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MICHIGAN
STATE HIGHWAY DEPARTMENT
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CONCRETE SPALLING ON PROJECTS 7-20, C6 AND 7-21, C2 ON US-41 IN UPPER PENINSULA

By

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Research Project 51 B-26

Research Laboratory
Testing and Research Division
Report No. 208
April 16, 1954

Concrete Spalling on Projects 7-20, C6 and 7-21, C2 on
US-41 in Upper Peninsula

On July 7, 1951, State Police reported considerable spalling of the concrete surface on US-41 between Alberta and Nestoria in Baraga County, Upper Peninsula. The spalling had occurred during the night of July 6, 1951. The pavement area associated with the spalling is located in projects 7-20, C6 and 7-21, C2 which adjoin each other. See Figure 1 for location of the two projects on US-41.

At the request of Mr. W. W. McLaughlin, Testing and Research Engineer, a visual inspection was made of the spalled area by Mr. Roy Fulton, who reported his findings to Mr. McLaughlin by letter dated Aug. 7, 1951. Subsequent to Mr. Fulton's work, the Research Laboratory was requested to make an additional study of the subject to determine what caused this unusual condition. A progress report on the work by the Research Laboratory was submitted to Mr. W. W. McLaughlin in a letter dated August 22, 1952.

The work completed at that time by the Research Laboratory offered nothing conclusive, but the results strongly indicated that the differential expansion characteristics of the aggregates contained in the concrete was largely responsible for the spalling. Consequently, the work of the Research Laboratory was directed toward exploring that possibility.

At the time the spalling occurred several observers suggested the possibility that lightning might have struck the pavement. However, the presence of large aggregate pieces of black laminated slate schist and granite at the bottom of each spalled piece strongly supported the material concept thereby encouraging further study in that direction. In this last phase of the work the lightning theory was given careful consideration because it was felt that some unusual motivating force must have been present to create sufficient

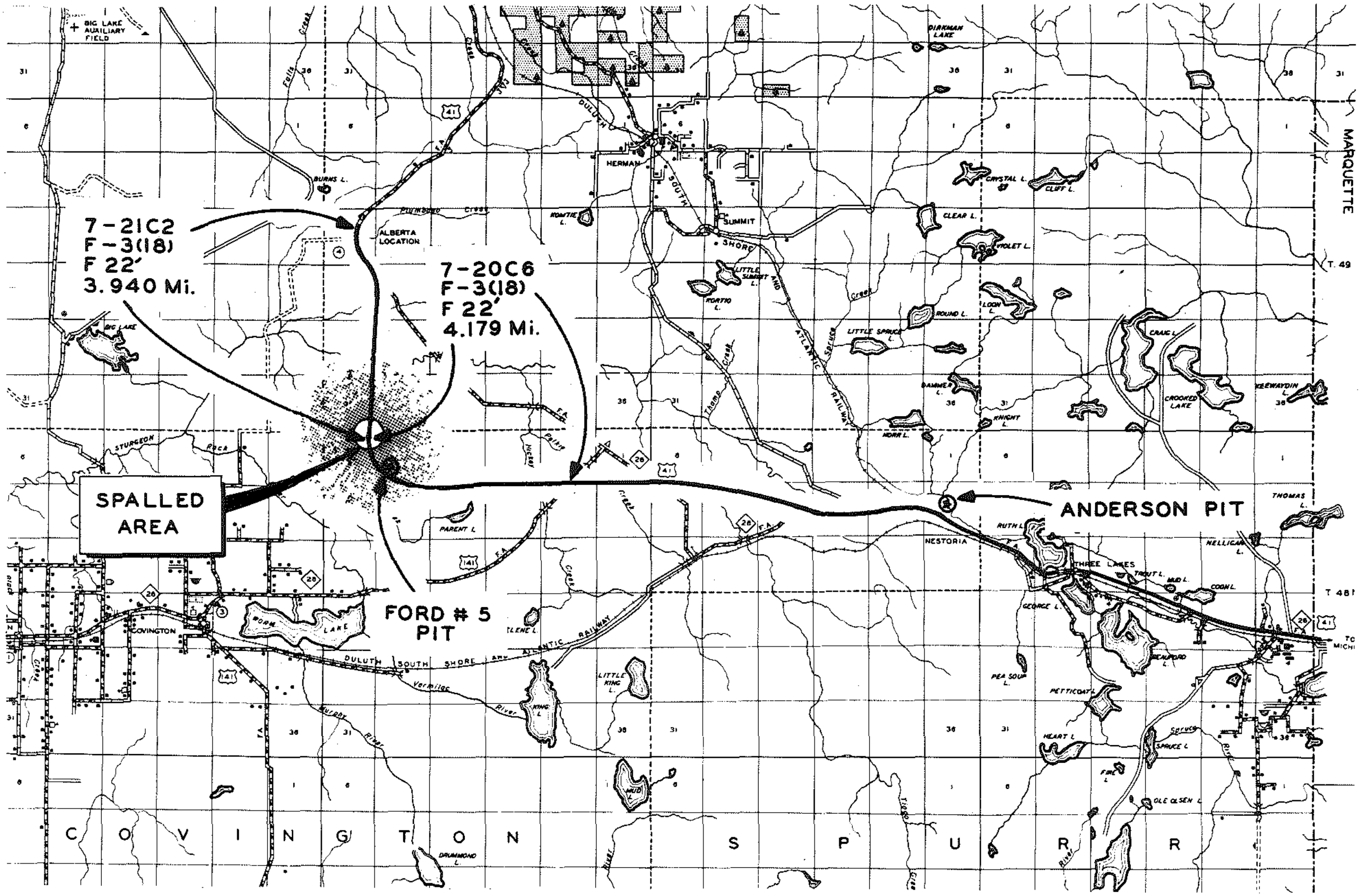

FIGURE I

LOCATION OF SPALLED AREAS

volume change to cause the concrete to shatter or spall within a very short period of time.

This report completes the investigation by the Research Laboratory. Sufficient evidence has been accumulated to support the conclusion that the spalling was the result of lightning striking the pavement during a thunderstorm. The sudden application of heat to the concrete by the lightning created sufficient internal pressure to cause the concrete to spall sporadically over a considerable area.

The main facts leading to this conclusion are enumerated below.

1. The incident occurred during an electrical thunderstorm.

2. The spalled area is located near the crest of a grade change which would be the logical place for a high electrical potential to develop during an electrical storm.

sharp edges etc

3. The fact that spalled pieces of concrete were scattered for a distance of several feet would indicate the sudden occurrance of a tremendous internal force. This is unlike normal spalling associated with freezing and thawing or slow thermal changes associated with normal weather conditions.

4. Spalling was confined to a definite area. of project No similar spalling was found on any other part of the two projects involved.

5. A condition survey in August, 1953 revealed no new spalling on either project as might be expected under normal service conditions.

6. Laboratory studies involving the aggregates used on each project and concrete cores revealed nothing which would lead one to suspect that the spalling could have been caused by moisture and temperature changes in the pavement on the night of July 6, 1951.

7. The spalling pattern is not unlike that of three cases reported in the Literature where it is definitely known that lightning struck a reinforced concrete pavement.

EFFECT OF LIGHTNING ON A
REINFORCED CONCRETE PAVEMENT

We were fortunate in finding four references to articles dealing with the subject of lightning striking reinforced concrete pavement. Each article has been presented below in full for comparative study with the US-41 incident.

1. EFFECT OF LIGHTNING ON A REINFORCED CONCRETE PAVEMENT,
Winston E. Wheat,* A. S. C. E. Proc, 52: 1331-3, Sept. 1926.

"The varied results of the action of the elements on rigid pavements has recently been the subject of much scientific investigation. Changes in temperature, frost action, and differences in moisture conditions create problems of real significance to the engineer engaged in the design of pavements, the importance of which can hardly be over-estimated.

The writer has recently had occasion to investigate the effect of another of Nature's forces--its most spectacular if not its most powerful--in contact with a reinforced concrete pavement. On the evening of October 12, 1925, during a thunderstorm in the vicinity of Pensacola, Fla., an 18-ft. reinforced concrete pavement of the 'Gulf Beach Highway' was struck by a bolt of lightning. The result was one quite contrary to that expected and only a careful investigation proved that the damage done to the pavement was the effect of the action of that element. This inspection was checked by B. D. Howe, Assistant Engineer, Louisville and Nashville Railroad Company.

At first thought, it would seem that lightning, striking a concrete pavement laid directly on a plain subgrade, would choose the shortest way to the earth, going directly through the slab. Instead, in this case, it traveled the pavement for a distance of 1,560 ft., about 780 ft. in each direction. The result is shown in Figs. 1, 2, and 3. (Figure 2 of text).

No damage to the pavement is evident except at the expansion joints, at 30-ft. intervals, where a gap of about 4 1/2 in. between the ends of the longitudinal wires of the steel mesh reinforcement, evidently formed an arc, suddenly generating heat sufficient to break out a small piece of concrete and scattering the aggregate for a considerable distance. Where the wires were bared, the galvanization was found to have been burned off. In all cases, the 5/8-in. asphalt expansion joint was melted away at the point of break, evidently having literally 'gone up in smoke'.

At each joint over the affected area only a small piece of concrete was broken out, or cracked, usually in a triangular shape at a corner of the slab, the piece being about 1 sq. ft. in area and extending slightly below the level of the reinforcement which was 2 in. below the surface. An interesting feature of the action of the lightning was that pieces of concrete broke out in nearly all cases on alternate sides of the road, as if it had traveled diagonally across the reinforcing mesh in each slab. In two cases the fracture

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FIG. 1.—VIEW OF ROAD WHERE LIGHTNING STRUCK.

FIG. 2.—TYPICAL BREAK IN ROAD AT POINT OF ARC.

FIG. 3.—ASPHALT BURNED OUT OF JOINT AT POINT OF ARC.

FIGURE 2

occurred in the center of the road, and in one of these a cup-shaped piece was broken out about 4 ft. back of the expansion joint. Another noticeable peculiarity was that in most instances the concrete was broken on one side of the joint only--the eastern side. This may be explained by the fact that the road was constructed from east to west. In laying the mesh, which came in sections, the ends were placed a varying distance back from the expansion joints, the exact amount depending on the overlapping of the sheets of reinforcement in the slab.

The pavement is of a 5 1/2 - 7 1/2 - 5 1/2-in. cross-section, 18 ft. wide, of 3,000 lb. concrete. The aggregates were washed river sand and gravel. In the breaks the coarse aggregate was fractured, as a rule, rather than the mortar.

The reinforcement consisted of a standard steel wire mesh, weighing 44 lbs. per 100 sq. ft., and of 3/4-in. round steel bars, placed parallel to and 4 in. back of the expansion joints.

The explanation of the effects of the lightning, as reached by Mr. Howe and the writer, may be outlined as follows. This pavement is laid on a pure, white, beach sand of indefinite depth. An unusually dry period had greatly lowered the ground-water level. Moisture is essential to 'grounding' lightning. Having struck the pavement the current ran down the steel wire to the end of the mesh near the expansion joint. There the line of least resistance was taken, which was across the width of the arc to the steel located across the joint, as this afforded less resistance than to pass through the concrete to the subgrade and thence through 20 ft., or more, of dry sand to where moisture conditions would permit a 'grounding'.

The slight damage done was easily repaired by filling the cavities with gravel and bituminous mixture. No other part of the road, which is 12 3/4 miles in length, has shown any breaks during the two years it has been open to traffic, and the reinforcement has effectually prevented serious cracking of the slabs."

2. <u>EFFECT OF LIGHTNING ON A REINFORCED CONCRETE PAVEMENT,</u>
A discussion of Mr. Wheat's paper, by T. A. Ross*, <u>A. S. C. E. Proc.,</u> 52: 1331-3, Sept. 1926.

"Following the author's description of the make-up of the reinforced concrete pavement in question and its natural condition--in effect, a series of mutually isolated metal screens laid along the ground surface, but electrically insulated from it by dry concrete and sand, the latter of considerable depth--it appears that here is something closely analogous to a power transmission line erected with a series of short gaps, at 30-ft. intervals, in its conductors and these, in turn, supported on an imperfect type of insulator, in this case a silicious sand of indefinite moisture content. While silicious sand is itself a fairly good insulator any moisture present in it will lower its insulating properties.

The behavior of power transmission lines under lightning conditions--the term 'conditions' is used advisedly--has been closely studied in recent years, and some of

* By T. A. Ross, Lt. Col. (Ret.) R. E.

only current emf creates magnetic field (not static)

the knowledge thus gained can be applied to this case. A cloud that has become charged to a high electrical potential, or pressure, is possessed of a magnetic field which creates, by induction, a potential of varying intensity in any metallic or other conducting body that comes within the influence of the field. As long as the cloud remains charged and floats in the neighborhood, there will be an electrical equilibrium between it and the conductor which it has influenced. As the cloud, still undischarged, floats away, the charge induced by it in the conductor dies down in the latter to normal earth potential, without giving any evidence of its having been present. Should the conductor in question happen to be a power line in operation, there will likewise be no evidence of its presence on the line, or any disturbance whatever of normal working conditions, as long as the charge remains 'bound' by the presence of the undischarged cloud.

This effect occurs, but this is the wrong mechanism.

Should, however, the cloud discharge itself close by, having approached so near to some 'earthed' body or conductor that its potential is able to break down the intervening air, then, at this same instant of discharge, the already charged conductor finds itself left in a state of high electrical tension which may be of the order of many hundreds of thousands of volts. No practical commercial insulation--let alone the fortuitous insulation supplied to a metal reinforcement by dry concrete and sand--can withstand such a pressure, and the conductor discharges itself to earth simultaneously with the cloud.

The power engineer provides for the contingency by connecting expensive but efficient lightning arresters to his apparatus. What is the highway engineer to do? It is submitted that he need do nothing. Under all normal conditions he will find reinforced concrete pavements so efficiently--or at least sufficiently--connected to and incorporated with the main body of earth that there will not be the least likelihood of their becoming charged to a higher potential than that of the earth. If a cloud should happen to discharge itself directly over a point on the highway that is a dispensation of Providence for which he cannot be expected to provide in his specifications. It is happening probably every day in the year without anyone being aware of it, or of any harm resulting. Many construction engineers will recall having dug up so-called 'fulgurites', particularly in sandy soil. These fused cores of earth--in appearance not unlike some stalactites--have been made by the lightning discharge as it passed down to the moister strata of the lower earth levels and there dissipated its energy. wrong

Referring to the 'Gulf Beach Highway', from the evidence presented by the author, the writer would deduce that the section of damaged roadway had become charged above earth potential in the manner described. Mr. Wheat does not give any direct evidence that the pavement was actually struck by a lightning discharge--the writer prefers the latter term to 'bolt of lightning'--nor is it necessary that it should have been in order to account for the damage done.

What probably happened was that the charged sections discharged themselves simultaneously with a lightning discharge in the immediate vicinity. The pavement was obviously not a good 'earth', but rather a well-insulated body, and, as such, lightning would not tend to discharge directly on it; on the other hand, it was itself in good condition to become charged prior to the lightning discharge.

The author states that the incident occurred during a thunderstorm. It is rather a pity that he did not say explicitly whether rain was falling at the time, or shortly before, because both are material. If one can assume either, an explanation is then available for the damage at the expansion joints, because there it would be most likely for moisture to penetrate and descend into the subgrade. In any event moister conditions would prevail under these joints than under the slab. In speaking of moisture, the term in this case is used relatively--an electrical potential of the order under consideration will discharge itself through moisture which only a chemical test would reveal, and through many feet of air as well--and the author's statement that moisture is essential for grounding lightning discharges must be read in that light.

Each section would discharge itself through the point of least resistance to earth--in this case the joints. The accompanying flash--in effect, a lightning discharge in miniature--would create steam and gas to disrupt material and heat to set fire to the asphalt filler.

The peculiarity that the concrete was usually broken at the eastern end only of each slab could be explained by the fact that the reinforcement approached more closely to that end, and thereby provided a shorter distance to earth; a contributing cause would be that if the pavement was laid on a down grade from west to east, the surface water in flowing off each slab toward its lower, or eastern end would tend to seep through the upper side of each expansion joint. In that case the high end of each slab would be the dryer and the low end the damper and, therefore, the better conductor to earth.

That the damage appeared on alternate sides of the pavement can also be explained by the reinforcement having been laid with its ends nearer the surface on alternate corners of each slab. In any case the writer would look for simple mechanical reasons, such as comparative measurements, to explain these phenomena in preference to searching for obscure electrical ones.

In spite of all precautions lightning will sometimes defeat the power engineer. An insulated conductor--be it a power transmission line or a 'Gulf Beach Highway'--once it has become charged by a high-potential cloud may be likened to a long pipe, open at both ends, and charged in the middle with dynamite. If the dynamite explodes it will wreak its damage in its immediate neighborhood--the open ends of the pipe are not going to help much. Like dynamite, analogies are sometimes dangerous, and this one must not be pushed too far. It will help one to realize, however, that a charged body will probably free itself of its 'bound' charge over the shortest path to earth and without much consideration of the insulating properties of that path. Thus, the power engineer may find many of his line insulators broken down by a lightning discharge without either his line being directly struck or his lightning arresters failing to operate. Incidentally, cases have occurred where power lines out of use and disconnected have yet broken down their insulators during a thunderstorm.

Similarly, it is not going to help much--even if it were practicable--to make pavement reinforcement electrically and mechanically continuous, without imparing the free expansion of the pavement, and then providing it with special connections to earth. As has been already pointed out, it is and always normally will be efficiently earthed by its very nature, and no possibility will ever arise of it being charged to a higher potential than the general body of the surrounding earth.

The circumstances and conditions described in the paper are so rarely met that it is probably better economy to face the cost of occasional small repairs rather than attempt to provide costly, and not always certain, protection against lightning for a pavement which is to be laid on very dry sand or earth. The danger to life is practically non-existent; it is certainly less than the normal risks involved in using the road for travel.

Steel-frame buildings, bridges, railroad and street railway tracks, etc., are by their very nature effectively earthed; they cannot acquire a 'bound' charge and can accept direct lightning discharges with impunity. This does not mean that certain types of structures should not be specially protected against lightning discharges and lightning conditions. Powder magazines and power transmission lines, for example, require special study for their own peculiar conditions on account of the extra risks involved. Neither is it enough to provide special protection for them; the protection equipment should be efficiently maintained and tested at regular intervals by expert engineers."

3. LIGHTNING STRIKES CONCRETE PAVEMENT IN GEORGIA,
   Charles T. Fisher,* Eng. News-Record, 89: 828, Nov., 1922.

(The complete text of this article with illustrations is presented in Figure 3.)

4. LIGHTNING STRIKES CONCRETE PAVEMENT IN GEORGIA,
   Searcy B. Slack,** Eng. News-Record, 105: 528, Oct. 2, 1930.

(The complete text with illustrations is presented in Figure 4.)

* State Commission of Highways, Binghamton, N.Y.
** Bridge Engineer, State Highway Board of Georgia.

Lightning Bolt Follows Reinforcing in Concrete Highway

BY CHARLES T. FISHER
State Commission of Highways, Binghamton, N. Y.

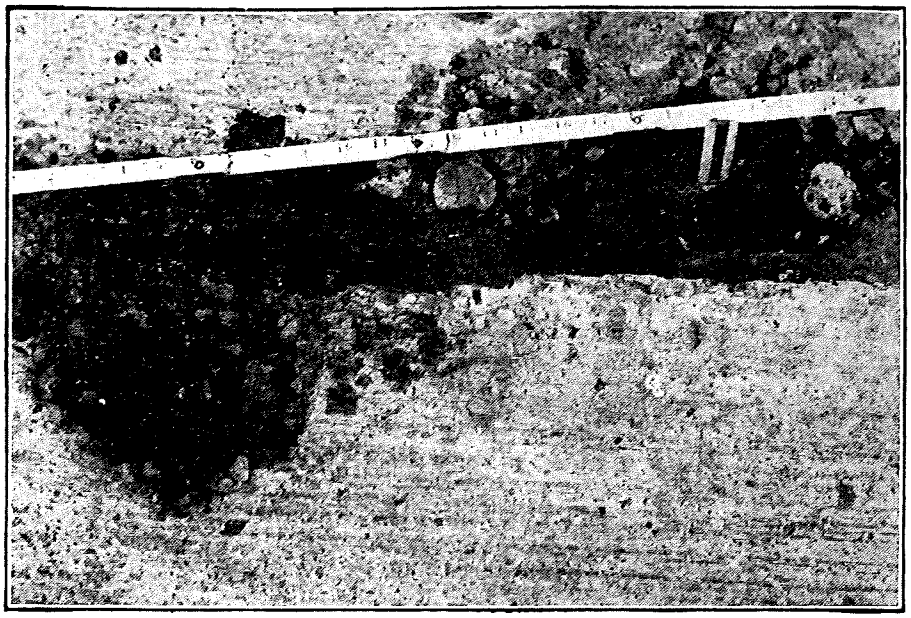


FIG. 1—EFFECT OF LIGHTNING BOLT AT JOINT

AN UNUSUAL case of damage to a highway by the elements occurred during the summer, when a section of reinforced-concrete pavement on a state highway near Sherburne, N. Y., was struck by lightning.

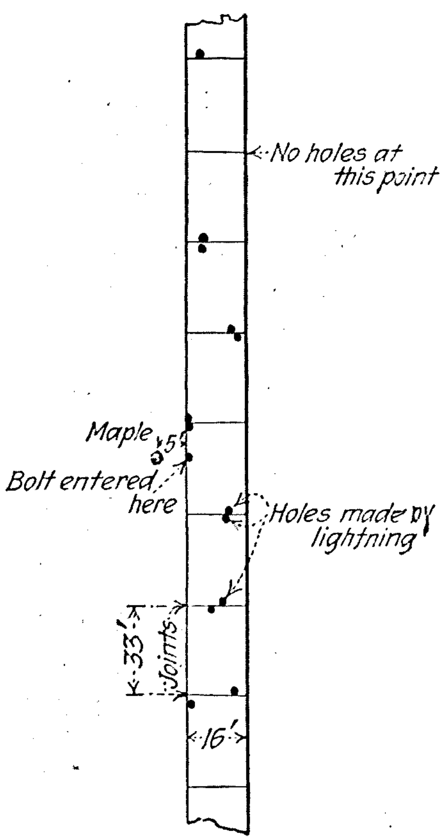


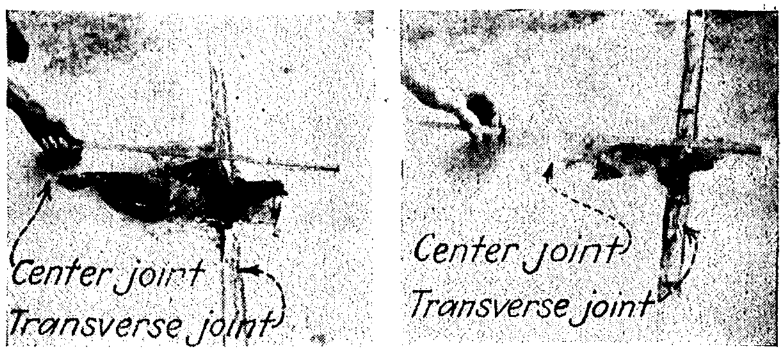
FIG. 2—PATH OF BOLT TRACED BY HOLES

The bolt first struck a maple tree which stood at the side of the road, and then entered the edge of the pavement and traveled along the metal reinforcement for about 100 ft. in both directions. At the point where it jumped from the tree to the pavement a small piece of concrete was broken out of the edge, and at the expansion joints, which are of $\frac{3}{8}$-in. bituminous material spaced on 33-ft. centers, holes in the surface about 5 in. in diameter and 3 in. deep were formed on both sides of the joint filler, indicating the path of the current in passing from the metal in one panel to the metal in the next.

Lightning Strikes Concrete Pavement in Georgia

By Searcy B. Slack
Bridge Engineer, State Highway Board of Georgia, East Point

On the afternoon of Sept. 11, 1930, lightning struck a concrete pavement between Griffin and Thomaston, Ga., on state route No. 3. This project is being built with federal aid and the contractor had completed about 9,000 ft. of paving. The paving is 20 ft. wide and has a 16-gage metal center joint with $\frac{1}{2}$-in.



LIGHTNING STRIKES PAVEMENT
At left—Point where lightning struck. The hole goes entirely through the pavement. The black area at the left is the metal center joint. At right—Transverse joint and center joint 300 ft. from where lightning struck. About twenty holes of this kind were knocked out at intersections of transverse and center joints.

dowels through the joints 4 ft. center to center. The transverse joints are at 50-ft. intervals and are of $\frac{1}{2}$-in. premolded asphaltic material. Dowels extend through the joints in the usual way. The bolt of lightning struck the pavement in the center at a transverse joint 1,400 ft. from the end of the job. A hole was knocked entirely through the pavement and a duck's nest of concrete was shattered out. The lightning traveled along the metal center joint 1,300 ft. in one direction and about 4,000 ft. in the other. It apparently arced over the transverse joints, knocking out small chunks of concrete on each side of them. At some of the joints arcing occurred at the top of the pavement, and it is presumed that at the other joints arcing occurred underneath the pavement, as there was a skip of several transverse joints where the pavement was affected on top.

About 150 ft. from the point where the bolt of lightning struck the pavement two men stood on the ground under a filling station shed and a man and woman were seated inside the filling station. The two men standing under the shed were knocked down by the shock, while the man and woman inside the station received no shock. The man in the filling station reports that he saw the lightning strike the pavement and saw a ball of fire roll along the center of the pavement.

FIGURE 4

SUMMARY OF EFFECT OF LIGHTNING STRIKING A REINFORCED CONCRETE PAVEMENT

1. Area affected may extend several thousand feet on each side of place struck as evidenced by extent of spalling.

2. Damage manifested by spalling of concrete at longitudinal and transverse joints and at pavement edge. May skip several transverse joints at a time.

3. Spalled pieces are about 1 square foot in area, triangular shape extending to or slightly below reinforcement steel.

4. Spalled pieces usually are shattered and scattered for a distance of several feet.

5. Spalled areas may be on opposite sides of road and broken from one side of joints only.

6. Spalls occur at gaps in reinforcement or where the continuity of the steel is broken.

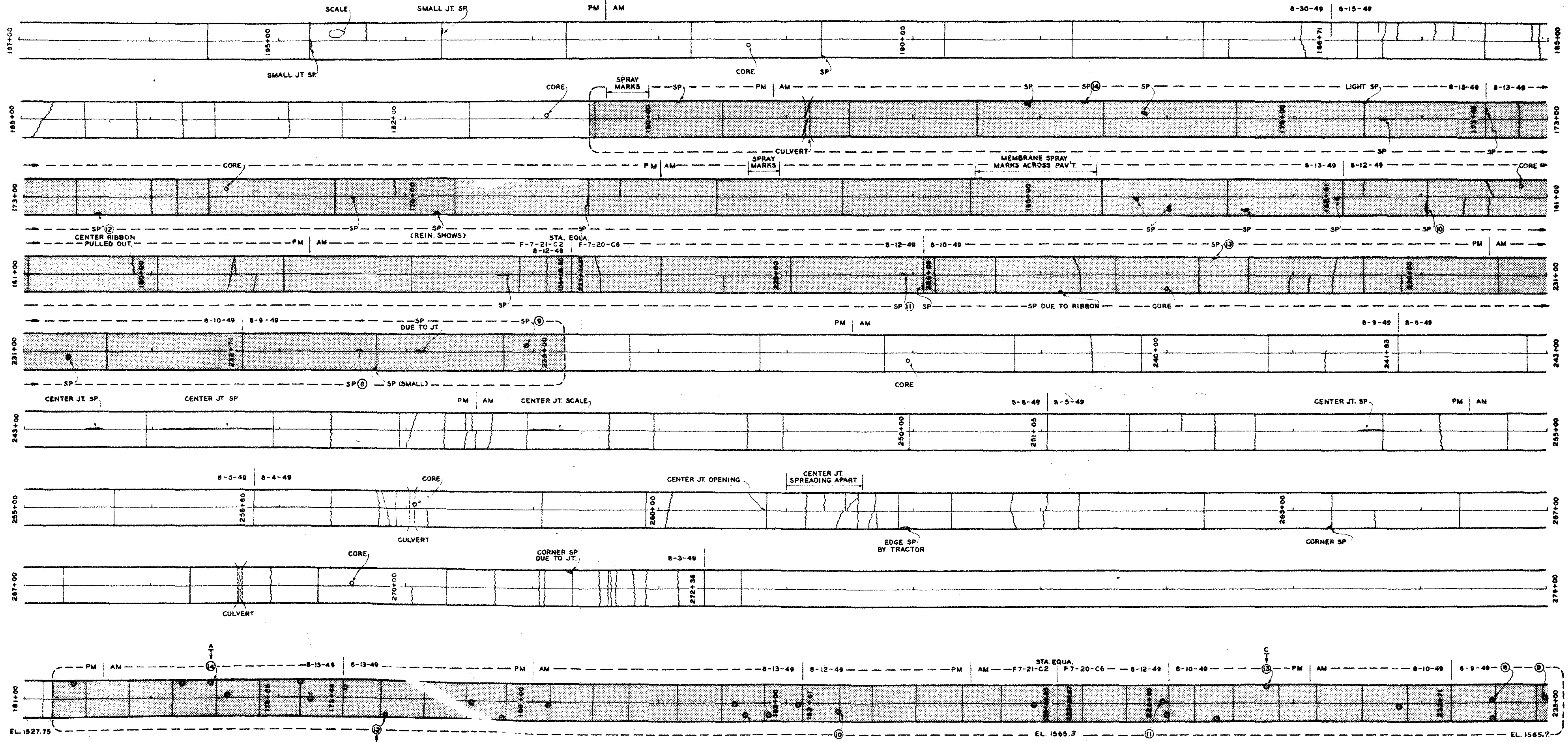
A Comparison of Michigan's Experience to that of Other States

As may be seen in Figure 5, the extent and occurrence of the spalls on US-41 follows the pattern description by Wheat (1) and Slack (4) and illustrated by Fisher (3) in that the areas affected amounted to several thousand feet in extent and throughout this area spalls appeared at joints and edges of pavement.

Figures 6 and 7, taken by Michigan State Police on the Morning of August 7, show the "Duck's nest" of shattered concrete pieces in and adjacent to the spalls as mentioned by Slack (4).

Figures 8, 9, 10 and 11 show how the concrete was removed down to and below the reinforcement as mentioned by Wheat (1). According to Wheat, an arc could have formed at these places, suddenly generating heat sufficient to break the concrete. Note in Figure 8 the free end of reinforcing steel where the electricity would have had to jump and arc. Also it would have had to jump from end of dowel shown in Figure 10. It could have jumped between reinforcing bars in Figure 11, thus causing an arc.

Figures 12, 13 and 14 show spalls where the lightning could have left or entered the pavement. Note free reinforcement bar in Figure 14. It would seem impossible for



RED = SPALLING

LOCATION AND EXTENT OF SPALLING - US 41
PROJECTS F7-21-C2 AND F7-20-C6
REPORTED TO HAVE OCCURRED THE NIGHT OF JULY 6-7, 1951

FIGURE 5

NOTE: CIRCLED NUMBERS INDICATE SPALLING ILLUSTRATED BY ACCOMPANYING PICTURES

FIGURE 6 – U. S. 41. PICTURE TAKEN BY STATE POLICE EARLY ON MORNING, JULY 7, 1951. NOTE SHATTERED CONDITION OF CONCRETE IN SPALLED AREA AND DISPLACEMENT OF SPALLED PIECES.

FIGURE 7 – U. S. 41. PICTURE TAKEN BY STATE POLICE EARLY ON MORNING, JULY 7 1951. NOTE RAGGED CONDITION OF SPALLED SURFACE AND WIRE REINFORCEMENT AT BOTTOM OF SPALL.

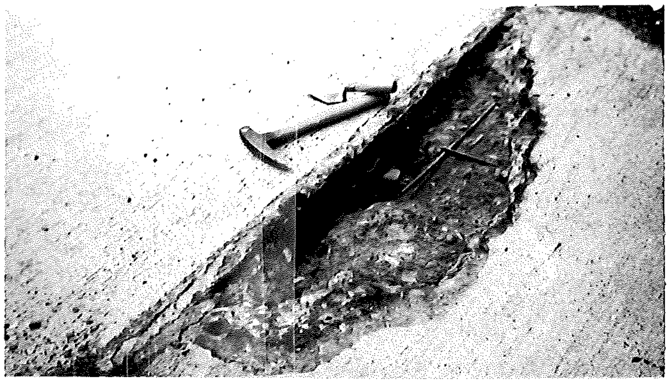


FIGURE 8 – SPALL AT CENTER JOINT, STA. 233+62 –F7–20, C6. NOTE FREE END OF WIRE REINFORCEMENT AND SPALL IS DEEPER THAN LEVEL OF REINFORCEMENT.

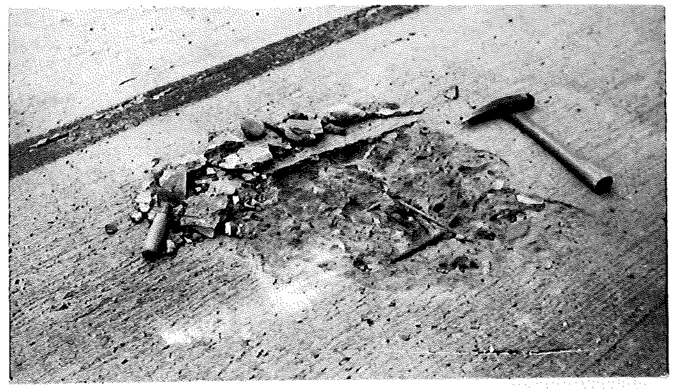


FIGURE 9 – SPALL AT INTERIOR OF SLAB AT STA. 234+95, F7–20, C6. HERE AGAIN REINFORCEMENT IS EXPOSED AND SPALL DEEPER THAN REINFORCEMENT.

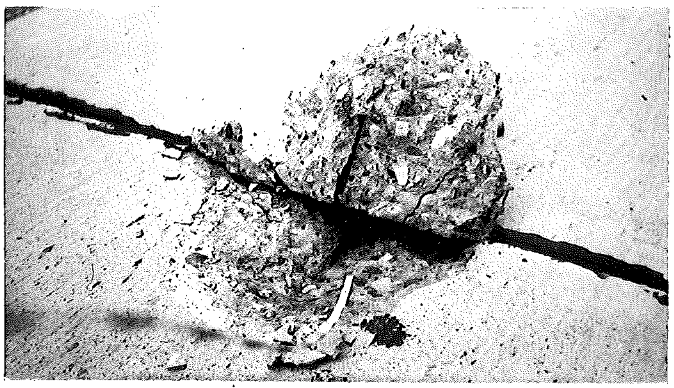


FIGURE 10 – SPALL OVER DOWEL BAR AT JOINT, STA. 161+95, F7–21, C2. NOTE REINFORCEMENT DOES NOT MEET DOWEL BAR AS IT SHOULD.

FIGURE 11 – SPALL AT CENTER JOINT, STA. 225+92 –F7–20, C6. NOTE TWO REINFORCEMENT BARS AT BOTTOM OF SPALL.

FIGURE 12 – SPALL AT PAVEMENT EDGE, STA. 172 + 40 LT. F7–21, C2.

FIGURE 13 – SPALL AT PAVEMENT EDGE, STA. 228+ 38 LT. F7–20, C6.

FIGURE 14 – SPALL AT PAVEMENT EDGE, STA. 176 +60 RT. F7–21, C2. NOTE EXPOSED REINFORCEMENT WIRE.

this to happen under normal spalling conditions. Fisher (3) mentions similar edge spalling where lightning jumped from a tree to pavement.

All three men (Wheat, Fisher and Slack) report preponderence of spalling at longitudinal and transverse joints. This is also a characteristic of the Michigan experience.

Differences in Michigan's Experience to That of Others

There were apparently two differences in the Michigan experience which should be mentioned. First, spalled areas appeared in the interior portion of the 99-foot slabs. This type of failure was not mentioned by the others. Second, in the Michigan experience, there was no evidence of melted joint seal material or burned reinforcement wire or disturbed grass. Mr. W. W. McLaughlin, who observed the pavement the next morning after the incident, makes the following statement:

> "On July 11th we met Mr. Osterman in L'Anse and accompanied him to the project. He gave us an account of his observations as well as information he had received from the State Police. Careful examination of the damaged areas disclosed no evidence of heat. Where damage occurred at longitudinal and contraction joints, neither the premolded bituminous joint material nor the asphalt joint sealing compound was affected. This is shown in Figures 8, 10, and 11 of Research Report No. 208; none of the wire reinforcing which was exposed showed the slightest evidence of being burned. Where edge damage occurred, there was no disturbance of the shoulder material. In fact, blades of grass adjacent to the edges were unaffected. This evidence of lack of heat is not in accord with conditions described by others where pavements have been struck by lightning.

Edward F. Vidro, of the Electrical Engineering Department at Michigan State College was asked to give his comments on the matter of destruction by lightning. His comments are presented below:

> In general, there are two types of lightning damage - that caused by burning, and that caused by shattering or spliting. Burning of the struck object usually occurs before the rain starts or before the object becomes wet. Shattering or splitting usually occurs during the rainstorm or when the object is wet. The presence of water on the object affords a lower resistance path for the electrical energy and thus permits the bolt to travel quickly to the ground without burning the object.

On a highway, the bolt may enter at any place and travel along the reinforcing bars in all directions until the energy is dissipated. This energy may cause considerable damage where an arc can be formed. Most joints usually contain some moisture and the presence of a large quantity of heat at this point would form steam at a high pressure. An analogy to this would be popcorn which expands many times its normal size with heat. This expansion takes place because of the trapped moisture in the corn. If the bolt travels quickly along the paths it might take, it may go directly to ground with little or no evidence of burning, provided that the surrounding surfaces are wet. The presence of flowing or still water in the vicinity of the joint offers a quick path for the electrical energy - such that there would be no excess heat present to melt the joint material. The presence of water over any area would prevent the bolt from jumping to the surrounding grass which, it itself, would be a good conductor because of the moisture it contains. Since running or still water would be a better conductor, the energy would follow the water paths into the ground and thus there would be little or no evidence of burning or fusing in the shoulder material.

GEOLOGY OF THE DAMAGED REGION

The damaged sections of the two pavement projects are located in NE 1/4 of sec. 6, 48 N, 33W, and SE 1/4 of sec. 31, 49 N, 33W of Baraga County. This area is covered by fairly thin glacial drift consisting of moraines and high plateaus. There are numerous outcrops of Proterozoic metamorphic rocks such as graphitic slates, gneiss, and mica schists. There is a great deal of iron bearing rock in this area, also. These bed rock formations lie very near to or at the surface. The nature of this region could very possibly enhance the opportunity for an electrical discharge.

LABORATORY STUDY OF AGGREGATES AND CORES FROM SPALLED PROJECTS

Records show that coarse aggregates used on the first part of Project 7-20, C6 came from Ford Motor Pit No. 5 (7-21) and that on August 2, at Station 282 ≠ 72, a change was made to aggregate from the Anderson Pit (7-22). This aggregate was used on the balance of Project 7-20, C6 and all of Project 7-21, C2. The location of these pits with respect to the Projects are shown in Figure 1. Cement and fine aggregate were the same of both projects, the cement being Huron AE from Petoskey and the fine aggregate coming from Champion Dishneau Pit. Only coarse aggregate from Anderson Pit was involved in the spalled sections of the two projects. The same mortar void design was used for both projects. Concrete mix design data are presented below for reference.

Average batch weights for the three days' pour for each project in the damaged area are:

Project F7-20, C6		Project F7-21, C2
7-3/4	Cement, sacks	7-3/4
1624 lbs.	F. A., wet	1615 lbs.
1552 "	4 A, wet	1547 "
1578 "	10 A, wet	1573 "
30.83	Mix water, gals.	33.27

Cement - Huron AE from Petoskey
F. A. - Champion Dishneau Pit
4 A - Anderson Pit No. 7 - 22
10 A - Anderson Pit No. 7 - 22

Certain physical and chemical properties of the coarse aggregate are presented in Table I. The only rock types in the aggregate to be questioned would be the schist and slate. The slate comprises about 15 percent of the total coarse aggregate.

Table I. Physical and Chemical Properties of Coarse Aggregate from Anderson Pit (7-22)

A. Petrographic Separation

Rock Type	Percent by weight according to sieve fractions					
	#4 - 3/8"	3/8 - 1/2"	1/2 - 3/4"	3/4 - 1"	1-1 1/2"	Average 6A-Grading
Granite	45.8	33.4	31.8	30.0	24.0	32.6
Granite, weathered	1.5	4.5	3.8	7.2	8.4	5.4
Quartzite	7.3	7.4	7.7	10.5	5.6	7.7
Gneiss & Schist	3.4	1.1	2.0	6.2	5.8	4.0
Diorite	12.7	14.4	18.4	10.2	9.2	12.3
Basalt	24.8	26.6	13.7	16.1	28.3	22.7
Slate	4.4	12.5	21.8	19.3	18.5	15.1
Chert	----	----	0.7	----	----	0.1
Limestone	----	0.1	----	----	0.4	0.1
						100.00

B. Magnesium Sulfate Soundness - 5 cycles

Fraction	Wt. Loss Percent
3/4 - 1 1/2"	1.71
3/8 - 3/4"	4.31
#4 - 3/8"	5.02

Loss on 6A grading = 3.21%

C. Soundness by Freeze and Thaw in Water - 25 cycles

Fraction	Wt. Loss Percent
3/4 - 1 1/2"	1.96
3/8 - 3/4"	4.55
# 4 - 3/8"	4.33

Loss on 6A grading = 3.28%

D. Specific Gravity and Absorption - 6A grading

Slate

Spg. (S.S.D.) - 2.705 Absorp. = 1.58

Other Rock Types

Spg. (S.S.D.) - 2.69 Absorp. = 0.95

Considering the weathered granite, schist and slate, the objectionable material would amount to approximately 20 to 25 percent. However, soundness tests show the aggregate to be well within specification limits.

Table II contains thermal coefficient of expansion data for several rock types, including the slate. The values presented in Table II were determined by cementing SR-4 strain gages to the cut and polished rock face and recording the strain for a definite temperature range. (See Figure 15) Results from the strain gage method were considerably lower than those previously reported as determined by the dilatometer method. We now strongly suspect an error in the dilatometer work since the results from the use of strain gages seem more logical and they compare favorably with values reported in the literature. As expected, the slate was found to have a higher coefficient of expansion than the other rocks with the exception of smokey quartzite, which had a slightly higher value than the slate.

The internal stresses produced by the thermal coefficient of expansion values given in Table II are not believed great enough to cause concrete spalling under concrete temperature extremes associated with climatic conditions reported for the period and location involved in the study.

To check this belief, beams were prepared with and without the slate aggregate. The mix design and materials were the same as in the spalled projects. These beams were subjected to a heat shock cycle consisting of 8 hours in an oven at 145° F. and a cold cycle in water for 16 hours at 55° F. The data plotted in Figures 16 and 17 show no significant effect of the slate as compared to other rock types at the end of 16 cycles. Also, there is no indication that a major difference might have occurred had the test been continued beyond the 16-cycle period.

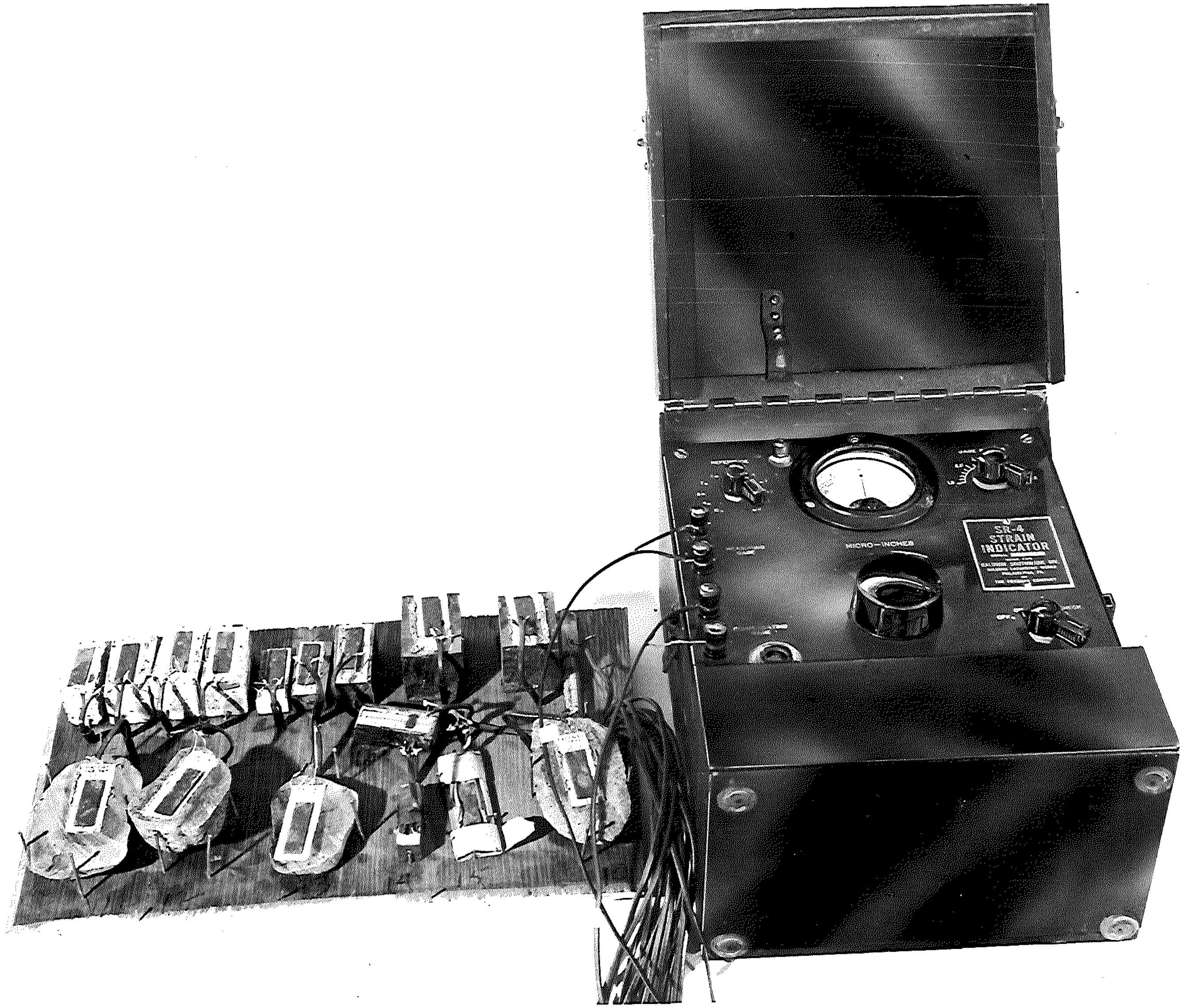


FIGURE 15

SR-4 STRAIN GAGE METHOD
FOR DETERMINING THERMAL COEFFICIENT OF EXPANSION
OF ROCK SPECIMENS.

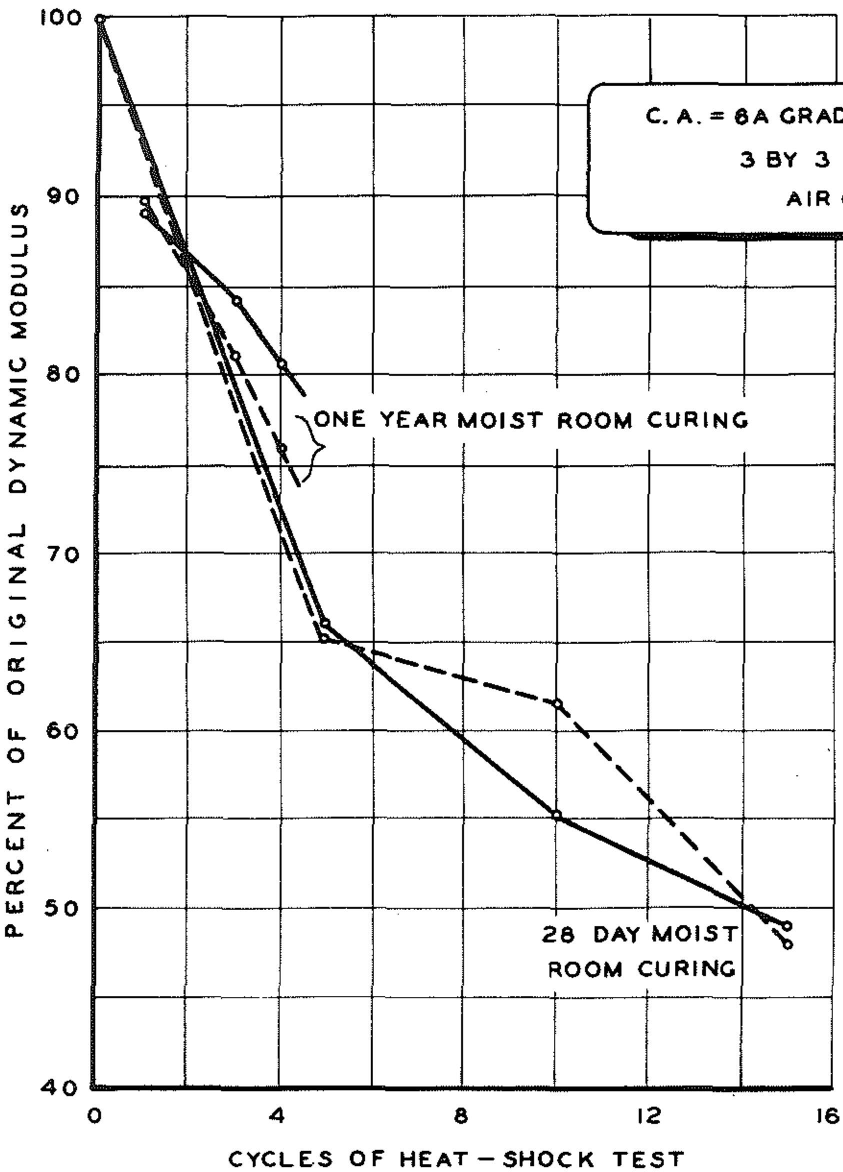


FIGURE 16

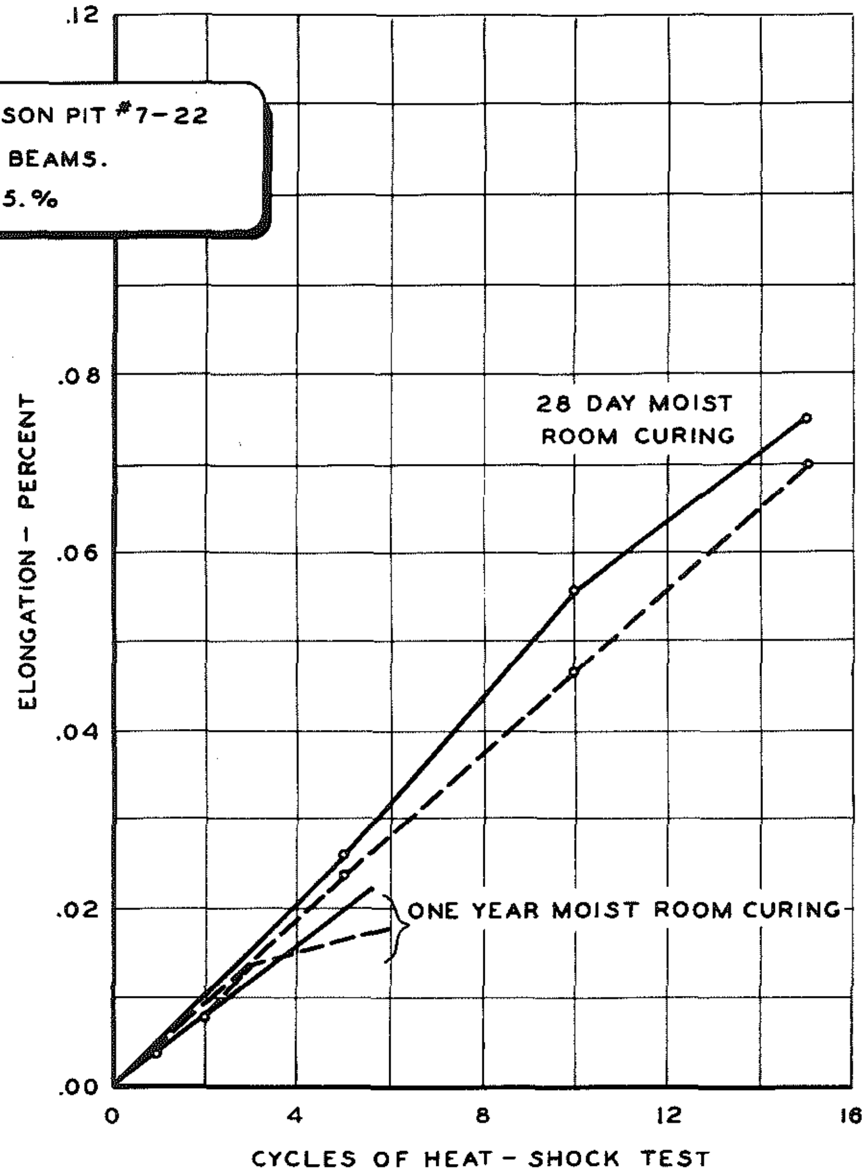


FIGURE 17

BANK RUN GRAVEL
GRAVEL MINUS SLATE

HOT CYCLE = 8 HOURS IN 145°F. OVEN. COLD CYCLE = 16 HOURS IN 55°F. WATER.

HEAT – SHOCK TEST ON AIR ENTRAINED CONCRETE.

Table II

Thermal Coefficient of Expansion of Coarse Aggregate

SR - 4 Strain Gage Method*

Rock Type	Coeff. of expansion (average of 3 runs)	Average coefficient for each rock-type	Coeff. value from literature
First Series (74^{o} to 139^{o} F.)		(in. 10^{-6} in./in. ^{o}F.)	
Granite			
1. Smokey, medium grain	4.62		
2. Smokey, medium grain	4.10	4.36	4.47**
3. Pink, medium grain	3.34		and
4. Pink, medium grain	3.41	3.41	4.68**
5. Pink, fine grain	3.48		
Slate			
1. Parallel to laminations	5.22		
2. Parallel to laminations	6.25		
3. Parallel to laminations	5.08	5.71	
4. Perpendicular to laminations	6.13		
5. Perpendicular to laminations	5.22		
Diorite			
1. Medium grain	3.92		
2. Medium grain	3.63	3.65	
3. Medium grain	3.40		
Quartzite			
1. Smokey	6.50	6.50	5.4* 6.58** (Ottawa Sand)
Fused Quartz			
1. Fused Quartz Rod	0.47		
Second Series (75^{o} to 138^{o} F.)			
Mortar from Spalled Pieces of Pavement, US-41			
1. Mortar (cut from spalled samples)	5.30		
2. "	4.83	5.17	
3. "	5.22		
4. "	5.32		

* E. J. Callan, ACI Journal, Feb. 1952.

** G. J. Verbeck & W. E. Hass, HRB Proceedings, 1950

The concrete in the beam specimens was subjected to temperature differences in excess of that which would be expected to occur with a local drop in air temperature from 80° F to 61° F. in the presence of rain as reported for the night of July 6, 1951, when spalling occurred. See weather information in Table III.

Core Tests

Information obtained from tests on cores taken from spalled areas is presented in Table IV. Compressive strength data from core specimens taken from Project 7-20, C6 were, in general, considerably lower than those from Project 7-21, C2. A similar reduction in static modulus is also noted. The reason for this marked strength difference is unexplainable unless the concrete could have been weakened in the cored area by lightning and resulting high temperature effects. Cores were not taken from the pavement outside of the spalled area.

Spalled Concrete

An examination of several spalled pieces revealed a number of interesting facts. In the first place, it was noted that with very few exceptions large aggregate particles were present at the fractured face. The large aggregate particles generally remained attached to the spalled piece. In the spalled specimens shown in Figure 18, such aggregate particles may be clearly seen. It was noted that the aggregate particles were not confined to any one particular rock type. This would tend to dispel any thought that any one type of rock was responsible for the spalling of the pavement.

Table III

Weather Data

Precipitation Record for July 7, 1951

Station	Inches of Rain for Hour Ending					
	2:00	3:00	4:00	5:00	6:00 A. M.	Total
Baraga	----	.03	.04	.02	.01	0.10
Kenton, US Forest	.57	.19	.01	.05	----	0.82
Huron Mt.	----	----	.08	.02	----	0.10

Temperature Record

	July 6, 1951		July 7, 1951	
	Minimum	Maximum	Minimum	Maximum
Kenton, US Forest	38^{o} F	81^{o} F	58^{o} F	83^{o} F
Huron Mt.	49	80	61	86

Table IV

Test Data From Cores Taken
Within Spalled Area

Station	Thermal Coefficient * in 10^{-6} in./in^{o} F ($73-223^{o}$ F)	Compressive Strength (psi)	Static Modulus in 10^{6} psi Test 1	Test 2	Average
Project F7-21, C2 - drilled		10-8-49			
161+23R	------	4920	-----	-----	-----
171+47R	------	4305	-----	-----	-----
180+89R	------	4300	-----	-----	-----
	Avg.	4508	-----	-----	-----
Project F7-20, C6 - drilled		10-5-49			
228+00R	------	5180	-----	-----	-----
237+95R	------	3615	-----	-----	-----
	Avg.	4398	-----	-----	-----
Project F7-21, C2 - drilled		10-14-52			
161+95L	3.90**	-----	4.03	4.32	4.18
163+15L	------	5800	4.29	4.77	4.53
174+50L	5.12	4460	4.18	3.78	3.97
176+60R	------	4260	4.24	3.86	4.05
	Avg.	4840			4.18
Project F7-20, C6 - drilled		10-14-52			
225+92R	------	2370	3.22	2.79	3.01
227+00R	5.00	3950	3.51	3.67	3.59
230+00R	4.91	5350	3.93	4.30	4.12
233+95R	------	2770	4.33	3.94	4.14
	Avg.	3613			3.72

* Measured between end studs mounted in core tops and bottoms.
** Measured on beam cut from spalled sample.

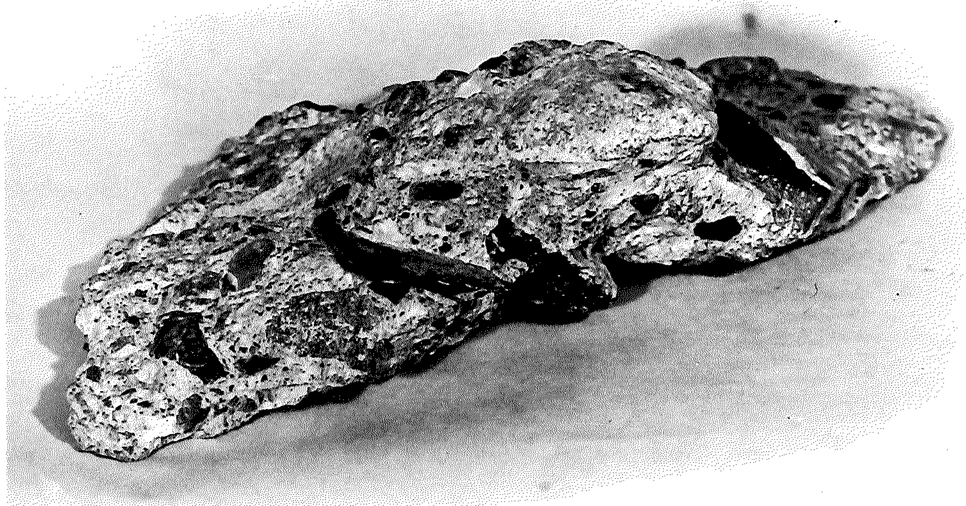


FIGURE 18

EXAMPLES OF SPALLED CONCRETE SHOWING LARGE PARTICLES OF COURSE AGGREGATE AT FACE OF SPALL.

CONCLUSIONS

1. The results of the laboratory study do not disclose any new evidence which would lead us to believe that the thermal properties of the aggregate could solely have caused spalling due to the drop in pavement temperatures which happened on the night of July 6, during a thunderstorm.

2. On the basis of the evidence presented herein, it is our considered opinion that lightning was the direct cause of spalling on US-41.