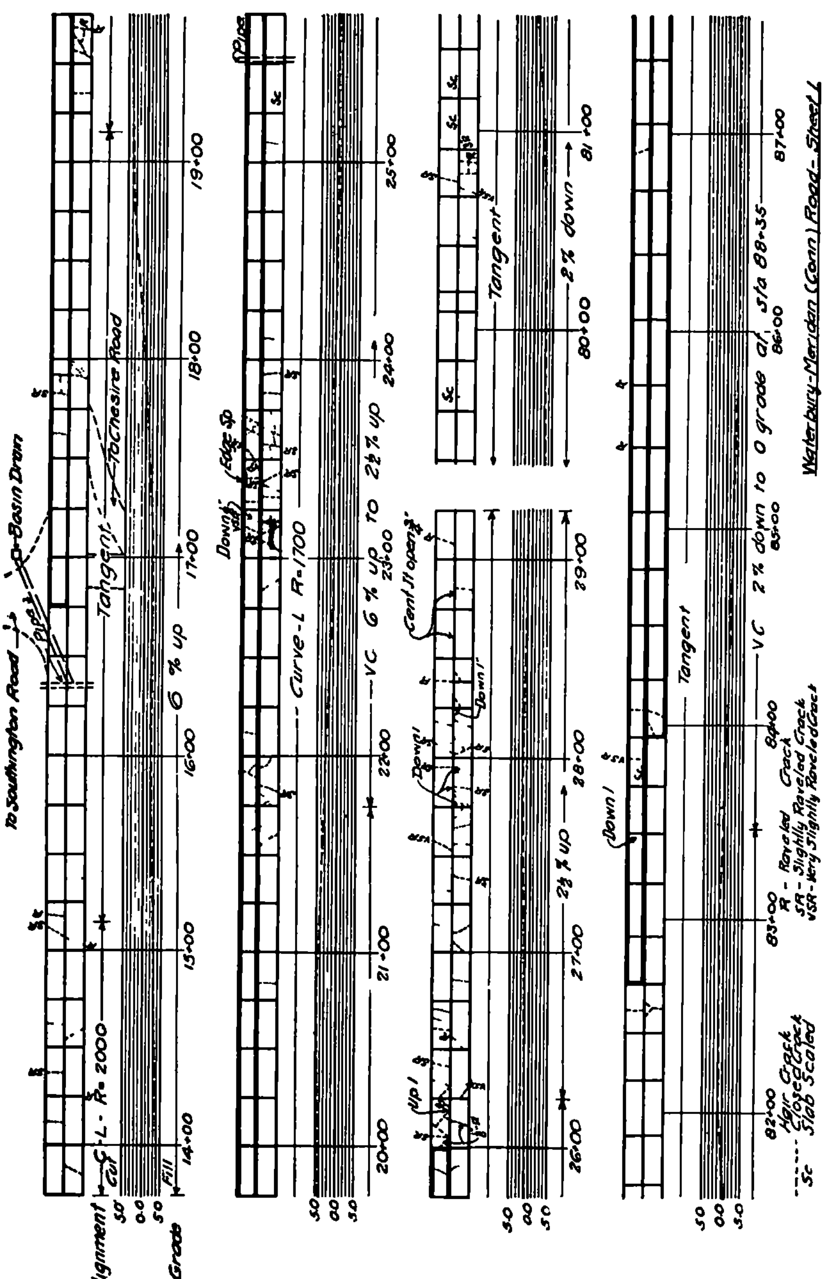
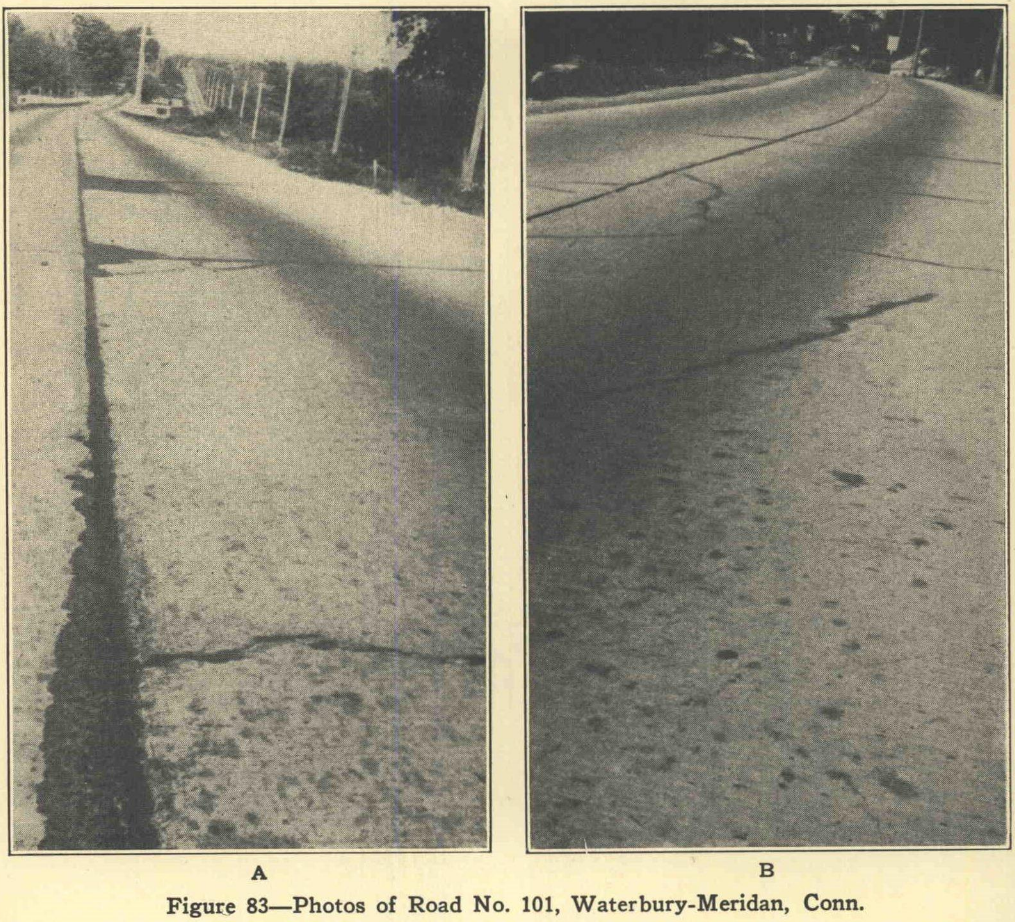


Figure 82—Sketch of Road No 101, Waterbury-Meridan, Conn.

center (station 77+00 to 78+00) and substantiates the statement made before that when 6-inch centers are contemplated, reinforcement of some type becomes a necessity. A view of the wide-open center crack, with accompanying side-edge displacement, is shown in Figure 81. Although in this case cracking was not appreciably reduced, separation of cracks was prevented by reinforcement.

Sketch of the *Waterbury-Meriden Road,* which contained the heaviest reinforcement encountered (7/8" bar mat placed near the bottom of the slab), is shown in Figure 82. Between stations 23 and 24 cracking in the plain and reinforced sections was about the same, while at station 26 the plain concrete section was badly cracked, while the adjacent section, reinforced, was not. View A, Fig. 83, shows the corner breaks in the plain sections along the center line of this road, and view B shows the tightness of crack in a badly cracked reinforced section.

Twelfth Street, Chicago.—Figure 84 illustrates how bars placed



A B

Figure 83—Photos of Road No. 101, Waterbury-Meridan, Conn.

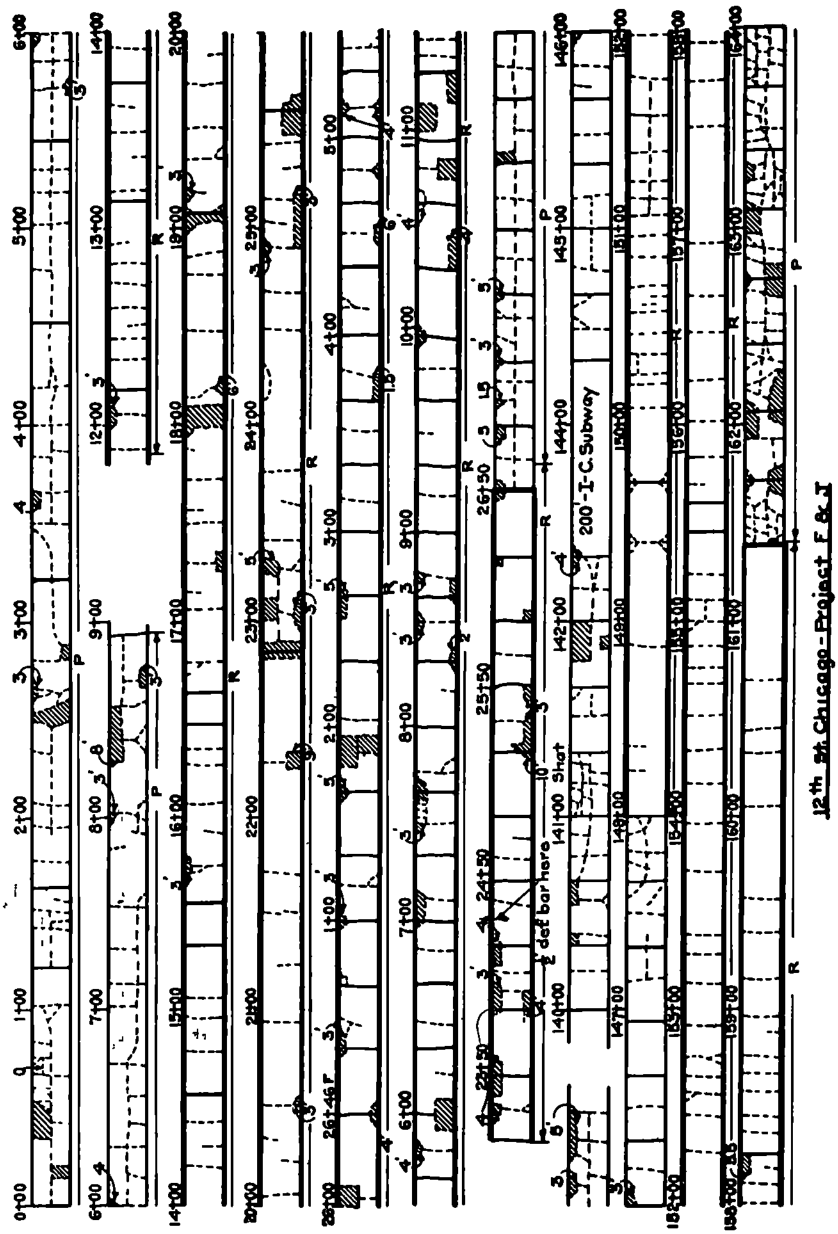


Figure 84—Sketch of Road Nos. 110-111, 12th Street, Chicago, Ill.

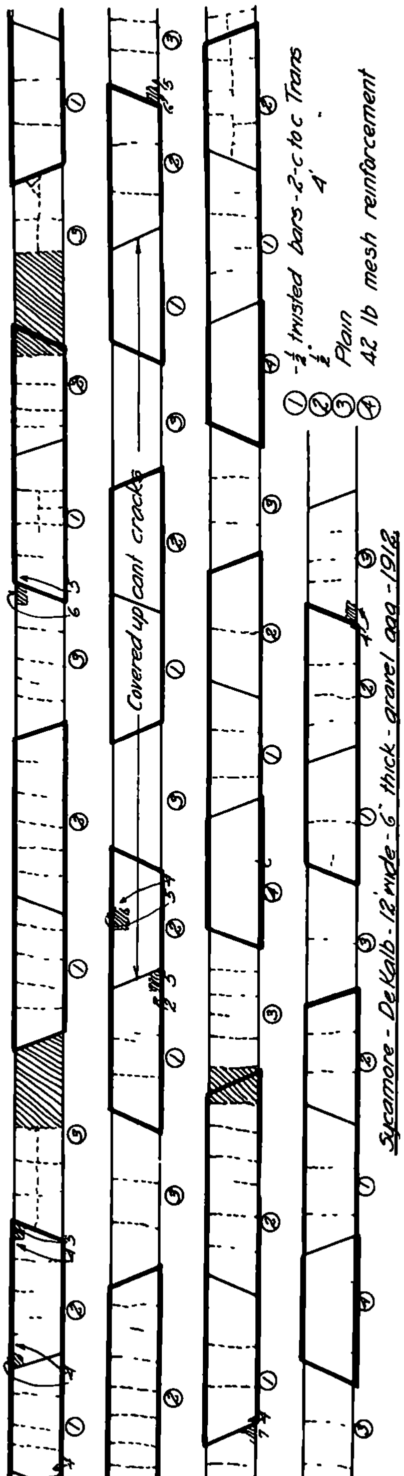


Figure 85—Sketch of Road No 108—DeKalb, Sycamore, Ill

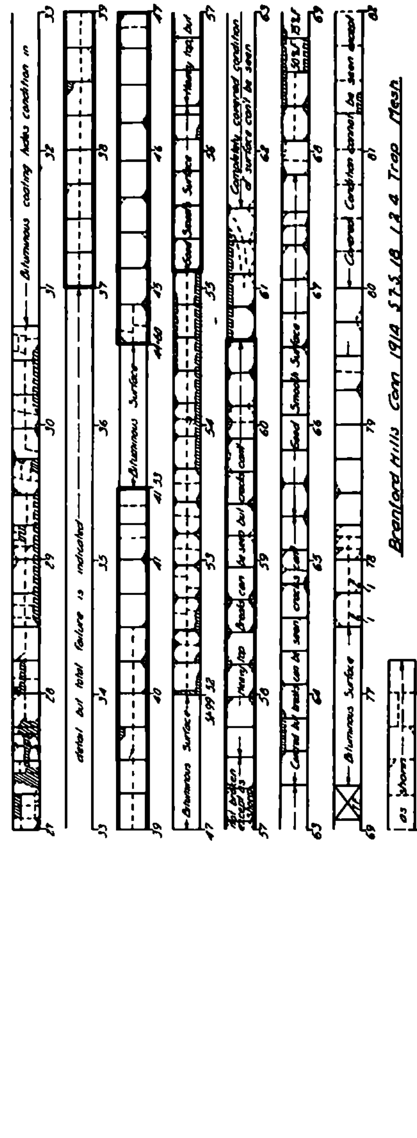


Figure 86—Sketch of Road No. 100—Branford Hills, Connecticut

transversely only, considerably reduced cracking, but offered no appreciable resistance to edge breakage The lack of breaking between stations 148 and 161+30 can be accounted for in part by two additional inches of concrete thickness used between these points

The DeKalb-Sycamore Road, Ill—Shown in Figure 85 Was considered most important, since it was the oldest reinforced road encountered, being constructed by Dean A N Johnson in 1912, it was the only experimental road in which test sections had been repeated and, because of its narrow width (12 feet), the results were considered applicable to modern center joint slabs That mesh reinforcement can be beneficial in center joint roads is shown by comparison of No 4 slabs (42-lb mesh, A S & W, 29-A) with all others in the road In two of these slabs, which were 50 feet long no crack of any kind could be found, while in the third there were but 2 short hair cracks, requiring no maintenance Every other slab in the road was cracked, and some had suffered considerable breakage While the average length of the mesh-reinforced slabs was about 50 feet, as originally constructed, the average length of the other slabs had been reduced by transverse cracks to about 16 feet

The Branford Hills Road, Conn—Shown in sketch 86 Was also a very interesting road, being constructed in 1913 It was only by co-operation of the Connecticut State Highway Department in furnishing a core drill that several of the reinforced sections were located The reduction in cracking and breakage in the reinforced sections is evident

As a final demonstration of what can be expected from the use of reinforcement there are shown in Figure 87 a number of plain concrete sections, and in Figure 88, adjacent reinforced sections For every plain concrete section shown in Figure 87, there is shown in Figure 88 a comparable reinforced section located in the same road

In these summary sketches are included thicknesses of 4 to 8 inches, widths of 12 to 20 feet, joint spacings of 25 to 200 feet, full-width and center-joint slabs, gravel and crushed stone aggregates, reinforcements varying from wire fencing to 170 lb bar mats, and ages 4 to 13 years The comparisons were secured from 21 roads, distributed in 9 different States

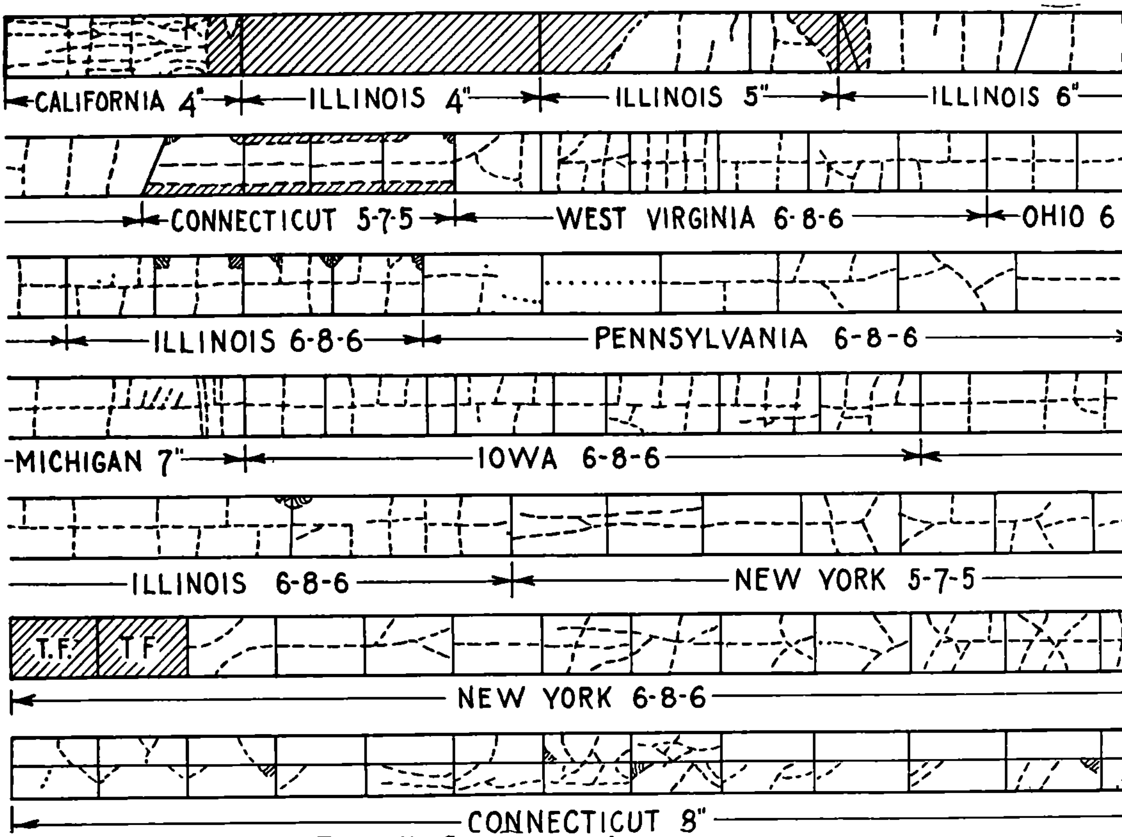


Figure 87—Summary sketches—plain concrete sections

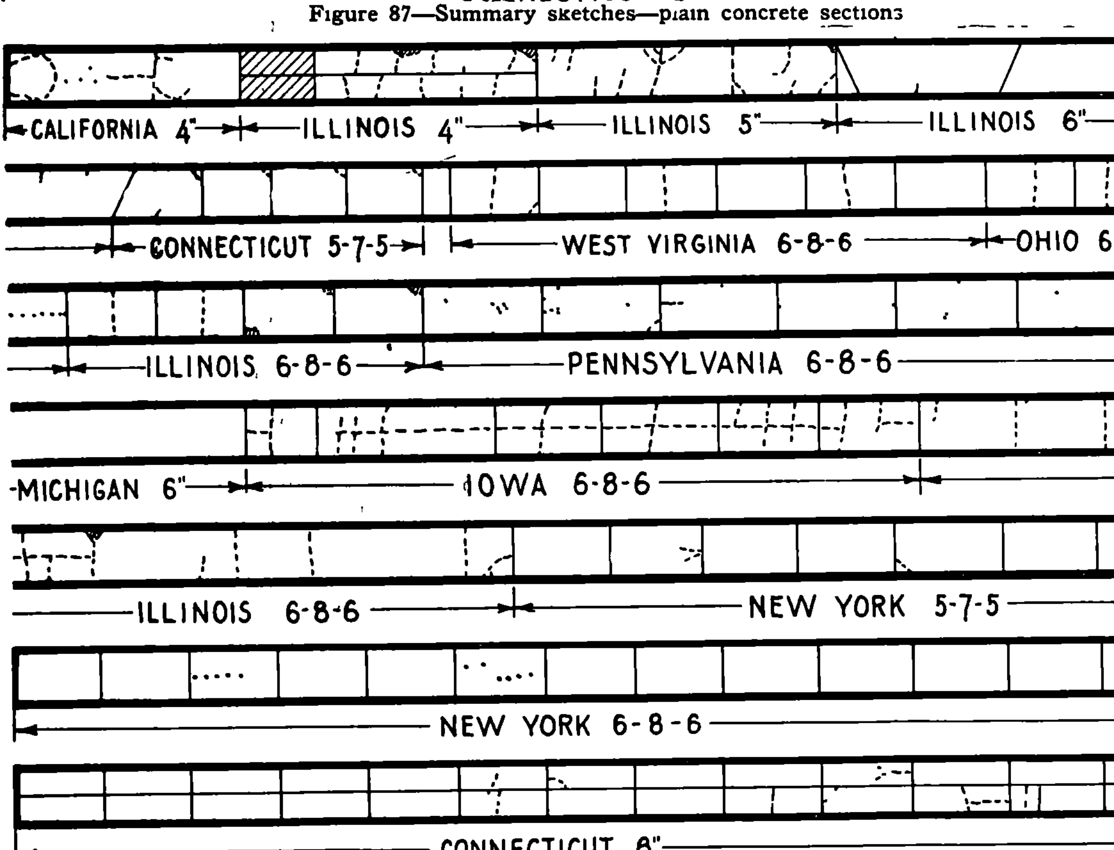


Figure 88—Summary sketches—reinforced slabs from same roads as sections shown in Figure 8