MISSOURI COOPERATIVE HIGHWAY RESEARCH PROGRAM
ADDENDUM REPORT 78-1A

INVESTIGATION OF ROADWAY DESIGN VARIABLES TO REDUCE D-CRACKING

15-YEAR STATUS REPORT

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

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16. Abstract

This investigation is a continuation of HPR Study No. 78-1 initiated to determine the effect of certain design variables on the occurrence of D-cracking. Eight reinforced portland cement concrete pavement test sections were constructed in 1977 in the northbound lanes on Route I-35, Daviess County. The report for this ten-year study was published in 1987. At that time, there was no D-cracking observed in any test section.

Each test section consisted of 15 pavement sections and 16 transverse joints. Variables included in this study were source and maximum size of the coarse aggregate (two-inch Burlington, one-inch Bethany Falls, and 3/4-inch Bethany Falls), whether a polyethylene moisture barrier was used, and type of base.

D-cracking was observed in three test sections during the survey conducted after 15 years of service. These test sections were all constructed with one-inch Bethany Falls limestone with no moisture barrier, and with an impermeable base. However, since the affected areas are relatively small and of low severity, additional monitoring of the test sections needs to be performed before the relative influence of each variable on D-cracking can be determined.

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INVESTIGATION OF ROADWAY DESIGN VARIABLES TO REDUCE D-CRACKING

STUDY NO. 78-1

ADDENDUM

15-YEAR STATUS REPORT

Prepared By

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

DIVISION OF MATERIALS AND RESEARCH

JANUARY 1993

INVESTIGATION OF ROADWAY DESIGN VARIABLES TO REDUCE D-CRACKING

EXECUTIVE SUMMARY

This investigation is a continuation of HPR Study No. 78-1 initiated to determine the effect of certain design variables on the occurrence of D-cracking. Eight test sections were constructed in 1977 in the northbound lanes on Route I-35, Daviess County. The report for this ten-year study was published in 1987. At that time, there was no D-cracking observed in any test section, although some transverse joints had very minor cracking that was expected to develop into D-cracking.

Each test section consisted of 15 pavement sections and 16 transverse joints. Variables included in the study were source and maximum size of the coarse aggregate, whether a polyethylene moisture barrier was used, and type of base. Specifically, the test sections were as follows:

Test Section Number	Coarse Aggregate Used	CA Maximum Size	Moisture Barrier Used	Base
1	Burlington	2"	No	Type 3 Aggregate
2	Bethany Falls	3/4"	Yes	Type 3 Aggregate
3	Bethany Falls	3/4"	No	Type 3 Aggregate
4	Bethany Falls	1"	No	Type 3 Aggregate
5	Bethany Falls	1"	No	Bituminous Base (Impermeable)
6	Bethany Falls	1"	No	Bituminous Base (Open-Graded)
7	Bethany Falls	1"	No	Portland Cement Treated Aggregate (Impermeable)
8	Bethany Falls	1"	Yes	Type 3 Aggregate

D-cracking was observed in three test sections during the survey conducted after 15 years of service. Most of the D-cracking was in test section 4, where it was observed at four of the sixteen transverse joints and affected a total area of about 30 square feet. Test sections 5 and 7 both had about three square feet of D-cracking at one transverse joint each.

These three test sections were all constructed with one-inch Bethany Falls limestone, with no moisture barrier, and with an impermeable base. However, since the affected areas are relatively small and of low severity, additional monitoring of the test sections needs to be performed before the relative influence of each variable on D-cracking can be determined.

Although the coarse aggregate size of D-crack prone aggregate was reduced to one-half inch maximum in 1990, the influence of the variables in this study on D-cracking and other types of pavement distresses continues to be of interest.

Additional surveys to monitor the developments on this project will be conducted in the future.

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INTRODUCTION

For many years, the durability of concrete pavements located in Northern and Western Missouri has often been reduced by D-cracking. D-cracking is generally associated with the use of marginal limestone coarse aggregates in concrete subject to freezing and thawing. Several studies, and several series of changes in pavement design, have been made beginning with changes made in 1967.

The changes made in 1967 provided for (a) higher quality aggregate than had previously been required, (b) reduced the maximum size of marginally frost resistance paving stone from two to one inch, (c) increased the percent fine aggregate from about 39 to 45 percent, and (d) required a four mil thick polyethylene moisture barrier placed between the pavement and the aggregate base. These changes were evaluated and all except the use of a polyethylene moisture barrier were found to be beneficial.

While the changes were found to be beneficial, the problem of D-cracking was of sufficient magnitude to continue to investigate other design criterion to improve pavement service life. In 1975, a field study using HPR funding was initiated to determine the effectiveness of certain design variables. The variables included a further reduction in maximum size of aggregate, type of base, and use of a 4 mil thick polyethylene moisture barrier. The project selected for incorporating various design variables was constructed in 1977 in the northbound lanes on Route I-35, Daviess County.

There were eight test sections constructed, each 922.5 feet in length. See Figures 1, 2, and 3 for the location of the project and test sections. The variables for each of the test sections were as shown on Table 1.

Table 1

LIST OF TEST SECTIONS AND VARIABLES

Test Section Number	Coarse Aggregate Used*	CA Maximum Size	Polyethylene Moisture Barrier Used	Base**
1	Burlington	2"	No	Type 3 Aggregate
2	Bethany Falls	3/4"	Yes	Type 3 Aggregate
3	Bethany Falls	3/4"	No	Type 3 Aggregate
4	Bethany Falls	1"	No	Type 3 Aggregate
5	Bethany Falls	1"	No	Plant Mix Bituminous Base
6	Bethany Falls	1"	No	Plant Mix Bituminous Base Using Type 4 Aggregate
7	Bethany Falls	1"	No	Portland Cement Treated Aggregate
8	Bethany Falls	1"	Yes	Type 3 Aggregate

* The Burlington Limestone had no known history of a D-cracking problem. The Bethany Falls Limestone was a local aggregate and assumed to be D-crack susceptible.

** The base for all the test sections was considered impermeable except on test section number 6 which was considered permeable and open-graded.

A fine aggregate used for all the test sections was Class B Grand River sand. The concrete mix for test section 1 had 38 percent fine aggregate. All other test sections had 45 percent fine aggregate.

A test section consisted of 15 pavement sections, each 61.5 feet in length, with 16 transverse contraction joints. Contraction joints were dowelled for load transfer. Each test section had the following common factors: (a) 9-inch reinforced portland cement concrete pavement, (b) same type and source of cement, (c) same source of fine aggregate, (d) 4-inch thickness of base course, and (e) shoulder design. Shoulder design through the project limits included a Type 4, permeable, open-graded aggregate for drainage. A typical cross section of the test sections may be seen in Figure 4.

Generally, the first observation of significant D-cracking of pavements made with aggregates with marginal frost resistance is 5 1/2 to 6 years. However, no D-cracking was observed in the eight test sections during the original seven year study time or three year extension. There were seven joints which had exhibited very minor cracking that were expected to possibly develop into D-cracking.

During the 10-year period, surveys were conducted annually. Results were published as MCHRP Report 78-1 (1). Material specifications, results of aggregate physical characteristics, and job mixes may be found in its appendices.

Since the 10-year report, surveys have been conducted in 1987, 1990, and 1992, with cores drilled in 1990. The Distress Identification Manual for the Long-Term Pavement Performance Studies (2) was used for the last survey. This manual is very similar to the Highway Pavement Distress

Identification Manual for Highway Condition and Quality of Highway Construction Survey (3) used for the previous 12 surveys. The surveys also noted D-crack type staining, although not a separate distress listed in these manuals, where joints or cracks had a discoloration in a D-cracking pattern, but no visible cracks.

RESULTS

Types of pavement distress and severity level of each type of distress noted are summarized in Table 2. As in the MCHRP Report 78-1, the quantity of distress shown includes both the passing and driving lane of each test section. The number and linear feet are given in Table 1 for cracks and spalling. Transverse and longitudinal cracks were considered separate cracks if they were in separate lanes or slabs. This procedure was used consistently throughout the surveys since cracks often do not line up exactly across a joint.

A brief description is given for each test section as follows.

Test Section #1
2" Burlington CA, w/o Polyethylene, Type 3 Aggregate Base

This section did not have any D-cracking or D-crack type staining, nor did it have any transverse cracks. There were two longitudinal cracks, both were rated moderate severity due to spalling and both run close to the centerline joint, see Photo 1. Most noticeable about this section were the numerous popouts as shown in Photo 2.

There were signs of pumping at each transverse joint. The criteria for moderate-severity pumping is some pumped material (fines) near the joint or crack; small semi-circular depressions may begin to form on AC shoulders adjacent to pumping. This was seen at shoulders along two of the transverse joints.

Five joints had a faulting reading of 1/8" or more.

Photo No. 1

TS #1. Longitudinal crack at slab 14.

Photo No. 2

TS #1. Popouts near joint 4.

Test Section #2
3/4" Local CA, w/Polyethylene, Type 3 Aggregate Base

This section did not have any D-cracking although transverse joint number 1 had some staining at the centerline. There was 1 moderate-severity longitudinal crack and 19 transverse cracks: 12 rated low severity (hairline cracks without spalling or faulting); 6 rated moderate severity (due to spalling less than 3 inches wide); and 1 rated high severity (due to spalling of 3 inches wide or more) shown in Photo 3. One transverse joint in the driving lane has been replaced as shown in Photo 4, probably due to spalling since over 6 feet of the joint was spalled in 1990.

The asphalt shoulder was broken up at several locations along the outside edge of the pavement as shown in Photo 5.

Six joints had a faulting reading of 1/8 inch or more.

Photo No. 3

TS #2. High-severity transverse crack at slab 8.

Photo No. 4

TS #2. Transverse joint repair at joint 6.

Photo No. 5

TS #2. Asphalt shoulder broken up at outside edge of pavement resulting in lane-to-shoulder dropoff at slab 13.

Test Section #3
3/4" Local CA, w/o Polyethylene, Type 3 Aggregate Base

This section did not have any D-cracking. Concrete was spalled out of a corner break at the centerline in the passing lane of joint number 8 and the area had some D-crack type staining, photo 6. This test section had 27 transverse cracks, having slightly more cracks of each severity level compared to the adjacent test section 2 which had the polyethylene sheeting moisture barrier.

Several areas of the asphalt shoulder next to the outside edge of pavement was broken up or missing, however, not as severely as in test section 2. Six joints had a faulting reading of 1/8 or more.

Photo No. 6

TS #3. Concrete spalling and staining at joint number 8 where only a corner break was noted prior to 1992 survey. Core was drilled in March 1990.

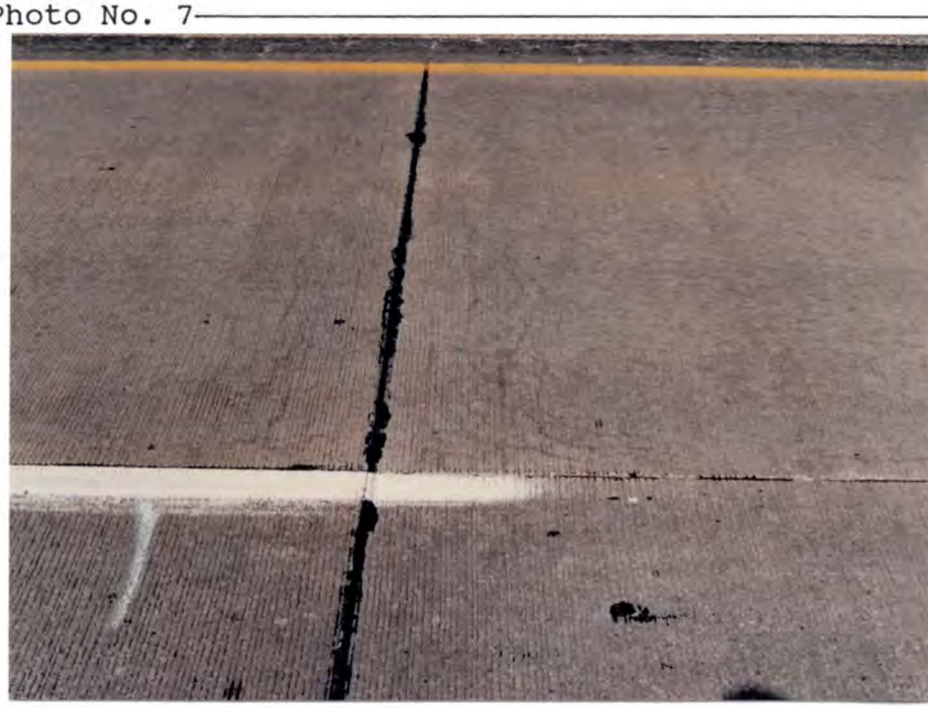
Test Section #4
1" Local CA, w/o Polyethylene, Type 3 Aggregate Base

This section had low-severity D-cracking at joints 1, 3, 6, and 7. See Photos 7 and 8. Most of the observed D-cracking (approximately 25 out of 30 square feet of affected area) was in the passing lane. Another joint had some D-crack type staining and six feet of high-severity spalling, as shown in Photo 9.

This section had 40 transverse cracks with a total length of 380 feet, more than any other test section. However, most of these cracks were low severity.

Six joints had a faulting reading of 1/8 inch or more.

Photo No. 7



TS #4. Low severity D-cracking at interior corners in passing lane of joint number 6.

Photo No. 8

TS #4. Close-up of D-cracking in passing lane at joint number 7. Core was drilled in 1990.

Photo No. 9

TS #4. Transverse spalling and some D-crack type staining in passing lane at joint number 14.

Test Section #5

1" Local CA, w/o Polyethylene, Bituminous Base

This section had a small area of low-severity D-cracking at the interior area along joint number 15, see Photos 10 and 11. The other joints in this section did not have any D-cracking or D-crack type staining.

This section had 25 transverse cracks. Fifteen of these cracks were rated either moderate or high severity.

Two joints had a faulting reading of 1/8 inch or more.

Photo No. 10

TS #5. Low-severity D-cracking at joint number 15.

Photo No. 11

TS #5. Close-up showing spalling of the transverse joint (on left) and low-severity D-cracking (2 fine closely-spaced curved cracks) at northwest corner at joint number 15.

Test Section #6
1" Local CA, w/o Polyethylene, Bituminous Base

This section is the only test section using Type 4 aggregate with permeable open-graded base on this project. It did not appear to have any D-cracking or D-crack type staining, and it is the only test section with 1" maximum size Bethany Falls and no moisture barrier that did not as yet have any D-cracking or D-crack type staining.

There were only two transverse cracks in this section, both rated moderate severity. This section also had 40 feet of longitudinal cracking, more than any other section.

None of the joints had a faulting reading of 1/8 inch or more.

Test Section #7
1" Local CA, w/o Polyethylene, Portland Cement Treated Aggregate Base

This section had a small area of low-severity D-cracking at the interior corners at joint number 15, see Photo 12, and some D-crack type staining at joint number 13.

This section had 15 transverse cracks. Eleven of these were rated either moderate or high severity.

Eight joints had a faulting reading of 1/8 inch or more.

Photo No. 12

TS #7. Close-up of low-severity D-cracking at northwest interior corner at joint number 15.

Test Section #8
1" Local CA, w/Polyethylene, Type 3 Aggregate Base

This section did not have any D-cracking or D-crack type staining. This section had 32 transverse cracks with a total length of 356 feet, more than any other section except test section 4. Twenty of the transverse cracks were rated either moderate or high severity. Photo 13 shows a typical high-severity and moderate-severity transverse cracks.

Seven joints had a faulting reading of 1/8 inch or more.

Photo No. 13

TS #8. Transverse cracks at slab number 6. Transverse crack in the driving lane (foreground) was rated high severity due to spalling greater than 3 inches wide and faulting of 1/4 inch. Transverse crack in the passing lane was rated moderate severity.

General

Neither D-cracking nor D-crack type staining was found associated with transverse or longitudinal cracks. There was a staining pattern seen in all the test sections using the local (Bethany Falls limestone) coarse aggregate as shown in Photos 14 and 15. The staining typically had a transverse or block pattern. Close inspection of this staining did not usually reveal any cracks.

Rust staining and spalling was seen in all of the test sections where the wire mesh was too close to the pavement surface. Most of this spalling was in the driving lane approximately 4 inches from the longitudinal joint as shown in Photo 16.

The shoulder design throughout the project limits included Type 4 aggregate for drainage. It was noted, however, that the aggregate where it intersected the foreslope was covered with 1 to 2 inches of soil and with a dense grass cover.

Photo No. 14

TS #3. Staining at slab number 15.

Photo No. 15

TS #5. Staining in driving lane of slab number 13.

Photo No. 16

TS #4. Concrete spalling at wire mesh in driving lane of slab numbers 4 and 5.

Coring Performed in 1990

Cores were drilled at interior corner in the passing lane and identified by test section number and number assigned to the transverse joint by which they were drilled as shown in Photo 17. Cores were cut into slabs, then ground and polished, and examined under a microscope. Cracks were marked on the slabs as shown in Photos 18, 19 and 20.

Test Section	Joint Number	Description
1	4	Minor cracks in or around a few of the coarse aggregates (CA) - Photo 20.
2	14	Minor cracks in or around CA. One crack at mid-depth across extended across slab - Photos 17 and 18.
3	8	Minor cracks in or around CA. Three cracks at or below mid-depth extended across slab - Photo 19.
4	7	Minor cracks in or around CA. One crack at mid-depth extended across slab.
5	5	Minor cracks in or around CA, mostly near the top of slab.
5	7	Minor cracks in or around CA.
6	14	Minor cracks in or around CA.
7	10	Minor cracks in or around CA.
7	13	Minor cracks in or around CA.
8	14	Minor cracks in or around CA.

These cores were drilled at the interior corners, typically at one foot away from both the transverse and longitudinal joints. Photographs were taken of the pavement location where the cores were drilled, of the cores, and of the marked slabs and these photographs are on file.

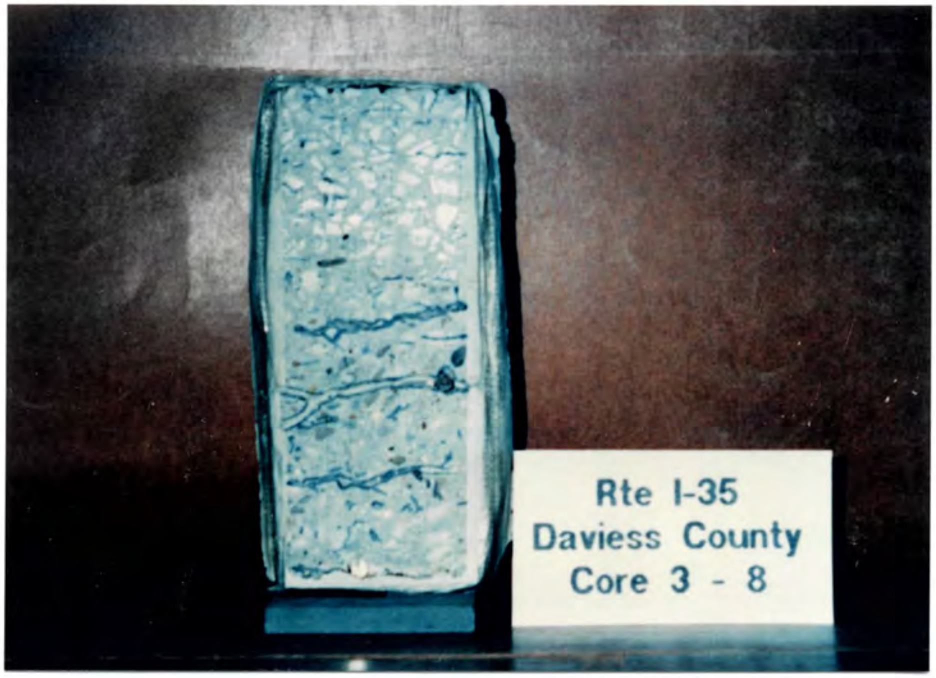
Photo No. 17

Core 2-14, drilled at joint number 14 of test section 2.

Photo No. 18

Core 2-14 after being sawed, ground and polished and after cracks were marked on the slab.

Photo No. 19



Polished slab from core 3-8, with cracks marked.

Photo No. 20

Polished slab from core 1-4, with cracks marked.

DISCUSSION

D-Cracking

After 15 years of service, D-cracking was observed at only six joints with a total affected area of 36 square feet.

Four of the D-cracked joints, with a total affected area of 30 square feet, were in test section number 4 which was constructed with 1 inch maximum size Bethany Falls, no moisture barrier, and a Type 3 aggregate base. Test section 5, constructed over dense graded bituminous plant mix base, and test section 7, constructed over a cement treated Type 1 aggregate base, both had about 3 square feet of D-cracking in one transverse joint each.

Analysis of variance (ANOVA) on the area of D-cracking at joints showed test section 4 had significantly more D-cracking than the other seven test sections and that there was no significant difference among the other seven test sections. A five percent significance level was used for all analyses.

There was no significant difference in D-cracked area among subsets of the test sections having a complete matrix of coarse aggregate size, type of base, or use of a moisture barrier. For example, there wasn't a significant difference in D-cracked area per joint among only test sections 4, 5, 6, and 7 which all had 1-inch maximum size Bethany Falls coarse aggregate and no moisture barrier, but different types of base. Likewise, a two-way analysis among test sections 2, 3, 4, and 8, which had a complete matrix of maximum size of

Bethany Falls coarse aggregate and whether a moisture barrier was used, also did not show significant difference. There was also no significant difference in D-cracking area between the driving and passing lanes.

The three test sections with D-cracking were all constructed with 1-inch Bethany Fall limestone, no moisture barrier, and a base that is considered impermeable. For each of these variables, there is another test section with only one of the three variables different which had no D-cracking as yet. For example, test section 2 constructed with 3/4-inch Bethany Fall limestone, no moisture barrier, and an impermeable base did not have any D-cracking.

Since the affected areas are relatively small and all were rated as low severity, additional monitoring of the test sections needs to be performed before the relative influence of each variable on D-cracking can be determined. Overall, the test sections are still performing better than originally expected.

Transverse Cracking

The amount of transverse cracking in both the number and total length was greatest on test sections 4 and 8, the two sections with 1-inch maximum size coarse aggregate and Type 3 aggregate base.

Test section 1 was constructed with 2-inch maximum size Burlington limestone coarse aggregate and had no transverse cracking. Test section 6 which was constructed over bituminous base using Type 4 aggregate had only 24 feet of transverse cracking

However, two-way analysis of variance performed on the linear feet of transverse cracking per 12-foot by 61.5-foot pavement slab showed few significant differences. The average length per lane and per test section were as follows:

Lane	Transverse Cracking (feet/slab)	Test Section	Transverse Cracking (feet/slab)
Driving	7.4	4	12.6
Passing	6.0	8	11.8
		5	8.8
		3	8.3
		2	5.7
		7	5.4
		6	0.8
		1	0.0

At a five percent significance level, the analysis showed no significant difference between the driving and passing lane. The difference in average transverse cracking is not significant between test sections unless greater than 6.1 feet per slab. Therefore, most individual tests between any two test sections showed no significant difference. There was no significant difference in transverse cracking between similar test sections with 1-inch maximum coarse aggregate size compared to those with 3/4-inch maximum size.

Transverse Spalling

The transverse joints on test sections 5, 6, and 7, which were constructed with special type bases, had more spalls than the other test sections. The average linear feet of spalling per lane and per test section are as follows:

Lane	Transverse Spalling (feet/12′ joint)
Driving	0.78
Passing	2.15

Test Section	Transverse Spalling (feet/12′ joint)
6	2.84
5	2.83
7	2.21
8	1.18
4	0.85
2	0.68
1	0.64
3	0.50

Analysis of variance showed that spalling of the transverse joints was significantly higher in the passing lane than the driving lane. The difference in average transverse spalling is not significant between test sections unless greater than 1.61 feet per 12-foot joint. Therefore, most individual tests between any two test sections showed no significant difference.

Pumping

The amount of pumping did not appear to have increased in the last five years since the MCHRP 78-1 report. Test section 1 had signs of pumping at every transverse joint. Some evidence of pumping was observed in each of the five test sections having a Type 3 aggregate base.

Faulting

Analysis of variance showed the driving lane had significantly more faulting than the passing lane. There was however no significant difference among the test sections.

CONCLUSIONS

1. D-cracking was observed on four of the sixteen joints in test section 4 which was constructed with 1-inch maximum size Bethany Falls coarse aggregate, no moisture barrier and Type 3 aggregate base. Total area affected was about 30 square feet.

2. D-cracking was observed at one joint each in test sections 5 and 7, both of which were constructed with 1-inch maximum size Bethany Falls coarse aggregate and no moisture barrier. Test section 5 was constructed with plant mix bituminous base, and test section 7 with portland cement treated aggregate base. The D-cracked affected area was about 3 square feet each at these two test sections.

3. Analysis of variance on the area of D-cracking per transverse joint showed that test section 4 had significantly more D-cracking than the other seven test sections. However analysis on subsets of the test sections having a complete matrix of coarse aggregate size, type of base, or use of a moisture barrier showed no significant difference in D-cracking.

4. Microscopic examination of slabs sawed from concrete cores drilled at interior corners in each test section showed minor cracking in the aggregates for all the test sections. The cores from tests sections 2 and 4 each had a horizontal crack extending across the core at about mid-depth. The core from test section 3 had three horizontal cracks extending across the core at or below mid-depth.

IMPLEMENTATION

Observation of the test sections will continue in order to determine the relative influence of the design variables in this study upon D-cracking and other pavement distresses.

REFERENCES

1. Investigation of Roadway Design Variables to Reduce D-Cracking", Missouri Cooperative Highway Research Program, Final Report 78-1, Missouri Highway and Transportation Department, Jefferson City, Missouri, September 1988.

2. Darter, Michael I.; Herrin, Stanley M.; and Smith, Roger E., Highway Pavement Distress Identification Manual for Highway Condition and Quality of Highway Construction Survey, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, The Federal Highway Administration, and National Cooperative Highway Research Program, Transportation Research Board, March 1979.

3. Distress Identification Manual for Long Term Pavement Performance Study, Strategic Highway Research Program SHRP-LTPP/FR-90-001, October 1990.

Table 2: Summary of Distresses

Test Section	1	2	3	4	5	6	7	8
D-CRACKING								
Low Severity				4(30 sf)	1(3 sf)		1(3 sf)	
JOINTS W/STAINING*		1	1	1			2	
CORNER BREAKS								
Low Severity	3	1		1		2	3	1
Moderate Severity					1			
TRANSVERSE CRACKS								
Low Severity		12(89′)	14 (92′)	24(199′)	10 (83′)		4(30′)	12(116′)
Moderate Severity		6(69′)	10(120′)	13(145′)	14(168′)	2(24′)	8(96′)	18(216′)
High Severity		1(12′)	3 (36′)	3 (36′)	1 (12′)		3(36′)	2 (24′)
LONGITUDINAL CRACKS								
Low Severity							3(7′)	1(2′)
Moderate Severity	2(24′)	1(12′)				3(40′)		1(6′)
SPALLING OF TRANSVERSE JOINTS								
Low Severity	41(20.3′)	41(15.9′)	34(14.8′)	30(15.0′)	59(82.4′)	57(59.8′)	72(60.1′)	29(26.8′)
Moderate Severity		3 (5.2′)	1 (0.3′)	3 (7.2′)	4 (8.2′)	6(30.0′)	3(10.7′)	5(11.0′)
High Severity		2 (0.6′)	1 (1.0′)	2 (5.0′)		1 (1.5′)		
SPALLING OF LONGITUDINAL JOINTS								
Low Severity	4(1.7′)	1(0.2′)		1(2.0′)	2(0.7′)		3(3.2′)	1(1.5′)
PATCH/PATCH DETERIORATION								
Low Severity		1						

The quantities above represent the number of individual distresses in both the driving and passing lanes of the test section, with total linear feet or square feet (sf) given in parentheses.

*Joints with D-crack type staining that may develop into D-cracking in the future.

Figure 1

General Location Map
For
Test Section
I-35, Daviess County

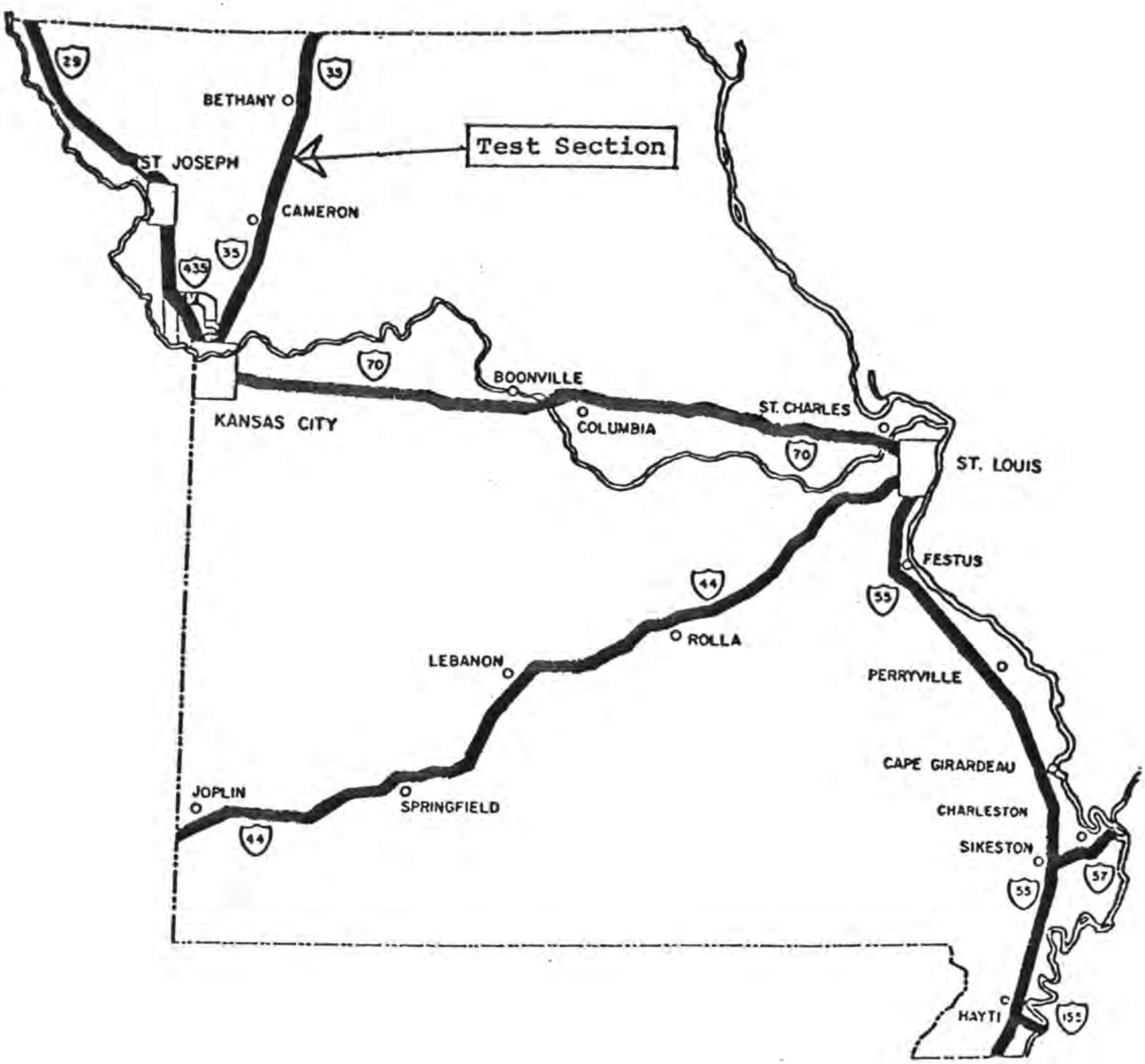


Figure 2

Detailed Location Map
For
Test Sections
I-35 (Northbound), Daviess County

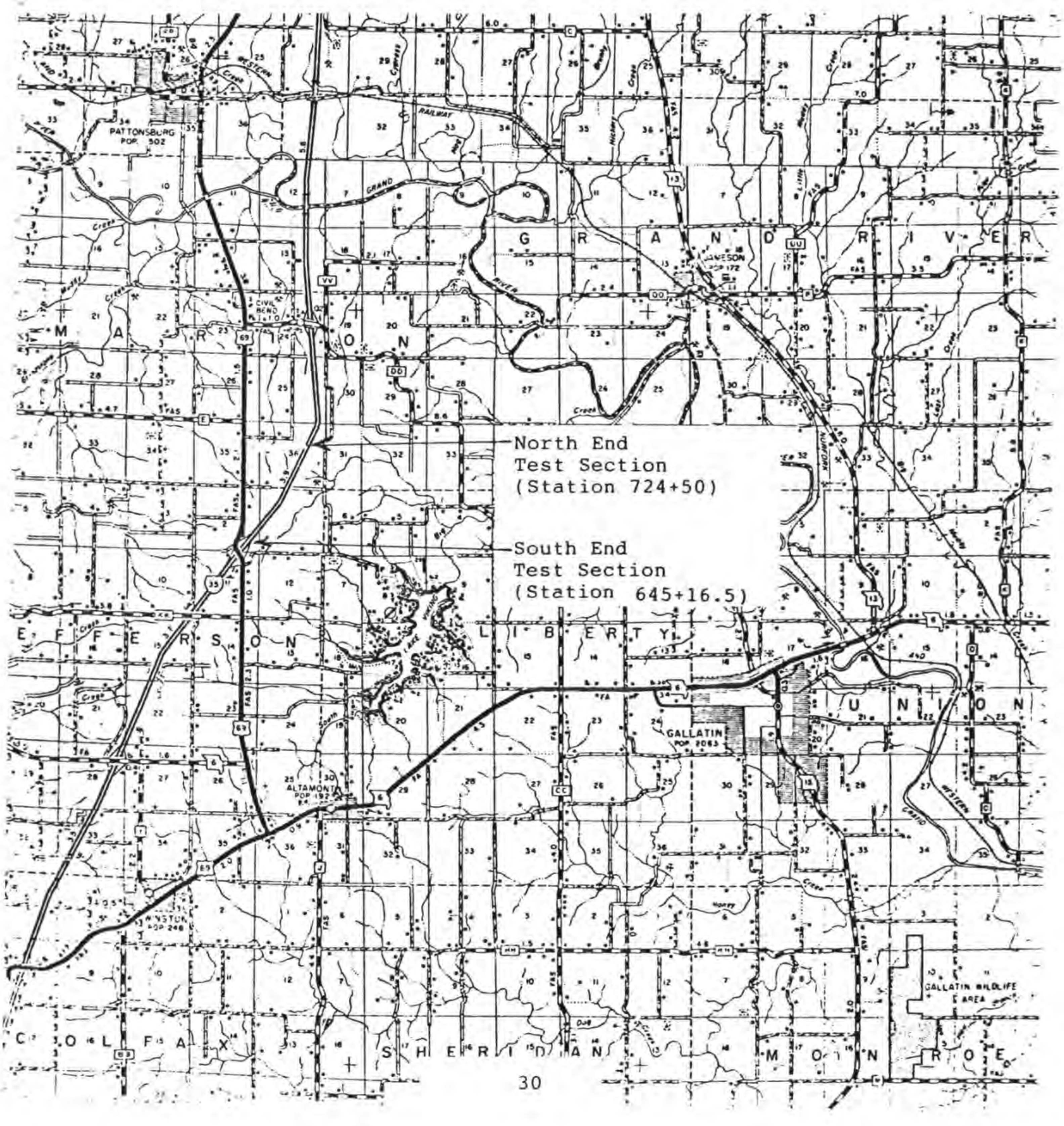
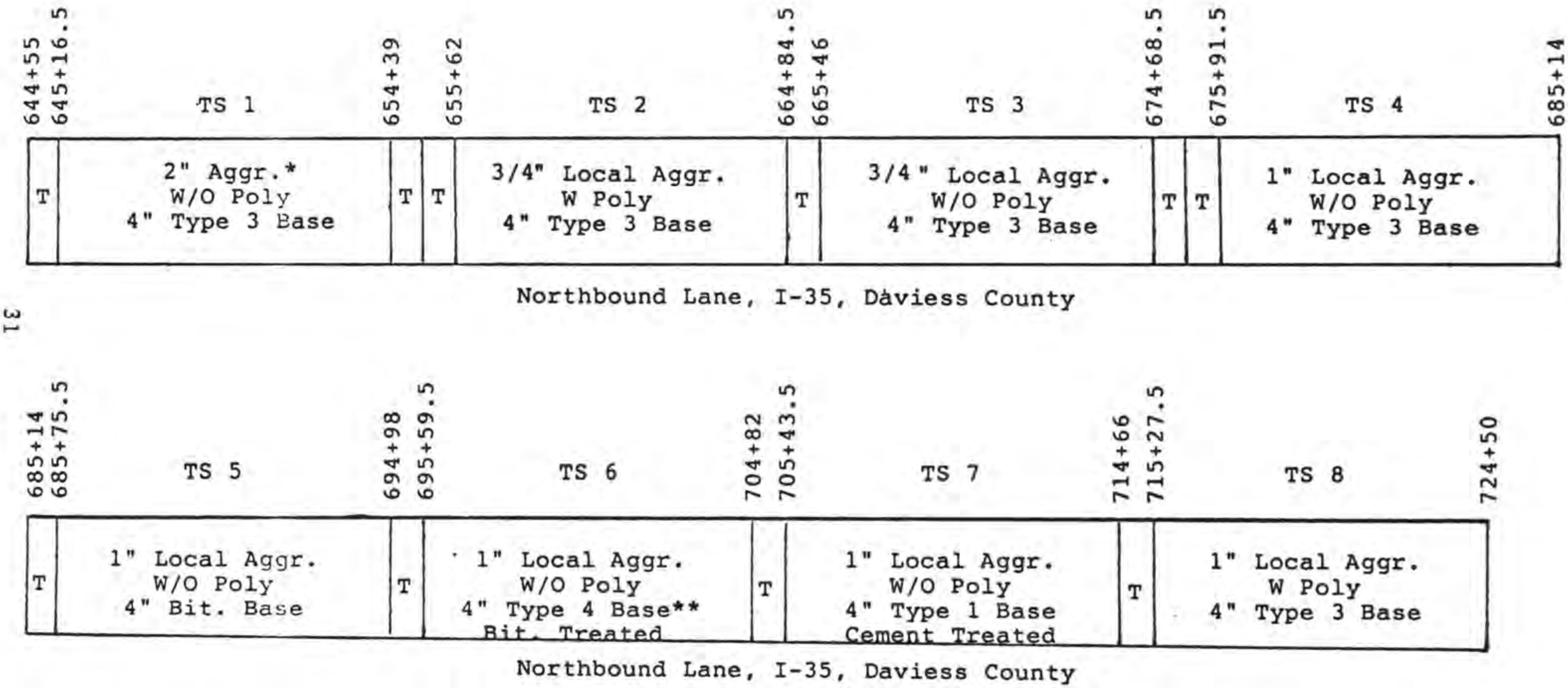


FIGURE 3

Layout and Description of Test Sections



LEDGEND:

* Aggregate with no known history of "D" Cracking (Burlington Limestone)
** Open graded aggregate base.
T = Transition Slab
NOTE: Stationing shown is for centerline of northbound lane.

Figure 4

Typical Cross Section of Test Sections