# Forensic Investigation of AC and PCC Pavements with Extended Service Life

## Volume 2: Petrographic Examination of PCC Core Samples at Lankard Materials Laboratory

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**16. Abstract**

The purpose of this research was to identify flexible and rigid pavements in Ohio with average and above average performance, and determine reasons for these differences in performance. The identification and implementation of factors linked to extended service life will improve performance statewide. FWD and ride quality profiles were measured to evaluate project uniformity, and material samples were obtained from a selected location on each project and tested in the laboratory to determine material properties. Volume 1 of the report includes: the project selection process, FWD and ride quality data, laboratory results of testing on base, subgrade and asphalt concrete pavement samples, and projected services lives using FWD data and the MEPDG. Volume 2 provides the results of laboratory tests and petrographic examinations on the Portland cement concrete cores. Volume 3 contains petrographic analysis of PCC pavement specimens in Cuyahoga County, Ohio containing Blast Furnace Slag Aggregate.

Flexible and rigid pavements in Ohio receiving no structural maintenance show an average condition rating of 68 after 20 and 30 years of service, respectively. This performance, coupled with no structural distress being observed on the pavements selected for study indicates pavement design procedures used in Ohio are meeting expectations. Among the items recommended to improve pavement performance include: 1) maintaining subgrade uniformity to minimize localized failures, 2) reducing amounts of Portland cement and using larger aggregate in 451 and 452 concrete, while continuing to test aggregate for D-cracking susceptibility, 3) increasing emphasis on ensuring that dowel bars maintain proper alignment during placement of PC concrete, and 4) continuing the use of performance grading and polymers when designing AC mixes on heavily traveled pavements. Other observations regarding the data used to reach these conclusions include: keeping the PMIS database current, retaining construction records for at least the design life of the pavements, being aware that the effect of surface cracks on flexible pavement performance depends upon whether the cracks are top-down or bottom-up, and the PMIS and straight-line diagrams should be consistent in identifying project limits, project numbers and paving materials.

Volume 2 of the report contains petrographic analysis of PCC pavement specimens.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: Volumes greater than 1000 L shall be shown in $m^3$. | | | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(°F-32)/9 or (°F-32)/1.8 | Celsius temperature | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ or psi | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.71 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 1.8°C + 32 | Fahrenheit temperature | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ or psi |

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised September 1993)

**FINAL REPORT**

# FORENSIC INVESTIGATION OF AC AND PCC PAVEMENTS WITH EXTENDED SERVICE LIFE: Volume 2: Petrographic Examination of PCC Core Samples at Lankard Materials Laboratory

State Job No. 134280(0)

By

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April 13, 2010

Prepared in Cooperation with the Federal Highway Administration and the Ohio Department of Transportation

# FORENSIC INVESTIGATION OF AC AND PCC PAVEMENTS WITH EXTENDED SERVICE LIFE: Volume 2: Petrographic Examination of PCC Core Samples at Lankard Materials Laboratory

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**ON**

**FORENSIC INVESTIGATION OF AC AND PCC PAVEMENTS WITH EXTENDED SERVICE LIFE: Volume 2: Petrographic Examination of PCC Core Samples at Lankard Materials Laboratory.**

**TO**

**OHIO RESEARCH INSTITUTE FOR TRANSPORTATION AND THE ENVIRONMENT (OHIO UNIVERSITY, ATHENS, OHIO)**

**APRIL 13, 2010**

**LANKARD MATERIALS LABORATORY, INC.
COLUMBUS, OHIO**

## INTRODUCTION AND BACKGROUND

While the overall performance of portland cement concrete (PCC) pavements and asphaltic concrete (AC) pavements in Ohio is satisfactory, certain projects have become known for particularly good or particularly poor performance. Poorly performing pavements gain the most notoriety because they require early maintenance, and efforts to learn the cause(s) of the poor performance can be time-consuming and costly. Conversely, when a pavement performs at or beyond expectations there is speculation as to the factors that influenced these outcomes.

It was reasoned that valuable insights could be gained in a study of ODOT PCC and AC pavements that have shown acceptable and/or exceptional performance in service. The present Research Study was developed with this potential in mind. Asphaltic concrete pavements are covered in Phase A of the study. PCC pavements are covered in Phase B of the study, the results of which are described in the present report.

For the Phase B study, cores were taken from twenty different ODOT PCC pavements which have shown performance that has been categorized as either “Excellent” or “Average.” The performance rating criteria for these categories have been described in detail in the written findings of Part A of the Research Study. These pavements were selected from plots of Pavement Condition Ratings versus Pavement Age on PCC pavement that had not received any structural maintenance at the time of the study. Pavements in both of the Rating Categories have shown performance that has been acceptable, and in several cases, exceptional.

For the present study no cores were taken from marginally or poorly performing PCC pavements. However, it is known that the most significant maintenance issues involving ODOT PCC pavements have historically been associated with (1) deterioration (cracking/spalling) of the transverse control joints, (2) mid-slab cracking, and (3) longitudinal cracking.

## Pavement Control Joint Issues

Prior to the 1970's, joint deterioration in ODOT PCC pavements could in many cases be traced to D-cracking coarse aggregate sources. Currently, aggregates that have been shown to be prone to D-cracking can only be used in ODOT pavements in the ASTM C 33 No. 8 gradation ($^3/_8$ in. maximum size). Because of these and other remedial practices, D-cracking is not currently viewed by ODOT engineers as a significant pavement durability issue. However, it is my opinion that, despite a significant positive impact of the remedial practices, D-Cracking remains a factor that may negatively affect long term durability of PCC in the vicinity of joints and cracks.

At the present time, ODOT PCC pavements are judged to have shown satisfactory performance if no structural maintenance is required for at least the first 20 years of service. Despite the advances made in mitigating the D-cracking situation, ODOT engineers still assume that when significant maintenance issues do arise they will most likely be related to the deterioration of control joints.

In response to this ongoing concern, one of the cores taken from each of the twenty PCC pavement sampling sites examined in the present study was taken through a control joint.

## Mid-Slab Cracking Issues

Mid-slab cracks are transverse cracks that develop in pavement slabs, and they typically are located at or near the center of a slab panel, whose length is defined by the control joint spacing. Over the years steps that were taken in response to the occurrence of mid-slab cracks have included (1) the use of steel mesh in the top portion of the slabs, and (2) reduction in control joint spacing (from as high as 60 ft. (18.3 m) to the current preferred spacing of 15 ft. [4.6 m]). Over the past ten years or so the use of steel mesh in ODOT PCC pavements has been discontinued as it is recognized that the use of jointed plain concrete with 15 ft (4.6 m) joint spacing is more cost effective.

It is our understanding that ODOT pavement engineers believe that the drying shrinkage strain potential and the curling strain potential of portland cement-based pavement concretes may play a role in both control joint performance and the onset and subsequent durability issues related to mid-slab cracking. This issue is addressed in the present report, as is the effect of thermally-induced strains in the pavement slabs.

Of the twenty PCC pavement sites selected for the present study, fourteen exhibit mid-slab cracking. On these projects a second core was taken through the mid-slab crack. At the other six PCC pavement sites the second core was taken in sound concrete in the center of the same slab from which the joint core was taken.

## Longitudinal Cracking

It is our understanding that longitudinal cracking has been an occasional problem in ODOT PCC pavements, but is not currently viewed as a major distress issue. Only one of the PCC pavement sites selected for the present study shows any longitudinal cracking (minor in this case).

## Scope and Objectives of the Present Study

The twenty joint cores and twenty mid-slab cores taken from twenty ODOT PCC pavement sites were examined petrographically and using other tests. These examinations and tests were chosen to provide,

- A characterization of the condition of the cores in the as-received state.
- A characterization of the cementitious phase of the concretes.
- A characterization of the fine and coarse aggregate phases of the concretes.
- A characterization of the entrained air void system of the concretes.
- A measurement of the density of the concretes.
- A characterization of pre-existing fractures in the concretes.
- A characterization of features of the control joints.
- A characterization of distress features and mechanisms.

Information was also made available to us regarding (1) the age of the pavements, (2) traffic counts, (3) control joint spacing, (4) the presence of steel mesh reinforcement, and (5) the type of base material. Physical property data obtained on companion PCC cores were provided by Ohio University personnel (compressive strength, tensile strength, and modulus of elasticity).

Using the findings of the examinations and tests on the PCC pavement cores and using other information available to us regarding relevant design and construction variables, a main objective of the study was to (1) identify, if possible, any material differences in the concretes that could account for the distinction between "Excellent" Performance and "Average Performance" in the ODOT PCC pavements, and, further, to (2) identify any material differences between ODOT PCC pavements in the Excellent/Average Category with those that could historically be categorized as having shown marginal or poor performance.

A corollary objective of the study was to identify those material or design factors that contributed most significantly to the satisfactory performance of the historical concretes, which could be put into more widespread practice to provide improved performance and durability in future ODOT pavement projects.

After all of the data were in and analyzed it became clear that the line of distinction between the ten concretes in the "Excellent Performance" category and the ten concretes in the "Average Performance" category is blurred. This outcome is most likely due to the fact that all twenty of these concretes have actually performed satisfactorily in service. On the basis of the properties and microstructural features that were measured and/or examined in the present study, there is no single property or variable that clearly stands out as explaining the difference between Excellent and Average pavement performance. So, for the purpose of further analyses of the data, all twenty of the Research Study concretes were figuratively placed within the category of "Satisfactory Performance".

Within the context of the "Satisfactory Performance" category, the data were examined from the point of view of identifying the factors that contributed to this outcome for all twenty of the Research Study pavements (relative to PCC pavement concretes that may have showed marginal or poor performance in the past). When this was done it became clear that for a given property category, substantial between-concrete differences for the concretes showing "Satisfactory

Performance" could be tolerated. It also became clear that, from a material point of view, major factors contributing to a satisfactory level of performance of these PCC pavements are the presence of intentional air entrainment, the quality of the coarse aggregate phase and the quality of the cementitious phase. These matters are fully explored in our report.

Of the twenty PCC concrete pavements examined here, one (Gallia County-State Route 7) has been in service for 63 years (constructed in 1946), and one (Athens County-US Route 33) has been in service for 51 years (constructed in 1958). Based on their longevity, the Gallia and Athens County pavements were given particular scrutiny in the present study to identify the factors contributing to this very high level of performance. Of the remaining 18 projects, most (15) were constructed during the period 1990 through 1997 (12 to 19 years of service).

Finally, in addition to the material variables that were measured and analyzed, data were also made available to us on a number of design and construction variables (joint spacing, joint sealant materials, base materials). These variables are also addressed in our report.

## DESCRIPTION OF THE PCC CORE SAMPLES AND CORING SITES

A summary of the core sampling parameters is presented below,

- A total of 44 cores were provided representing two cores from each of 18 sampling sites and 4 cores from each of 2 sampling sites.
- There is a total of 20 PCC Sampling Sites in 11 different Ohio counties (shown in Figure 1).
- One core was taken through a transverse control joint and one core was taken through a mid-slab crack at each of the twenty sites (or in sound concrete at mid-slab in the absence of a crack for six of the sites).
- All of the cores have a diameter of 4 in. and all were taken through the full depth of the pavements, which range from 8 in. to 12 in.
- Ten cores were taken at Sampling Sites where the Pavement Performance is rated as "Excellent". Ten cores were taken at Sampling Sites where the Pavement Performance is rated as "Average."
- The age of PCC pavements rated as "Excellent" ranges from 1946 to 1997. The age of PCC pavements rated as "Average" ranges from 1958 to 1996.
- All 20 of the control joint cores were received in at least two pieces, with the main separation plane being the control joint crack fracture plane.
- Of the 20 mid-slab crack cores, all but 6 were received in at least two pieces, with the main separation plane being the mid-slab crack fracture plane. There were no mid-slab cracks on six of the PCC pavement projects.

A summary of the historical and site data for the 44 cores provided to LML is provided in Tables A-1 through A-11 in Appendix A. Information is provided on (1) the core labeling information as assigned by OU, (2) the date the cores were provided to LML, (3) the pavement construction date, (4) the Ohio County in which the pavement is located, (5) the pavement highway route number, (6) the mile marker and lane direction at the coring site, and (7) the pavement performance rating.

A map showing the location of the Ohio Counties from which the PCC pavement cores were taken is shown in Figure 1. Counties which have pavement projects with an "Excellent" Performance Rating (or both "Excellent" and "Average") are shown in red. Counties which have only a pavement project with an "Average" Performance Rating are shown in blue.

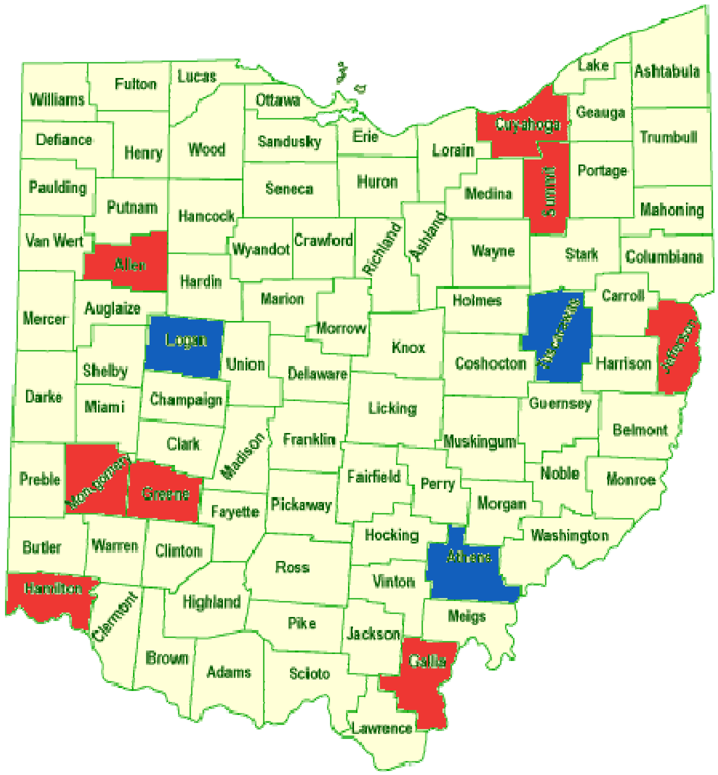



**Figure 1. Map showing the eleven Ohio Counties where PCC Pavement Projects evaluated in Phase B of the Research Study are located.**

Salient features of the distribution of the pavement projects in the State include the following,

- Four of the counties are the site of a single pavement project having the “Excellent” Performance Rating (Gallia, Greene, Hamilton, and Allen)
- Two of the counties are the site of a single pavement project having the “Average” Performance Rating (Tuscarawas and Logan)
- Two of the counties are the sites of one pavement project rated as “Excellent” and one rated as “Average” (Jefferson and Summit).
- Montgomery County is the site of two pavement projects rated as “Excellent”.
- Six of the 20 pavement sampling sites are located in Cuyahoga County, including two rated as “Excellent” and four rated as “Average”.

Reference to Figure 1 shows that there is a broad swath with a North-South orientation in the center of the state with no PCC pavement representation. There is a possibility that this bias may be related in part to the distribution of coarse aggregate sources in the state. Figure 2 is a Bedrock Geologic Map of Ohio, which shows that the strike of the bedrocks is north-south. Rocks that are available for mining in the central North-South corridor of the state are primarily Devonian and Mississippian sedimentary rocks.

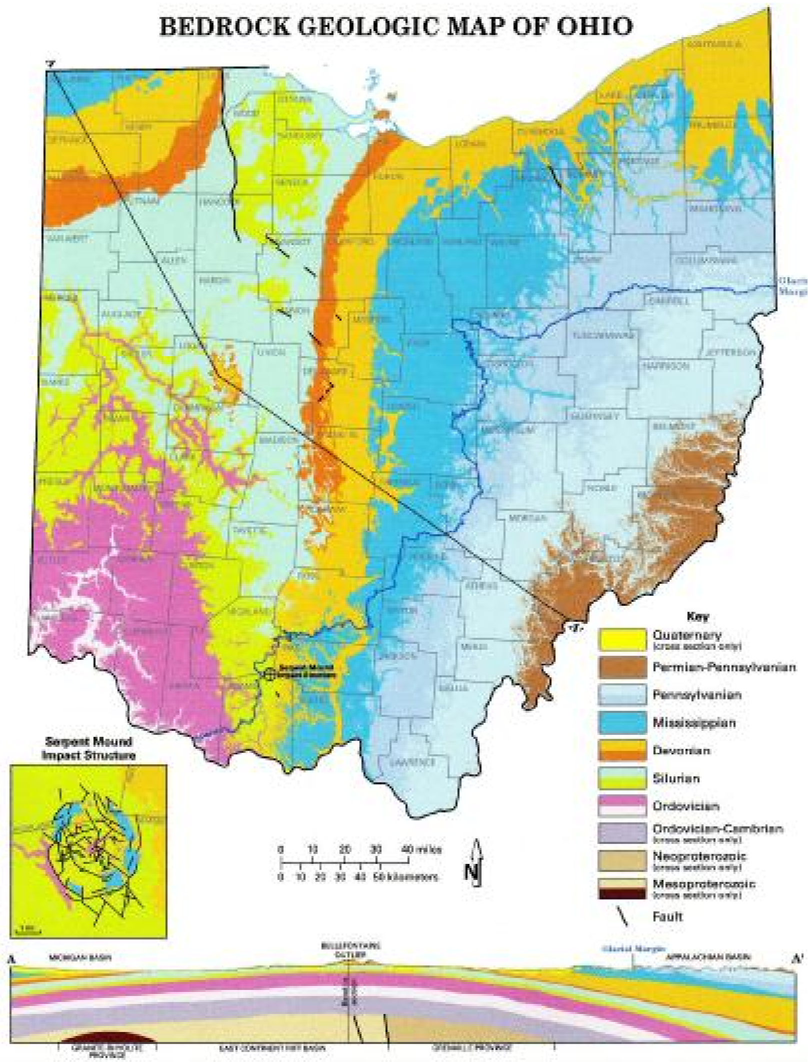



**Figure 2. Bedrock Geologic Map of Ohio (Ohio Department of Natural Resources)**

The PCC cores were taken by Ohio University personnel. An example of the coring operation on a control joint site and a mid-slab crack site is shown in Figures 3 and 4 respectively.


**Figure 3. Coring through a control joint on State Route 682 in Athens County, Ohio in May, 2009. This pavement received an "Average" Performance Rating.**

**Figure 4. Coring through a mid-slab crack on State Route 682 in Athens County, Ohio in May, 2009. This pavement received an "Average" Performance Rating.**

## CORE EXAMINATION PROCEDURES

The examination and testing of the PCC pavement cores was conducted following the relevant guidelines of the following American Society for Testing and Materials (ASTM) Standard Practices and Standard Test Methods.

- ASTM C 856 is "Standard Practice for the Petrographic Examination of Hardened Concrete."
- ASTM C 457 is "Standard Practice for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete."
- ASTM C 642 is "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete."

The examination and testing of the cores provided the opportunity for,

- Characterization of the condition of the cores in the as-received state.
- Characterization of the cementitious phase of the concretes.
- Characterization of the fine and coarse aggregate phases of the concretes.
- Characterization of the entrained air-void system of the concretes.
- Measurement of the density of the concretes.
- Characterization of pre-existing fractures in the concretes.
- Characterization of features of the control joints.
- Characterization of distress mechanisms.

The primary tool used in the petrographic examination of the cores is the stereomicroscope (Olympus SZX-12) at magnifications from 7X to 100X. Standard photographic documentation of features of interest was made at magnifications of 1X to 5X. An example of a typical microstructure of the pavement concretes is shown in Figure 5, which is a 3.3X enlargement of a lapped surface of the mid-slab crack core taken from pavement on State Route 39 in Tuscarawas County, Ohio. This view shows the gravel coarse aggregate particles (yellow dots) and the natural sand fine aggregate particles (red dots) embedded in the gray cementitious matrix of the concrete. The nominal maximum size of the coarse aggregate in this example is ¾ in. Zero to 10 percent of the coarse aggregate particles may pass through the No. 4 sieve (sieve openings of 4.75 mm). Ninety five to 100 percent of the sand particles pass through a No. 4 sieve.

**Figure 5. Lapped surface of Core TUS-39 taken at a mid-slab crack on State Route 39, in Tuscarawas County, Ohio. Coarse aggregate particles (siliceous gravel) are marked with a yellow dot. A few of the fine aggregate particles (natural sand) are marked with a red dot.**

The next sections of the present report present the findings and implications of the petrographic characterization of the four main components of the concretes, which include (1) the cementitious phase, (2) the fine aggregate phase, (3) the coarse aggregate phase, and (4) the entrained air void system. Additional detail on the examination procedures and methodology is presented here. In these discussions the data developed on concretes taken from PCC pavements having the "Excellent" performance rating are compared with the data developed on concretes taken from PCC pavements having the "Average" performance rating. Discussions also touch on how the two concretes that have shown exceptional performance (Gallia-7 and Athens-33) fit into the overall performance issues picture. Strength and modulus of elasticity data obtained on companion PCC pavement cores by Ohio University project personnel are also considered in these analyses.

In the discussions, our assessment of the factors influencing the performance of the pavements also takes into account a number of relevant pavement design and construction variables including (1) pavement thickness, (2) control joint spacing, (3) presence of steel mesh reinforcement, and (4) type of base material.

In summary, each of the principal material, design, and construction variables is discussed with regard to the outcomes of our examination and tests as they relate to the performance of the PCC pavements in service. These conclusions/opinions can strictly apply only to the concretes representing the twenty pavement projects used in the present study. However, based upon the manner in which the twenty pavement projects were selected, it is a premise of the Research Study that the findings can confidently be used to recommend guidelines for future improvements in PCC pavement longevity and performance.

## CEMENTITIOUS PHASE:INFLUENCE ON PAVEMENT PERFORMANCE

The characterization data obtained in this phase of the study include the following,

- The type of cement(s) used in the concretes.
- The water to cementitious material ratio of the cementitious phase.
- The cement paste content.
- The cement content.
- Carbonation of the cementitious phase of the concretes.

### The Type of Cements Used in the Concretes

The cements used in the pavement cores examined here include (1) straight portland cement, and (2) a binary blend of portland cement and fly ash. Fly ash is identified in stereoscopic examinations at high magnification (≥ 50X) on the basis of the unique small size and spherical shape of individual fly ash particles (on lapped and/or acid etched surfaces).

Consideration was also given to the possible presence of ground granulated blast furnace (GGBF) slag cement in two of the pavement concretes (Jefferson-7 and Jefferson-22). These concretes also contain blast furnace slag as the coarse aggregate. Slag cement is identified either by (1) the unique green color that it imparts to the cementitious phase of the concrete, and/or (2) on the basis of the unique size and shape of individual slag cement particles as viewed at high magnifications (≥ 100X) in thin sections. The cementitious phase in the Jefferson county cores does show a green coloration, although the presence and the intensity of the green color varied widely from top to bottom in the cores. I subsequently concluded that the green coloration in the cementitious phase came from the slag coarse aggregate, not slag cement.

The cementitious constituents of the concretes representing each of the twenty coring sites are shown in Table B-1 in Appendix B. For the twenty coring sites studied, nine of the pavement concretes contain only portland cement as the cementitious constituent; nine of the concretes contain the portland cement/fly ash blend, and two of the concretes contain the portland cement/slag cement blend.

The distribution of the cements in the core concretes on the basis of the Excellent/Average Pavement Performance Rating is shown below.

| Pavement Performance Rating | Cementitious Constituents, Percent of Total Concretes in Each Category | | |
|---|---|---|---|
| | Straight Portland Cement | Portland Cement & Fly Ash | Portland Cement & Slag Cement |
| **Excellent (10)** | 40 | 60 | 0 |
| **Average (10)** | 70 | 30 | 0 |

The majority (60%) of pavements in the "Excellent" performance category contain fly ash as a supplementary cementitious material. ODOT's Option 1 specification allows a substitution of 15 percent fly ash in the Class C concrete (510 lb of portland cement and 90 lb of fly ash).

The majority (70%) of pavements in the "Average" performance category are straight portland cement mixes, containing no supplementary cementitious materials.

These findings support the following conclusions,

1. Satisfactory pavement performance has been achieved in concrete containing two different types of cementitious materials, including (1) straight portland cement, and (2) a binary blend of portland cement and fly ash.

2. The use of fly ash in ODOTs Class C pavement concretes (per current ODOT specifications) can be expected to provide comparable performance in service relative to a straight portland cement Class C concrete.

3. The use of fly ash in ODOTs Class C pavement concretes (per current ODOT specifications) *may* provide improved performance in service relative to a straight portland cement Class C concrete.

4. The exclusive use of binary cementitious blends for future ODOT PCC pavement construction should be considered from the point of view of (1) concrete cost, (2) improved long term durability, and (3) sustainability.

## The Water to Cementitious Material Ratio of the Cementitious Phase

There is no standard procedure for the measurement of the water to cementitious material ratio (w/cm) of the cementitious phase in hardened concrete. Petrographic estimates of w/cm are made on the basis of a number of features of the hardened cement paste phase that reflect differences in w/cm. These features include (1) color, (2) hardness, (3) rate of water absorption, (4) relative abundance of unhydrated portland cement grains, and (5) the appearance of fresh fracture surfaces. Information on concrete compressive strength and density, if available, can also be used to strengthen the reliability of the petrographic estimate. It is commonly thought that a petrographic estimate of w/cm made by a qualified petrographer is within ± 0.03 of the actual value. Others place this range at ± 0.05.

The concrete that has been used most widely in ODOT pavements in the past 20 to 30 years has been the concrete identified in the document entitled "State of Ohio, Department of Transportation, Construction and Materials Specifications (January 1, 2002 edition) as "Class C". The standard ODOT Class C concrete has a target cement content of 600 lb per cubic yard and a maximum allowable water to cementitious material ratio (w/cm) of 0.50. Options in the ODOT specifications permit a reduction in cement content of 50 $lb/yd^3$ (30 $kg/m^3$). Allowable coarse aggregates include gravel, limestone, and slag for the ASTM C 33 No. 57 and No. 67 coarse aggregate (1 in. and ¾ in), and gravel and limestone for the ASTM C 33 No. 8 coarse aggregate (3/8 in.)

The estimated w/cm of the cement paste phase of the concretes representing each of the twenty ODOT pavement coring sites are shown in Table B-2 in Appendix B. The average w/cm of the twenty concretes is 0.45. The fact that the w/cm of the ODOT pavement concretes examined here is below the maximum allowed in the specification is not unexpected. This is due to the fact that the pavement concretes are typically machine-placed at a relatively low slump.

The distribution of the w/cm of the cementitious phase in the core concretes on the basis of the Excellent/Average Performance Rating is shown below.

| Pavement Performance Rating | Average Value of Water to Cementitious Material Ratio (w/cm) of the Concretes | Range of Values of Water to Cementitious Material Ratio (w/cm) of the Concretes |
|---|---|---|
| **Excellent (10)** | 0.46 | 0.42 to 0.48 |
| **Average (10)** | 0.44 | 0.42 to 0.45 |

These findings support the following conclusions and significant observations,

1. The most widely used ODOT pavement concrete (Class C) has a target maximum w/cm of 0.50. All twenty of the Research Study concretes have an estimated w/cm less than 0.50. The placement of the concretes at a relatively low slump using paving machines has led to good control over this variable.

2. The water to cementitious material ratio (w/cm) of the cementitious phase is comparable in the ten concretes rated as “Excellent” performers relative to the ten concretes rated as “Average” performers.

3. Estimated at a value of 0.45, the w/cm of the twenty pavement concretes is acceptable for concretes in this pavement application. Relevant committees of the American Concrete Institute (318, 201) recommend a maximum w/cm of 0.45 for exposed concretes in severe weather exposure applications when deicing chemicals are used.

4. The ODOT requirement for maximum w/cm should be retained in the interest of (1) satisfactory levels of strength, (2) low permeability, and (3) long-term durability.

Figure 6 shows the effect of water-cement ratio on the permeability of mature hardened portland cement paste. At a w/cm at or below 0.45, hardened portland cement paste has a very low permeability, which is an important feature regarding the freeze/thaw durability of concretes exposed in a severe weather environment. Low permeability is also an important feature of concretes regarding the ingress of chloride-laden waters, which may come into contact with embedded steel dowels or mesh.

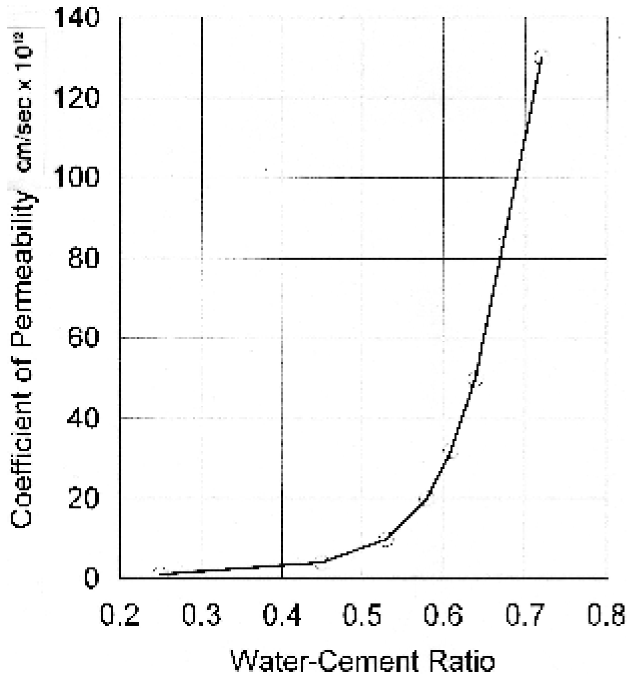



**Figure 6. The effect of water-cement ratio on the permeability of mature hardened portland cement paste (Powers et. al. 1954).**

<u>**Cement Paste Content of the Concretes**</u>

The cement paste content is a measured value that is obtained as part of the ASTM C 457 procedure. In the present study the modified point count method of the ASTM C 457 was used. The measured cement paste content of the concretes representing each of the twenty coring sites is shown in Table B-3 in Appendix B. The average value of cement paste contents for the twenty concretes is 27.5 percent. The distribution of cement paste content values in the core concretes on the basis of the Excellent/Average Performance Rating is shown below.

| **Pavement Performance Ranking** | **Average Value of Cement Paste Content for the Concretes, %** | **Range of Values of Cement Paste Content for the Concretes, %** |
|---|---|---|
| **Excellent (10)** | 26.8 | 20.3 to 29.5 |
| **Average (10)** | 28.1 | 22.0 to 31.0 |

Table B-4 in Appendix B shows the absolute volume values for the ODOT Class C concrete containing the No. 57 limestone aggregate when the w/cm is 0.45. The theoretical cement paste content at a w/cm of 0.45 and an air content of 6 percent is 27.8 percent.

As shown in Table B-3 (Appendix B), two of the concretes have a measured cement paste content in the 20 to 22 percent range and four of the concretes have a measured cement paste content in the 29 to 31 percent range.

The findings support the following significant observations regarding the measured cement paste content of the pavement concretes,

1. The *average* cement paste content of the twenty pavement concretes examined here is in reasonable agreement with the expected value based upon the mix design for the ODOT Class C concrete at a w/cm of 0.45.

2. There is no significant different in the *average* cement paste content of the ten "Excellent" performing concretes relative to the ten "Average" performing concretes.

3. Relatively large differences in cement paste concrete can be tolerated without adversely affecting long-term durability as long as the water to cementitious material ratio (w/cm) is at a satisfactory low level (≤ 0.50).

## Cement Content of the Concretes

The ODOT Class C concrete calls for a cement content of 600 lb/yd$^3$ (356 kg/m$^3$), while the options with water reducing admixtures allows a cement content of 550 lb/yd$^3$ (326 kg/m$^3$). Cement content can not be directly measured on hardened samples of concrete. However, knowledge of the measured value of the cement paste content, along with estimates of the w/cm provides the opportunity to estimate the cement content of the hardened concrete.

For a straight portland cement Class C concrete, the expected cement paste content is 27.3 percent for the 600 lb/yd$^3$ (356 kg/m$^3$) mix, and 25.1 for the 550 lb/yd$^3$ (326 kg/m$^3$) mix (at a w/cm of 0.45 and an air content of 6 percent). In addition to the cement content of the concrete, the cement paste content is affected by both the w/cm and the air content of the concrete.

For the twenty pavement concretes of the Research Study the grand average value of the cement paste content is 27.5 percent. For fifteen of the twenty project concretes the range in the measured value of w/cm was 25.9 percent to 29.5 percent. Considering the variability in air content (to be discussed) this represents fairly tight proportioning control.

Of particular interest with respect to the cement content variable is the result obtained on the Gallia County-State Route 7 concrete (GAL-7). As discussed previously, this PCC pavement has exhibited exceptional performance as judged by its 63 years of service. The measured cement paste content on this portland cement concrete is 20.3 percent and the estimated w/cm is 0.48. Based upon these numbers the estimated cement content for the GAL-7 concrete is 430 lb/yd$^3$ (255 kg/m$^3$). This concrete also contains a 2 in. maximum size coarse aggregate, which is one of the factors making it possible to use a reduced cement content. Although this is a single example, the use of a low cement content made possible by the use of larger coarse aggregate makes sense from a performance point of view. At a w/cm at or below 0.50, concretes having a cement content in, say, the 480 to 520 lb/yd$^3$ range would provide for reduced values of drying shrinkage strains and curling strains. In recent times, concrete mixes of this type are widely used in commercial floor slab construction. The experience with the GAL-7 pavement concrete provides an incentive for considering experimentation with the use of lower cement content mixes (while maintaining an acceptably low w/cm) for future ODOT PCC pavement construction.

## Carbonation of the Cementitious Phase of the Concretes

A hardened portland cement concrete surface exposed to the atmosphere can experience carbonation. Carbonation is the reaction of atmospheric carbon dioxide ($CO_2$) with the hydrated portland cement phases; most particularly calcium hydroxide. The pore water solution in portland cement concrete is highly basic, with a pH typically in the range of 13 to 14. When carbonation occurs, the pH is reduced, often to a neutral value of 7, or even lower.

In pavement applications the portion of the pavement that can experience carbonation is the pavement wearing surface (which is exposed to the atmosphere). In the present study the depth of carbonation of the wearing surface of the pavement cores was measured by applying a pH indicating solution (phenolphthalein) to fresh saw-cut surfaces. The saw-cuts are made perpendicular to the plane of the wearing surface. The phenolphthalein (in an alcohol solution) is applied in a light mist form to the concrete surface. If the surface has a pH above 10 (i.e. is not carbonated), the phenolphthalein produces a bright red color. If the pH is below 10, there is no color change in the concrete and the concrete exhibiting this behavior is judged to be carbonated. The actual pH of the concrete was checked by applying a universal indicating solution to the fresh saw-cut surfaces of the cores. The universal indicating solution is Rainbow Indicator, a proprietary product produced by Germann Instruments Company in Evanston, Illinois. Through the use of distinctive color changes, this indicating solution can identify pH regions ranging from 5 to 13.

Figure 7 shows a saw-cut surface of the core from State Route 682 in Athens County, Ohio [ATH-682 (CR)] following the application of the phenolphthalein solution. The saw-cut is perpendicular to the plane of the pavement wearing surface. No carbonation has occurred in the cementitious phase in those portions of the surface that are red in color. In this core only portions of the topmost 0.5 mm thickness of the wearing surface are carbonated.

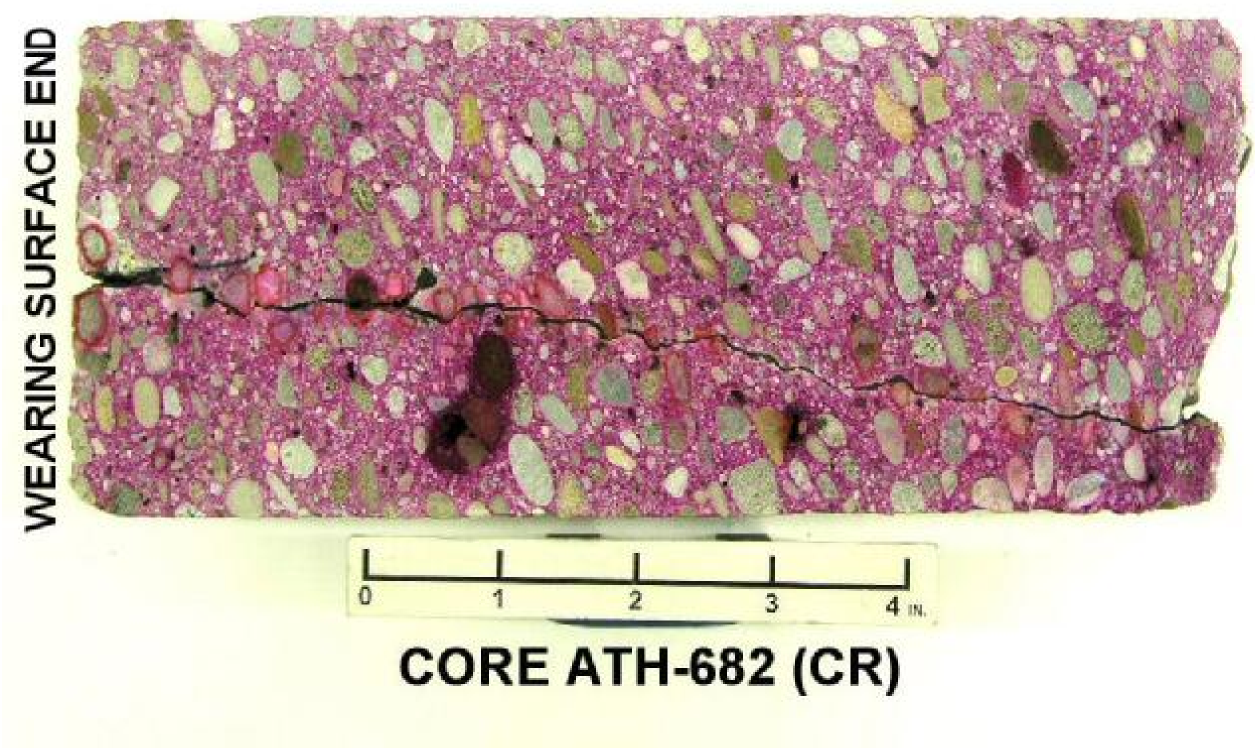



**Figure 7. Saw-cut surface of Core ATH-682 (CR) following the application of the phenolphthalein pH indicating solution. No carbonation has occurred in the red colored area (essentially the entire thickness of the core).**

The depth of carbonation of the wearing surface was measured on cores from all twenty of the pavement sites. In all cases the depth of carbonation was very shallow, with a result similar to that shown in Figure 7. The deepest level of carbonation was 3 mm in the cores examined here, which is still considered to be shallow. The absence of deeper levels of carbonation in the pavement cores is attributed to the good quality (low permeability) of the cementitious phase in the concretes.

## COARSE AGGREGATE PHASE: INFLUENCE ON PAVEMENT PERFORMANCE

Characterization data were obtained on the fine and coarse aggregate phases in the concretes. For the coarse aggregate phase the characterization parameters include the five shown below. The criteria used to rate or rank the values of the given parameters are provided in the Tables that are identified parenthetically below (provided in Appendix C).

1. The type and size gradation of the aggregates (Table C-1).
2. A rating of the quality of the cement paste/aggregate bond (Table C-2).
3. A rating of the presence and extent of any cement-aggregate reactions (Table C-3).
4. A rating of the extent of cracking in the aggregate particles attributable to freezing and thawing (Table C-4).
5. A rating of the overall condition of the coarse aggregate particles at the time of coring (Table C-5).

### Coarse Aggregate Type and Size

The cores taken from 20 different ODOT PCC Pavement project sites contained one of five different coarse aggregate sources, including,

- 3/8 in. (10 mm) maximum size gravel (ASTM C 33 No. 8 gradation).
- 3/8 in. (10 mm) maximum size crushed limestone (ASTM C 33 No. 8 gradation).
- ¾ in. (19 mm), 1 in. (25 mm ), or 2 in. (51 mm) maximum size gravel (ASTM C 33 No. 57, 67, or 467 gradation).
- ¾ in. (19 mm) or 1 in. (25 mm) maximum size crushed limestone (ASTM C 33 No. 57 or 67 gradation).
- ¾ in. (19mm) or 1 in. (25 mm) maximum size slag aggregate (ASTM C 33 No. 57 or 67 gradation).

Additional detail regarding the type of coarse aggregate is provided in Tables C-6 through C-9 in Appendix C. These tables also provide a complete listing of the Aggregate Characterization Rating values for the twenty pavement concretes examined here. Table C-10 lists the coarse aggregate supplier for most of the Research Study concretes.

Table C-1 (Appendix C) shows the type of coarse aggregate used in the concretes evaluated in the present study; grouped according to the Pavement Performance Rating of Excellent or Good. These data are summarized below.

| **Pavement Performance Rating** | **Type of Coarse Aggregate<br>Percent of Each Concrete Category Having the Indicated Aggregate** | | | | |
|---|---|---|---|---|---|
| | **3/8 in. Gravel** | **3/8 in. Crushed Limestone** | **¾, 1 in. or 2 in. Gravel** | **¾ or 1 in. Crushed Limestone** | **¾ or 1 in. Slag** |
| **Excellent (10)** | 20 | 30 | 20 | 20 | 10 |
| **Average (10)** | 10 | 50 | 10 | 10 | 20 |

The tabulated data shown below shows the distribution of the coarse aggregate in the concretes on the basis of the county of origin for the pavement project.

| **Pavement Performance Rating** | **Ohio Counties Having the Indicated Aggregate in Pavement Concretes taken from that County** | | | | |
|---|---|---|---|---|---|
| | **3/8 in. Gravel** | **3/8 in. Crushed Limestone** | **¾, 1 in. or 2 in. Gravel** | **¾ or 1 in. Crushed Limestone** | **¾ or 1 in. Slag** |
| **Excellent (10)** | Montgomery (2) | Cuyahoga(2)<br>Summit | Gallia<br>Hamilton | Greene<br>Allen | Jefferson |
| **Average (10)** | Athens | Cuyahoga (3)<br>Logan<br>Summit | Tuscarawas | Athens | Jefferson<br>Cuyahoga |

As is obvious from the tabulated data, ODOT PCC pavements having an Excellent or an Average rating have been constructed using all five of the cited aggregate types. Of the five types listed here the most commonly used aggregate in the twenty project sites is the 3/8 in. crushed limestone. This aggregate was used on eight (40 percent) of the twenty projects. As shown in Table C-1 (Appendix C) the concrete taken from State Route 7 in Gallia County has a 2 in. maximum size gravel coarse aggregate. This pavement was constructed in 1946. In all of the other pavements the maximum size of the coarse aggregate is 1 in., ¾ in., or 3/8 in.

## **Quality of the Cement Paste/Coarse Aggregate Bond**

Optimum strength properties are obtained in concretes (1) when there is a tight, uninterrupted bond between the cement paste and the aggregate particles, and (2) when the quality of the cement paste in direct contact with the aggregate particles is comparable to that of the cement paste in the remaining bulk of the concrete. The criteria used to rate the quality of the coarse aggregate bond in the present study are summarized in Table C-2 (Appendix C). The Rating Descriptors of Excellent-Good-Fair-Low-Poor are based upon petrographic estimates of (1) bond continuity and tightness, and (2) the quality of the cement paste in direct contact with the aggregate particles.

In the majority of the concretes examined here the tightness of the bond of the cement paste to the aggregate particles is satisfactory. This is not the case regarding the *quality* of the cement paste in contact with the aggregate particles in some of the concretes.

The thin layer of cement paste in direct contact with the aggregate particles in concretes is commonly referred to as the Interfacial Transition Zone (ITZ). Ideally, the w/cm and related properties of the cement paste in the ITZ are comparable in quality to those properties in the cement paste in the concrete as-placed. Occasionally this is not the case and the cement paste in the ITZ may be softer, weaker, and more porous due to a higher w/cm or to the presence of a greater proportion of non-cementitious cement hydrates (calcium hydroxide). An example of this microstructural features is shown in Figure 8. Figure 8 is an enlarged stereomicroscopic view (25X) of a lapped surface of Core CUY-176-12-S (JT). The lighter color of the affected cement paste phase is due to the elevated w/cm.

One possible explanation for this microstructural feature is as follows. Coarse aggregate particles are often in the saturated condition when they are introduced into the concrete. Once the concrete has been placed, the temperature within the concrete rises due to the exothermic cement hydration reactions. As the absorbed water in the aggregate particles heats up, it expands. As there is no new empty volume within the aggregate particle to accept this new increased water volume, the excess water moves out into the concrete. If the concrete is still in a fluid state, the excess water can enter the cement paste that is in contact with the aggregate particle and increase its w/cm.

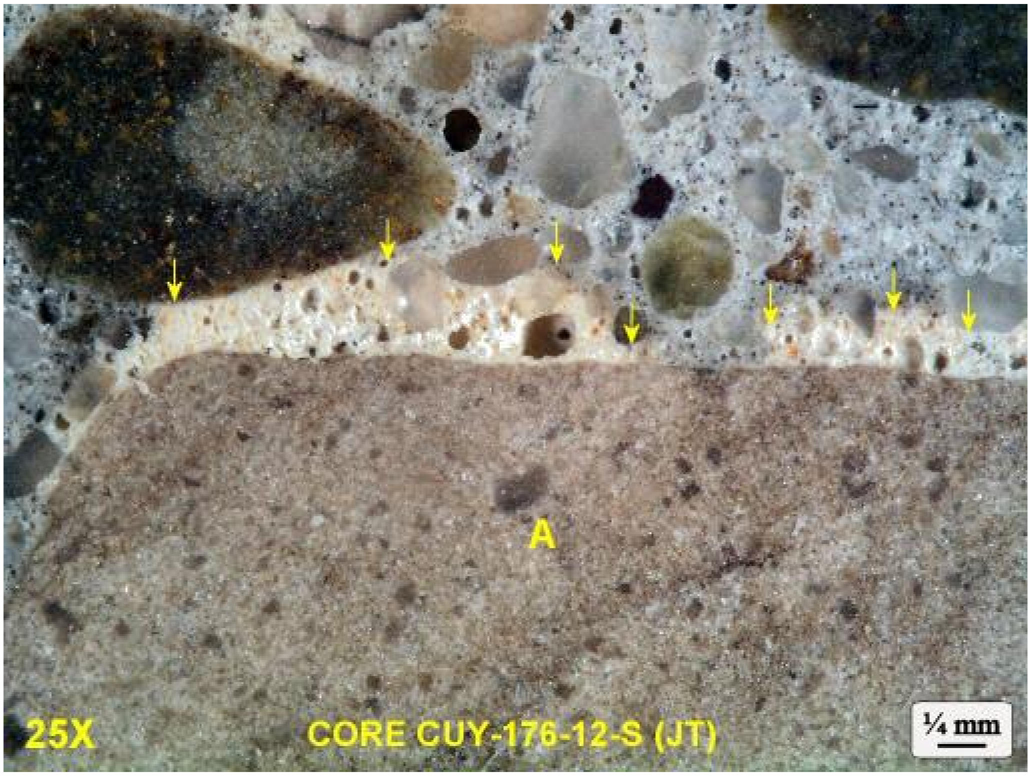



**Figure 8. Lapped surface (25X) of Core CUY-176-12-S (JT) showing a region of elevated w/cm cement paste (below the arrows) in contact with a limestone coarse aggregate particles (A).**

The Rating Number for each of the twenty project concretes are summarized in Tables C-6, C-7, C-8 and C-9 in Appendix C. The data are presented below in a form that shows the breakdown on the basis of the Pavement Performance Ratings. A number of the pavement concretes examined here show some evidence of the aforementioned paste/aggregate bond feature. This includes 25 percent of the "Excellent" performers and 55 percent of the "Average" performers. In all cases it is this feature of the cement paste/aggregate bond that has resulted in a reduced rating for bond quality in these pavement concretes.

| Pavement Performance Rating | Rating of the Quality of the Cement Paste/Aggregate Bond, Percent of concretes showing indicated rating | | | | |
|---|---|---|---|---|---|
| | Excellent | Good | Fair | Low | Poor |
| Excellent (10) | 0 | 60 | 30 | 0 | 10 |
| Average (10) | 10 | 30 | 40 | 10 | 10 |

The presence of this ITZ feature is expected to have a reducing effect on the measured strength of the concretes. This issue is discussed in the section of the report covering strength results.

**Cement-Aggregate Reactions Associated with Coarse Aggregate Particles**

Chemical reactions can occur in portland cement concretes, which involve chemical interactions between constituents in the concrete pore water and certain types of aggregates. The reactions are known as "alkali-silica reactions", which is commonly referred to by the acronym "ASR", and "alkali-carbonate reactions", which are commonly referred to as "ACR."

These cement-aggregate reactions can be progressive and destructive. The distress created by the reactions within the concrete takes the form of cracking that can affect both the offending aggregate particles and the cementitious phase adjacent to the particles. In worst case situations the severity and extent of distress is enough to cause a removal and replacement of the affected concrete.

Historically, cement-aggregate reactions have not been a durability problem for Ohio's pavement concretes. I am aware of only two instances where destructive cases of ASR activity were identified in ODOT PCC pavement concrete. Despite this, it is not unusual to find petrographic evidence of some *minor level of non-destructive* cement-aggregate reaction activity in PCC concretes made with Ohio's aggregates. Diagnostic features that confirm the presence of reaction activity in concretes that are examined petrographically include, (1) direct identification of ASR gel, (2) discoloration of cement paste that has been intruded by ASR gel, (3) distinctive cracking in reactive aggregate particles, (4) distinctive cracking in reactive aggregate particles that extends into the adjacent cementitious phase, (5) the presence of darkened reaction rims on the surfaces of offending aggregate particles at their point of contact with the cementitious phase, and (6) a softening (gelatinization) of an offending aggregate particle.

In the project concretes examined here no petrographic evidence was found for any alkali-carbonate reaction (ACR) activity. Evidence was found of *very limited and non-destructive* alkali-silica reaction (ASR) activity in some of the concretes. In the stereomicroscopic examination of lapped and fracture surfaces, occasional deposits of what had the appearance of ASR gel were observed as coatings on air void surfaces. This suspect ASR material was excavated from the concretes that showed this feature and the material was analyzed using energy dispersive x-ray spectroscopy procedures (EDX) as part of a scanning electron microscope (SEM) examination (using a JEOL

Model JSM-840A SEM). Figure 8 shows the EDX spectrum (20X) of suspected ASR material excavated from Core TUS-39 (Tuscarawas County State Route 39 – 1990 pavement project). This is a typical pattern for alkali-silica gel, showing a dominance of calcium and contributions of the alkali elements sodium (Na) and potassium (K).

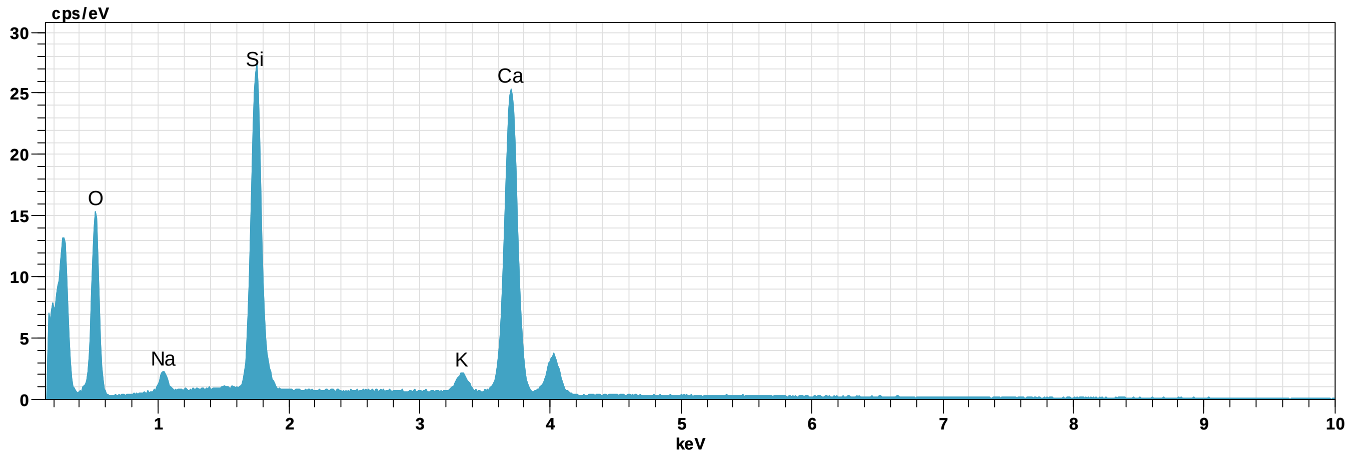



**Figure 9. EDX spectrum (20X) of alkali-silica gel excavated from Core TUS-39.**

The Rating Criteria used here to quantify the extent of the ASR activity in the Research Study concretes are No-No*-Very Limited-Common. A rating of "No" means that no ASR activity associated with coarse aggregate particles was seen in the petrographic examination (see Table C-3, Appendix C). A "No*" rating means there were two or three instances where suspect ASR gel was detected as a coating on air voids adjacent to siliceous coarse aggregate particles. For this rating there was no cracking associated with the aggregate particles. A rating of "Very Limited" is similar to the "No*" rating except that there was minor cracking associated with the particles. In no instances was ASR activity rated as "Common" in the twenty pavement concretes examined here.

The Cement-Aggregate Reaction Ratings for each of the twenty project concretes are summarized in Tables C-6, C-7, C-8 and C-9 in Appendix C. The data are presented below in a form that shows the breakdown on the basis of the Pavement Performance Ratings. These findings support the following conclusions regarding the presence and consequences of ASR activity in the ODOT pavement concretes.

1. A very limited amount of alkali-silica reaction (ASR) activity was detected in about half of the twenty pavement concretes examined here.

2. The ASR activity identified in these concretes is not destructive and ASR has had no effect on the performance of the concretes to date and is not expected to have any effect in the future.

| **Pavement Performance Rating** | **Evidence of Destructive Cement-Aggregate Reactions Associated with the Coarse Aggregate, Percent of Concretes showing indicated rating** | | | |
|---|---|---|---|---|
| | **No** | **No*** | **Very Limited** | **Common** |
| **Excellent (10)** | 50 | 40 | 10 | 0 |
| **Average (10)** | 60 | 20 | 20 | 0 |

## Freeze/Thaw-Related Cracking in Coarse Aggregate Particles

Three different types of coarse aggregates were used in the Research Study concretes including (1) gravels, (2) slag, and (3) crushed carbonate rocks (limestones/dolomitic limestone). Maximum size for the limestones include $^3/_8$ in., ¾ in. and 1 in.; for the gravels, $^3/_8$ in., ¾ in., 1 in. and 2 in.; and for the slag ¾ in. and 1 in. Taking into account both lithologic type and maximum size there are eight different coarse aggregates in the twenty project concretes. A listing of the aggregate sources for the Research Study concretes is given in Table C-10 in Appendix C.

A nearly universal common feature of these coarse aggregates is the fact that they have experienced many years of service and have shown an acceptably low amount of cracking distress due to freezing and thawing conditions. This assessment takes into account the fact that the cores examined here were taken through joints and mid-slab cracks, where full moisture penetration of the slab thickness would be expected to be greatest.

Historically and currently there have been problems with D-cracking in some of the coarse aggregate sources in Ohio. The Portland Cement Association conducted an extensive study of this phenomenon for ODOT in the 1970s (Klieger and Stark, 1974 and Stark, 1976). The proneness of a given aggregate source to D-Cracking was quantified by subjecting air-entrained concrete beam specimens to freezing and thawing cycles and measuring permanent expansions in the beams as a

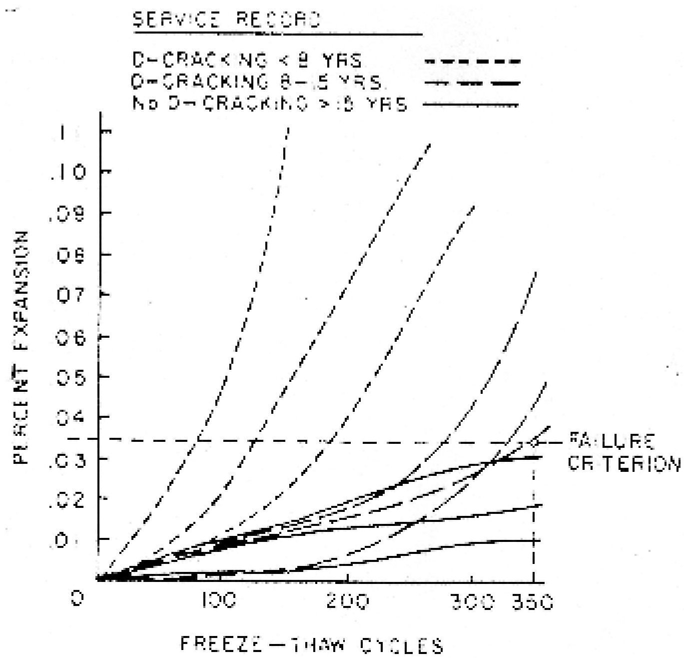



**Figure 10. Relationship between aggregate service record for sources of Ohio carbonate coarse aggregate sources and the expansion of air-entrained concrete beams containing the aggregates in laboratory freezing and thawing tests. (Stark, 1976)**

function of the number of cycles (two cycles per day). In these tests the service history of the aggregates as-related to the D-cracking problem was known. The result of the tests on a number of these aggregate sources is shown in Figure 10. There are large differences in both the rate of expansion and the magnitude of expansion in the test beams. As these are air-entrained concretes the permanent expansion in the beams is attributed primarily, if not solely, to repeated episodes of expansions in the saturated aggregate particles on freezing and thawing.

Petrographic examination of the test beams in the PCA study revealed a pattern of cracking in the aggregate particles themselves. An example of one of these coarse aggregate particles is shown in Figure 11. Distinctive features in this typical example are that there is multiple cracking in the particle and a number of the cracks pass into the adjacent cementitious matrix phase of the concrete. In the present petrographic examination the percentage of coarse aggregate particles showing cracking diagnostic of freeze/thaw-related cracking in service was assessed. For the twenty Research Study concretes, nine showed no evidence at all of service related cracking, and ten showed a minor amount (1% to 5% of total particle count) of this feature. The concrete taken from the Athens County US Route 33 pavement showed around 10 percent of the coarse aggregate

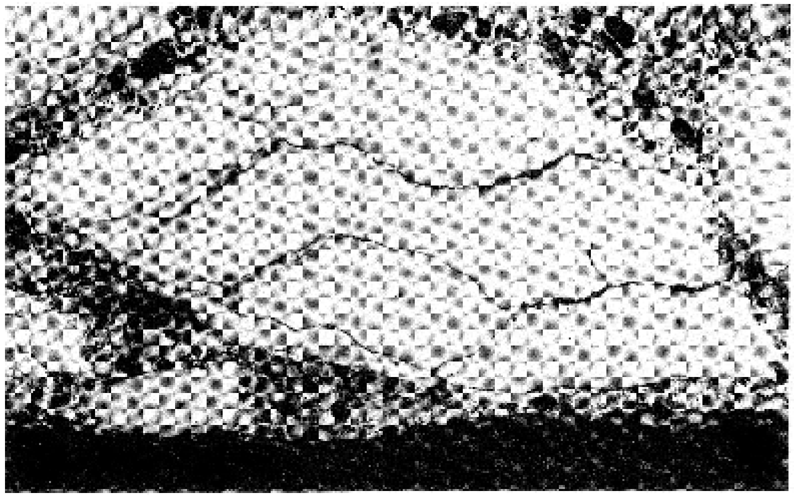


**Figure 11. Example (2.5 X) of a fractured carbonate coarse aggregate particle (Ohio source) in an air-entrained concrete beam specimen used in a laboratory freezing and thawing test (Stark, 1976).**

particles (1 in. limestone) with these diagnostic cracking features. All of the joints in this 51 year old pavement had been replaced in the past.

The lesson learned from the past and present study is that virtually all of the natural coarse aggregate sources that contain sedimentary rock types exhibit some degree of expansion when they undergo freezing in a water-saturated condition. The rate at which this occurs and the magnitude of expansions are widely variable between aggregate sources.

An example of the most common manifestation of the D-Cracking phenomenon is shown in Figure 11 (Stark, 1976). Water passes down through the joint fracture to increase the moisture content in the base material and the bottom of the pavement slab in the vicinity of the joint. The moisture content of the base and slab is expected to diminish as the lateral distance from the joint plane increases. The inverted V-Shaped distribution of moisture in the slab produces the type of cone-shaped fracture in the concrete as shown in Figure 12.

Examples of this cone fracture pattern, which is diagnostic of this type of freeze/thaw related distress are shown in Figure 13 for Joint Cores GAL-7 and ATH-682. The Gallia County pavement has been in service for 63 years and the Athens county pavement for 33 years. Both of these concretes contain a siliceous gravel, which includes some sedimentary rock types.

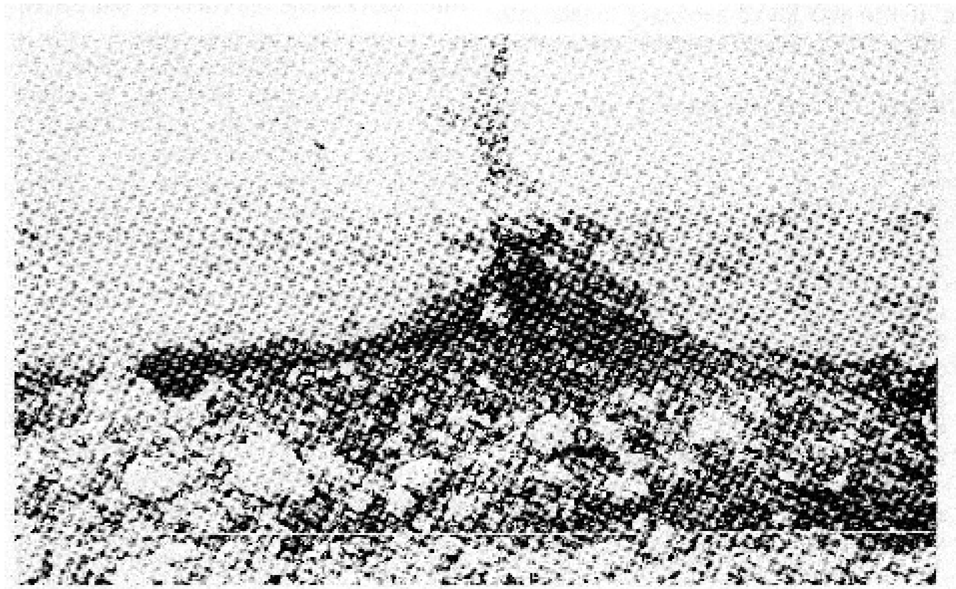


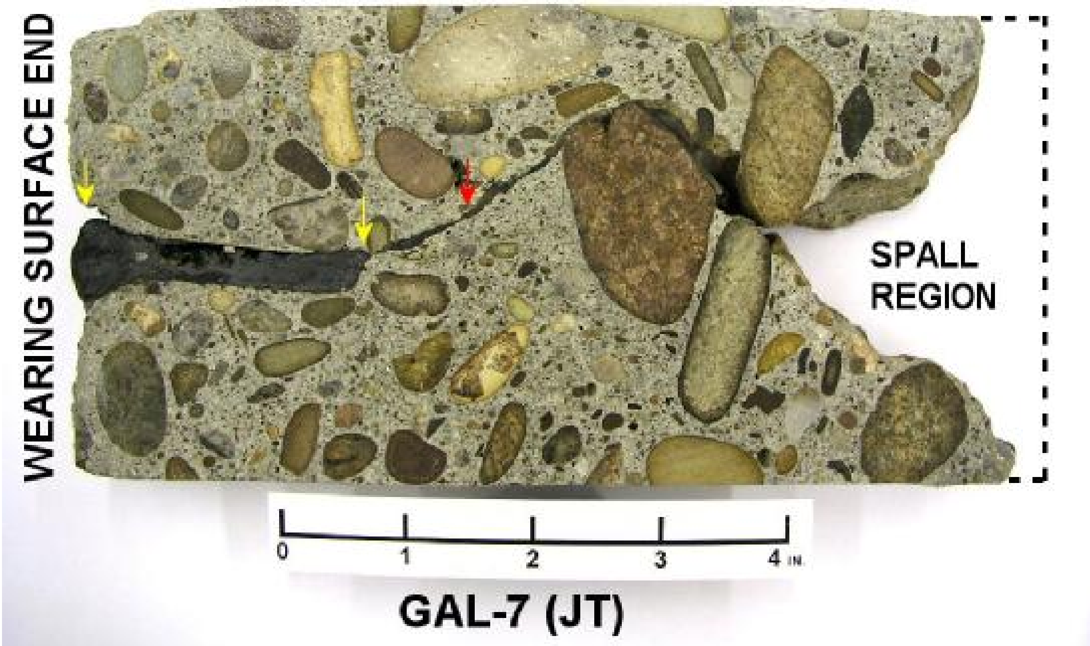
**Figure 12. Transverse cross-section of a PCC pavement at a joint line in which severe D-Cracking has developed. The white line shows the original bottom of the pavement slab, the lower half of which has disintegrated into rubble (Stark, 1970).**

The coarse aggregate in the Gallia-7 pavement is a 2 in. maximum size siliceous gravel composed of siltstones, chert, sandstones, and igneous rock types. The aggregate source is identified as Ohio River Sand and Gravel, Martinsville, West Virginia.

The Athens County State Route 682 pavement has been in service for 33 years. The coarse aggregate is a 3/8 in. maximum size siliceous gravel composed of siltstones, sandstones, chert, igneous rock types, quartz and quartzite, with trace amounts of limestone. The aggregate source is identified as #8 Gravel, Richards, Apple Grove.

All of the joints were replaced on the Athens County US Route 33 pavement (built in 1958) indicating that it has experienced the type of joint failures shown in Figure 13. The coarse aggregate on this project is a 1 in. maximum size limestone of unknown origin.

Of the other seventeen Research Study concretes fifteen show virtually no cone-type fractures on either the joint core or the mid-slab crack core. Very small cone fractures are present on the bottom end surface of Cores CUY-176-11-S and CUY-176-12 S.



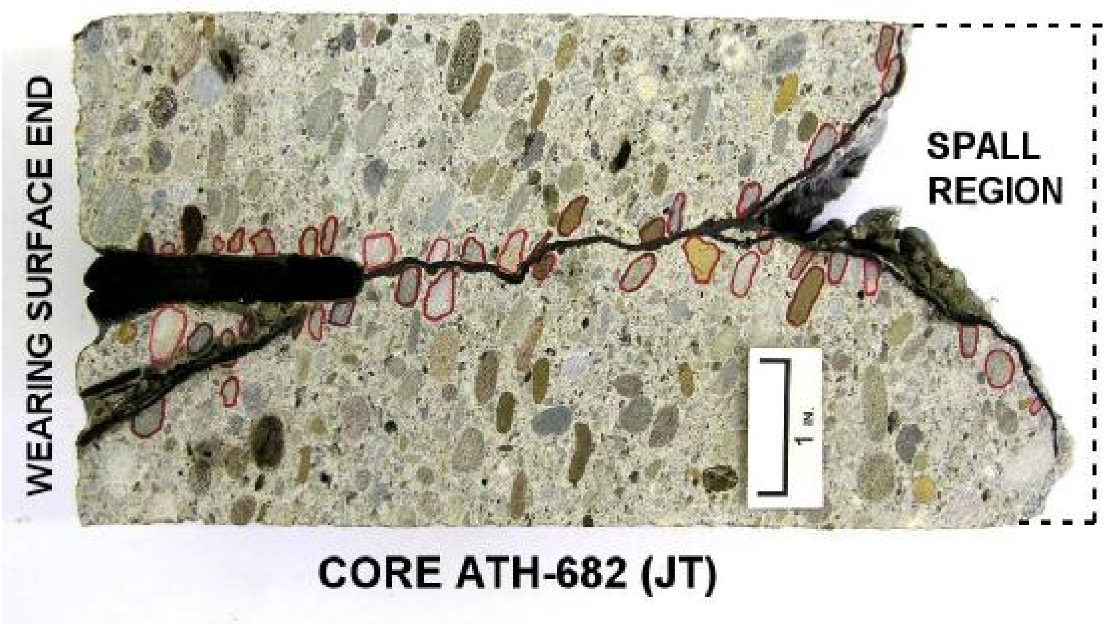




**Figure 13. Section views of Joint Cores GAL-7 (JT) and ATH- 682 (JT) showing cone-shaped regions of spalling in the bottom of the cores. The Gallia County pavement has been in service for 63 years; the Athens County pavement for 33 years.**

In our petrographic examination evidence was sought of freeze/thaw-related distress in the aggregate particles. As illustrated by the example shown in Figure 11, the diagnostic features of this source of cracking include,

- There typically will be multiple cracking in the offending aggregate particle.
- The cracks often will not be tight.
- The cracks likely will extend into the adjacent cementitious phase.
- The cracks will be most prevalent (or only in) the near-top or in the bottom of the core, or along major crack fracture planes in the concrete.

The Rating Criteria used here to identify the presence and extent of freeze/thaw-related cracking involving the coarse aggregate particles in the Research Study PCC pavement cores are described in Table C-4 in Appendix C. The Rating Descriptors are "None" in those cores where none of the coarse aggregate particles show any evidence of these microstructural features. There are then four other categories where the percent of coarse aggregate particles that are judged to show the features are quantified, with 1% to 5% being the low end of the range, and 20% or higher being the upper end of the range.

The Coarse Aggregate Freeze/Thaw Involvement Ratings for each of the twenty project concretes are summarized in Tables C-6, C-7, C-8 and C-9 in Appendix C. The data are presented below in a form that shows the breakdown on the basis of the Pavement Performance Ratings.

| **Pavement Performance Rating** | **F/T Performance of the Coarse Aggregate (Percent of Particles that show F/T-Related Cracking)** | | | | |
|---|---|---|---|---|---|
| | **None** | **1% to 5 %** | **5% to 10%** | **10% to 20%** | **20% and Higher** |
| **Excellent (10)** | 50 | 50 | 0 | 0 | 0 |
| **Average (10)** | 40 | 50 | 0 | 10 | 0 |

The summary of these findings regarding the evidence for freeze/thaw-related distress in the coarse aggregate phases of the pavement concretes are summarized below.

1. For the full population of the twenty pavement concretes there is no evidence of any freeze/thaw- related damage in coarse aggregate particles in half of the concretes.

2. Joint cores from the pavements in Gallia County (State Route 7) and Athens County (State Route 682) show the distinctive cone-spall in the bottom of the core. This feature indicates that there has been some involvement of D-Cracking in these old pavements over the years. Over the remaining intact concrete, only 1% to 5% of the coarse aggregate particles show any freeze/thaw-related cracking distress.

3. Most of the remaining Research Study pavement concretes show only a very minor amount of freeze-thaw-related distress (1% to 5%), which has had no adverse effect on the performance of the concretes and the joints..

4. A moderate level of freeze/thaw related distress (10% to 20%) was observed in the pavement concrete represented by Core ATH-33 (Athens County US Route 33-a 1958 pavement project). All of the original joints had been replaced in this 51 year old concrete at the time the core was taken.

5. It is concluded that all of the coarse aggregates in the present study are highly resistant to freeze/thaw related damage of the type previously associated with D-Cracking distress in ODOT pavements. Although all of the joints have been replaced on US Route 33 in Athens County, the bulk of this 1958 PCC pavement is still serviceable. This feature of the twenty project concretes is one of the main factors contributing to the satisfactory performance of the pavements.

## Overall Condition of the Coarse Aggregate Particles at the time of Examination

The construction date of the PCC pavements examined on this project ranges from 1946 to 1996. The breakdown by decades is,

- 1940 to 1950 = 1 Project (GAL-7)
- 1951 to 1960 = 1 Project (ATH-33)
- 1961 to 1970 = None
- 1971 to 1980 = 1 Project (ATH-682)
- 1981 to 1990 = 6 Projects (HAM-126, JEF-22, JEF-7, TUS-39, CUY-252, MOT-35)

- 1991 to 2000 = 11 Projects

The age of the pavement concretes at the time of our examination ranges from 13 years to 63 years. The Rating of Overall Condition of the coarse aggregate particles in the pavement cores (shown in Figure C-5 (Appendix C) is based on their physical condition. This is mainly a petrographic assessment of the presence, extent, and origin of cracking in the aggregate particles. This assessment involved observations and estimates to determine for each concrete,

- What percent of the particles show cracking?
- Are there single or multiple cracks in a single particle?
- Are the cracks tight?
- Do the cracks extend into the adjacent cement paste (infrequently, commonly)?
- Is the cement paste/aggregate bond physically disrupted?
- Is the cracking due to the effects of freezing and thawing?
- Can cracks in the crushed aggregates be attributed to the crushing and sizing operation?

The Rating Scale of the Overall Condition of the coarse aggregate particles is given in Table C-5 (Appendix C) as Excellent-Good-Fair-Low-Poor. The "Excellent" Rating confirms that for the examined concrete "There is no cracking in any of the particles that is related to service conditions." For the "Poor" Rating "The origin of cracking in over 50 percent of the particles is in question."

The Overall Condition of the Coarse Aggregate Ratings for each of the twenty project concretes are summarized in Tables C-6, C-7, C-8 and C-9 in Appendix C. The data are presented below in a form that shows the breakdown on the basis of the Pavement Performance Ratings.

These findings lead to the following conclusions regarding the quality of the coarse aggregates in the pavement concretes examined here.

| Pavement Performance Rating | Overall Condition of the Coarse Aggregate Particles | | | | |
|---|---|---|---|---|---|
| | **Excellent** | **Good** | **Fair** | **Low** | **Poor** |
| **Excellent (10)** | 30 | 70 | 0 | 0 | 0 |
| **Average (10)** | 30 | 60 | 10 | 0 | 0 |

1. The coarse aggregate phase in nineteen of the twenty ODOT pavement concretes examined here is judged to be in “good” to “excellent” condition following 13 to 63 years of service in a severe weather environment application. There is no significant difference in the ratings for the “Excellent” and “Average” performing pavement concretes.

2. Only the concrete taken from the 1958 Athens County US Route 33 pavement received a rating below excellent or good. The “fair” rating assigned to this concrete indicates a moderate involvement of the coarse aggregates in past distress issues in this concrete (as discussed later in the report).

3. None of the twenty pavement concretes examined here received a “low” or “poor” rating regarding the overall condition of the coarse aggregate particles at the time of our examination.

## FINE AGGREGATE PHASE: INFLUENCE ON PAVEMENT PERFORMANCE

For the fine aggregate phase the characterization parameters are the five shown below.

1. Natural or manufactured sand?
2. Maximum particle size of the sands.
3. Identification of the rock and mineral constituents of the sands
4. Identification of the presence and extent of cement-aggregate reactions involving the sand particles.
5. A rating of the overall quality of the sands.

The fine aggregate in all 20 of the pavement concretes is a natural sand. The rock and mineral constituents of the sands in each of the concretes are identified in Tables D-1 and D-2 in Appendix D. The sands are of either river or glacial deposit origin. The sands contain as many as twelve different rock/mineral types, with a maximum particle size of 4.5 mm to 5 mm. The dominant mineral phase in all of the sands is quartz, which is expected due to the high hardness and chemical resistance of this mineral. Sand-sized particles of siltstone, sandstone, and carbonate rock types (limestone/dolomitic limestones) are also common.

All of the sands contain shale particles, which typically are softer and more porous than the other rock/mineral types of the sands. Shale is the second most abundant constituent of the concrete from US 30 in Allen County (ALL-30). In the other concretes shale is the fourth to the ninth most abundant constituent of the sand. The shale particles have not had any adverse effect on the performance of the pavement concretes.

All but one of the pavement concrete sands contain chert, ranging from the third most abundant constituent to the ninth most abundant. Chert is one of the silica minerals that is known to be potentially alkali-silica reactive. The same criterion used to rate the extent and occurrence of alkali-silica reaction activity for the coarse aggregates was used for the fine aggregate phases of the pavement concretes. Only five of the concretes showed any evidence of alkali-silica reaction activity, which was limited to only a few chert particles (or in two cases to siltstone particles). An example of a reacted chert particle is shown in Figure 14, which is a 25X view of a lapped surface


**Figure 14. Lapped section view (25X) of Core CUY-176-10-S (CR) showing a reacted chert aggregate particle (C) from the sand phase of the concrete. Cracks in the chert particle have advanced a short distance into the adjacent cementitious phase of the concrete (arrows).**

of Core CUY-176-10-S (CR). Cracks in the chert particle extend for a short distance into the adjacent cementitious phase of the concrete. Note the white secondary deposits in the entrained air voids, indicating periodic high levels of moisture saturation at this site.

The overall quality of the sands in the Research Study PCC pavement concretes was rated on the basis of (1) rock and mineral content, (2) current condition of the particles, (3) particle size gradation, and (4) absence of any significant involvement in destructive cement-aggregate reactions. The sands were judged on the basis of these criteria to receive either a “Satisfactory” or an “Unsatisfactory” rating. All received a “Satisfactory” rating.

## AIR VOID SYSTEM & DENSITY: INFLUENCE ON PAVEMENT PERFORMANCE

ODOT's Class C concrete is intended to be air-entrained. When No. 57 or No. 67 coarse aggregate is used the specified air content is 6 ± 2 percent. When No. 8 coarse aggregate is used the specified air content is 8 ± 2 percent.

The function of air entrainment is to protect the cementitious phase of the concrete from the effects of freezing and thawing while it is in a state of critical moisture saturation. The parameters used to quantify the quality of the air void system include (1) total air void content, (2) specific surface area of the air voids, and (3) spacing factor of the air voids. As reflected in the ODOT specifications, the historical level of total air void content has been 6 percent for ¾ in. and 1 in. aggregate concrete, and 8 percent for $^3/_8$ in. aggregate concrete. The higher air content for the latter is tied to the expectation that the cementitious material content will be higher relative to the coarser aggregate mixes. This is not the case for the ODOT Class C mixes however, as the target cementitious material content for the $^3/_8$ in. aggregate concrete is the same as for the ¾ and 1 in. aggregate concrete (600 lb/yd$^3$ [356 kg/m$^3$]for the standard mix).

The tolerance for air content in the ODOT specification is plus or minus 2 percent. The American Concrete Institute Committee's that address the air entrainment issue allow a tolerance for total air content of plus or minus 1 ½ percent for field-placed concrete.

As stated in the ASTM C 457 Standard, for air entrained concretes designed in accordance with accepted procedures the specific surface area is usually in the range of 600 to 1000 in$^2$/in$^3$ (24 to 43 mm$^{-1}$) and the spacing factor is usually in the range of 0.004 to 0.008 in. (0.1 to 0.2 mm). ASTM C 457 also teaches that the spacing factor is generally regarded as the most significant indicator of the durability of the cement paste matrix to freezing and thawing exposure of the concrete.

All of the pavement concretes examined in the Research Study are air-entrained. Characterization of the air void system in the project concretes was done using the modified point count procedure of ASTM C 457, "Standard Practice for the Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." This procedure provides a measurement of (1) the total air void content, (2) the specific surface area of the air void system, and (3) the air void spacing factor. Related information was obtained in the stereoscopic microscope examination of the project concretes in the form of (1) the amount and origin of other types of voids in the concretes, (2) the size and distribution of the entrained air voids in the cores, and (3) the presence and extent of secondary deposits in the air voids.

Tables E-1 through E-3 in Appendix E provide information on the measurement parameters used and the results obtained in the ASTM C 457 air void characterization measurements for all 20 of the project concretes.

## Total Air Void Content

All of the concretes examined in the present study are air entrained. For Class C concretes containing ¾ in. or 1 in. maximum size coarse aggregate the ODOT air content requirement is 6 % ± 2 %. For Class C concretes containing 3/8 in. maximum size coarse aggregate the ODOT air content requirement is 8 % ± 2 %. The total air void content data (average value and range) for the twenty project concretes are shown below in a form that shows the breakdown on the basis of the Pavement Performance Ratings.

| Pavement Performance Rating | Average Value of Total Air Void Content of the Concretes, % | Range of Values of Total Air Void Content of the Concretes, % |
|---|---|---|
| **Excellent (10)** | 6.0 | 3.4 to 9.2 |
| **Average (10)** | 6.8 | 1.9 to 8.4 |

## Air Void Specific Surface Area

The specific surface area value relates to the total surface area of the air voids relative to the total volume of the air voids. This number is the square inches (or square centimeters) of air void surface area per one cubic inch (or cubic centimeter) of volume occupied by the air voids.

For concretes that are intentionally air entrained it is desired and expected that the specific surface area will be at least 600 $in^2/in^3$ (24 $mm^{-1}$). It is not uncommon for this value to be in the range of

700 $in^2/in^3$ to 900 $in^2/in^3$ (28 to 36 $mm^{-1}$). When some of the newest air entraining admixtures are used it is possible to routinely produce air void systems with a specific surface in the range of 1000 $in^2/in^3$ to 1200 $in^2/in^3$ (40 to 48 $mm^{-1}$).

The specific surface area measurement is dependent on the size and number of entrained area voids contained in a given volume of the hardened concrete. The larger the specific surface area value the smaller the air void diameters and the greater the number of the air voids. When no air entraining agents are used it is expected that the entrapped air content will typically be less than 2 percent and the specific surface area will typically be less than 600 $in^2/in^3$ (24 $mm^{-1}$).

The specific surface area values (average value and range) for the twenty project concretes are shown below in a form that shows the breakdown on the basis of the Pavement Performance Ratings.

| **Pavement Performance Rating** | **Average Value of Air Void Specific Surface Area for the Concretes, $in^2/in^3$ ($mm^{-1}$)** | **Range of Values of Air Void Specific Surface Area for the Concretes, $in^2/in^3$ ($mm^{-1}$)** |
|---|---|---|
| **Excellent (10)** | 771 (31) | 516 to 1339 (21 to 54) |
| **Average (10)** | 713 (29) | 529 to 877 (21 to 35) |

## Air Void Spacing Factor

The spacing factor parameter is a measurement (in length) of the maximum distance that water needs to travel during a freezing event within a sample of hardened concrete to reach an entrained air void. Laboratory work conducted at the Portland Cement Association laboratories in Skokie, Illinois in the 1930s and 1940s showed that the concretes of that time typically showed a satisfactory level of freeze/thaw durability if the air void spacing factor was below 0.0080 in.

The air void spacing factors (average value and range) for the twenty project concretes are shown below in a form that shows the breakdown on the basis of the Pavement Performance Ratings.

| Pavement Performance Ranking | Average Value of Air Void Spacing Factor of the Concretes, in. (mm) | Range of Values of Air Void Spacing Factor of the Concretes, in. (mm) |
|---|---|---|
| **Excellent (10)** | 0.0061 (0.15) | 0.0036 to 0.0097 (0.09 to 0.24) |
| **Average (10)** | 0.0061 (0.15) | 0.0040 to 0.0110 (0.1 to 0.28) |

All twenty of the PCC pavement concretes evaluated in the Research Study are air entrained. The air void parameter raw data summary is given in Appendix E. The tabulated data below show that not all twenty of the Research Study concretes meet the relevant target values of the air void parameters as described above.

| | |
|---|---|
| **Number of the Twenty Research Study Concretes Meeting the ODOT Requirement for Total Air Void Content** | 3/8 in Aggregate = 10 of 11 |
| | ¾ and 1 in. Aggregate = 7 of 9 |
| **Number of the Twenty Research Study Concretes Meeting the Guideline for Maximum Air Void Spacing Factor of 0.008 in. (0.2 mm)** | 3/8 in Aggregate = 11 of 11 |
| | ¾ and 1 in. Aggregate = 7 of 9 |
| **Number of the Twenty Research Study Concretes Meeting the Guideline for Minimum Air Void Specific Surface Area of 600 in2/in3 (24 mm$^{-1}$)** | 3/8 in Aggregate = 8 of 11 |
| | ¾ and 1 in. Aggregate = 6 of 9 |

Reference can be made to Appendix E to learn which of the Research Study concretes do not meet the relevant target values of the air void parameters. Three of the more significant features of these data are,

1. Despite the fact that a minority of the concretes do not meet the minimum requirements of the air void parameter standards, none of the twenty concretes shows any evidence of

freeze/thaw distress (cracking) in the cementitious phase that originated within the cementitious phase (as opposed to originating in coarse aggregate particles), except in those instances where the air void cavities are filled with secondary deposits and there is access to moisture ingress (joint and mid-slab crack fracture planes).

2. Concrete taken from State Route 7 in Gallia County has seen 63 years of service in a severe weather environment. This concrete, which has a 2 in. maximum size coarse aggregate, has a total air void content of 3.4 percent, a specific surface area of 516 $in^2/in^3$, and a spacing factor of 0.0097 in. A section view of the core taken from the mid-slab crack region of this pavement [GAL-7 (CR)] is shown in the top photograph of Figure 15. The only crack in the core is the mid-slab crack (yellow arrows), which passes around some of the coarse aggregate particles (yellow dots) and through other of the coarse aggregate particles (red dots). Although by contemporary standards the entrained air void system is substandard, there is no freeze/thaw-related cracking distress (or distress of any type) in the concrete on either side of the mid-slab crack. With the exception of the bottom ½ in. or so of the core, the air voids are virtually free of any secondary deposits.

3. Concrete taken from ramp pavement on State Route 176 in Cuyahoga County has seen 15 years of service. This slag aggregate concrete has a total air void content of only 1.9 percent, a specific surface area of 708 $in^2/in^3$ (28 $mm^{-1}$), and a spacing factor of 0.0110 in (0.28 mm). A section view of the core taken from the mid-slab crack region of the pavement [Core CUY-176-10-S (CR)] is shown in the bottom photograph of Figure 15. The yellow arrows point to the mid-slab crack, which passes through and around slag coarse aggregate particles. In addition to the fact that the total air content is very low (1.9 %), many of the air voids are filled with secondary deposits. This feature is shown in the top photograph of Figure 16. Beyond the mid-slab crack there are two tight horizontal cracks in this core at depths of 2 and 4 in. (5 and 10 cm) below the plane of the wearing surface (red arrows in the bottom photograph of Figure 15). An enlarged view of one of these cracks is shown in the bottom photograph of Figure 16, which shows that the cracks pass around rather than through the slag aggregate particles. The low air void content and the infilling of the entrained air voids suggests that these cracks can be attributed to the effects of freeze/thaw on the cementitious phase. However, the presence of near-surface horizontal cracking in other slag aggregate concretes also suggests that other sources of stress may be in play here; a situation that is currently being explored in other work. The only other cracks in the CUY-176 (10) core concrete are a few very tight and local cracks attributed to ASR activity in chert aggregate particles from the fine aggregate phase.

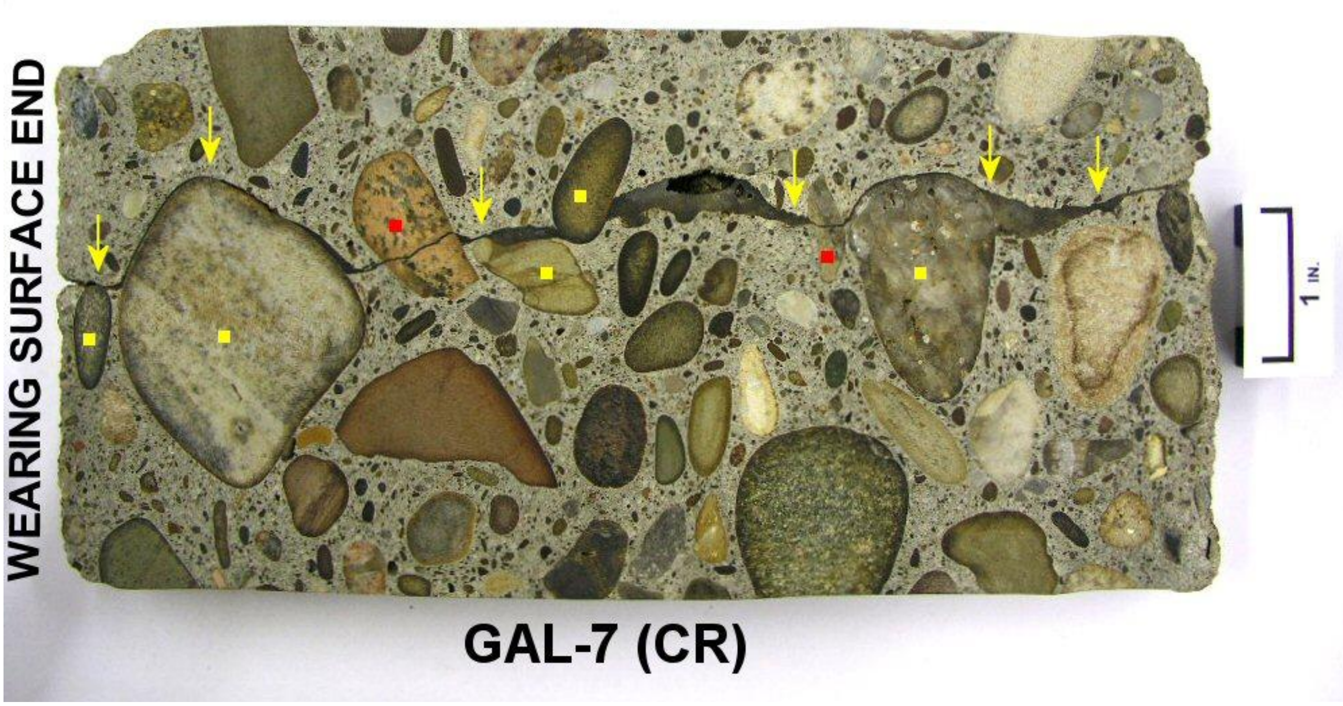
The findings of this phase of the study confirms that the entrained air void sytem in the Research Study concretes has fulfilled its intended function of adequately protecting the main body of the cementitious matrix phase from the effects of freezing and thawing. This is true even in those instances where the parameters of the air system fall outside of the recommended values. Local and limited damage has occurred in some the concretes in which the air voids have been filled with secondary deposits and moisture accessibility has been high (i.e. along mid-slab crack and joint fracture planes).

In a previous study of PCC pavements for ODOT (Lankard, 2006), it was concluded that as long as the pavement concrete had been intentionally air entrained and if it contained a low w/cm (ca. 0.45 or lower), that the cementitious phase of the concrete was adequately protected even in those instances where the air void parameters were not fully compliant with current standards. The acceptable freeze/thaw resistance of these ODOT pavement concretes despite lacking features of the historically recommended air-void system parameters was attributed to (1) the likelihood that the concrete did not in most cases reach a level of critical moisture saturation relative to the freeze/thaw exposure conditions that were experienced, (2) the low w/cm of the concretes, (3) the fact that the concretes all contained some level of intentional air entrainment, and (4) the less severe freeze/thaw conditions in the field relative to those experienced by laboratory specimens subjected to freeze/thaw testing. The findings of the cited 2006 study and the findings of the present study provide evidence to support an opinion that a modest reduction in the requirement of total air content could be implemented without any adverse effect of the freeze/thaw resistance of the cementitious matrix component of the pavement concretes. This is particularly true for the Class C concretes containing No. 8 coarse aggregates, which now calls for 8% ± 2% air. Inasmuch as the target cement content on this concrete is 600 lb/yd$^3$ (356 kg/m$^3$) (The same as for No.57/67 aggregate mixes), the 6% target value can be imposed without any risk.

## Concrete Density

The density of the pavement cores was measured using the water immersion procedure of ASTM C 642 following a 48 hour water-soaking period. A density measurement made on water-saturated hardened concrete is expected to correlate with the original unit weight of the fresh concrete. The water-saturated density values (average value and range) for the twenty project concretes are shown below in a form that shows the breakdown on the basis of the Pavement Performance Ratings.

| Pavement Performance Ranking | Average Value of Density for the Concretes, lb/ft$^3$ (kg/m$^3$) | Range of Values of Density for the Concretes, lb/ft$^3$ (kg/m$^3$) |
|---|---|---|
| **Excellent (10)** | 143.8 (2304) | 138.7 to 147.7 (2222 to 2366) |
| **Average (10)** | 141.8 (2272) | 138.9 to 145.8 (2225 to 2336) |



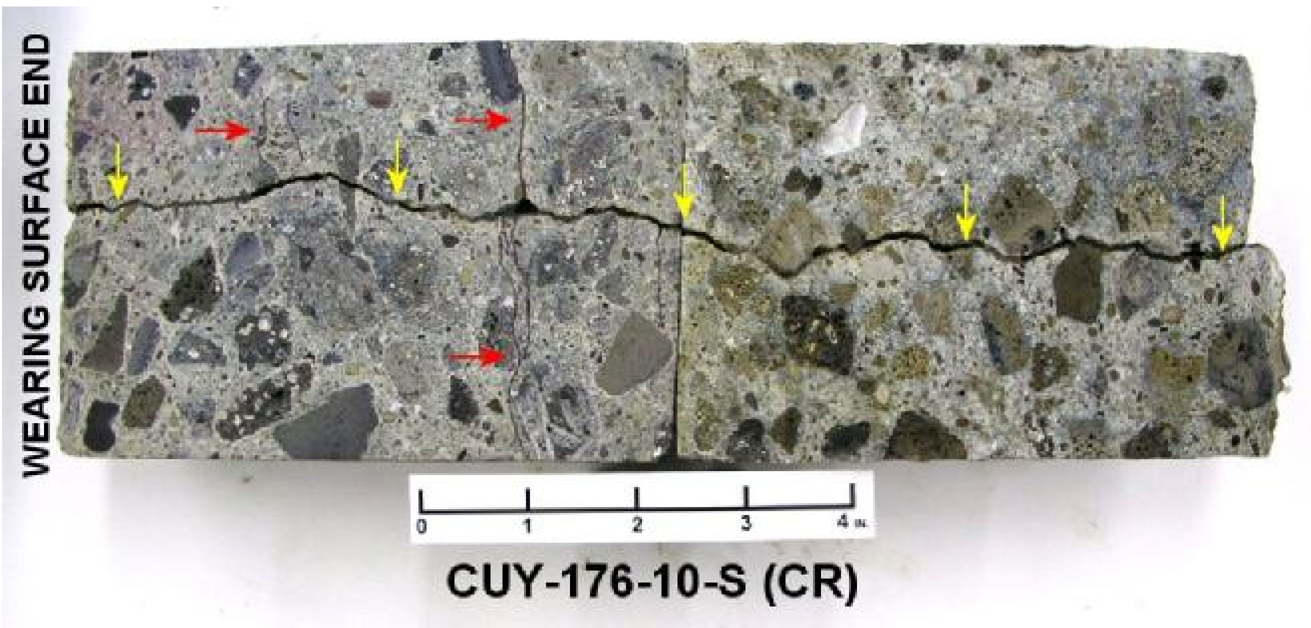
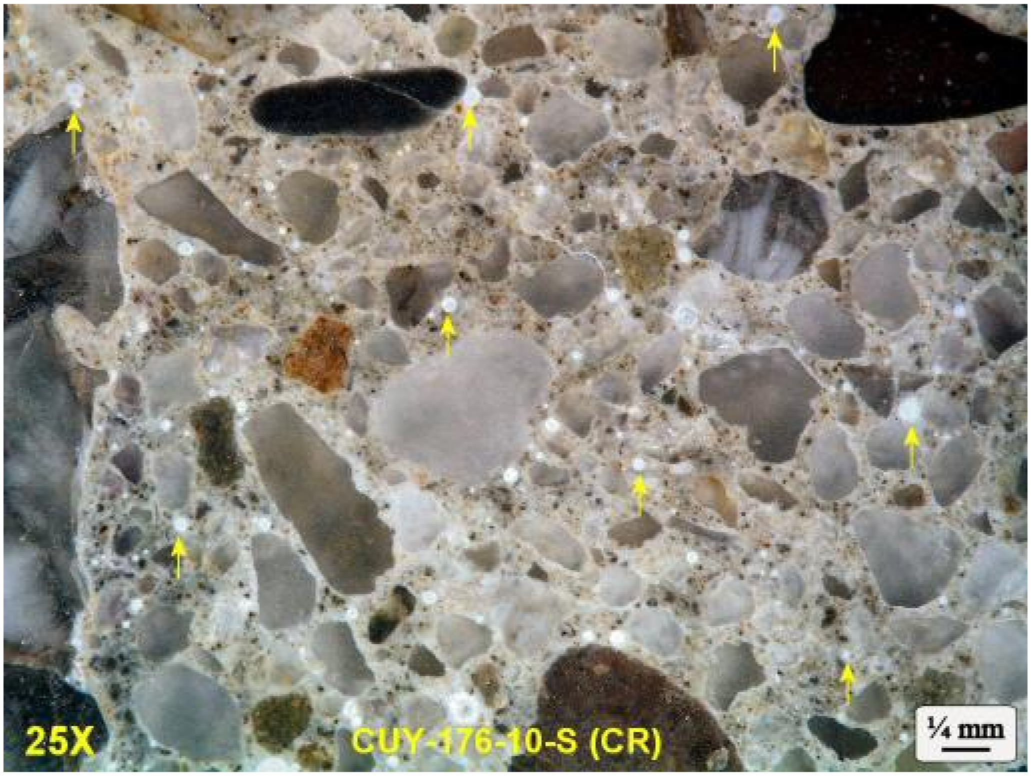




**Figure 15. Lapped section views perpendicular to the plane of the wearing surface of Cores GAL-7 (CR) and CUY-176-10-S (CR). Both cores were taken through a mid-slab crack (yellow arrows). The coarse aggregate in the GAL-7 core is a 2 in. maximum size siliceous gravel. The red arrows in the bottom photograph point to horizontal cracks that pass through the cementitious matrix phase and around the slag coarse aggregate particles in the CUY-176-10-S (CR) core.**



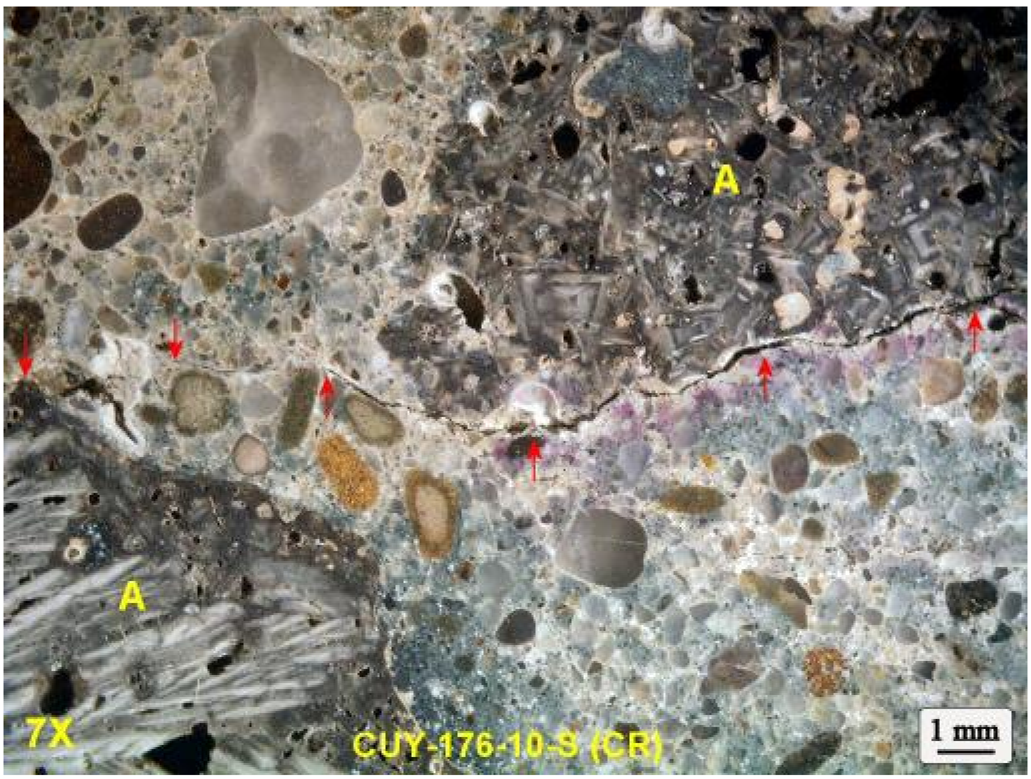




**Figure 16. Lapped section views (7X and 25X) perpendicular to the plane of the wearing surface of Core CUY-176-10-S (CR). The yellow arrows in the top photograph point to a few of the entrained air voids that are filled with secondary deposits. The red arrows in the bottom photograph point to a crack in the cementitious matrix that passes around two of the slag coarse aggregate particles (A).**

The grand average density value for the twenty Research Study pavement concretes is 142.8 $lb/ft^3$ (2288 $kg/m^3$), which is almost identical to the theoretical value of the Class C concrete at a w/cm of 0.45 and an air content of 6 percent, of 142.7 $lb/ft^3$ (2286 $kg/m^3$). There is a loose relationship between total air void content and unit weight (density), although the fit is not precise inasmuch as density is also affected by cement paste content and aggregate content, which are somewhat variable in the project concretes.

## STRENGTH/ELASTIC PROPERTIES: INFLUENCE ON PAVEMENT PERFORMANCE

Measurements were made at Ohio University of compressive strength, split tensile strength, static modulus of elasticity, and thermal expansion on companion cores of the twenty pavement concretes that were examined in our laboratory. These data are summarized in Tables F-1 through F-5 in Appendix F (except thermal expansion). These tables also show for the project concretes (1) the type of coarse aggregate, (2) the water to cementitious material ratio, (3) the total aggregate content, (4) the total air void content, and (5) the quality of the cement paste/coarse aggregate bond. In Table F-5, the concretes are ranked according to decreasing values of compressive strength.

### Concrete Compressive Strength

The compressive strengths reported here were measured on 4 in. diameter cores using the procedures outlined in ASTM C 42, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." Data were obtained on three (sometimes four) cores from each of the twenty project sites. The grand average compressive strength for the twenty project concretes is 6250 psi (44 MPa) and the range is 3760 psi to 8720 psi (30 to 60 MPa). The specified compressive strength of the ODOT Class C concrete is a minimum of 4000 psi (28 MPa) at 28 days. If it is assumed that the 28 day strength is around 75 percent of the ultimate strength, the expected ultimate strength would be a minimum value of 5330 psi (37 MPa).

The distribution of the compressive strengths on the basis of the Excellent/Average Pavement Performance Rating is shown below (MPa values in parentheses).

| **Pavement Performance Rating** | **Compressive Strength, psi (MPa)** | |
|---|---|---|
| | **Average** | **Range** |
| **Excellent (10)** | 6180 (43) | 4880-8410 (34 to 58) |
| **Average (10)** | 6310 (44) | 3760-8720 (26 to 60) |

The data tabulated below show the compressive strength of the project concretes as affected by the type of coarse aggregate. The number of data points for each aggregate category is shown in parentheses following the aggregate name.

| Coarse Aggregate Type | Compressive Strength, psi (MPa) | |
|---|---|---|
| | Average | Range |
| **No. 8 Crushed Limestone (8)** | 5510 (38) | 3760-8720 (26-60) |
| **No. 57 or No. 67 Crushed Limestone (3)** | 7120 (49) | 6110-8410 (42-58) |
| **No. 8 Gravel (3)** | 5930 (41) | 4880-7990 (34-55) |
| **No. 57 or 67 Gravel (2)** | 6680 (46) | 6490-6860 (45-47) |
| **No. 467 Gravel (1)** | 7850 (55) | - |
| **No. 57 or No. 67 Slag (3)** | 6810 (47) | 6260-7340 (43-51) |

With reference to the data shown in Appendix F and to the tabulated data shown above, the salient features of the compressive strength data are,

1. There is no significant difference in the average compressive strength value between the two pavement performance rating categories (6180 – 6310 psi [43 - 44 MPa]).

2. There is no significant difference in the range of compressive strength values between the two pavement performance rating categories (ca. 4300 psi to 8500 psi [30 to 59 MPa]).

3. There is a surprising large project to project range in the compressive strength of the project concretes in each of the pavement performance category ratings.

4. The current compressive strength of two of the project concretes is less than the 28 day minimum value of 4000 psi [28 MPa](CUY-176-11-S and CUY-176-12-S @ ca. 3800 psi). Both of these concretes contain a No. 8 limestone coarse aggregate

5. The current compressive strength of three of the project concretes is higher than 4000 psi (28 MPa), but is less than the expected minimum value of the ultimate compressive strength

of ca. 5300 psi [37 MPa] (CUY-322, MOT-202, and MOT-35). The coarse aggregate in these concretes have the No. 8 gradation.

6. There is a relatively large difference in the compressive strength of the eleven concretes containing the No. 8 aggregates (limestone and gravel) versus the nine concretes containing the No. 57, 67, or 467 aggregates (average of 5720 psi [39 MPa]) for the former and 6910 psi [48 MPa] for the latter).

7. Seven of the eight concretes containing the No 8 limestone aggregate show the lowest values of compressive strength for the project concretes. The concrete showing the highest level of compressive strength (LOG-33) also contains this aggregate.

8. In addition to the correlation between coarse aggregate size and compressive strength, there is some correlation between compressive strength of the pavement concretes and total air void content. This is an expected correlation. Seven of the ten concretes having a compressive strength in the 6110 to 8720 psi (42 to 60 MPa) range have a total air void content under 7.0 percent. Six of the of the ten concretes having a compressive strength in the range of 3760 to 5850 psi (26 to 40 MPa) have an air content in the 7.0 to 9.2 percent range.

9. There is some correlation between the compressive strength of the project concretes and the quality of the cement paste aggregate bond. Seven of the ten concretes having a compressive strength in the 6110 to 8720 psi (42 to 60 MPa) range have a paste/aggregate bond quality rating of Excellent or Good. Only three of the ten concretes having a compressive strength in the range of 3760 to 5850 psi (26 to 40 MPa) have a paste/aggregate bond rating of Good.

10. For the twenty project concretes, nine showed a within-series (3 cores) range of 1000 to 2000 psi (7 to 14 MPa).

## Concrete Split Tensile Strength

The tensile strengths reported here were measured on three 4 in. diameter cores using the procedures outlined in ASTM C 496 "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens." The grand average split tensile strength for the twenty project concretes is 610 psi (4.2 MPa) and the range is 490 psi to 830 psi (3.4 to 5.7 MPa). The distribution of the split tensile strengths on the basis of the Excellent/Average Pavement Performance Rating is shown below. With reference to the data shown in Appendix F and to the tabulated data shown above, the salient features of the split tensile strength data are,

1. There is no significant difference in the average compressive strength value between the two pavement performance rating categories (600 to 630 psi [4.1 to 4.3 MPa]).

| Pavement Performance Rating | Split Tensile Strength, psi (MPa) | |
|---|---|---|
| | Average | Range |
| **Excellent (10)** | 630 (4.3) | 515-830 (3.6-5.7) |
| **Average (10)** | 600 (4.1) | 490-630 (3.8-4.3) |

2. For fifteen of the twenty concretes the tensile strength lies between 540 and 640 psi (3.7 to 4.4 MPa). The tensile strength for concrete MOT-35 is an outlier, at a value of 830 psi (5.7 MPa). This concrete has one of the lowest values of compressive strength at 4880 psi (34 MPa)

3. There is no clear correlation between the compressive strength and the tensile strength of the project concretes (despite the expectation that there would be a correlation).

**Concrete Modulus of Elasticity**

The modulus of elasticity data reported here were measured on 4 in. diameter cores using the procedures outlined in ASTM C 469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." Data were obtained on three cores from nineteen of the twenty project sites, and two cores from the Gallia-7 site. The grand average modulus of elasticity for the twenty project concretes is 4.93 x $10^6$ psi (3.54 x $10^4$ MPa) and the range is 2.72 to 7.16 x $10^6$ psi (1.88 to 4.94 x $10^4$ MPa). The distribution of the modulus of elasticity measurements on the basis of the Excellent/Average Pavement Performance Rating is shown below.

| Pavement Performance Rating | Static Modulus of Elasticity, x $10^6$ psi (x $10^4$ MPa) | |
|---|---|---|
| | Average | Range |
| **Excellent (10)** | 5.52 (3.93) | 4.37-7.16 (3.02-4.94) |
| **Average (10)** | 4.33 (2.99) | 2.72-5.76 (1.88-3.97) |

With reference to the data shown in Appendix F and to the tabulated data shown above, the salient features of the modulus of elasticity data are,

1. The average modulus of elasticity of the Excellent Performing pavements is substantially higher than the modulus of the Average Performing pavements ($5.52 \times 10^6$ psi vs $4.33 \times 10^6$ psi [$3.93 \times 10^4$ vs $2.99 \times 10^4$ MPa])

2. There is a relatively large project to project range in the elastic modulus of the project concretes in each of the pavement performance category ratings.

3. There is no clear correlation between the compressive strength and the modulus of elasticity of the project concretes (despite the expectation that there would be a correlation).

## Measurement of Thermal Expansion of the Concretes

Ohio University also performed measurements of the coefficient of thermal expansion on companion cores to the ones measured in our laboratory. These data are reported in Volume 1 of the present study.

## INFLUENCE OF FACTORS AFFECTING PAVEMENT PERFORMANCE: SUMMARY

As was discussed in the Introduction Section of the present report, as regards the selection criteria for the candidate pavements, the line of distinction between the ten concretes placed in the "Excellent Performance" category and the ten concretes placed in the "Average Performance" category is blurred. All twenty of the candidate pavements have, in fact, performed "satisfactorily" in service. The pavement cores provided to us for the present examination were taken through control joints and mid-slab crack joints. Fourteen of the twenty project pavements have mid-slab cracking, which is considered to be a distress feature. For most of the pavements, there is some cracking and spalling distress along the mid-slab crack lines, and there is some cracking and spalling distress along the control joint lines. But, beyond these specific local distress sites, the pavement concrete lying between the control joints and the mid-slab cracks is, for the most part, in good condition and is showing no unacceptable levels of distress. This fact alone is telling. It is obvious, and no great surprise, that what distress there is, is at locations where water has access to the full depth of the pavement slabs. Logically, concretes that will perform most satisfactorily in such an environment are those that are most resistant to damage related to the imposition of freeze/thaw cycling conditions when the concrete is in a state of critical moisture saturation.

What was learned in the evaluation of the mechanical and physical properties and microstructural features of the twenty satisfactorily performing pavement concretes examined here was that fairly wide variations in most of these factors could be tolerated without having an adverse effect on the performance of the pavements in service. The few factors that are common to all twenty of the Research Study concretes that can explain their satisfactorily performance in service are those that are known to influence the freeze/thaw resistance of concrete in severe weather environments. These factors include.

1. All twenty of the concretes have a <u>satisfactorily low (ca. 0.45) water to cementitious material ratio</u> (w/cm). The site to site range in w/cm is tight in the concretes (0.42 to 0.48).

2. All of the concretes have a <u>good quality coarse aggregate</u> that has shown good long-term resistance to the effects of freeze/thaw cycling. In historical terms, these are coarse aggregates that are not prone to early participation in the D-Cracking type of distress.

3. All of the concretes are <u>air-entrained.</u> The air-entrainment has had the desired effect of adequately protecting the cementitious phase of the concretes, even in those instances where the air content has been below the current ODOT target minimum value of 4.0 percent.

I believe that these three material factors are the key to the satisfactory long-term performance in the twenty ODOT Research Study concretes.

Of the twenty ODOT PCC pavements examined here, one (Gallia County, State Route 7) has been in service for 63 years (constructed in 1946) and one (Athens County, US Route 33) has been in service for 51 years (constructed in 1958). Of the remaining 18 projects, most (15) were constructed during the period 1990 through 1997 (12 to 19 years of service). On the basis of their longevity, it is reasonable to categorize the Gallia-7 and Athens-33 pavements as exceptional and attempt to identify the factors contributing to this very high level of performance. This is done in the following sections of the present report.

There are several of the candidate pavement sites that were selected on the basis of the fact that they ostensibly were similar in construction, but which performed "differently". These sites include,

- Cuyahoga County, State Route 176 (placed in 1996)
- Jefferson County, US Route 22 and State Route 7 (placed in 1990).
- Summit County, Interstate Route 76 (placed in 1992).

Individual attention is given to these sites in the following sections of the report in an effort to gain deeper insights into the differences in performance. For this exercise, more detail is provided on design and construction variables.

Finally, six of the twenty Research Study sites are pavements that have shown no mid-slab cracking to date. Individual attention is given to these sites in the following sections of the report, which also focus on design and construction variables in addition to concrete property data.

## GALLIA COUNTY SR 7 PAVEMENT (CONSTRUCTED IN 1946)

The fact that an ODOT PCC highway pavement constructed 63 years ago is still in service and that relatively little structural maintenance has been required is quite extraordinary, even though the ADT and truck traffic is low. The pavement has experienced the same Ohio weather conditions and fluctuations as the other projects in the study. Of the twenty pavement projects evaluated here, this pavement, constructed in 1946 as State Route 7 in Gallia County, is unique in its longevity. The cores from this project were taken near Mile Marker 8 in the northbound lane of State Route 7.

Field notes made by Ohio University personnel for this coring site are,

> *"Old pavement in very good condition for its age. Some transverse cracks and joints on project replaced because of faulting. Coring and sampling section was in excellent condition with a couple of minor transverse cracks and spalling."*

A brief review of some of the pertinent features of this project is shown below,

- The control joint spacing is 40 ft (12 m); many are the original joints.
- The average daily traffic (ADT) was 260 in 1988 and 400 in 2006 (mostly cars and light trucks. The total traffic count over the past 63 years is around 7 million.
- Pavement thickness is 8 inches (20 cm).
- The slabs contain steel mesh reinforcement
- The joints were formed, not saw-cut and the dowels used are smooth cylindrical bars, ¾ in. (19 mm) in diameter, and 15 in. (38 cm) long. Currently used bars are 1 ¼ in. (3 cm) in diameter.
- The base material is 6 to 12 inches (15 to 30 cm) of "SS 112"
- The gravel coarse aggregate has a nominal maximum size of 2 inches (5 cm). All other pavements in our study have a maximum size of $^{3}/_{8}$ in., ¾ in. or 1 in. (10, 19, or 25 mm).

### Mid-Slab Crack Core: GAL-7 (CR)

Figure 17 is a lapped surface of the core taken through a transverse mid-slab crack in the Gallia County State Route 7 pavement (Core GAL-7[CR]). The core was received in two pieces separated along the mid-slab crack.

The arrows in Figure 17 follow the path of the mid-slab crack. The crack passes *around* most of the coarse aggregate particles (yellow dots) and *through* fewer of the coarse aggregate particles (red dots). Features of interest regarding the mid-slab crack include,

- The fact that the crack passes through some of the aggregate particles confirms that the concrete had achieved some elevated level of strength at the time the crack occurred. This strongly indicates that the control joints functioned satisfactorily in this pavement slab.
- There has been very little loss of material (spalling) along the crack. Counting from the left in Figure 17, material has been lost between the 3rd and 4th arrows and between the 5th and 6th arrows. The amount of material lost is estimated at 1 to 2 percent (based upon the total volume of material in the core).
- Beyond the mid-slab crack, there is no other cracking (or distress of any type) in the core concrete.
- The intact coarse aggregate particles provide an excellent example of the intended function of aggregate interlock.
- Core GAL-7 contains no reinforcing steel so no assessment can be made of the condition or location of the steel mesh in the pavement slab.

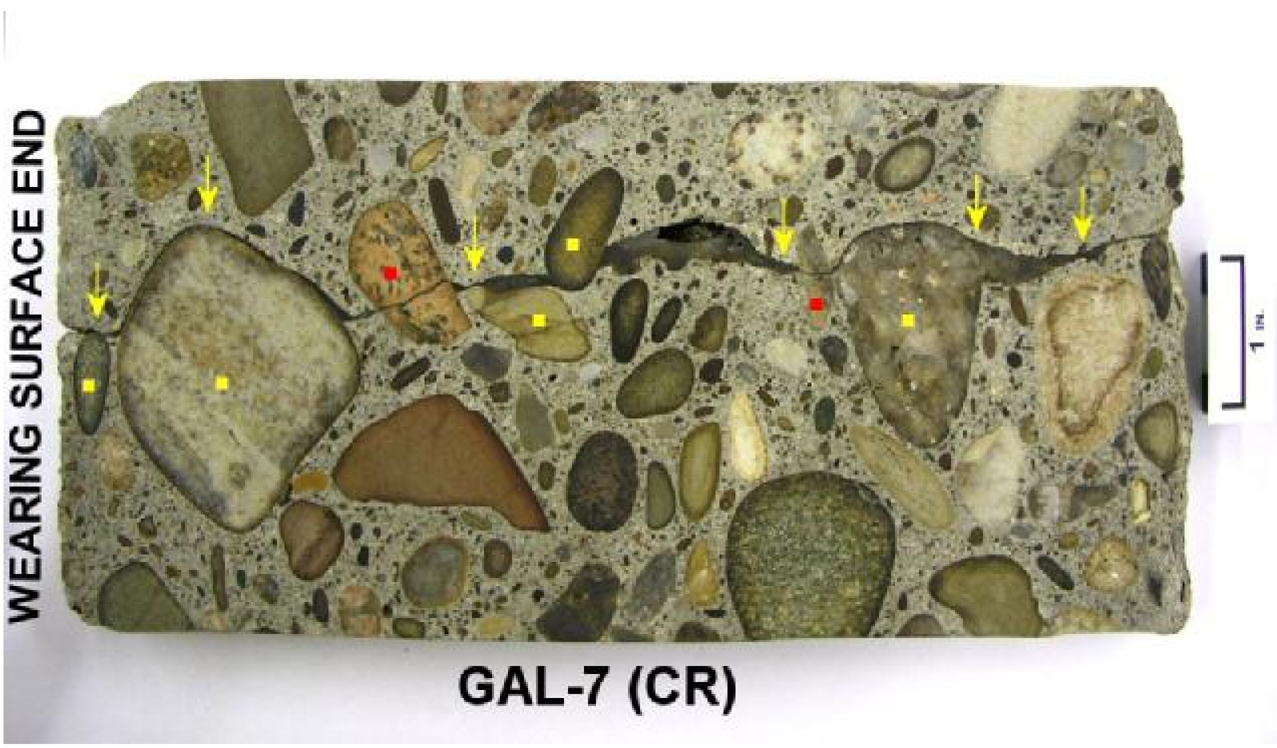



**Figure 17. Lapped surface of Core GAL-7 (CR) showing the full depth (8 in.) mid-slab crack.**

In the tabulated data presented below, a comparison is made between some of the relevant properties of the GAL-7 core concrete and the target/expected values of these parameters for ODOT's Class C Concrete.

| Comparison Between | w/cm | Cement Paste Content, % | Cement Content, lb/yd$^3$ (kg/m$^3$) | Aggregate Max Size, in. (mm) | Total Aggregate Content, v/o | Total Air Void Content, % | Comp. Strength psi (MPa) |
|---|---|---|---|---|---|---|---|
| **GAL-7 Core Concrete** | 0.48 | 20.3 | 430 (255) | 2 (50) | 76 | 3.4 | 7850 |
| **Target or Expected Value for ODOT Class C Concrete[(a)]** | 0.45 | 27.8 | 600 (356) | 3/8 to 1 (10 to 25) | 65 | 6.0 | 4000 (28 days) |

(a) At a w/cm of 0.45. Allowable maximum w/cm is 0.50

Relative to the current ODOT Class C concrete, the GAL-7 pavement concrete placed in 1946,

- Has a significantly lower cement content (430 vs 600 lb/yd$^3$ [255 vs 356 kg/m$^3$]).
- Has a larger coarse aggregate (2 in. [5 cm] vs. 1 in. [2.5 cm]or smaller).
- Has a higher total aggregate content (76 % vs. 65 %).
- Has a lower air content (3.4 % vs. 6.0 %).

Although the total air content of the GAL-7 concrete is only 3.4 %, the concrete is air-entrained. As shown in Table E-1 (Appendix E) the specific surface area is 516 in$^2$/in$^3$ (21 mm$^{-1}$), which is moderately lower than the desired minimum value of 600 in$^2$/in$^3$ (24 mm$^{-1}$). The spacing factor of the GAL-7 concrete is 0.0097 in. (0.25 mm), which is moderately higher than the desired maximum value of 0.0080 in. (0.2 mm). Despite these apparent shortcomings the GAL-7 concrete has survived 63 Ohio winter seasons with no significant freeze/thaw damage.

## Control Joint Core: GAL-7 (JT)

The control joint spacing on this 1946 ODOT pavement project is 40 ft. The joints were formed (not saw-cut) and the smooth dowels used have a diameter of ¾ in. A photograph of a lapped surface of Joint Core GAL-7 (JT) is shown in Figure 18.

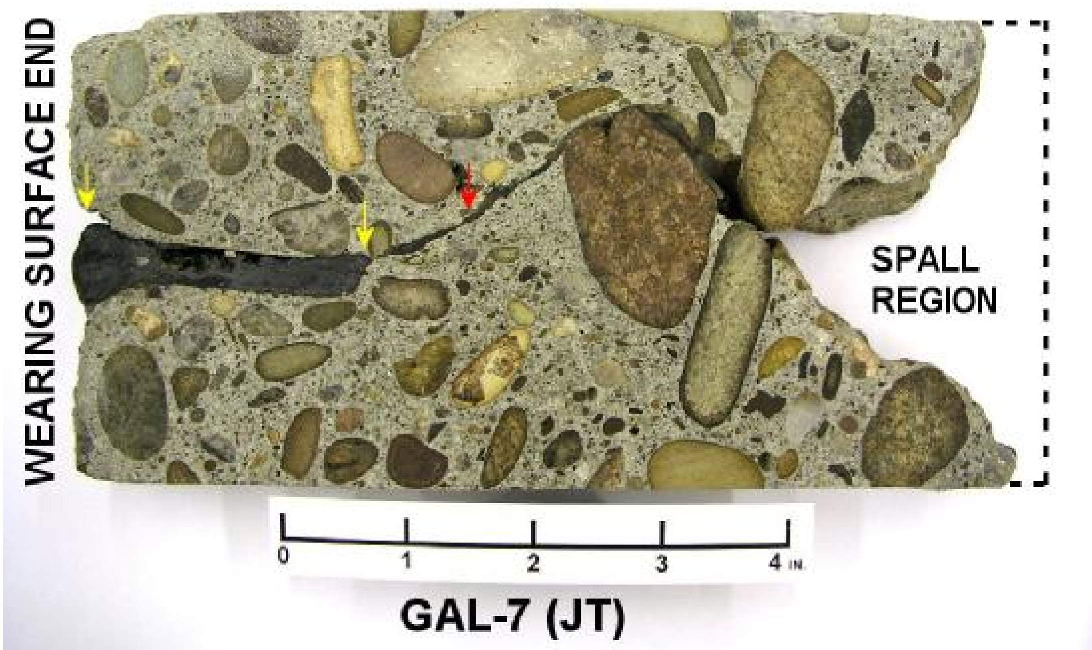



**Figure 18. Lapped surface of Joint Core GAL-7 (JT).**

The yellow arrows in Figure 18 mark the depth of the formed portion of the joint which covers the top 2 ½ in. (63 mm) of the core. The joint sealant is a sanded hot mix, composed of a bituminous binder and a natural sand having a particle size of 0.2 mm to 2 mm.

Documents that form part of the GAL-7 construction plans provide more detail on the joint construction, as follows,

> *CONTRACTION JOINTS – Impressed contraction joints shall be formed by impressing a bar or devise into the newly deposited concrete before initial setting. The devise or bar shall be removed as soon as the concrete is in such condition as to preclude distortion or injury to the concrete. The groove thus formed shall be of the dimensions detailed. After the joint is formed, it must be protected from dirt or foreign matter until the filler is added.*

*POURED JOINT SEAL – The bituminous material for filling impressed joints shall meet the requirements of Section M-5.6 F-1 of the General Specifications. The filler shall be handled in such a manner that it will be confined to the joint and in nowise mar the surface.*

Additional information gained from the project plans regarding joint construction is,

- The dowel bars are 15 in. long, 15 in. on centers, and mid-depth in the 8 in. slabs.
- There is a sketch showing an ideal shape for the contraction joint impression. It is a trapezoid, 3/8 in. (10 mm) wide at the top, ¼ in. (6 mm) wide on the bottom, and 3 in. (8 cm) deep.

It is evident from the GAL-7 joint core examined here that after the impression tool was removed, the pavement slab was allowed to crack before the liquid joint filler was placed. As shown in Figure 18 the joint filler has penetrated for a short distance into the joint crack. It is remarkable that the original joint sealant material has remained intact, sound, and still elastomeric after 63 years of service. Although the GAL-7 joint core was received in two pieces, the joint sealant was tenaciously bonded to one half of the core and had fractured within the concrete on the other core half.

As shown in Figure 18 there has been some cracking and spalling of the concrete adjacent to the joint crack at and near to bottom of the GAL-7 core.. The dashed lines outline the original dimensions of the core (original pavement thickness is 8 in. (20 cm) and the current core thickness is 7 ½ in. [19 cm]). Relative to the original area of the lapped surface shown in Figure 18, the loss of the cone-shaped area due to spalling is estimated at 18 percent. The concrete surfaces defining the spalled region are fracture surfaces showing both aggregate fracture and aggregate pullout. The fracture surfaces are quite clean. As discussed previously this cone-shaped fracture is characteristic of freeze/thaw related cracking due to a higher level of moisture in the bottom of the slab in the vicinity of a joint or crack. The fact that so little material has been lost over the 63 year service life is attributed in large part to (1) the excellent freeze/thaw resistance of the coarse aggregate and (2) the effectiveness of the joint sealant material.

The Gallia County State Route 7 PCC pavement differs significantly in a number of respects relative to current ODOT constructions. While acknowledging the relatively low daily traffic count and minimal truck traffic on this pavement, these differences offer some insights into potential improvements in performance for future ODOT pavement construction.

- Relative to the current ODOT Class C concrete, the Gallia-7 concrete has a low cementitious material content and a large total aggregate content. Both of these features are made possible by the use of a 2 in. (5 cm) maximum size coarse aggregate. The low cementitious material content and high aggregate content are expected to result in a concrete that has improved volume stability (reduced drying shrinkage strain potential and reduced curling strain potential). This expectation is reinforced by the results of a study of D-cracking that was conducted for ODOT by PCA during the period 1975 through 1990 (Stark, 1991). One finding of this 1991 study was that, although a reduction in the maximum size of coarse aggregate to $^3/_8$ in. (10 mm) provided improved resistance to D-Cracking, the move did increase the frequency of transverse cracks in the pavements.

- Combined with a good quality cementitious matrix phase (low w/cm), the larger coarse aggregate provided a true aggregate interlock function in both the control joint and the mid-slab crack.

- For the concrete proportions used in the Gallia-7 concrete, a slab thickness of 8 in. performed in an exceptional manner.

- The control joint design differs in a number of ways from current designs. The most significant differences are (1) the use of ¾ in. (19 mm) diameter dowel, (2) the use of a hot mix sanded bituminous joint filler material, and (3) the joint opening is formed, rather than saw-cut, and has a trapezoidal shape. As stated in the field notes, only "some" of the control joints have been replaced on the project (despite the fact that the joint spacing is 40 ft (12 m). It is difficult to ignore the conclusion that this is a superior joint design that should be considered for future construction; at least for lower traffic volume pavements.

- It is reasonable to expect that historically and currently, misalignments between dowels do occur. It is also reasonable to conclude that even slight misalignments in the dowels result in a failure of the control joints to fully function as intended. In my opinion it is highly likely that this situation is a major factor contributing to the formation of mid-slab cracks in unreinforced PCC pavements. It is also reasonable to conclude that the smaller diameter dowels in the Gallia-7 pavement would be more capable of accommodating misalignments relative to the larger diameter, stiffer steel dowels in use today. This reasoning also leads to a conclusion that low elastic modulus composite dowel bars might also provide a more forgiving feature as regards the effect of dowel bar misalignment on joint performance.

- The relatively low air content of the Gallia-7 concrete (3.4 %) is evidence that intentional air entrainment does not have to meet the target value of the low end of the current ODOT range (4 %) to be effective. While the presence of secondary deposits in the air voids is a common occurrence, many of the entrained are voids are only partially filled or are free of secondary deposits. Fully-filled air voids are most common in the bottom two inches of both the joint and the mid-slab GAL-7 cores. This outcome can be attributed (at least in part) to the long-term presence of the hot-melt bituminous sealant material in the joint core and to the tortuous and constricted crack path that is manifest in the mid-slab crack core (Figure 17). In the cited PCA study (Stark, 1991) the researchers found that there was a "somewhat lower incidence of D-Cracking where hot-poured joint sealant was used, compared with the use of neoprene sealants or no sealants". It was noted however that the "incidence of D-Cracking in all cases was relatively high.

- Equally important to the 63 year service life of this pavement is the exceptional freeze/thaw resistance and mechanical durability of the siliceous gravel coarse aggregate. The coarse aggregate source is identified (Table C-10) as "Ohio River Sand and Gravel, New Martinsville, West Virginia.

## ATHENS COUNTY US ROUTE 33 (1958 PROJECT – ALL JOINTS REPLACED)

This 1958 ODOT pavement project was given an "Average" performance rating despite the fact that all of the original joints had been replaced. Field notes for this pavement are,

> *"1958 project with all joints sawed-out and replaced, probably in 1999. Minor transverse cracks about every other 60 ft.(18.3 m) slab. Some spalling at transverse and longitudinal joints. High steel observed in some longitudinal joint spalls.*

Pavement design and concrete property data for the cores from this project are summarized below.

- Design Thickness of Pavement = 9 inches (23 cm). The thickness of the joint core examined here is 9 in. (23 cm). The thickness of the mid-slab crack core is 8 ¾ in. (22 cm).
- Control Joint Spacing = 60 ft (18.3 m).
- Reinforced (451) = The pavement is mesh-reinforced (451). The cover depth of the mesh is 4 in. in the mid-slab crack core.
- Base Material = 6 in. (15.2 cm) of 310.
- Average Daily Traffic (ADT) = 1535 in 2006.
- Cementitious Constituents = Only portland cement

| **Coarse Aggregate** | **Estimate of w/cm** | **Cement Paste Content, %** | **Total Air Void Content, %** | **Density, lb/ft$^3$ (kg/m$^3$)** | **Comp. Strength, Psi (MPa)** | **Split Tensile Strength, Psi (MPa)** | **Static Modulus of Elasticity x $10^6$ psi (x $10^4$ MPa)** |
|---|---|---|---|---|---|---|---|
| 1 in. Limestone | 0.45 | 30.3 | 6.6 | 143.6 (2300) | 6850 (47) | 620 (4.3) | 4.10 (2.83) |

The compressive strength of the ATH-33 concrete is above the average value of compressive strength for the 10 "Average" performance pavement concretes.

The cement paste content of the ATH-33 concrete (30.3 %) is above the average value of cement paste content for the 10 “Average” performance pavement concretes, which is 28.1 %. The estimated cement content of the ATH-33 concrete is 665 lb/yd$^3$ (395 kg/m$^3$).

## Condition of the Control Joint on Athens County US Route 33

Many of the control joints on this 1958 pavement were replaced in 1984, after the pavement had been in service for 26 years. In 1999, the remainder of the original joints were replaced, a tied concrete shoulder was added, and the pavement surface was ground. The original pavement on the project that remains has been in service for 51 years. These outcomes should qualify the pavement as showing exceptional performance.

The top photograph in Figure 19 shows this joint core [ATH-33 (JT)] in the condition in which we received it. In service a saw-cut was made in the original pavement concrete to receive the repair concrete. The saw-cut passed through the mesh in the original concrete. As shown in the bottom photograph of Figure 19, there has been light corrosion of the mesh strand and there is a crack in the original concrete extending from the mesh strand. The joint sealant is a liquid bituminous material poured over a backer rod.

Virtually the entire original 9 in. (23 cm) thickness of the original concrete is still intact in the joint core. The bottom half of the repair concrete was received as rubble. There are heavy secondary deposits in the air voids in both the original and the repair concrete. The coarse aggregate in both of the concretes is a 1 in. maximum size limestone, but from two different sources. As shown in the top photograph of Figure 19 the fracture plane defining the bottom end surface of the intact piece of the repair concrete has a diagonal orientation relative to the plane of the wearing surface. This “cone” shape of the distressed material in the bottom of the pavement is characteristic of the D-cracking type of distress. Similar distress has not occurred in the original concrete, which strongly indicates that the cracking and spalling in the repair concrete is primarily due to high expansions of saturated coarse aggregate particles during freezing events. The fact that the original pavement concrete on one side of the joint is still fully intact strongly indicates that the coarse aggregate in the original concrete has good, freeze/thaw resistance. In fact the disintegration and slumping of the repair concrete may explain the presence of the diagonal crack (and incipient spall) in the top 1 inch or so of the original concrete (Figure 19) from a loss of support.

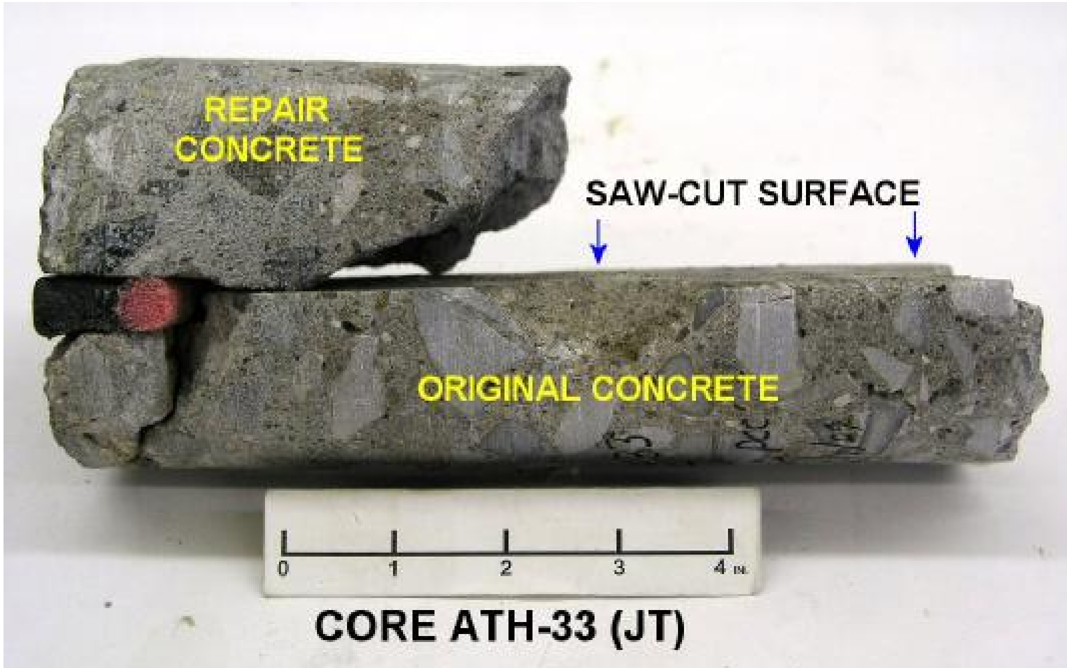
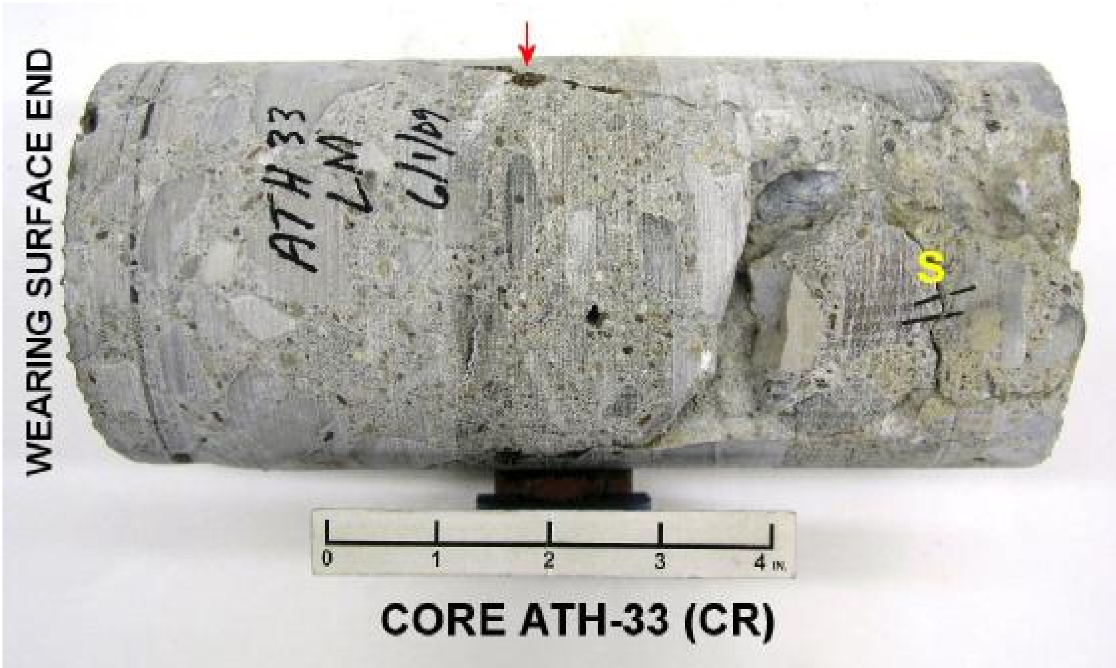




**Figure 19. Two views of the control joint core taken from the pavement on Athens County US Route 33. The current joint is a replacement that was installed in 1999 in this 51 year old pavement (original construction 1958). The arrow in the bottom photograph points to a steel mesh layer, which shows light corrosion on the saw-cut surface of the original concrete. A crack originating at the mesh is highlighted with a black marking pen.**



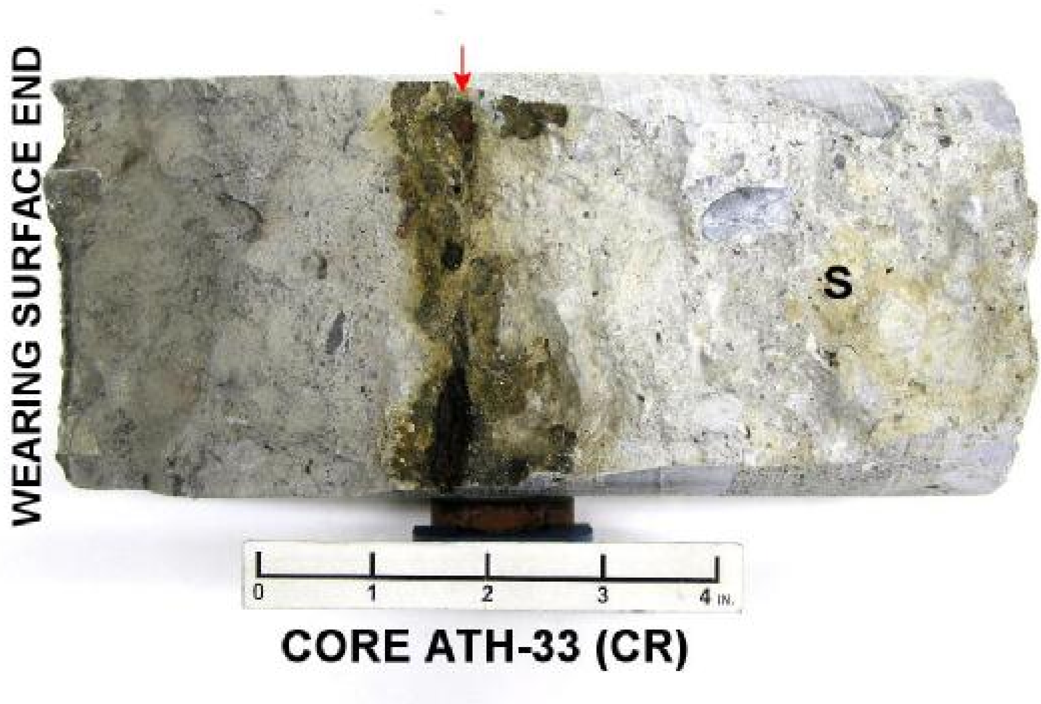




**Figure 20. Two views of the mid-slab crack core taken from the pavement on Athens County US Route 33. The top photo is the core in its as-received condition. The arrow points to the steel mesh strand (corroded) that is contained in the crack plane. The cover over the mesh is 3 ¾ in. Spalled pieces of the core are shown in the area marked "S".**

## Condition of the Mid-Slab Crack Concrete on Athens US Route 33

Two views of this core [ATH-33 (CR)] in the as-received condition are shown in Figure 20. There is a steel mesh layer in the mid-slab crack plane, which shows a moderate amount of corrosion. The diagonally oriented mid-slab crack fracture plane separates the core into a number of pieces. The small pieces in the area marked “S” broke off during the coring operation. The portion of the core bottom that has spalled is characteristic of the cone-shaped spalls described earlier.

For our examination the core pieces were re-assembled (epoxy adhesive) and saw-cuts were made perpendicular to the plane of the wearing surface and perpendicular to the plane of the mid-crack fracture surface. A lapped surface of one of these saw-cuts is shown in Figure 21. Features of interest include the following,

- At the time the core was taken, the concrete in which the crack is contained was in reasonably sound condition. Compare to the repair concrete material spalled and lost in the ATH-33 joint core (Figure 19).

- The mid-slab crack passes both around and through coarse aggregate particles. The yellow dots in Figure 21 identify the fractured coarse aggregate particles. The crack-fractured particles are in the top, middle and bottom of the core indicating that (1) the crack occurred at a time when the concrete had a relatively high level of tensile strength, and (2) the crack likely occurred as a single event.

- The yellow arrows in the top portion of Core ATH-33 (CR) point to horizontal cracks near the wearing surface (Figure 21). The cracks, which are incipient spalls, are highlighted with a black marking pen. These cracks pass through some of the aggregate particles that they intersect. The location and orientation of the cracks suggest that they were formed after the formation of the mid-slab crack. Again, subsidence in the slab at this point due to spalling along the bottom of the slab may be involved in this type of cracking.

- The entire bottom end surface of the core is a fracture surface in the concrete, representing the loss of a thin layer of the original pavement concrete (ca. ¼ in. (6 mm) or so). This crack, and others at this bottom location (blue arrows) angle diagonally upward as they approach the vertically oriented mid-slab crack (blue arrow, Figure 21). The location and orientation of these cracks indicate that they were formed as a result of freezing events. The cracks likely originated in the cement paste in which the air void system has been compromised by in-fill of the air voids by secondary deposits.

- Many of the entrained air voids are filled with white secondary deposits (primarily ettringite). This feature is most prevalent in concrete adjacent to the mid-slab crack, and in the concrete near the top and bottom end of the core. An example is shown in the bottom photograph of Figure 21.

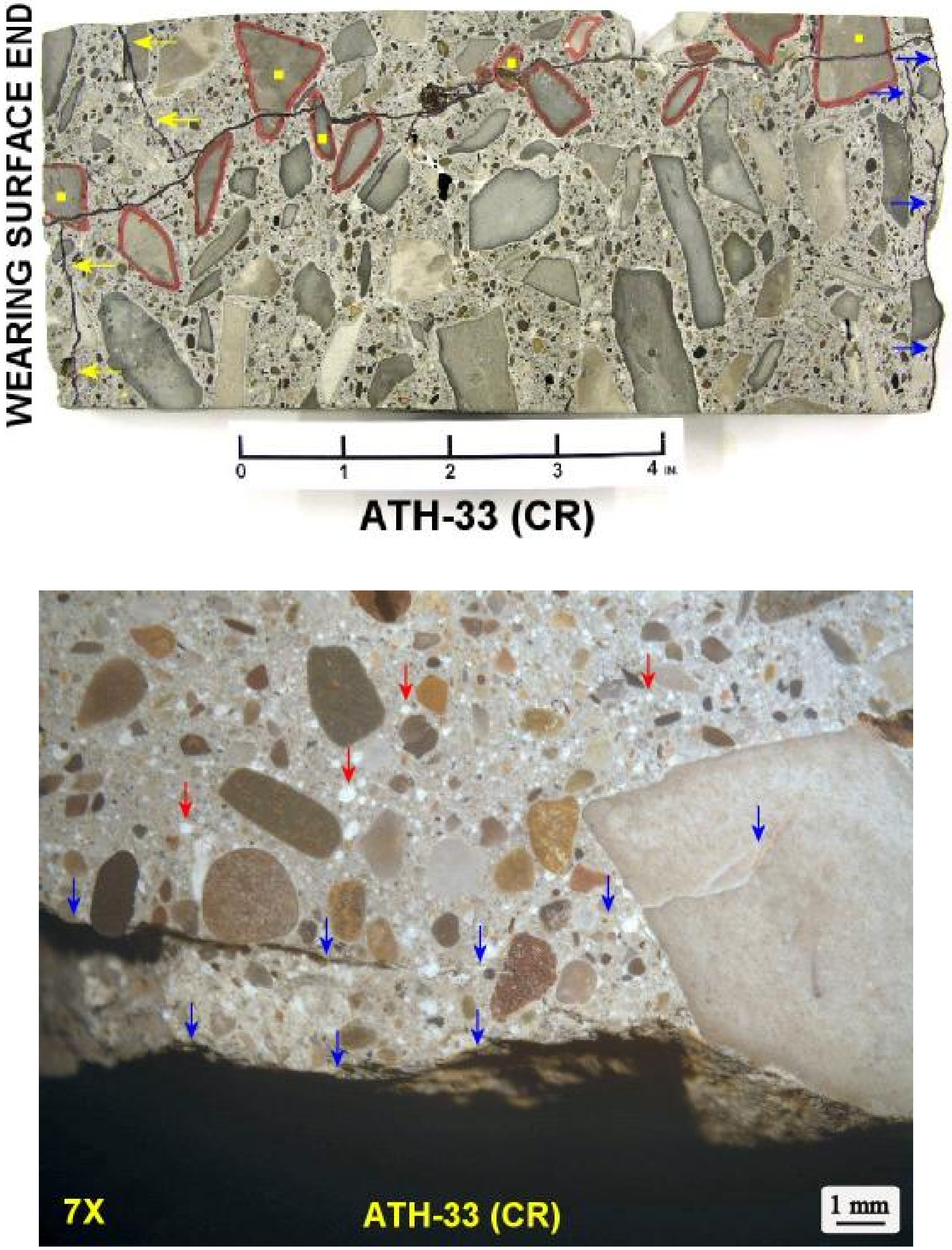



**Figure 21. Two views of the mid-slab crack core taken from the pavement on Athens County US Route 33. The mid-slab crack passes through some of the coarse aggregate particles in its path (yellow dots). Horizontal cracks near the wearing surface terminate at the mid-slab crack (yellow arrows). The blue arrows point to cracks at and near the bottom end surface of the core. The red arrows point to a few of the numerous entrained air voids that are filled with white secondary deposits.**

The pavement comprising this portion of US Route 33 in Athens County has been in service for 51 years. It also deserves a pavement performance rating of exceptional despite the fact that by 1999 all of the original joints had been replaced. The following salient points are made regarding this project.

1. Features the Athens-33 concrete share with the Gallia-7 concrete include (1) a low w/cm, (2) air entrainment, and (3) a coarse aggregate that has shown good freeze/thaw resistance.

2. The large control joint spacing on this project (60 ft [18.3 m]) likely resulted in wide openings of the control joints, leading to water ingress and faulting. Despite this the pavement and joints performed satisfactorily for at least 26 years before the first of the original joints were replaced. This fact establishes the coarse aggregate as having good freeze/thaw resistance. Information on the source of the limestone aggregate was not available.

3. Some of the freeze/thaw cracking damage in the joint and mid-slab crack cores is likely due to mal-functioning of the air voids in the concrete in contact with the base and in the concrete along the crack fractures planes (due to infilling of the air voids with secondary deposits).

4. Corrosion of the mesh reinforcement in the vicinity of the joints and mid-slab cracks is a minor source of cracking distress in the core concrete.

## SUMMIT COUNTY I-76: (TWO SECTIONS/DIFFERENT PERFORMANCE)

The project on Interstate 76 in question here was constructed in 1992. Pavement in the westbound lanes was given an “Excellent” performance rating. Cores taken from the westbound lanes are labeled “SUM-76-15-W”. The “15” is the nearest mile marker to the coring site.

Pavement in the eastbound lanes was given an “Average” performance rating. Cores taken from the eastbound lanes are labeled “SUM-76-15-E”. The “15” is the nearest mile marker to the coring site.

Field notes for the two sections are quoted below.

For the westbound pavement (Excellent Rating),

> *“Minor spalling and corner breaks. No transverse cracking.’*

For the eastbound pavement (Average Rating),

> *“Some transverse cracking toward end of sampling area. Horizontal mid-depth cracking at dowel bars.”*

The most significant difference in the performance rating is the <u>absence of mid-slab cracking in the westbound pavement sections.</u>

Variables that show similar values for the two pavements are shown below, followed by variables that show different values for the two pavements.

### <u>Variables that show Similar Values for the Two Pavements</u>

Design variables of the Summit County I-76 pavements are listed below for comparative purposes. It will be seen that many are similar for the eastbound and westbound pavement sections.

- <u>Design Thickness of Pavement</u> = 11 inches (same for both sections). Thickness of westbound core examined here is10 ¾ in. Thickness of eastbound core is 11 ¼ in.

- <u>Control Joint Spacing</u> = 21 ft (same for both sections).

- <u>Reinforced (451)</u> = Both sections specified as reinforced (451). Cores from both sections do contain a mesh layer. Cover depth of the mesh is 3 ¼ in. in both the eastbound and westbound cores.

- Base Material = 1 in. of 403: 3 in. of 301: and 4 in. of 304 specified for both sections. The 403 and 301 are both HMAC.

- Average Daily Traffic (ADT) = 12,210 for both sections.

Material, strength, and elastic property data for the eastbound and westbound Summit County I-76 cores are listed below in tabulated form for comparative purposes.

| LML Core Number | Core ID Number | Cementitious Constituents | Coarse Aggregate | Estimate of w/cm | Cement Paste Content, % | Total Air Void Content, % | Density, lb/ft$^3$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|
| 33/34 | SUM-76 (15W) (Excellent) | Portland Cement and Fly Ash | No. 8 Crushed Limestone | 0.44 | 29.5 | 7.0 | 141.3 (2264) |
| 37/38 | SUM-76 (15E) (Average) | Portland Cement and Fly Ash | No. 8 Crushed Limestone | 0.44 | 27.7 | 6.3 | 143.1 (2292) |

| LML Core Number | Core ID Number | Compressive Strength, psi (MPa) | Split Tensile Strength, psi (MPa) | Modulus of Elasticity, x $10^6$ psi (x $10^4$ MPa) |
|---|---|---|---|---|
| 33/34 | SUM-76 (15W) (Excellent) | 5490 (38) | 620 (4.2) | 5.71 (3.94) |
| 37/38 | SUM-76 (15E) (Average) | 5650 (39) | 630 (4.3) | 5.44 (3.76) |

The comparative data just listed provides strong evidence in support of a conclusion that these fourteen design, construction, and material variables are not the cause of the difference in performance in the eastbound and westbound pavements on this Section of Summit County I-76. In addition the condition of the concrete at the control joint is also similar for the two projects.

## Condition of the Summit-76 Joint Cores

The features of interest for the joint cores from the two Summit County sites are shown in Figures 22, 23, and 24. Figure 22 shows two views of Core SUM-76-15-E (JT). The top photograph shows the 11 ¼ in. (29 cm) long core in its as-received condition. The arrow in the photograph points to the bottom of the 2 ½ in. (6 cm) saw-cut that was made for the control joint. A considerable amount of material in the control joint fracture plane has been lost through spalling (estimated at 5% based upon the total volume of the core). For the present study a gray epoxy was poured into the void created by the loss of the spalled material. The bottom photograph in Figure 11 is a view perpendicular to the control joint crack fracture plane with the gray epoxy in-fill. In addition to the material already lost through spalling there is other cracking in the concrete in the control joint. These cracks, which are marked with a black marking pen in Figure 22, are parallel to the original crack fracture plane and pass into the core for a distance of about ¼ in. (6 mm) from the edges of the existing spall.

Enlarged stereomicroscopic views (7X and 10X) of a lapped surface of Core SUM-76-15-E (JT) are shown in Figure 23, which provide examples of the peripheral cracking along the joint fracture plane. The views shown in Figure 23 are identified as Sites A and B in Figure 22. Salient features of these peripheral cracks and the concrete in this portion of the core are as follows,

- The cracks are present throughout the length of the core below the saw-cut.
- Through most of the length of the core the crack planes are parallel to the original control joint fracture plane.
- Within the bottom 1 in. or so of the core the cracks bend abruptly to become parallel to the ground surface.
- The cracks typically pass through the coarse aggregate particles and some of the fine aggregate particles. Within a given aggregate particle there are often multiple cracks and the cracks fracture planes are parallel (see top photo in Figure 23).

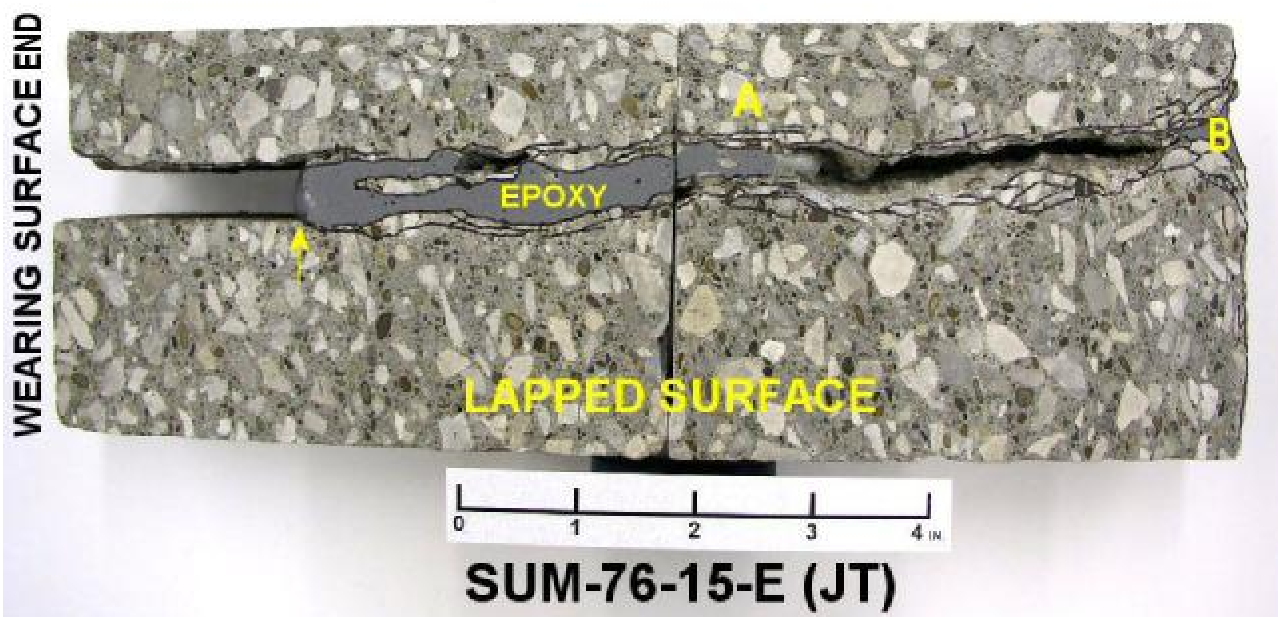




**Figure 22. Two views of the core taken through a control joint on the Summit County Interstate 76 pavement project (Core SUM-76-15-E [JT]). The arrow points to the bottom of the joint saw-cut. The letters "A" and "B" identify sites of the enlarged views shown in Figure 23.**

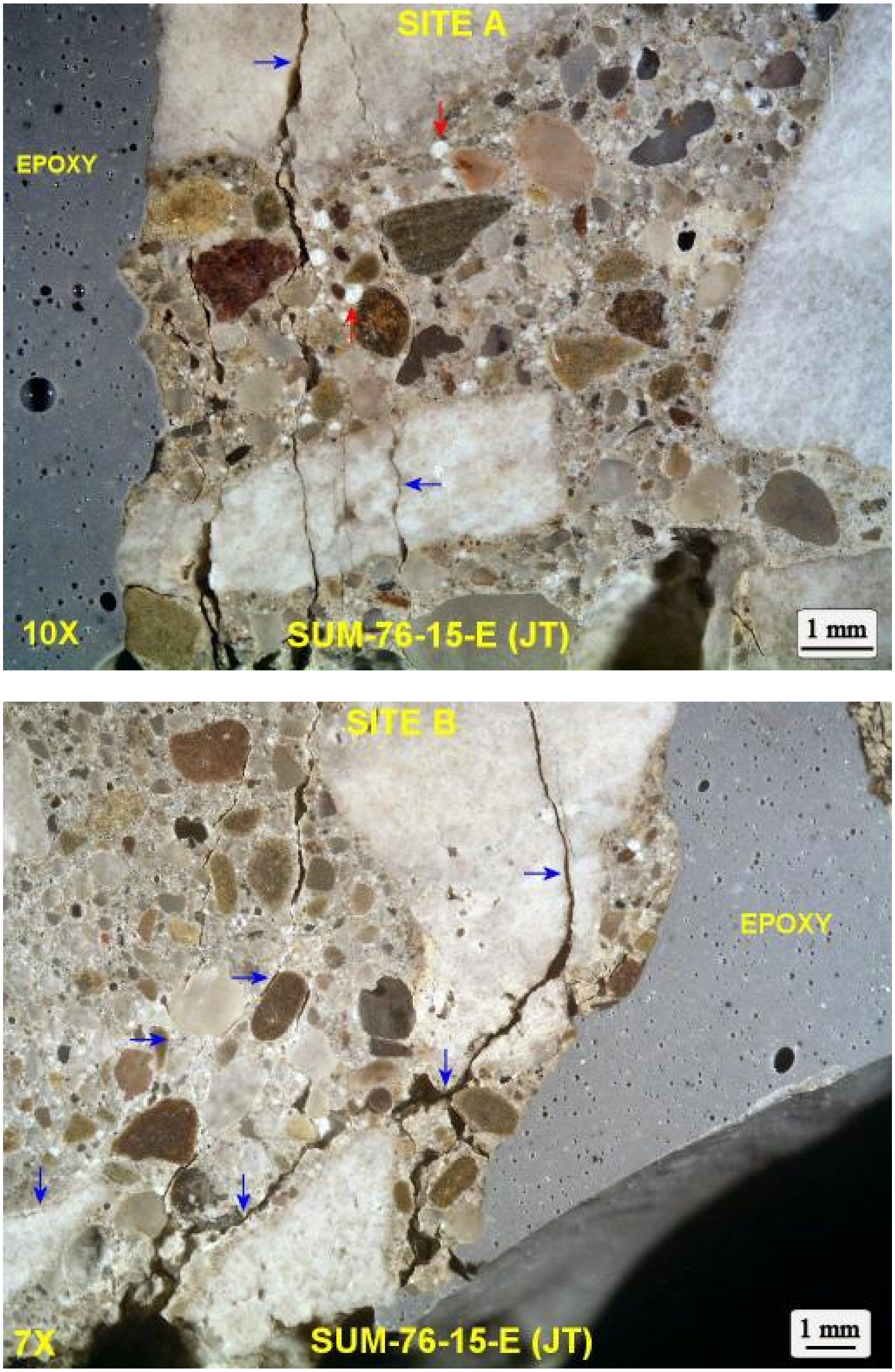



**Figure 23. Two enlarged views (7X and 10X) of a lapped surface of Core SUM-76-15-E (JT) showing peripheral cracking (blue arrows) in the concrete adjacent to the joint crack fracture plane. The red arrows point to two of the numerous entrained air voids that are filled with white secondary deposits. Sites A and B are identified in Figure 11.**

- The majority of entrained air voids in the vicinity of the cracks are completely filled with white secondary deposits. A few of the cracks are also filled with secondary deposits.

- There is no other cracking in the core concrete beyond that just described.

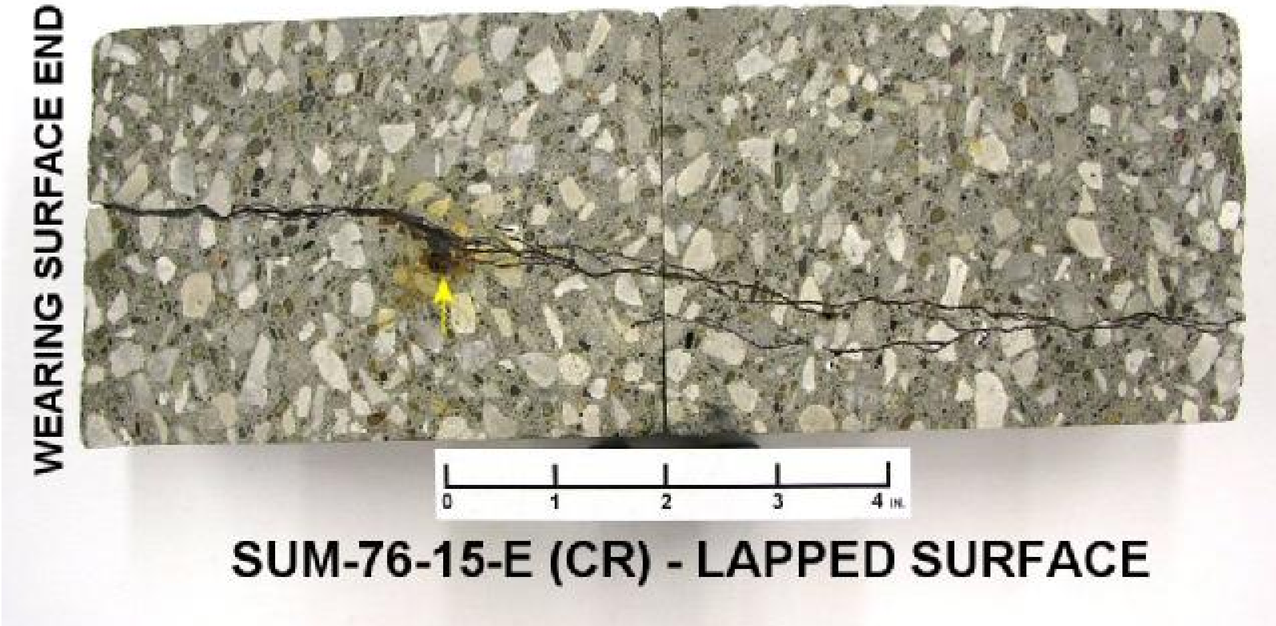
The red arrows in the top photograph of Figure 23 point to a few of the numerous entrained air voids that are completely filled with white secondary deposits. These deposits include both ettringite and calcium hydroxide. The presence of the secondary deposits is confirmation that there was been a prolonged exposure of this portion of the concrete to moisture. An obvious access route of the moisture is downward from the pavement slab surface through the control joint crack.

Microstructural features similar to those just described for the SUM-76-15-E (JT) joint core in Figures 22 and 23 are also present in the mid-slab crack core taken in the eastbound lane of I-76 in Summit County [SUM-76-15-E (CR)], and in the control joint core taken in the westbound lane [SUM-76-15-W (JT)]. Examples of these features are shown in Figure 24.

## <u>Condition of Cores SUM-76-15-W (JT) and SUM-76-15-E (CR)</u>

A lapped surface of the mid-slab crack core taken in the eastbound lane of I-76 in Summit County [SUM-76-15-E (CR)] is shown in the top photograph of Figure 24. The full depth mid-slab crack passes around the steel mesh layer (yellow arrow), which shows mild corrosion. The steel corrosion product has diffused into the adjacent cement paste in the vicinity of the mesh strand. There is peripheral cracking parallel to the main crack in this core. The nature of these cracks and their orientation is similar to the cracking in the eastbound joint core [SUM-76-15-E (JT)], but there has been no spalling of material in the mid-slab crack core.

A lapped surface of the control joint core taken in the westbound lane of I-76 in Summit County [SUM-76-15-W (JT)] is shown in the bottom photograph of Figure 24. The features and nature of the cracking and associated spalling of material in the westbound joint core are very similar to those observed and described previously in the eastbound joint core. The estimated material loss for the eastbound Summit County joint core is 5 percent, compared to a comparable 7 percent for the westbound joint core.



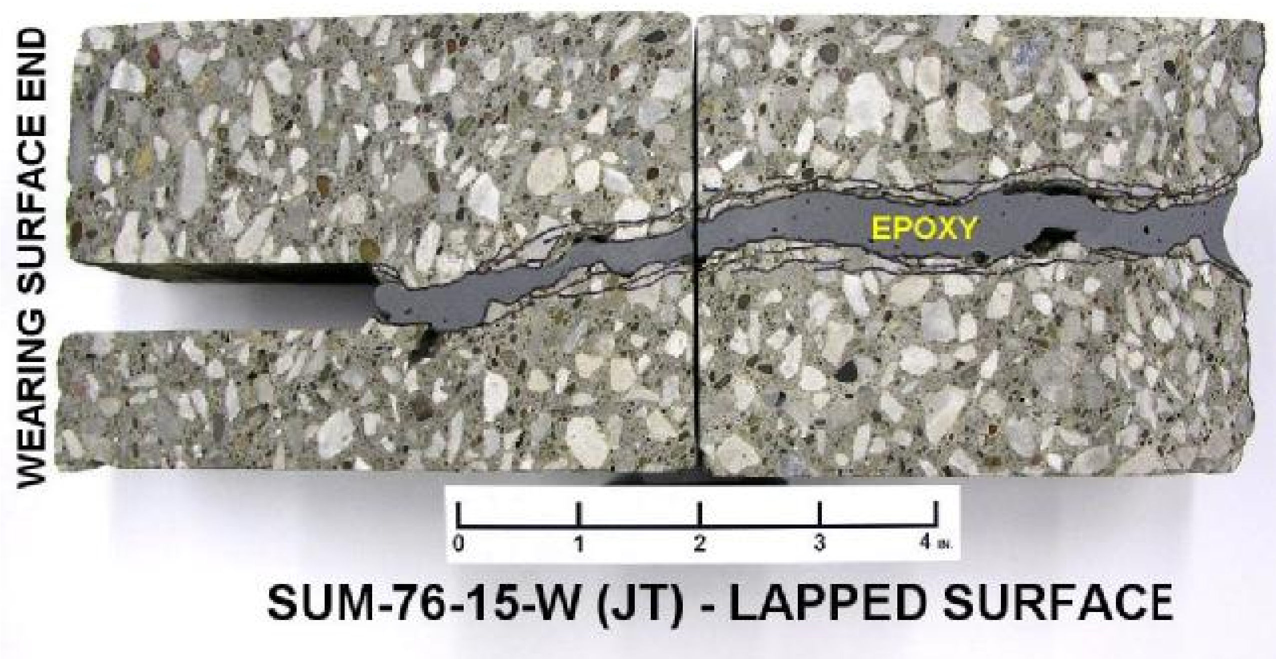




**Figure 24. The top photograph is a lapped surface of the mid-slab crack core from the eastbound Summit County I-76 project [Core SUM-76-15-E (CR)]. Cracks in the core are marked with a black marking pen. The arrow points to a steel mesh strand which shows mild corrosion activity. The bottom photograph is a lapped surface of the joint core from the westbound Summit County I-76 project [Core SUM-76-15-W (JT)]. Cracks in the core are marked with a black marking pen.**

The pattern and microstructural features of the cracks just described in all three of the Summit-76 cores are similar. The cracking is attributed to freeze/thaw cycling distress that originated within the cementitious phase, where the functionality of the entrained air void system has been compromised by the infill of the void cavities with secondary deposits. The cracks that pass through the aggregate particles are not typical of the cracks that develop in D-Crack prone coarse aggregate particles (compare Figures 11 and 23).

As stated at the outset in this Section of the report for these Summit County I-76 projects, the pavement in the westbound lanes was given an "Excellent" performance rating, while the pavement in the eastbound lanes was given an "Average" performance rating. The higher rating for the westbound pavement was based on the absence of mid-slab cracking, which is present in the eastbound pavement. As just discussed in some detail, no significant differences were found in any of the design and material variables just covered for the eastbound and westbound pavements and core concrete. To summarize, these variables include,

- Pavement thickness
- Pavement joint spacing
- Pavement reinforcement (steel mesh) and the position of the reinforcement.
- Base materials and design.
- Average Daily Traffic.
- Cementitious constituents of the concrete, water-cement ratio, and cement paste content.
- Type of coarse and fine aggregate.
- Air entrainment and total air void content.
- Unit weight (density)
- Compressive strength, tensile strength, and modulus of elasticity
- Overall quality of the concrete (good in both cases).
- Pattern and nature (origin) of the cracking in the control joint cores.

## A Condition that is Different for the Eastbound & Westbound Summit I-76 Cores

The primary factor leading to a lower pavement performance rating for the eastbound pavement project is the presence of mid-slab cracking. No mid-slab cracking is present in the westbound lanes. During the coring on this Summit County project it was observed that cracks were present at the level of the dowels in the control joint concrete in the eastbound pavement. The crack planes are parallel to the ground as shown in Figure 25. The cracks are being referred to here as "horizontal cracking". These cracks are not present in the westbound joint cores.


**Figure 25. One of the cores taken from a control joint on the eastbound lanes of the Summit County I-76 project showing what is being referred to as "horizontal cracking" at the dowel level. This type of cracking is not present in the joint cores taken from the westbound I-76 lanes.**

The arrows in Figure 25 point to sites where the cracks pass through coarse aggregate particles. This feature confirms the crack was formed at a time when the concrete had achieved much of its ultimate tensile strength. In the photograph the cracks appear to be free of dirt and/or secondary deposits, indicating that the crack likely was created during the coring operation. It may have been a pre-existing very tight crack in the concrete.

There is no corrosion of the epoxy-coated dowel in this core, so the cracking can not be attributed to this potential source of stress. The cracking can be explained by any eccentricity in the position of one or more of the dowels, particularly in the horizontal plane. The failure of the control joints to function as intended can account for the presence of mid-slab cracking in the eastbound pavements.

Other projects which have horizontal cracking through dowels in the control joints include (1) Allen County US Route 30 and (2) Cuyahoga County State Route 176 at Southbound Mile Marker 10. The same situation may have occurred in the joint core from Cuyahoga County State Route 252, where the bottom of the as-received joint core was in pieces.

**JEFFERSON COUNTY (SAME PROJECT/DIFFERENT ROUTE/DIFFERENT PERFORMANCE)**

PCC pavements were constructed on US Route 22 and State Route 7 in Jefferson County on the same project in 1990. The State Route 7 pavement received an "Excellent" performance rating and the US Route 22 pavement received an "Average" rating. Despite the difference in performance rating both pavements showed mid-slab cracking. Also, despite the performance ratings, the State Route 7 pavement (Excellent Performance) is currently in worse condition than the US Route 22 pavement (Average Performance). This situation is reflected in the field notes for the two pavement sites.

For the US Route 22 pavement (Average Performance) the field notes are,

> "*Moderate transverse cracking and spalling"*

For the State Route 7 pavement (Excellent Performance) the field notes are,

> *"Moderate to severe transverse cracking with spalling and faulting. Multiple cracks per slab".*

Based upon the OU field note observations and on the condition of the cores provided to us on this project, it appears that in 2009 the US Route 22 pavement is in better condition than the State Route 7 pavement in Jefferson County. One possible explanation for this anomaly is that the Pavement Condition Ratings (PCR) on which the selections were made were developed in 2004.

Design variables for the Jefferson County pavements are listed below for comparative purposes. It will be seen that many are similar for the JEF-7 and JEF-22 pavement sections.

- Design Thickness of Pavement = 9 inches (23 cm). Thickness of JEF-22 cores examined here is 9 ¼ in. and 9 ¾ in. (24 cm and 25 cm). Thickness of JEF-7 cores is 9 in. (23 cm).
- Control Joint Spacing = 27 ft for both routes (both skewed).
- Base Material = Base material is 6 in. of 310 T2 for both routes.
- Average Daily Traffic (ADT) = JEF-22 is 3750 and JEF-7 is 1980 (both 2007)

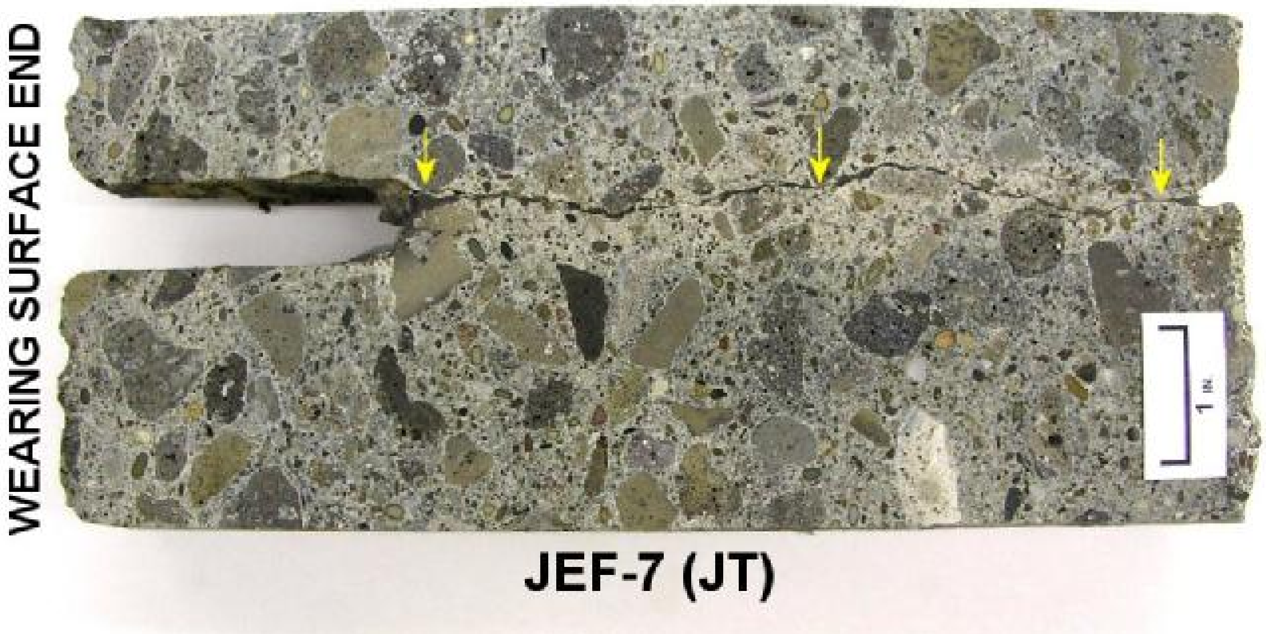
Material, strength, and elastic property data for the JEF-7 and JEF-22 cores are listed below in tabulated form for comparative purposes.

| LML Core Number | Core ID Number | Cementitious Constituents | Coarse Aggregate | Estimate of w/cm | Cement Paste Content, % | Total Air Void Content, % | Density, lb/ft$^3$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|
| 15/16 | JEF-7 (Excellent) | Portland Cement | ¾ in. Slag | 0.46 | 26.4 | 6.1 | 140.1 (2244) |
| 13/14 | JEF-22 (Average) | Portland Cement | 1 in. Slag | 0.42 | 27.9 | 5.2 | 143.9 (2305) |

| LML Core Number | Core ID Number | Compressive Strength, psi (MPa) | Split Tensile Strength, psi (MPa) | Modulus of Elasticity x $10^6$ psi (x $10^4$ MPa) |
|---|---|---|---|---|
| 15/16 | JEF-7 (Excellent) | 6830 (47) | 540 (3.7) | 5.32 (3.67) |
| 13/14 | JEF-22 (Average) | 7340 (51) | 490 (3.4) | 5.76 (3.98) |

The comparative data just provided provides strong evidence in support of a conclusion that the thirteen design, construction, and material variables discussed above are similar and are not the cause of the difference in pavement performance on these Jefferson County pavements.

Insights into the factors affecting the performance of the two projects were gained through an examination and characterization of the current condition of the cores.



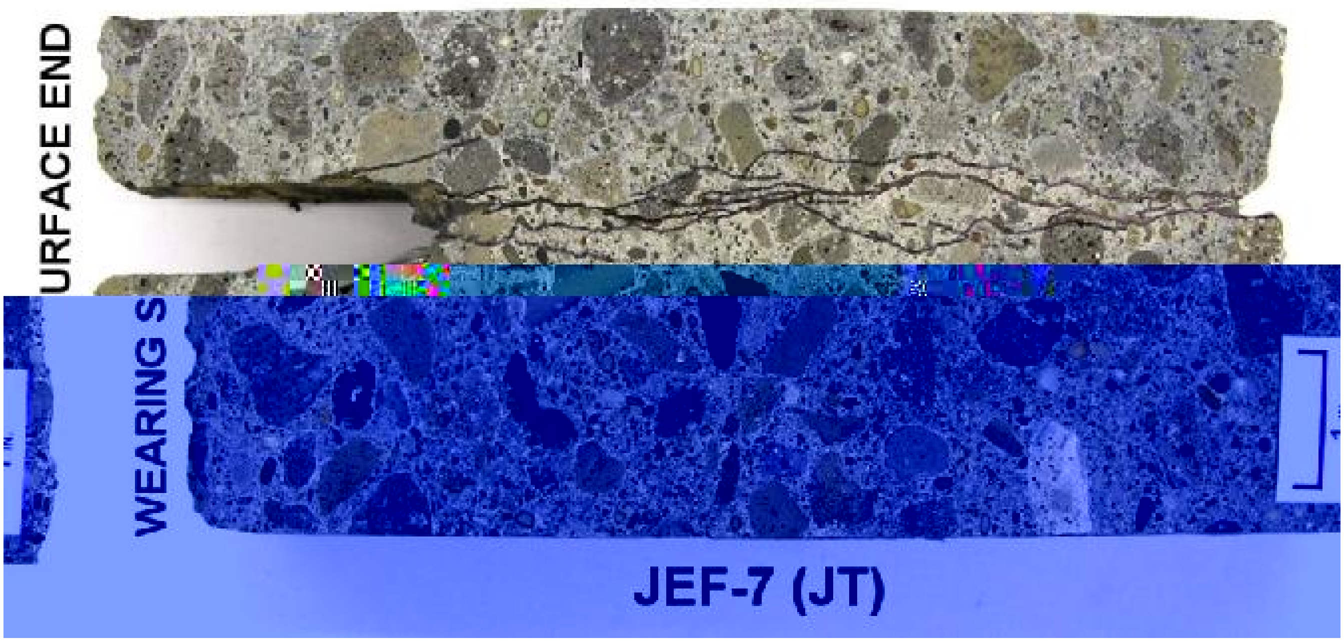




**Figure 26. Two views of the same lapped surface of the control joint core from the Jefferson County State Route 7 pavement. The arrows in the top photograph point to the primary control joint crack. Other cracks that can only be seen with the aid of the microscope are highlighted with a black marking pen in the bottom photograph.**

## Jefferson County State Route 7 Pavement

Two views of the same lapped surface of the control joint core [JEF-7(JT)] are shown in Figure 26. The surface shown is perpendicular to the plane of the core wearing surface and perpendicular to the plane of the primary control joint crack. The arrows in the top photograph point to the primary control joint crack. Other cracks that can only be seen with the aid of the microscope are highlighted with a black marking pen in the bottom photograph. The pattern and microstructural features of the cracks are similar to those described previously for the Summit County joint and mid-slab crack cores (Figures 23 and 23). The cracks pass around some of the slag coarse aggregate particles and through others. In those instances where the cracks pass through the aggregate particles it is typically only a single crack that originated in the cementitious matrix phase. There is not multiple randomly oriented cracking in the affected slag aggregate particles.

Two views of the same lapped surface of the mid-slab crack core [JEF-7 (CR)] from this pavement are shown in Figure 27. The surface shown is perpendicular to the plane of the core wearing surface and perpendicular to the plane of the primary control joint crack. The arrows in the top photograph point to remnants of the initial mid-slab crack that formed in the pavement slab. A considerable amount of material has cracked and spalled (Spall Region) along the mid-slab crack line. Prior to spalling this portion of the core concrete was cracked in a manner showing the same pattern and features as the highlighted cracks in the JEF-7 joint core (bottom photograph of Figure 26). The yellow arrow in the bottom photograph of Figure 27 points to a small remnant region of these microscopic cracks in the JEF-7 mid-slab crack core. The cracks are parallel to the fracture plane of the initial mid-slab crack.

The red arrows in the bottom photograph of Figure 27 point to horizontal fractures in the JEF-7 mid-slab crack core. The fracture planes of these cracks are parallel to the plane of the core wearing surface. These are single, sharp cracks which intersect the spall region at a right angle. It is conjectured that these cracks form as a result of repeated traffic impacts at the site of the mid-slab crack. The disintegration of the concrete lying along the mid-slab crack plane translates into a loss of support for the overlying portion of the pavement slab. It is as if there is a void there of the size shown in Figure 27. This condition means that the top portion of the pavement concrete is cantilevered due to the undercut of the spall zone. Eventually, under traffic loads, the concrete cracks as shown in the bottom photograph of Figure 27 (red arrows)

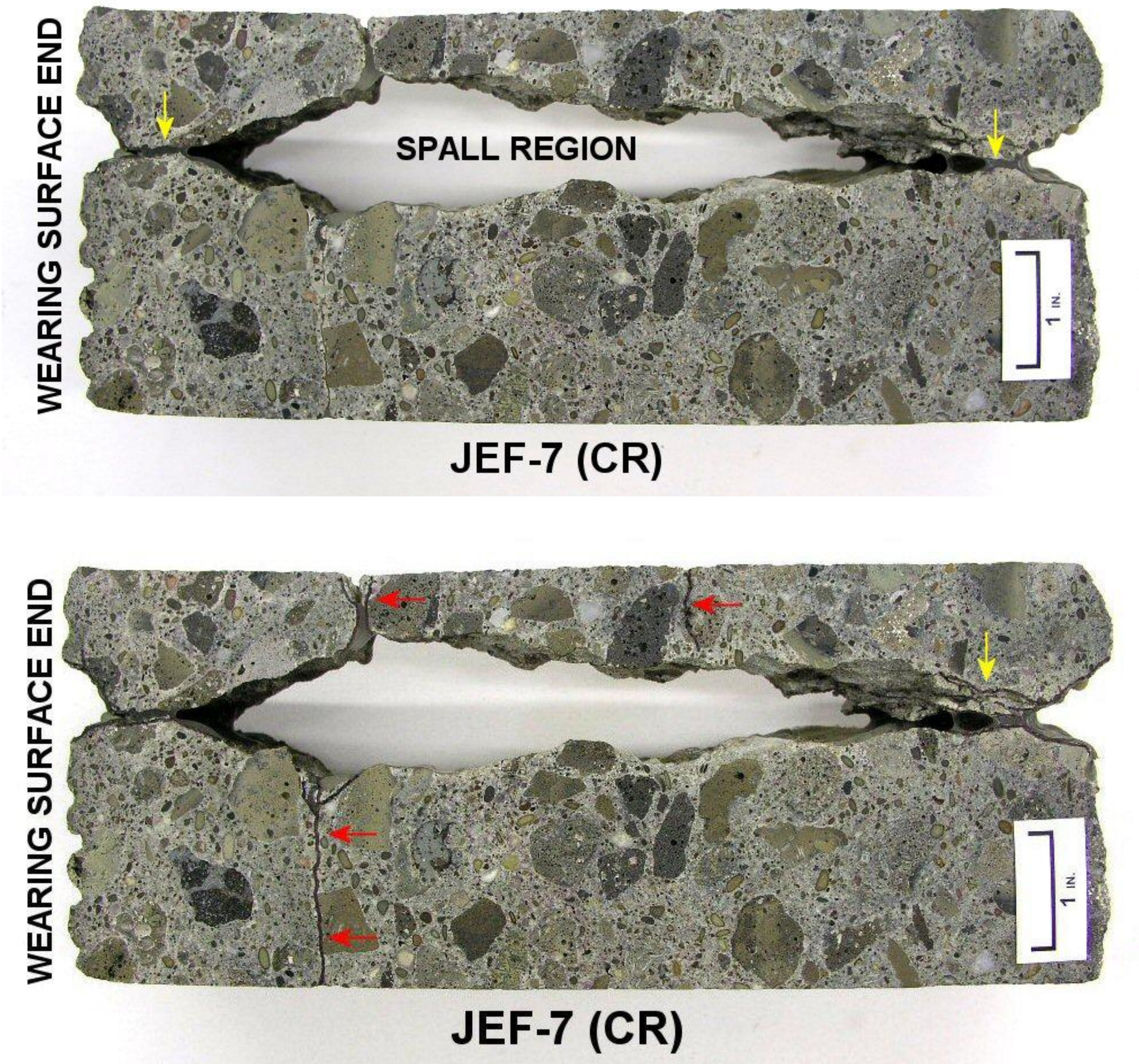



**Figure 27. Two views of the same lapped surface of the mid-slab crack core from the Jefferson County State Route 7 pavement. The arrows in the top photograph point to remnants of the primary control joint crack. A considerable amount of material has cracked and spalled along the primary crack line. The red arrows in the bottom photograph point to horizontal cracks in the core. The yellow arrow in the bottom photograph points to a network of fine microscopic cracks that have been highlighted with a black marking pen.**

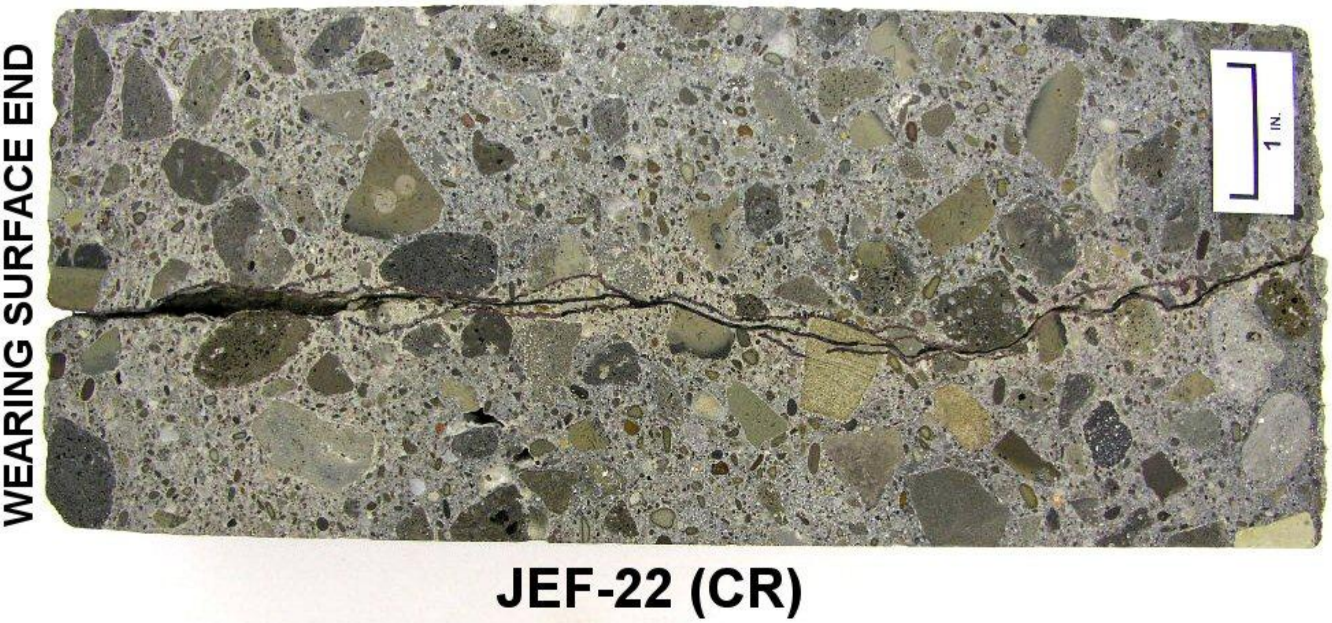
## Jefferson County US Route 22 Pavement

Figure 28 shows lapped surface views of the cores taken from a joint [JEF-22(JT)] and from a mid-slab crack [JEF-22(CR)]. The surfaces are perpendicular to the plane of the wearing surface of the cores and perpendicular to the primary crack fracture plane. In comparing Figure 28 with Figures 26 and 27, it is seen that the pattern and nature of the peripheral microscopic cracking in the Jefferson County US Route 22 cores is similar to these features in the Jefferson County State Route 7 cores.

One significant fact that has not yet been pointed out is that, despite the fact that these two pavements were constructed on the same project and have many similarities, one difference is the exposure conditions. Even though the projects are in relatively close proximity, it is reasonable to expect that the drainage conditions and precipitation would be somewhat different for the two sites.

The evidence presented here strongly indicates that the origin and nature of the cracking (and subsequent spalling) of concrete along the joint and mid-slab crack fracture planes is the same. That is, the peripheral cracking originates in the cementitious matrix phase of the concretes as a result of freezing events while in a state of critical moisture saturation. The vulnerability of the cementitious phase in this portion of the core is due to infilling of the entrained air voids with secondary deposits, which obviates the intended function of the air voids. The greater amount of cracking and spalling in the State Route 7 cores (relative to the US Route 22 cores) can be viewed simply as an advanced stage of the same deterioration mechanism.

One unusual aspect of the joint core from the Jefferson County US Route 22 joint core is that the joint is formed, rather than saw-cut. The feature is shown by the red arrows in the bottom photograph of Figure 28, and indicates that this is a construction joint, not a control joint. In referring to this photograph it is seen that the concrete on one side of the joint is cracked, while that on the other side of the joint is not cracked. The concrete on either side of the joint is from two different batches. Relative to the un-cracked concrete, the cracked concrete has a higher air void content and the overall size (diameter) of the voids is smaller. In both concretes the majority of air voids are either partially or fully in-filled with white secondary deposits (primarily fibrous ettringite). This infilling is more extensive in the cracked concrete than in the un-cracked concrete. The implications of this condition have not yet been worked out.



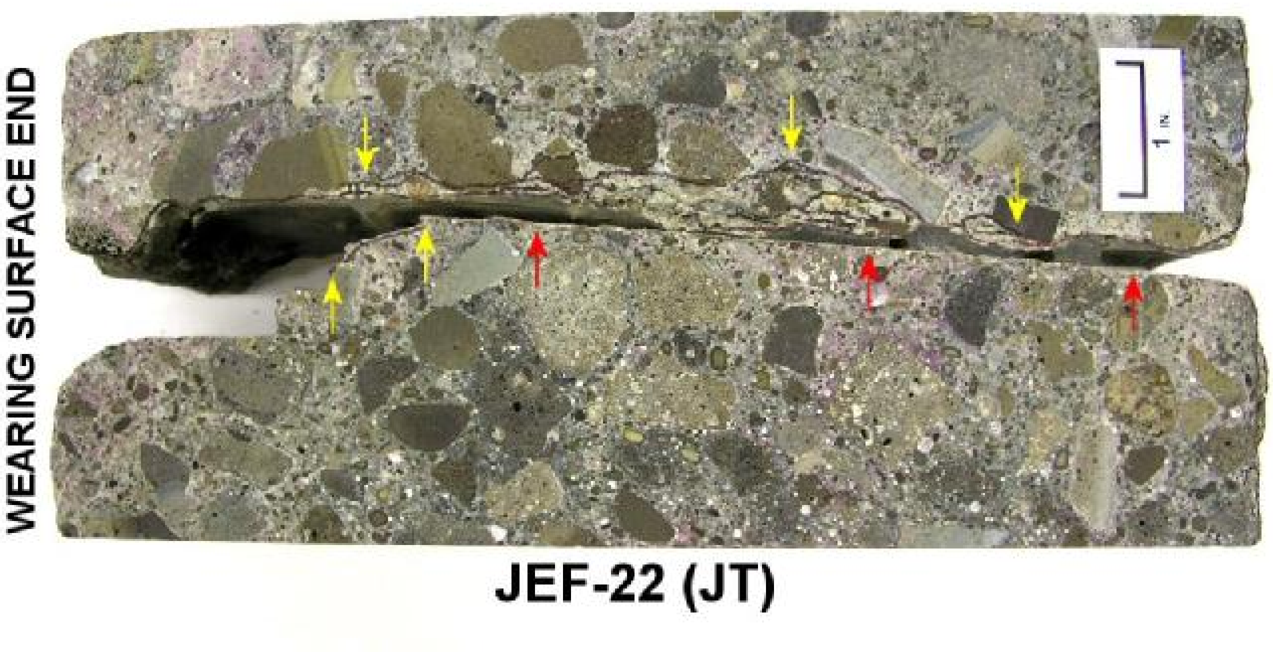




**Figure 28. Lapped surfaces of Jefferson County US Route 22 pavement mid-slab crack core (CR) and control joint core (JT). In both photographs cracks in the concrete have been highlighted with a black marking pen. The red arrows in the bottom photograph point to a formed surface in the joint core. The region of cracking and spalling along the joint line is bracketed by the yellow arrows.**

## CUYAHOGA COUNTY STATE ROUTE 176 (TWO SECTIONS, DIFFERENT RIDE QUALITY)

This project was constructed in 1996. The two Sections of the project in question here are (1) the Section at Mile Marker 11 on the Southbound Lanes, and (2) the Section at Mile Marker 12 on the Southbound Lanes. The cores from these sections are labeled CUY-176-11-S and CUY-176-12-S respectively. Both sections were given a pavement performance rating of "Average". The difference in the two sections is a difference in ride quality. However, it is also noted that there is no mid-slab cracking in Section 11-S, while there is in Section 12-S.

Field notes for Section 11-South are,

> *"Smooth section of Project 305(96) Pavement surface in very good condition. No cracking. Some mid-depth horizontal cracking noted at dowel bars, and slag stuck to bottom of cores."*

Field notes for Section 12-South are

> *Rougher section of Project 305(96). Pavement in good condition, but air voids present in cores.*

Variables that show similar values for the two pavements are shown below, followed by variables that show different values for the two pavements.

### Variables/Factors that are Similar for the Two Pavement Sections

- Design Thickness of Pavement = 12 inches (30 cm). Thickness of Section 11-S cores is 12 in. (30 cm). Thickness of Section 12-S cores is 11 ½ in. and 12 in. (29 and 30 cm).
- Control Joint Spacing = 21 ft (6.4 m) is the same for both sections.
- Reinforced (451) = Both sections specified as reinforced (451). Cores from Section 11-S contain no steel. The mid-slab crack core from Section 12-S has a mesh layer with 3 ¼ in. of cover.
- Base Material = Both sections have 6 in. (15 cm) of 310 T2 base.
- Average Daily Traffic (ADT) = 2975 for both sections.

Material, strength, and elastic property data for the two Route 176 section cores are summarized listed below in tabulated form for comparative purposes.

| LML Core Number | Core ID Number | Cementitious Constituents | Coarse Aggregate | Estimate of w/cm | Cement Paste Content, % | Total Air Void Content, % | Density, lb/ft$^3$ (kg/m$^3$) |
|---|---|---|---|---|---|---|---|
| 23/24 | CUY-176-11-S (Average) | Portland Cement | No. 8 Crushed Limestone | 0.43 | 28.3 | 8.4 | 138.9 (2225) |
| 25/26 | CUY-176 - 12-S (Average) | Portland Cement | No. 8 Crushed Limestone | 0.43 | 27.6 | 8.4 | 138.5 (2219) |

| LML Core Number | Core ID Number | Compressive Strength, psi (MPa) | Split Tensile Strength, psi (MPa) | Modulus of Elasticity x $10^6$ psi (x $10^4$ MPa) |
|---|---|---|---|---|
| 23/24 | CUY-176-11-S (Average) | 3760 (26) | 600 (4.1) | 3.83 (2.64) |
| 25/26 | CUY-176 - 12-S (Average) | 3820 (26) | 540 (3.7) | 3.60 (2.48) |

**Control Joint Cores (Cuyahoga County-176)**

Another similarity in the two pavement sections is the condition of the concrete in the cores taken from the control joints. Lapped surface views of the two joint cores are shown in the bottom photographs of Figures 29 and 30. The surfaces are perpendicular to the plane of the wearing surface and perpendicular to the joint fracture plane. Both cores in these 13 year old pavements are in good condition. In the cited photographs the joint crack fracture plane passes around most of the limestone coarse aggregate particles (No. 8); passing through several of the particles near the bottom end surface of the cores. Unlike the situation described previously for the Summit County cores (17 years of service) and the Jefferson County cores (19 years of service), most of the entrained air voids in the concrete adjacent to the primary joint crack are free of any significant amounts of secondary deposits. Thus, the entrained air void system is functional in this concrete. There are just a very few of the microscopic cracks peripheral to the primary joint crack. These microscopic cracks are present at sites where air-void infill has occurred. This situation is viewed as an early stage of the development of the extensive type of cracking that was described previously for the Summit County cores (Figures 22, 23, and 24) and the Jefferson County cores (Figures 26, 27, and 28).

The blue arrows in Figures 29 and 30 point to horizontal/diagonal cracks in the very bottom of the cores, which is the first step in the development of the cone-shaped spalls described previously.

## Mid-Slab Crack Cores (Cuyahoga County-176)

Lapped surface views of the two mid-slab crack cores are shown in the top photographs of Figures 29 and 30. The surfaces are perpendicular to the plane of the wearing surface and perpendicular to the joint fracture plane. Both cores are in good condition.

In Core CUY-176-12-S (top photograph in Figure 30) the mid-slab crack goes through the full thickness of the core and passes around and through the No. 8 limestone coarse aggregate particles. This microstructural feature confirms that this mid-slab crack formed at a later date than the joint crack. There is no peripheral cracking adjacent to the primary crack and the entrained air voids are mostly free of secondary deposits in the concrete adjacent to the crack. The red arrow in the top photograph of Figure 30 points to remnants of slag aggregate base still adhered to the pavement concrete.

In Core CUY-176-11-S (top photograph in Figure 29) there is no full depth mid-slab crack. There are two shallow [≤ 3 in. (76 mm)] vertical cracks originating in the wearing surface that typically pass through No. 8 limestone coarse aggregate particles. As shown in the cited photograph there is ca. ¾ in. (19 mm) thickness of the slag aggregate base still adhered to the pavement concrete. It is conjectured that powder-sized particles of the slag could have hydrated to form the cohesive slab base material. It can be speculated that this feature of the bonding of the pavement concrete to the solidified slag aggregate base material may have played a role in minimizing the mid-slab cracking in the CUY-176-11-S pavement, forming instead of one primary mid-slab crack, a larger number of narrower cracks.

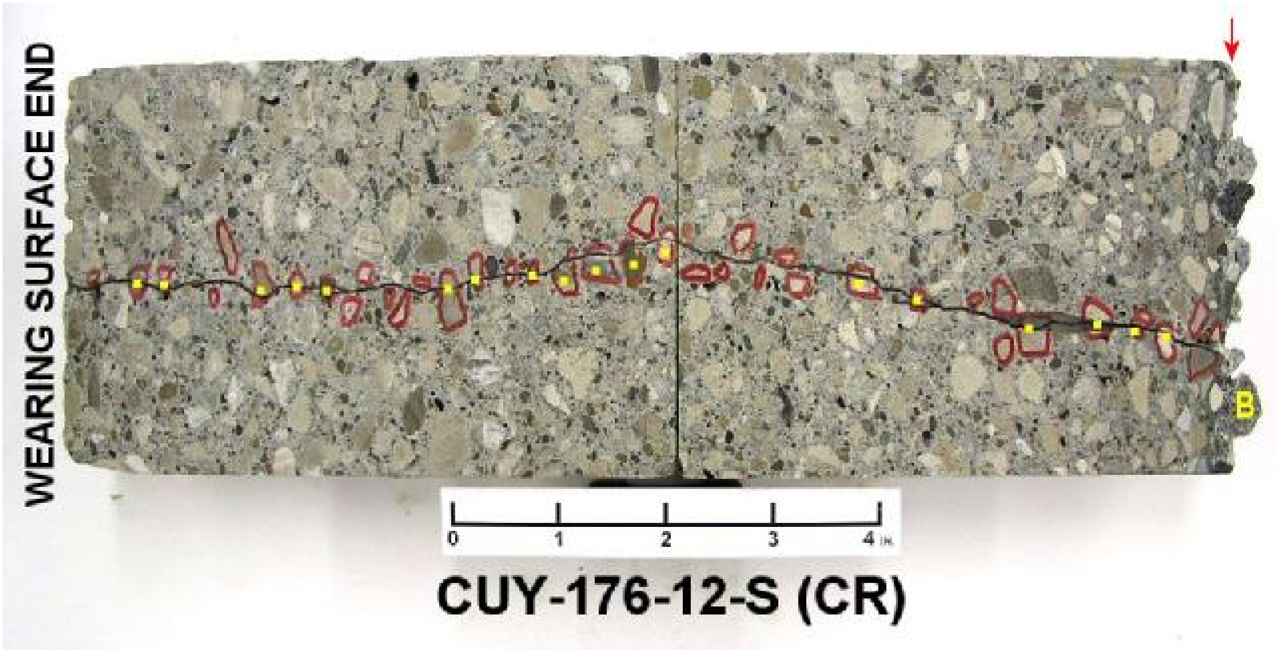
## Factors Affecting Ride Quality in the Cuyahoga County State Route 176 Pavements

The presence of mid-slab cracks in Pavement Section 12 (with accompanying curling) may have had a slight negative effect on ride quality for this section. However, of the other material, design, and construction variables examined and described here, none can account for the difference that was measured in the ride quality of Sections 11 and 12 (Southbound) of this project. These variables include,

- Pavement thickness
- Pavement joint spacing
- Pavement reinforcement (steel mesh).
- Base materials and design.
- Average Daily Traffic.
- Cementitious constituents of the concrete, water-cement ratio, and cement paste content.
- Type of coarse and fine aggregate.
- Air entrainment and total air void content.
- Unit weight (density)
- Compressive strength, tensile strength, and modulus of elasticity
- Overall quality of the concrete (good in both cases).
- Nature of the cracking in the control joint cores.
- The joint seal reservoir in 11-S (JT) was cut in one saw pass; two passes for 12-S (JT).



**Figure 29. Lapped section view of Cuyahoga County State Route 176 cores taken from a slab mid-point (top photograph) and over a control joint at Mile Marker 11-South (bottom photo). Cracks in the cores are highlighted with a black marking pen. Coarse aggregate particles in the path of the cracks are outlined with a red pen. The yellow dots identify aggregate particles through which the crack passes. The blue arrows point to a fracture plane that forms the bottom surface of the joint core. The "B" label identifies slag base material adhered to the pavement concrete.**



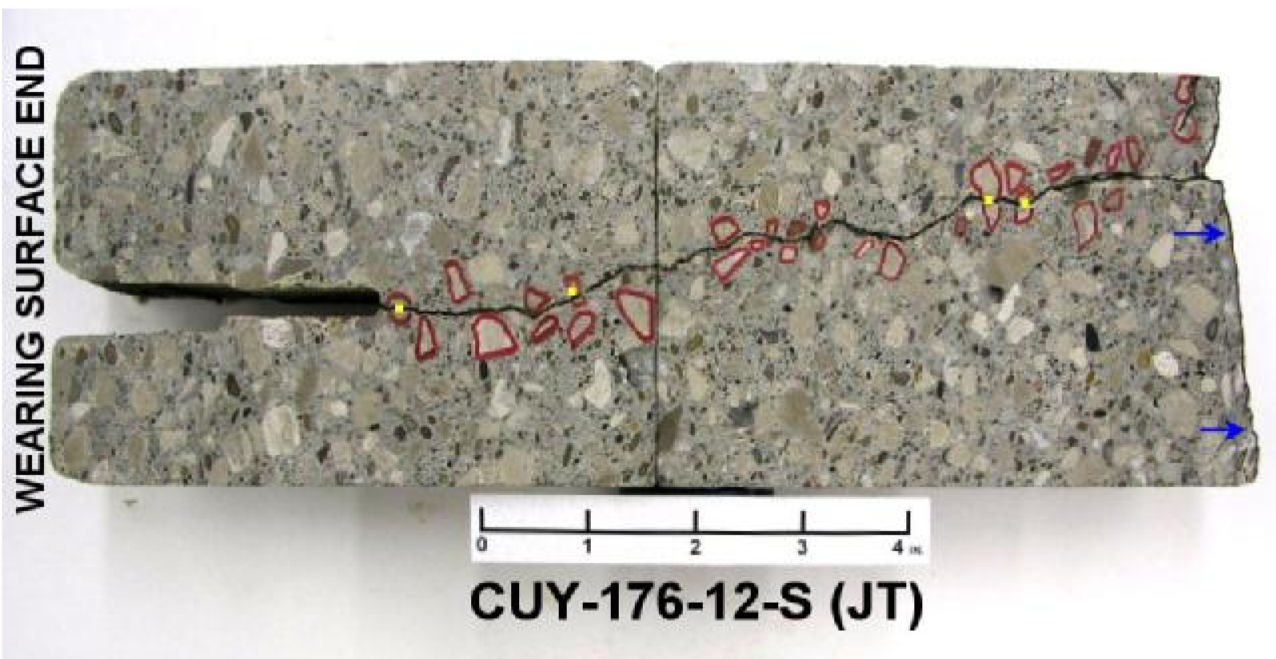




**Figure 30. Lapped section view of Cuyahoga County State Route 176 cores taken over a mid-slab crack (top photograph) and over a control joint at Mile Marker 12-South (bottom photo). Cracks in the cores are highlighted with a black marking pen. Coarse aggregate particles in the path of the cracks are outlined with a red pen. The yellow dots identify aggregate particles through which the crack passes. The blue arrows point to a fracture plane forming the bottom end surface of the core. The "B" label indentifies slag base material adhered to the pavement concrete.**

## FACTORS AFFECTING MID-SLAB CRACKING IN THE RESEARCH STUDY PAVEMENTS

Mid-slab cracking of PCC highway pavements has long been a problem for transportation departments in Ohio, and in many other states. The trend to thicker pavement sections and to reduced slab lengths in recent years have reduced the frequency of the problem, but have not eliminated it. The issue here is a full slab width transverse crack, which typically occurs at or near the middle of the slab (relative to its length). It is not known with certainty at what point the crack forms relative to the time of construction (although this would be useful information to have).

Typically it is a single crack and not multiple cracks that form in a given slab. This fact supports an opinion that (1) contractive tensile stresses developed in the slab at some time, (2) the formation of the mid-slab crack served to relieve the tensile stresses that caused the crack to form in the first place, and (3) the formation of the crack is due to restrained shrinkage strains in the slab.

The sources of tensile strains in highway PCC slabs include at least the following,

- Drying Shrinkage Strains.
- Thermal Contraction Strains.
- Contractive Strains Accompanying the Loss of Moisture from the Concrete.

The factors that influence the magnitude of the elastic shrinkage strains in highway PCC slabs include at least the following,

- Concrete Composition (Aggregate Volume, Paste Volume, Water Content).
- Coarse Aggregate Properties (Modulus of Elasticity, Coefficient of Thermal Expansion).
- Composite Concrete Properties (Modulus of Elasticity, Coefficient of Thermal Expansion, Tensile Creep Strain Potential).
- Date of Placement of the Pavement (Low Ambient Temperatures vs. High Ambient Temperatures on the day of placement).

Tensile creep (inelastic strains) of concrete subjected to tensile stresses has the potential to reduce the magnitude of tensile stresses in pavement slabs, but it is a property that is seldom measured. It is expected that a higher creep strain potential would be associated with higher cement paste contents and higher water to cementitious material ratios.

Based upon past experience with random cracking of PCC concrete slabs on grade, the design and environmental factors that are known to have the greatest influence on the potential for crack formation include,

- Design and Proper Functioning of the Control Joints.
- Slab length relative to Slab Thickness.
- Restraint Due to Sub-Grade Friction (and other sources of physical restraint).

With the above discussions as background, the next section of the report examines the mid-slab cracking issue as it relates to the pavements evaluated in the current study.

## Mid-Slab Cracking in the Research Study Pavements

Six of the twenty Research Study pavements have virtually no mid-slab cracking. These six include,

- Greene County – State Route 35 (Constructed 1997)
- Allen County – US Route 30 (Constructed 1997)
- Cuyahoga County – State Route 176 (Constructed 1996)
- Cuyahoga County – State Route 322 (Constructed 1993)
- Summit County – Interstate Route 76 (Constructed 1992)
- Logan County – State Route 33 (Constructed 1994)

Tables G-1 and G-2 (Appendix G) provide a comparison of the most relevant material, design, and construction variables for these six pavement projects. The variables include,

- Pavement thickness (10, 11, and 12 in. {25, 28, and 30 cm})
- Control joint spacing (Five at 21 ft {6.4 m} and one at 15 ft {4.6 m}

- Base material and design (three of the six are free draining)
- Presence of mesh reinforcement (Five of the six have mesh)
- Condition of the joint concrete (Minor material loss along joint crack)
- Type of coarse aggregate (All six have limestone coarse aggregate)
- Coarse aggregate freeze/thaw rating (All six have excellent rating)
- Total aggregate content (Ranges from 61.7 % to 69.0 %)
- Total air content (Ranges from 4.2 % to 9.2 %)
- Compressive strength (Ranges from 3760 to 8720 psi {26 to 60 MPa})
- Tensile strength (Ranges from 570 to 710 psi {3.9 to 4.9 MPa})
- Modulus of Elasticity (Ranges from 3.83 to 5.89 x $10^6$ psi)

As discussed below, the factors that had the greatest influence on the "no-midslab-cracking" outcome for the Research Study pavements include (1) base material and design, and (2) coarse aggregate type and quality.

**Base Material and Design**

The breakdown of the base material for the twenty Research Study projects is shown below.

- Standard 304 Base = One project
- Standard 310 Base = Four projects
- 310 T2 (Improved drainage) = Nine projects
- 403/310/304 Base = Two projects (Asphaltic Concrete Base Component)
- NSDB/304 Drainable Base = Two projects
- ATFDB/304 Drainable Base = One project
- SS 112 Base = One project

Reference to Table G-1 (Appendix G) shows that of the six crack-free pavements, three were placed on a free-draining base (Greene-35, Allen-30, and Logan-33). The two Cuyahoga County pavements were placed on 310 T2 base, which is characterized as "drainable, but not free draining". The westbound lane of Summit-76 is the only one of the six pavements placed on an asphaltic concrete composite base.

The correlation of the crack-free performance in three of the six projects with the use of a free-draining base material is obvious. The reason that a free-draining base material had a favorable influence on the elimination of mid-slab cracking in the three cited cases (above) is not completely understood, although the effect of this factor on strains associated with moisture cycling within the concrete may be involved. It can be speculated that any factor that can diminish the long-term, cyclic expansive and contractive strains in a PCC pavement slab in Ohio service would have a favorable influence on the proneness to cracking. With a standard base material it is expected that the bottom portion of the pavement slabs would be more prone to cyclic wetting/drying conditions. With an increase in moisture content there is a concomitant expansion in the concrete. This situation would be expected to produce differential strains in the pavement slab as the top portion of the slab dries out following a precipitation event. The composite asphaltic concrete base material could also provide the same scenario.

## Sub-Grade Restraint

The Cuyahoga 176-11-S core showed a unique feature that may have played a role in the crack-free performance of this pavement. This feature is shown in Figure 31. Slag aggregate was used as the base material on this project, which was designed as a 310 T2 base. It is our understanding that the "T2" designation implies a change in gradation of the Standard 310 base to achieve a better drainage.

As shown in Figure 31 the slag aggregate base has solidified and a thin layer of the solidified base is bonded to the pavement concrete. The solidification of the slag base is not unexpected as fine particles of the slag can react with water to provide cementitious hydrate binding phases similar to those in portland cement. In effect, the base becomes a weak substrate concrete that is bonded to the pavement concrete.

**Figure 31. Lapped surface view of Core CUY-176-11-S, which was taken at the mid-point of a pavement slab on this project. This project did not show any full depth mid-slab cracking. There are two shallow vertical cracks in the top portion of the core, which have been highlighted with a black marking pen. The 310 T2 slag aggregate base material (B) is adhered to the pavement concrete.**

If the condition shown in Figure 31 prevailed throughout the project it is expected that any movement in the pavement slab (expansions or contractions from any source) would be restrained. With a global restraint such as this in place, there would be a unique opportunity for stress relief to occur through tensile creep of the concrete. The net effect could be that which is experienced with continuously reinforced concrete pavements (CCRP) in which numerous tight and narrowly spaced transverse cracks occur rather than a few wide cracks. As seen in Figure 31, there are two shallow cracks within 3 in. (8 cm) of each other. The 310 base material for the crack free Cuyahoga-322 project is also prepared with slag aggregate.

## Limestone Coarse Aggregate

Of the twenty Research Study pavement concretes, eleven contain a carbonate coarse aggregate. All six of the mid-slab crack-free pavements contain a carbonate coarse aggregate (limestone or dolomitic limestone). There is a basis for claiming that concretes containing carbonate aggregates should be less prone to mid-slab cracking than siliceous aggregate concretes. This basis is the relative thermal expansion of concretes containing these two aggregate sources, which are shown in the tabulated data below (from Mindess, et. al. 2003).

| Type of Aggregate in the Concrete | Coefficient of Thermal Expansion, x $10^{-6}$ in/in/F | Coefficient of Thermal Expansion, x $10^{-6}$ cm/cm/C |
|---|---|---|
| **Limestone** | 3.3 | 6 |
| **Dolomitic Limestone** | 4 to 5.5 | 7 to 10 |
| **Quartzite** | 6.1 to 7.2 | 11-13 |
| **Sandstone** | 6.1 to 6.7 | 11 to 12 |

The thermal expansion of concrete containing a siliceous coarse aggregate could in the most extreme case have a thermal expansion/contraction that is double that of an otherwise comparable concrete containing a carbonate coarse aggregate.

The finding that all six of the mid-slab crack-free pavement concretes contain a carbonate coarse aggregate strongly suggests that thermal strains may be the dominant material variable influencing the formation of mid-slab cracks in ODOT's PCC pavements.

## Control Joint Design and Function

I have examined numerous concrete samples from slab-on-grade commercial floor slabs that have experienced unacceptable random cracking. A common cause of the cracking in these applications is issues resulting in a failure of the joints to function as intended, which include (1) a failure to install the joints in a timely manner, and (2) a failure to saw-cut the joints to the proper depth. A related issue is improper spacing of the control joints.

Steel load-transfer dowels have been used in the control joints in ODOT PCC pavements for many years. The proper functioning of a doweled joint requires that the dowel bars be aligned in a parallel plane in both the horizontal and vertical elevations (i.e., in plan and section views). The term "proper functioning" as used here means that the pavement slabs are free to move longitudinally in unrestricted fashion (i.e., as if the dowels weren't there). It is reasonable to assume that any misalignment of control joint dowels will restrict free longitudinal movement. The greater the number of misaligned dowels and the greater the degree of misalignment the more pronounced the restriction in longitudinal movement will be.

It is reasonable to assume that perfect alignment of the dowels in PCC pavement control joints can never be realized in practice. It is my opinion that it is highly likely that dowel bar misalignment has a major influence on the mid-slab cracking problem. It also stands to reason that a greater flexibility of the dowels (relative to the 1 ¼ in. bars currently in use) could better accommodate misalignments. The experience with the Gallia-7 pavement makes a strong case for this point of view. The dowels used on the Gallia-7 pavement are smooth, cylindrical, ¾ in. diameter bars. Despite the fact that the control joint spacing on this 8 in. (20 cm) thick pavement is 40 ft (12 m), there are long stretches on this pavement (ca. ¼ mile) where the original joints are still in place, and not all of the slabs show transverse cracking.

Without question the performance of the control joints on the Gallia-7 pavement is extraordinary. The lesson here is that dowels bars that are more easily "bent" can better accommodate bar misalignments relative to the larger diameter, stiffer steel dowels in use today. It is difficult to ignore the conclusion that the use of smaller diameter dowels is a superior joint design that should be considered for future construction; at least for lower traffic volume pavements. For high traffic pavements requiring the use of larger bars, the use of a "softer" steel alloy (i.e., more malleable) could be considered. This reasoning also leads to speculation that low elastic modulus composite dowel bars might also provide a more forgiving feature as regards the effect of dowel bar misalignment on joint performance.

## OVERVIEW SUMMARY AND CONCLUSIONS

Twenty Ohio Department of Transportation (ODOT) portland cement concrete (PCC) pavements were selected for evaluation in the present Research Study {State Job No. 134280(0)}. The pavements, twelve to sixty three years in age, were selected on the basis of their demonstrated satisfactory performance in service. Ten of the concretes were placed within an "Excellent Performance" category and ten were placed within an "Average Performance" category. The primary objective of the study is to identify the material, design, and construction factors that have contributed to the good performance of these pavements in service throughout the state. The focus of the work reported here is on the material properties of the portland cement concretes, although pavement design factors, construction factors, and environmental factors are also considered and have been given equal weight in the study. The intention of the study is to learn what has provided the satisfactory performance in the selected pavements that can be applied to the planning and conduct of future ODOT PCC pavement projects.

### Pavement Rating Criteria

After all of the data were in and analyzed it became clear that the line of distinction between the ten concretes in the "Excellent Performance" category and the ten concretes in the "Average Performance" category is blurred. This outcome is most likely due to the fact that all twenty of these concretes have actually performed satisfactorily in service. On the basis of the properties and microstructural features that were measured and/or examined in the present study, there is no single property or variable that clearly stands out as explaining the difference between the Excellent and Average pavement performance ratings. So, for the purpose of further analyses of the data, all twenty of the Research Study concretes were figuratively placed within the category of "Satisfactory Performance".

Within the context of the "Satisfactory Performance" category, the data were examined from the point of view of identifying the factors that contributed to this outcome for all twenty of the Research Study pavements (relative to PCC pavement concretes that may have showed marginal or poor performance in past service). When this was done it became clear that for a given property category, substantial between-concrete differences for the concretes showing "Satisfactory Performance" could be tolerated.

Of the twenty PCC concrete pavements examined here, one (Gallia County-State Route 7) has been in service for 63 years (constructed in 1946), and one (Athens County-US Route 33) has been in service for 51 years (constructed in 1958). Of the remaining 18 projects, most (15) were constructed during the period 1990 through 1997 (12 to 19 years of service). On the basis of their longevity, it seemed reasonable to describe the Gallia-7 pavement and the Athens-33 pavement as showing exceptional performance, and attempt to identify, if possible, the factors contributing to this very high level of performance; which has been done.

## Cores Provided for the Study and Examination Procedures

Four inch diameter PCC pavement cores were provided to our laboratory by Ohio University workers for the present study. Two cores were provided from each of the twenty PCC pavement sites. One core was taken through a transverse control joint and a second core was taken through a mid-slab crack in those instances where this feature was present (fourteen of the twenty sites). The age of the Research Study pavements ranges from 63 years (constructed in 1946) to 12 years (constructed in 1997). The pavement projects are located in eleven Ohio counties, all of which are either in the eastern third or western third of the state. None of the selected pavements are within the central north-south corridor of the state. As discussed in our report, the nature of the bedrock geology in the state may be a factor regarding this bias.

For the present study no cores were taken from marginally or poorly performing PCC pavements. However, it is our understanding that the most significant durability and maintenance issues involving ODOT PCC pavements have historically been associated with (1) deterioration (cracking/spalling) of the transverse control joints, (2) mid-slab cracking, and (3) longitudinal cracking. The joint deterioration and mid-slab crack issues have been most dominant. This situation prompted the decision to obtain cores from these two locations for the Research Study. The examination procedures used for the study are presented in the section of the present report entitled “Core Examination Procedures”, and include petrographic examinations and physical property measurements (density, compressive strength, tensile strength, modulus of elasticity, and coefficient of thermal expansion).

## Material Factors Influencing Pavement Performance

The next five sections of the report examine the influence of a number of material factors of the concretes on what has been judged to be a satisfactory performance of these ODOT pavements in service. These factors include,

- The composition and quality of the cementitious phase
- The type and quality of the coarse aggregate phase
- The type and quality of the fine aggregate phase
- The parameters of the entrained air void system
- Compressive strength, tensile strength, and modulus of elasticity (these property measurements were made at and by Ohio University)

For most of these pavement projects the concrete used is ODOT's Class C concrete. Without exception, the twenty ODOT portland cement-based pavement concretes share the following features, which have led to their satisfactory performance.

- A good quality cementitious phase attributed in large part to a satisfactorily low water to cementitious material ratio (range of 0.42 to 0.48 for the twenty concretes). Cementitious materials include (1) straight portland cement in eleven of the concretes, and (2) a binary blend of portland cement and fly ash in nine of the concretes.
- There is evidence to support an opinion that the use of a portland cement/fly ash blend provides equivalent pavement performance relative to a straight portland cement mix, and possibly can provide improved performance.
- A good quality coarse aggregate that has shown good durability and resistance to the effects of freeze/thaw cycling. The coarse aggregate is a carbonate rock in eleven of the concretes and a siliceous rock in nine of the concretes. Gradations range from ASTM C 33 No. 8 ($^3/_8$ in. maximum size) to No. 467 (2 in. maximum size).
- A good quality fine aggregate in the form of natural sands that have chemically resistant and hard quartz particles as the dominant mineral phase.
- All of the concretes are air-entrained. Although some of the air void parameters in some of the concretes do not strictly meet current minimum standards, all of the air void systems have provided adequate protection to the cementitious phase. Exceptions here are instances where a majority of the air voids have been filled with secondary deposits.

- The low w/cm and air entrainment of the concretes are necessary, but not sufficient conditions for providing a satisfactory level of performance for the pavements. Equally important is the requirement for a coarse aggregate phase that has a high level of durability and good resistance to the effects of freezing and thawing. All twenty of the Research Study concretes share these features.

## Freeze/Thaw Resistance

The dominant role of the freeze/thaw distress mechanism is confirmed by the fact that the primary pavement maintenance problems for ODOT are those that involve the concrete at and near (1) the transverse control joints, and (2) mid-slab cracks and other transverse cracks. At these locations surface water can gain access to the full depth of the pavement slabs by percolating through the full depth joint and crack fracture planes. This scenario results in repeated exposures of the concrete adjacent to the cracks to higher levels of moisture saturation than the concrete away from the joints and cracks. Even in pavements that show early joint deterioration the concrete in the portions of the slab away from the joint most often remains in satisfactory condition. These findings support an opinion that it is the water entering the pavement from the top, rather than water entering from the underlying base at the bottom that is the primary culprit promoting concrete distress in the joint and transverse crack regions. This opinion is strengthened by observations made in the 1991 PCA study for ODOT (Stark, 1991) in which it was shown that the use of a polyethylene vapor barrier in contact with the bottom of pavement slabs actually resulted in a slightly greater incidence of D-Cracking compared with companion sections without vapor barriers.

It is the repeated cycles of freezing and thawing when the concrete in the joint and crack regions is critically saturated that can lead to cracking and spalling distress. In those instances where the concrete has a low w/cm, is air-entrained, and has a durable coarse aggregate the cracking/spalling can take many years to become a maintenance issue. That has been the case for the twenty concretes examined here, where the age ranges from 13 to 63 years. As revealed in the present study, when freeze/thaw-related damage does occur in concrete in the joint and crack regions, it takes two forms and is progressive.

- In one form of the distress <u>cracks develop in the concrete adjacent to and parallel to the primary joint or mid-slab crack.</u> In the concretes examined here, this type of cracking is attributed to the filling of the entrained air voids with secondary deposits due to the repeated moisture cycling. The infilling of the air voids obviates their intended function of protecting the cementitious phase from the effects of the freeze/thaw cycling. The cracks in this type of distress are closely spaced, are parallel to the primary crack fracture plane, and can cover the full thickness of the pavement slab. This type of distress is progressive and as evidenced in the present study can affect concrete up to one half inch or so on either side of the primary crack. In advanced stages of this type of distress, the locally disintegrated concrete may be in rubble form and incapable of sustaining a live load from traffic. As shown in some examples in the present study, this is one mechanism that can account for the spalling that is common along joint and transverse crack lines.

- In the second form of freeze/thaw-related distress revealed in our study, the <u>cracking and subsequent disintegration of the concrete originates in the concrete in the bottom of the pavement slab.</u> In those instances where the base material does not provide for drainage, the water saturation level in the base and in the concrete will be highest in the region under the primary joint crack or transverse crack. The moisture distribution within the base and the concrete that the base is in contact with has the shape of the bell curve, with the highest moisture content directly under the crack. When the saturated concrete experiences freezing and thawing cycles, damage can occur either (1) within the cementitious phase in which the air entrainment has been compromised, or (2) in coarse aggregate particles that are susceptible in some degree to freeze/thaw damage. As shown in several instances in the present study, the resultant expression of damage from this distress source is a cone-shaped region of cracked and disintegrated concrete lying directly under the joint crack. In the concretes studied here it is concluded that the primary damage of this type has been due to a compromised air void system. No sedimentary rock type is completely immune to this type of damage, but in the concretes examined here it is concluded that the aggregate particles are not the primary source of the limited distress that has occurred.

It is clear from these findings that satisfactory levels of performance can be obtained in ODOT's PCC pavements if the construction can be made to assure the attainment in the concrete of (1) a good quality cementitious phase with a low w/cm, (2) a satisfactory entrained air void system, and (3) a durable coarse aggregate source that is resistant to the effects of freezing and thawing while in a state of critical moisture saturation. The first two parameters listed here (w/cm and entrained air) can be successfully assured with the imposition of good construction supervision in the field. The selection and availability of a suitably durable coarse aggregate is an equally important factor.

Once these three material parameters are adequately addressed, the next steps to be taken to achieve even higher levels of durability and maintenance free performance will be those that <u>minimize or eliminate the ingress of surface moisture down through the joint crack and any transverse cracks</u> in the pavement slabs. With regard to limiting moisture ingress through the control joint cracks, good insights were learned from the examination of the Gallia-7 pavement that has been in service since 1946 (63 years). With regard to limiting moisture ingress through the transverse cracks, the most direct solution is to eliminate the transverse cracks. Insights into this matter were also gained in the present study.

## Unique Features of the Gallia County Pavement (SR -7)

The PCC pavement comprising a portion of State Route 7 in Gallia County was constructed in 1946. This 63 year old pavement is currently characterized as being "in very good condition for its age". Many of the original control joints are still in place on this pavement and there are stretches of the roadway where there is no transverse cracking. Surprisingly, many of the material and design variables that have been shown to be important for satisfactory performance of the other nineteen Research Study pavements are not common to the Gallia-7 pavement. An examination of these differences provides important insights into the factors that control the proper functioning of the control joints and which can minimize unwanted transverse cracking. Relative to the other pavements in the study and relative to current ODOT practice the unique features of the Gallia-7 pavement are discussed below.

- Control joint spacing is 40 ft. (12 m). Current ODOT joint spacing is 15 ft. (4.6 m). Despite the large joint spacing a number of the original control joints are still in place and transverse cracking is minor in portions of the project. It can not be denied that the control joints on the Gallia-7 pavement have functioned properly to produce this desired result for these unusually long slabs. Unique features contributing to this desired outcome include (1) a smaller diameter dowel relative to current practice, and (2) good aggregate interlock provided by a good quality, 2 in. (5 cm) maximum size coarse aggregate.

- Pavement thickness is 8 in. (20 cm). The majority of the Research Study pavements are 10 to 12 in. (25 to 30 cm). Current ODOT practice calls for 12 in. (20 cm) thick slabs. Is frictional resistance to movement lower in thinner slabs?

- Control joint dowels are smooth steel bars that are ¾ in. (19 mm) in diameter, 15 in.(38 mm) long, on 15 in. (38 cm) centers. Dowels in use today are 1 ¼ in. in. diameter on 12 in. (31 cm) centers. It can be reasoned that any misalignment of the control joint dowels, (particularly lateral misalignment) can restrict the movement of the joint, thus making the formation of mid-slab or other transverse between-joint cracks more likely. The use of ¾ in. (19 mm) diameter dowels have provided exceptional joint performance with a joint spacing of 40 ft. (12 m) in the Gallia-7 pavement. It can be reasoned that the smaller diameter (and more flexible) dowels were better able to accommodate misalignments without adversely affecting the movement of the joint. Other means of providing more flexibility in the dowels are discussed in the report.

- The control joints were formed and subsequently sealed with a sanded hot-mix bituminous sealant (meeting the requirements of Section M-5.6 F-1 of the general specifications). The sealant for a majority of the Research Study pavements is pre-formed rubber. The original joint sealing material is still in place in the Gallia-7 joint core examined here and retains its elastomeric properties. The ability of this material to truly seal the control joint crack has been demonstrated.

- The concrete is air-entrained, but the total air content is only 3.4 percent. The point is made that the air content can be below the current target minimum value of 4 percent, without compromising the effectiveness and intended function of the air void system. The results of previous work for ODOT that goes into more detail regarding this issue is cited in the present report (Lankard, 2006).

- The maximum size of the coarse aggregate is 2 in. (5 cm). The siliceous gravel coarse aggregate has shown exceptional durability and freeze/thaw resistance. The importance of the freeze/thaw resistance of the coarse aggregate phase as it affects the overall durability of the pavement concrete is discussed in detail in the present report.

- The total aggregate content of the GAL-7 concrete is 76 percent. The target total aggregate content for the ODOT Class C concrete is ca. 65 percent. The used of larger sized coarse aggregates permits a reduction in the cementitious material content of the concrete. The benefits to be gained from of the use of larger size coarse aggregate in ODOT pavement concretes are discussed in detail in the present report and include (1) improved volume stability, (2) reduced drying shrinkage and curling strain potential, and (3) improved opportunities for the aggregate interlock mechanism to function along joint and crack lines.

- The estimated cement content of the GAL-7 concrete is 430 lb/yd$^3$ (255 kg/m$^3$) The target cement content for the standard ODOT Class C concrete is 600 lb/yd$^3$ (356 kg/m$^3$). The potential benefits of a reduced cement content on pavement concrete performance are discussed in the report.

## Other Material and Design Factors Influencing Mid-Slab Cracking

Beyond the unique insights provided by the Gallia-7 pavement, the overall findings of the present study have provided evidence of other factors that can affect the onset and severity of mid-slab cracking, which include (1) the coefficient of thermal expansion of the pavement concrete, (2) drainage issues connected with the base material, and (3) restraint associated with the base material.

- All six of the mid-slab crack-free pavements in the Research Study contain a carbonate coarse aggregate (limestone or dolomitic limestone). The coefficient of thermal expansion of concretes containing siliceous coarse aggregate can be up to double that of carbonate aggregate concretes. The finding that all six of the mid-slab crack-free pavement concretes contain a carbonate coarse aggregate strongly suggests that thermal strains may play a dominant role in the formation of mid-slab cracks (and other transverse cracks) in ODOT's PCC pavements.

- Six of the twenty Research Study pavements had no mid-slab cracking. A free-draining base system was used in three of these projects (GRE-35, ALL-30, and LOG-33. None of the other fourteen pavement projects in which mid-slab cracking did occur used a free-draining base, (although the 310 T2 and 304 base materials are characterized as "drainable, but not free-draining). The reason that free-draining base material had a favorable influence on the elimination of mid-slab cracking in the three cited cases is not completely understood, although the effect of this factor on strains associated with moisture cycling within the concrete may be involved.

- Slag aggregate was used as the base material on one of the pavement projects where mid-slab cracking did not occur. The fine particles in the slag reacted with water in a manner similar to portland cement to form a binder, resulting in cohesion within the slag base material. In effect this base material is a weak concrete, and it bonded to the pavement concrete. The possible beneficial effect of this restrained movement in the bonded pavement slabs as related to the elimination of transverse cracking on this project is discussed in the report.

## LESSONS LEARNED FROM THE RESEARCH STUDY

Lessons learned from the present study include insights regarding material and design factors that affect long-term PCC pavement performance. The concluding statements offered here highlight features of current practice that should be continued, as well as modifications that can be considered to provide improved long term performance. The modifications recommended for consideration are focused on steps that appear to have the potential to (1) better assure proper functioning of control joints and to (2) eliminate or minimize mid-slab cracking.

### Current ODOT Practice for PCC Pavement

Current material requirements that have been shown to provide good performance can continue to be implemented and enforced. They include,

- The target maximum water to cementitious material ratio (w/cm) of 0.50. The placement of the pavement concretes by machine, combined with diligent on-the-job supervision assures that the pavement concretes are placed at a w/cm below 0.50.

- The continued use of air entrainment. As discussed in the present report consideration can be given to a reduction in the target maximum allowable air content (particularly when ASTM C 33 No. 8 aggregates are used).

- Continue to restrict the maximum size of coarse aggregate to ASTM C 33 No. 8 ($^3/_8$ in. maximum size) for those aggregate sources that have a suspect D-cracking record.

## Modifications in Current Practice to be Considered

The steps listed below are those that, based upon the results of the present study appear to offer opportunities for (1) assuring the proper functioning and reducing maintenance requirements of control joints and (2) minimizing or eliminating mid-slab and other transverse cracks.

- Encourage, or even require the use of supplementary cementitious materials in the concretes. Nine of the twenty Research Study concretes have a binary blend of portland cement and fly ash as the cementitious material. Such use has a favorable environmental and economic benefit, and may result in improved concrete durability.

- Reduce the cement content of pavement concretes concomitant with an increase in the maximum size of the coarse aggregate. This step is expected to improve the volume stability of the concrete, reduce drying shrinkage strain potential, and reduce curling strain potential, leading to reduced frequency of transverse cracking associated with drying shrinkage.

- Increase the maximum size of coarse aggregate to 2 in. (5 cm) or even higher. In addition to improving volume stability, this step is expected to improve the aggregate interlock function, resulting in reduced faulting of cracks in unreinforced PCC pavements. The aggregate sources selected for these concretes must have a good service record, with low proneness to D-Cracking.

- Consider the exclusive used of carbonate coarse aggregates as a means of reducing the chance of mid-slab cracking. All six of the Research Study pavements that have no mid-slab cracking issues have limestone coarse aggregates. The coefficient of thermal expansion of carbonate aggregate concretes can be up to half of that of siliceous aggregate concretes.

- Consider a return to the use of sanded hot mix bituminous joint sealants. The type of hot mix sealant used in the Gallia-7 pavement in 1946 is still in place today and retains its elastomeric properties. There is evidence presented in the present report that it is primarily water entering the joints from the top of the slab that is most troublesome.

- Consider the use of load-transfer dowels that are more flexible than the 1 ¼ in. steel bars in use today. This step presumes that dowel misalignments are a major cause of the failure of control joints to function as intended. Providing some "give" in the dowels could mitigate this problem. In the case of the Gallia-7 pavement this was apparently achieved through the use of ¾ in. diameter dowels. The use of composite material dowels (fiber glass-reinforced polymers) could also be considered in this light.

- For the present, continue the practice of 15 ft. (4.6 m) control joint spacing for unreinforced PCC pavements. However, the results of the present study show that it is possible to produce PCC pavements with larger joint spacings that do not have a mid-slab cracking problem. Five of the six ODOT pavements in the present study with no mid-slab cracking have a joint spacing of 21 ft. (6.4 m). Some sections of the Gallia-7 pavement with a 40 ft.

(12 m) joint spacing are transverse crack free after 63 years. The Athens-33 pavement with a 60 ft. (18 m) joint spacing shows "minor transverse cracks about every other slab". With the potential economic benefits that fewer joints offer (initial construction and maintenance), future experimentation should still include the option of expanding the current 15 ft. limit.

- Three of the six Research Study pavements that show no mid-slab cracking have free-draining bases. None of the fourteen project pavements that had mid-slab cracking had a free draining base. Future thinking could look deeper into this aspect of base design as it affects the formation of transverse slab cracking.

It is hoped that the findings of the unique Research Study conducted here can be factored into future plans for exploring changes that can be made in concrete material selection and proportioning, and in pavement design that will lead to improved long-term durability and performance in ODOT PCC pavements.

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# APPENDIX A

# TABLES A-1 THROUGH A-6

# HISTORICAL AND SITE DATA FOR PCC CORES

# LML PROJECT NO. 5536
# STATE JOB NO. 134280(0)

Table A-1. HISTORICAL AND SITE DATA FOR OHIO UNIVERSITY PAVEMENT CORES - (LML PROJECT 5536)

| LML Core Number | Ohio University Core I.D. Number | Date Core Provided | Pavement Construction Date | County | Highway Route Number | Mile Marker | Lane Direction | Pavement Performance Ranking |
|---|---|---|---|---|---|---|---|---|
| 1 | GAL-7 (CR) | 05/29/09 | 1946 | Gallia | State Route 7 | 8 | Northbound | Excellent |
| 2 | GAL-7 (JT) | 05/29/09 | 1946 | Gallia | State Route 7 | 8 | Northbound | Excellent |
| 3 | ATH-682 (CR) | 5/29/09 | 1976 | Athens | State Route 682 | 1 | Northbound | Average |
| 4 | ATH-682 (JT) | 5/29/09 | 1976 | Athens | State Route 682 | 1 | Northbound | Average |
| 5 | ATH-33 (CR) | 6/09/09 | 1958 | Athens | US Route 33 | 13 | Eastbound | Average |
| 6 | ATH-33 (JT) | 6/09/09 | 1958 | Athens | US Route 33 | 13 | Eastbound | Average |
| 7 | GRE-35 (CR) | 6/30/09 | 1997 | Green | State Route 35 | 19 | Westbound | Excellent |
| 8 | GRE-35 (JT)) | 6/30/09 | 1997 | Green | State Route 35 | 19 | Westbound | Excellent |

Note: Core diameter is 4 in. unless otherwise noted. “CR” = core taken through a crack. “JT” = core taken through a joint.

Table A-2. HISTORICAL AND SITE DATA FOR OHIO UNIVERSITY PAVEMENT CORES - (LML PROJECT 5536)

| LML Core Number | Ohio University Core I.D. Number | Date Core Provided | Pavement Construction Date | County | Highway Route | Mile Marker | Lane Direction | Pavement Performance Ranking |
|---|---|---|---|---|---|---|---|---|
| 9 | HAM-126 (CR) | 7/07/09 | 1990 | Hamilton | State Route 126 | 12 | Eastbound | Excellent |
| 10 | HAM-126 (JT) | 7/07/09 | 1990 | Hamilton | State Route 126 | 12 | Eastbound | Excellent |
| 11 | ALL-30 (CR) | 7/31/09 | 1997 | Allen | US Route 30 | 22 | Eastbound | Excellent |
| 12 | ALL-30 (CR) | 7/31/09 | 1997 | Allen | US Route 30 | 22 | Eastbound | Excellent |
| 13 | JEF-22 (CR) | 7/31/09 | 1990 | Jefferson | US Route 22 | 15 | Eastbound | Average |
| 14 | JEF-22 (JT) | 7/31/09 | 1990 | Jefferson | US Route 22 | 15 | Eastbound | Average |
| 15 | JEF-7 (CR) | 7/31/09 | 1990 | Jefferson | State Route 7 | 19 | Southbound | Excellent |
| 16 | JEF-7 (JT) | 7/31/09 | 1990 | Jefferson | State Route 7 | 19 | Southbound | Excellent |

Note: Core diameter is 4 in. unless otherwise noted. “CR” = core taken through a crack. “JT” = core taken through a joint.

**Table A-3. HISTORICAL AND SITE DATA FOR OHIO UNIVERSITY PAVEMENT CORES - (LML PROJECT 5536)**

| LML Core Number | Ohio University Core I.D. Number | Date Core Provided | Pavement Construction Date | County | Highway Route Number | Mile Marker | Lane Direction | Pavement Performance Ranking |
|---|---|---|---|---|---|---|---|---|
| 17 | TUS-39 (CR) | 7/31/09 | 1990 | Tuscarawas | State Route 39 | 4 | Eastbound | Average |
| 18 | TUS-39 (JT ) | 7/31/09 | 1990 | Tuscarawas | State Route 39 | 4 | Eastbound | Average |
| 19 | CUY-82 (CR) | 8/10/09 | 1994 | Cuyahoga | State Route 82 | 3 | Eastbound | Excellent |
| 20 | CUY-82 (JT) | 8/10/09 | 1994 | Cuyahoga | State Route 82 | 3 | Eastbound | Excellent |
| 21 | CUY-176 (CR) | 8/10/09 | 1994 | Cuyahoga | State Route 176 | 10 | Southbound | Average |
| 22 | CUY-176 (JT) | 8/10/09 | 1994 | Cuyahoga | State Route 176 | 10 | Southbound | Average |
| 23 | CUY-176 (CR) | 8/10/09 | 1996 | Cuyahoga | State Route 176 | 11 | Southbound | Average |
| 24 | CUY-176 (JT) | 8/10/09 | 1996 | Cuyahoga | State Route 176 | 11 | Southbound | Average |

Note: Core diameter is 4 in. unless otherwise noted. "CR" = core taken through a crack. "JT" = core taken through a joint.

Table A-4. HISTORICAL AND SITE DATA FOR OHIO UNIVERSITY PAVEMENT CORES - (LML PROJECT 5536)

| LML Core Number | Ohio University Core I.D. Number | Date Core Provided | Pavement Construction Date | County | Highway Route Number | Mile Marker | Lane Direction | Pavement Performance Ranking |
|---|---|---|---|---|---|---|---|---|
| 25 | CUY-176 (CR) | 8/10/09 | 1996 | Cuyahoga | State Route 176 | 12 | Southbound | Average |
| 26 | CUY-176 (JT) | 8/10/09 | 1996 | Cuyahoga | State Route 176 | 12 | Southbound | Average |
| 27 | CUY-322 (LM1) | 8/17/19 | 1993 | Cuyahoga | State Route 322 | 10 | Eastbound | Excellent |
| 28 | CUY-322 (LM2) | 8/17/09 | 1993 | Cuyahoga | State Route 322 | 10 | Eastbound | Excellent |
| 29 | CUY-322 (LM3) | 8/17/09 | 1993 | Cuyahoga | State Route 322 | 10 | Eastbound | Excellent |
| 30 | CUY-322 (JT) | 8/17/09 | 1993 | Cuyahoga | State Route 322 | 10 | Eastbound | Excellent |
| 31 | CUY-252 (JT) | 8/17/19 | 1984 | Cuyahoga | State Route 252 | 4 | Northbound | Average |
| 32 | CUY-252 (CR) | 8/17/19 | 1984 | Cuyahoga | State Route 252 | 4 | Northbound | Average |

Note: Core diameter is 4 in. unless otherwise noted. “CR” = core taken through a crack. “JT” = core taken through a joint.

Table A-5. HISTORICAL AND SITE DATA FOR OHIO UNIVERSITY PAVEMENT CORES - (LML PROJECT 5536)

| LML Core Number | Ohio University Core I.D. Number | Date Core Provided | Pavement Construction Date | County | Highway Route Number | Mile Marker | Lane Direction | Pavement Performance Ranking |
|---|---|---|---|---|---|---|---|---|
| 33 | SUM-76-15-W (LM) | 8/17/09 | 1992 | Summit | Interstate 76 | 15 | Westbound | Excellent |
| 34 | SUM-76-15-W (JT) | 8/17/09 | 1992 | Summit | Interstate 76 | 15 | Westbound | Excellent |
| 35 | SUM-76-15-E (LM1) | 8/17/19 | 1992 | Summit | Interstate 76 | 15 | Eastbound | Average |
| 36 | SUM-76-15-E (LM2) | 8/17/19 | 1992 | Summit | Interstate 76 | 15 | Eastbound | Average |
| 37 | SUM-76 15-E (CR) | 8/17/09 | 1992 | Summit | Interstate 76 | 15 | Eastbound | Average |
| 38 | SUM-76 15-E (CR) | 8/17/09 | 1992 | Summit | Interstate 76 | 15 | Eastbound | Average |
| 39 | MOT-35 (CR) | 8/24/09 | 1988 | Montgomery | US Route 35 | 14 | Westbound | Excellent |
| 40 | MOT-35 (JT ) | 8/24/09 | 1988 | Montgomery | US Route 35 | 14 | Westbound | Excellent |

Note: Core diameter is 4 in. unless otherwise noted. “CR” = core taken through a crack. “JT” = core taken through a joint.

**Table A-6. HISTORICAL AND SITE DATA FOR OHIO UNIVERSITY PAVEMENT CORES - (LML PROJECT 5536)**

| LML Core Number | Ohio University Core I.D. Number | Date Core Provided | Pavement Construction Date | County | Highway Route Number | Mile Marker | Lane Direction | Pavement Performance Ranking |
|---|---|---|---|---|---|---|---|---|
| 41 | MOT-202 (CR) | 8/24/09 | 1991 | Montgomery | State Rte 202 | 3 | Northbound | Excellent |
| 42 | MOT-202 (JT) | 8/24/09 | 1991 | Montgomery | State Rte 202 | 3 | Northbound | Excellent |
| 43 | LOG-33 (JT) | 8/31/09 | 1994 | Logan | US Rte 33 | 24 | Westbound | Average |
| 44 | VAN-30 (Base) | 8/31/09 | ? | Van Wert | US Rte 30 | 18 | Eastbound | ? |

Note: Core diameter is 4 in. unless otherwise noted. “CR” = core taken through a crack. “JT” = core taken through a joint.

# APPENDIX B

# TABLES B-1 THROUGH B-4

## CEMENTITIOUS MATERIAL PROPERTY AND COMPOSITIONAL DATA

**LML PROJECT NO. 5536**
**STATE JOB NO. 134280(0)**

**Table B-1. Cementitious Constituents of Average and Excellent Pavement Projects (5536)**

| Pavement Performance Ranking | Cementitious Constituents, Percent of Total Concretes in Each Category | | |
|---|---|---|---|
| | Straight Portland Cement | Portland Cement & Fly Ash | Portland Cement & Slag Cement |
| **Excellent (10)** | 40 | 60 | 0 |
| **Average (10)** | 70 | 30 | 0 |



**EXCELLENT**

**GAL-7 (CR) = PC**
**GRE-35 (CR) =PC & FA**
**HAM-126 (CR) =PC & FA**
**ALL-30 (CR) = PC & FA**
**JEF-7 (JT) = PC**
**CUY-82 (CR) = PC & FA**
**CUY-322 (CR) = PC**
**SUM-76-15-W (CR) = PC & FA**
**MOT-35 (CR) = PC & FA**
**MOT-202 (CR) = PC**

**AVERAGE**

**ATH-682 (CR) = PC**
**ATH-33 (CR) = PC**
**JEF-22 (CR) = PC**
**TUS-39 (CR) = PC**
**CUY-176-10-S = PC & FA**
**CUY-176-11-S = PC**
**CUY-176-12-S = PC**
**CUY-252 (CR) = PC**
**SUM-76-15-E (CR) = PC & FA**
**LOG-33(JT) = PC &FA**

**Table B-2. Water to Cementitious Material Ratio (w/cm) for Average and Excellent Pavement Projects (5536)**

| Pavement Performance Ranking | Average Value of Water to Cementitious Material Ratio (w/cm) of the Concretes | Range of Values of Water to Cementitious Material Ratio (w/cm) of the Concretes |
|---|---|---|
| **Excellent (10)** | 0.46 | 0.42 to 0.48 |
| **Average (10)** | 0.44 | 0.42 to 0.45 |



**EXCELLENT**

**GAL-7 (CR) = 0.48**
**GRE-35 (CR) =0.48**
**HAM-126 (CR) = 0.45**
**ALL-30 (CR) = 0.42**
**JEF-7 (JT) = 0.46**
**CUY-82 (CR) = 0.48**
**CUY-322 (CR) = 0.46**
**SUM-76-15-W (CR) = 0.44**
**MOT-35 (CR) = 0.45**
**MOT-202 (CR) = 0.47**

**AVG = 4.59/10 = 0.459**

**AVERAGE**

**ATH-682 (CR) = 0.45**
**ATH-33 (CR) = 0.45**
**JEF-22 (CR) = 0.42**
**TUS-39 (CR) = 0.43**
**CUY-176-10-S = 0.44**
**CUY-176-11-S = 0.43**
**CUY-176-12-S = 0.43**
**CUY-252 (CR) = 0.45**
**SUM-76-15-E (CR) = 0.44**
**LOG-33 (JT) = 0.46**

**AVG = 4.40/10 = 0.44**

Table B-3. Cement Paste Content of Concretes for Average and Excellent Pavement Projects (5536)

| Pavement Performance Ranking | Average Value of Cement Paste Content for the Concretes, % | Range of Values of Cement Paste Content for the Concretes, % |
|---|---|---|
| **Excellent (10)** | 26.8 | 20.3 to 29.5 |
| **Average (10)** | 28.1 | 22.0 to 31.0 |



**EXCELLENT**

**GAL-7 (CR) = 20.3**
**GRE-35 (CR) =26.8**
**HAM-126 (CR) =25.9**
**ALL-30 (CR) = 28.1**
**JEF-7 (JT) = 26.4**
**CUY-82 (CR) = 26.9**
**CUY-322 (CR) = 29.1**
**SUM-76-15-W (CR) = 29.5**
**MOT-35 (CR) = 28.1**
**MOT-202 (CR) = 26.7**

**AVG =267.8/10 = 26.8**

**AVERAGE**

**ATH-682 (CR) = 27.1**
**ATH-33 (CR) = 30.3**
**JEF-22 (CR) = 27.9**
**TUS-39 (CR) = 22.0**
**CUY-176-10-S = 31.0**
**CUY-176-11-S = 28.3**
**CUY-176-12-S = 27.6**
**CUY-252 (CR) = 29.4**
**SUM-76-15-E (CR) = 27.7**
**LOG-33 (JT) = 30.3**

**AVG = 281.6/10 = 28.1**

**Table B-4. Mix Design ODOT Class C Concrete (Limestone Aggregate) Based on a Water-Cement Ratio of 0.45**

| Concrete Constituent | lb of Constituent per Cubic Yard of Concrete | Specific Gravity (Density) of Constituent, $lb/ft^3$ | Cubic feet of Constituent per Cubic Yard of Concrete |
|---|---|---|---|
| Cement | 600 | 196.6 | 3.05 |
| Fine Aggregate [(a)] | 1285 | 165.4 | 7.77 |
| Coarse Aggregate [(b)] | 1630 | 167.2 | 9.75 |
| Water (0.45) | 270 | 62.4 | 4.33 |
| Entrained Air© | (6 %) | - | 1.62 |
| Totals | 3785 | - | 26.52 |

(a) Assumes a fine aggregate specific gravity of 2.65

(b) Assumes a fine aggregate specific gravity of 2.68

(c) The target air content is 6 % .

(d) Theoretical Unit Weight = 3785/26.52 = 142.7 $lb/ft^3$ .

Theoretical Cement Paste Content = 7.38/26.52 = 27.8 %.

Water to Cementitious Material Ratio (w/cm) = 270/600 = 0.45

# APPENDIX C

# TABLES C-1 THROUGH C-10

# COARSEAGGREGATE PROPERTY AND PERFORMANCE DATA

# LML PROJECT NO. 5536
# STATE JOB NO. 134280(0)

**Table C-1. Coarse Aggregate Type of Average and Excellent Pavement Projects (LML Project 5536)**

| Pavement Performance Ranking | Type of Coarse Aggregate Percent of Each Concrete Category Having the Indicated Aggregate | | | | |
|---|---|---|---|---|---|
| | 3/8 in. Gravel | 3/8 in. Crushed Limestone | ¾ or 1 in. Gravel | ¾ or 1 in. Crushed Limestone | ¾ or 1 in. Slag |
| **Excellent (10)** | 20 | 30 | 20 | 20 | 10 |
| **Average (10)** | 10 | 50 | 10 | 10 | 20 |

**EXCELLENT**

**GAL-7 (CR) = 2 in Gravel**
**GRE-35 (CR) =3/4 in. Crushed Limestone**
**HAM-126 (CR) =1 in. Gravel**
**ALL-30 (CR) = ¾ in. Crushed Limestone**
**JEF-7 (JT) = ¾ in. Slag**
**CUY-82 (CR) = 3/8 in. Crushed Limestone**
**CUY-322 (CR) = 3/8 in. Crushed Limestone**
**SUM-76-15-W (CR) = 3/8 in. Crushed Limestone**
**MOT-35 (CR) = 3/8 Gravel**
**MOT-202 (CR) = 3/8 Gravel**

**AVERAGE**

**ATH-682 (CR) = 3/8 in. Gravel**
**ATH-33 (CR) = 1 in. Crushed Limestone**
**JEF-22 (CR) = 1 in. Slag**
**TUS-39 (CR) = ¾ in. Gravel**
**CUY-176-10-S = 1 in. Slag**
**CUY-176-11-S = 3/8 in. Crushed Limestone**
**CUY-176-12-S = 3/8 in. Crushed Limestone**
**CUY-252 (CR) = 3/8 in. Crushed Limestone**
**SUM-76-15-E (CR) = 3/8 in. Crushed Limestone**
**LOG-33 (JT) = 3/8 Crushed Limestone**

**Table C-2. Rating Criteria for the Quality of the Bond Between the Cement Paste and the Coarse Aggregate Particles in the PCC Pavement Cores (LML Project 5536).**

- **"Excellent" = Virtually all of the bonds are tight and uninterrupted. There are few or no instances of elevated w/cm in the paste in contact with the aggregate particles.**
- **"Good" =The great majority (≥95%) of all of the bonds are tight and uninterrupted. There are few (≤ 5 %) or no instances of elevated w/cm in the paste in contact with the aggregate particles.**
- **"Fair" = A large majority (≥ 75%) of the bonds are tight and uninterrupted. A large majority (≥ 75%) of the particles show no instances of elevated w/cm in the paste in contact with the aggregate particles.**
- **"Low" = 50 % to 75 % of the bonds are tight and uninterrupted. 50 % to 75% of the particles exhibit some evidence of elevated w/cm in the paste in contact with the aggregate particles.**
- **"Poor" = Less than 50 % of the bonds are tight and uninterrupted. Greater than 75% of the particles exhibit some evidence of elevated w/cm in the paste in contact with the aggregate particles.**

**Table C-3. Rating Criteria for Identifying the Presence and Extent of Cement-Aggregate Reactions Involving the Coarse Aggregates in the PCC Pavement Cores (LML Project 5536).**

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- **"No" = No positive identification of ASR gel. No ASR-type cracking (or cracks of any type) in rimmed aggregate particles.**
- **"No*" = A few (one to three) instances of "positive" identification of ASR gel. Cracks in a few rimmed coarse aggregate particles. The cracks do not extend into the adjacent cement paste.**
- **"Very Limited" = A few instances of positive identification of ASR Gel and cracking in rimmed coarse aggregate particles that extends into the adjacent cement paste.**
- **"Common" = Instances of ASR gel, rimmed and cracked aggregate particles, and instances of cracks in rimmed particles that extend into the adjacent cement paste.**

**Table C-4. Rating Criteria for Identifying the Presence and Extent of Freeze/Thaw-Related Cracking involving the Coarse Aggregates in the PCC Pavement Cores (LML Project 5536).**

---

**None = None of the coarse aggregate particles show cracking that is due to F/T.**

**1% to 5% of the coarse aggregate particles show F/T-related cracking.**

**5 % to 10 % of the coarse aggregate particles show F/T-related cracking.**

**10 % to 20 % of the coarse aggregate particles show F/T-related cracking.**

**20 % or more of the coarse aggregate particles show F/T-related cracking.**

**Table C-5. Rating Criteria for Identifying the Overall Condition of the Coarse Aggregate Particles in the PCC Pavement Cores at the Time of Coring (LML Project 5536).**

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- **“Excellent” = There is no cracking in any of the particles that is related to service conditions. The particles look like the day that they went into the concrete.**
- **“Good” = 95 % of the particles show no cracking related to service conditions. There are a few instances (≤ 5 %) where the origin of cracks in the particles is in question.**
- **“Fair” = The origin of cracking in 5 % to 25 % of the particles is in question.**
- **“Low” = The origin of cracking in 25 % to 50 % of the particles is in question.**
- **“Poor” = The origin of cracking in over 50 % of the particles is in question.**

Table C-6. SUMMARY OF COARSE AGGREGATE DATA (LML PROJECT 5536)

| LML Core Number | Core Identification Number | Pavement Build Date | Pavement Ranking | Type of Coarse Aggregate | Nominal Maximum Size, inch | Quality of the Cement Paste Aggregate Bond | Evidence of Destructive Cement-Aggregate Reactions? | Evidence of F/T-Related Cracking in Aggregate Particles? | Overall Condition of the Coarse Aggregate Particles |
|---|---|---|---|---|---|---|---|---|---|
| 1 | GAL-7 (CR) | 1946 | Excellent | Siliceous Gravel | 2 | Good | No* | 1% - 5% | Good |
| 3 | ATH-682 (CR) | 1976 | Average | Siliceous Gravel | $^3/_8$ | Excellent | No* | 1% - 5% | Good |
| 5 | ATH-33 (CR) | 1958 | Average | Crushed Limestone | 1 | Fair | Very Limited | 10% - 20% | Fair |
| 7 | GRE-35 (CR) | 1997 | Excellent | Crushed Dolomitic Limestone | $^3/_4$ | Good | No* | None | Good |
| 9 | HAM-126 (CR) | 1990 | Excellent | Carbonate Gravel | 1 | Good | No | 1% - 5% | Good |

Table C-7. SUMMARY OF COARSE AGGREGATE DATA (LML PROJECT 5536)

| LML Core Number | Core ID Number | Pavement Build Date | Pavement Ranking | Type of Coarse Aggregate | Nominal Maximum Size, inch | Quality of the Cement Paste Aggregate Bond | Evidence of Destructive Cement-Aggregate Reactions? | Evidence of F/T-Related Cracking in Aggregate Particles? | Overall Condition of the Coarse Aggregate Particles |
|---|---|---|---|---|---|---|---|---|---|
| 11 | ALL-30 (CR) | 1997 | Excellent | Dolomitic Limestone | 3/4 | Fair to Low | No | None | Good |
| 13 | JEF-22 (CR) | 1990 | Average | Slag | 1 | Good | No | 1% -5% | Good |
| 16 | JEF-7 (JT) | 1990 | Excellent | Slag | 3/4 | Good | Very Limited | 1% -5% | Good |
| 17 | TUS-39 (CR) | 1990 | Average | Siliceous Gravel | 3/4 | Good | Very Limited | None | Good |
| 19 | CUY-82 (CR) | 1994 | Excellent | Dolomitic Limestone | 3/8 | Good | No | None | Excellent |

## Table C-8. COARSE AGGREGATE DATA (LML PROJECT 5536)

| LML Core Number | Core ID Number | Pavement Build Date | Pavement Ranking | Type of Coarse Aggregate | Nominal Maximum Size, inch | Quality of the Cement Paste Aggregate Bond | Evidence of Destructive Cement-Aggregate Reactions? | Evidence of F/T-Related Cracking in Aggregate Particles? | Overall Condition of the Coarse Aggregate Particles |
|---|---|---|---|---|---|---|---|---|---|
| 21 | CUY-176-10-S (CR) | 1994 | Average | Slag | 1 | Good | No* | None | Excellent |
| 23 | CUY-176-11-S (CR) | 1996 | Average | Crushed Limestone | 3/8 | Poor | No | None | Excellent |
| 25 | CUY-176-12-S (CR) | 1996 | Average | Crushed Dolomitic Limestone | 3/8 | Fair | No | 1% to 5% | Excellent |
| 29 | CUY-322 (CR) | 1993 | Excellent | Crushed Limestone | 3/8 | Poor | No* | None | Excellent |
| 32 | CUY-252 (CR) | 1984 | Average | Crushed Dolomitic Limestone | 3/8 | Low | No | 1% to 5% | Good |

## Table C-9. COARSE AGGREGATE DATA (LML PROJECT 5536)

| LML Core Number | Core ID Number | Pavement Build Date | Pavement Ranking | Type of Coarse Aggregate | Nominal Maximum Size, inch | Quality of the Cement Paste Aggregate Bond | Evidence of Destructive Cement-Aggregate Reactions? | Evidence of F/T-Related Cracking in Aggregate Particles? | Overall Condition of the Coarse Aggregate Particles |
|---|---|---|---|---|---|---|---|---|---|
| 33 | SUM-76-15-W (CR) | 1992 | Excellent | Crushed Dolomitic Limestone | 3/8 | Good | No | None | Excellent |
| 37 | SUM-76-15-E (CR) | 1992 | Average | Crushed Dolomitic Limestone | 3/8 | Fair | No | 1% to 5% | Good |
| 39 | MOT-35 (CR) | 1988 | Excellent | Siliceous Gravel | 3/8 | Fair | No | 1% to 5% | Good |
| 41 | MOT-202 (CR) | 1991 | Excellent | Siliceous Gravel | 3/8 | Fair | No* | 1% to 5% | Good |
| 43 | LOG-33 (JT) | 1994 | Average | Crushed Limestone | 3/8 | Fair | No | None | Excellent |

## Table C-10. COARSE AGGREGATE SOURCE DATA (LML PROJECT 5536)

| Material Suppliers for Concrete Pavements | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Co./Rt.** | **Project** | **General Contractor** | **Cement** | **Sand** | **Coarse Aggregate** | **Fly Ash** | **Comments** |
| ALL 30 | 746(97) | Miller Bros. | State Materials | National Napoleon | #57 Crushed National at Lima | Class F State Matls. | JMF |
| ATH 33 | 235(58) | Data not available | | | | | |
| ATH 682 | 625(76) | Great Lakes | Marquette | Blazer, Chauncey | #8 Gravel, Richards Apple Grove | | |
| CUY 82 | 438(94) | Great Lakes | Lafarge | Lafarge Shalersville | #8 Limestone National at Carey | | JMF |
| CUY 176 | 683(94) | Great Lakes | ESSROC, Bessemer | Lafarge Shalersville | Slag Lafarge, LTV, Cleveland | | |
| CUY 176 | 305(96) | Great Lakes | Lafarge | Lafarge Shalersville | #8 Limestone Lafarge at Marblehead | | JMF |
| CUY 252 | 901(84) | Great Lakes | Dundee | Std. Slag Shalersville | #8 Limestone Marblehead Stone | | |
| CUY 322 | 1019(93) | Great Lakes | St. Marys | Lafarge Shalersville | #8 Limestone Marblehead Stone | | JMF |
| GAL 7 | 352(46) | Holderman | Columbia | Ohio River S&G New Martinsville, WV | Ohio River S&G New Martinsville, WV | | |
| GRE 35 | 19(97) | Lane | Cemex | Phillips S & G Alpha | #57 Limestone Melvin in Melvin | Class F Duke Energy | JMF |
| HAM 126 | 997(90) | Geupel | Lehigh | America Aggr. Fairfield | #57 Gravel - America Aggregates, Fairfield | | |
| JEF 7, 22 | 8008(90) | Kokosing | ESSROC | Spring Industries Midvale | #57 Slag Std. Lafarge, Weirton WV | | |
| LOG 33 | 845(94) | Miller Bros. | Medusa | Union Aggr. Prospect | #8 Limestone East Liberty | | |
| MOT 35 | 343(88) | Ruhlin | Southwest | American Aggr. Xenia | #57 Limestone Amer. Aggr.., Xenia | | |
| MOT 202 | 678(91) | Data not available | | | | | |
| SUM 76 | 996(93) | Ruhlin | Cemex | Allied Corp. Massilon | #8 Limestone Martin Marietta Woodville | Class F Clev. Ill. | JMF |
| TUS 39 | 907(90) | Holloway | Medusa | SR 416 S & G New Phil. | # 57 Gravel, SR 416 S & G New Philadelphia | | |

# APPENDIX D

# TABLES D-1 AND D-2

# FINE AGGREGATE DATA

**LML PROJECT NO. 5536**
**STATE JOB NO. 134280(0)**

Table D-1.  FINE AGGREGATE CHARACTERIZATION DATA: (LML PROJECT 5536)

| LML Core Number | Core Identification Number | Maximum Sand Size, mm | Rock/Mineral Type | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Quartz | Siltstone | Sand-stone | Limestone | Igneous | Chert | Shale | Feldspar | Iron Oxides | Other |
| 1 | GAL-7 (CR) | 5 | 1 | 2 | 4 | 5 | 10 | 3 | 9 | 8 | 7 | 6 |
| 3 | ATH-682 (CR) | 5 | 1 | 3 | - | 2 | 6 | 5 | 4 | 7 | 9 | 8, 10 |
| 5 | ATH-33 (CR) | 3.5 | 1 | 3 | - | 2 | 4 | 5 | - | 8 | 6 | 7 |
| 7 | GRE-35 (CR) | 3 | 1 | 3 | 5 | 2 | 4 | 7 | 6 | 9 | 10 | 8, 11 |
| 9 | HAM-126 (CR) | 5 | 1 | 6 | 7 | 2 | 4 | 3 | 5 | 8 | 10 | 9, 11-13 |
| 11 | ALL-30 (CR) | 3 | 1 | 10 | 9 | 3 | 4 | 6 | 2 | 7 | - | 5,8 |
| 13 | JEF-22 (CR) | 4.5 | 1 | 2 | 4 | 3 | 6 | 5 | 7 | 8 | 9 | 10-11 |
| 16 | JEF-7 (JT) | 4 | 1 | 2 | 4 | 3 | 6 | 5 | 9 | 7 | 8 | 10-12 |
| 17 | TUS-39 (CR) | 5 | 1 | 2 | 4 | 3 | 6 | 5 | 9 | 7 | 8 | 10-12 |
| 19 | CUY-82 (CR) | 4 | 1 | 2 | 4 | 3 | 5 | - | 6 | 7 | 9 | 8, 10 |
| 21 | CUY-176-10-S (CR) | 4.5 | 1 | 2 | 3 | 4 | 6 | 9 | 7 | 8 | 5 | 10 |

Table D-2. FINE AGGREGATE CHARACTERIZATION DATA: (LML PROJECT 5536)

| LML Core Number | Core Identification Number | Maximum Sand Size, mm | Rock/Mineral Type | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Quartz | Siltstone | Sand-stone | Limestone | Igneous | Chert | Shale | Feldspar | Iron Oxides | Other |
| 23 | CUY-176-11-S (CR) | 4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 10 | 8 | 9, 11-12 |
| 25 | CUY-176-12-S (CR) | 4.5 | 1 | 2 | 3 | 4 | 5 | 7 | 6 | 9 | 8 | 10-11 |
| 29 | CUY-322 (CR) | 3 | 1 | 2 | 3 | 4 | 9 | 8 | 6 | 5 | 7 | 10 |
| 32 | CUY-252 (CR) | 5 | 1 | 3 | 4 | 2 | 5 | 9 | 8 | 7 | 6 | 10-11 |
| 33 | SUM-76-15-W (CR) | 4.5 | 1 | 2 | 4 | 3 | 6 | 5 | 9 | 7 | 8 | - |
| 37 | SUM-76-15-E (CR) | 4.5 | 1 | 2 | 3 | 4 | 6 | 5 | 9 | 7 | 8 | 10-12 |
| 39 | MOT-35 (CR) | 4.5 | 1 | 3 | 6 | 2 | 4 | 5 | 7 | 8 | 10 | 9 |
| 41 | MOT-202 (CR) | 4.5 | 1 | 3 | 7 | 2 | 6 | 5 | 4 | 8 | 9 | 10 |
| 43 | LOG-33 (JT) | 4 | 1 | 2 | 6 | 3 | 5 | 7 | 4 | - | 8 | 9 |

# APPENDIX E

# TABLES E-1 through E-3

# AIR VOID SYSTEM AND DENSITY DATA

**LML PROJECT NO. 5536**
**STATE JOB NO. 134280(0)**

Table E-1. AIR VOID SYSTEM AND DENSITY DATA: LML PROJECT 5536)

| LML Core Number | Core Identification Number | ASTM C 457 Measurement Parameters | | | | Specific Surface Area, $in^2/in^3$ | Air-Void Spacing Factor, in. | Total Air Void Content, % | Concrete Density, $lb/ft^3$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Voids Per Inch | Traverse Length, in. | Traverse Area, $in^2$ | Number of Stops | | | | |
| 1 | GAL-7 (CR) | 4.4 | 113.3 | 45.0 | 2266 | 516 | 0.0097 | 3.44 | 146.9 |
| 3 | ATH-682 (CR) | 10.6 | 91.5 | 63.8 | 1829 | 561 | 0.0064 | 7.55 | 141.9 |
| 5 | ATH-33 (CR) | 14.4 | 105.5 | 60.0 | 2110 | 869 | 0.0051 | 6.64 | 143.6 |
| 7 | GRE-35 (CR) | 9.3 | 100.3 | 65.6 | 2005 | 878 | 0.0059 | 4.24 | 146.1 |
| 9 | HAM-126 (CR) | 7.4 | 101.5 | 66.6 | 2029 | 589 | 0.0080 | 5.03 | 146.4 |
| 11 | ALL-30 (CR) | 8.2 | 100.7 | 66.6 | 2014 | 637 | 0.0076 | 5.16 | 147.7 |
| 13 | JEF-22 (CR) | 8.5 | 101.7 | 67.0 | 2034 | 658 | 0.0073 | 5.16 | 143.9 |
| 16 | JEF-7 (JT) | 9.3 | 100.9 | 62.8 | 2018 | 611 | 0.0071 | 6.10 | 140.1 |
| 17 | TUS-39 (CR) | 10.1 | 102.3 | 71.0 | 2047 | 529 | 0.0055 | 7.62 | 145.8 |
| 19 | CUY-82 (CR) | 16.4 | 101.2 | 44.0 | 2024 | 946 | 0.0041 | 6.92 | 141.0 |

Table E-2. AIR VOID SYSTEM AND DENSITY DATA: LML PROJECT 5536)

| LML Core Number | Core Identification Number | ASTM C 457 Measurement Parameters | | | | Specific Surface Area, $in^2/in^3$ | Air-Void Spacing Factor, in. | Total Air Void Content, % | Concrete Density, $lb/ft^3$ |
|---|---|---|---|---|---|---|---|---|---|
| | | Voids Per Inch | Traverse Length, in. | Traverse Area, $in^2$ | Number of Stops | | | | |
| 21 | CUY-176-10-S (CR) | 3.4 | 101.1 | 48.0 | 2021 | 708 | 0.0110 | 1.93 | 141.4 |
| 23 | CUY-176-11-S (CR) | 16.8 | 100.6 | 44.0 | 2011 | 802 | 0.0042 | 8.35 | 138.9 |
| 25 | CUY-176-12-S (CR) | 17.3 | 97.8 | 43.0 | 1955 | 821 | 0.0040 | 8.44 | 138.5 |
| 29 | CUY-322 (CR) | 14.4 | 91.2 | 36.0 | 1824 | 629 | 0.0050 | 9.16 | 138.7 |
| 32 | CUY-252 (CR) | 15.4 | 91.7 | 23.4 | 1834 | 755 | 0.0048 | 8.18 | 139.4 |
| 33 | SUM-76-15-W (CR) | 17.0 | 91.3 | 44.0 | 1825 | 975 | 0.0044 | 6.96 | 141.3 |
| 37 | SUM-76-15-E (CR) | 13.8 | 91.3 | 44.0 | 1826 | 877 | 0.0050 | 6.30 | 143.1 |
| 39 | MOT-35 (CR) | 16.8 | 90.5 | 40.0 | 1810 | 1339 | 0.0036 | 5.03 | 145.8 |
| 41 | MOT-202 (CR) | 12.3 | 91.1 | 35.5 | 1822 | 590 | 0.0054 | 8.34 | 143.4 |
| 43 | LOG-33 (JT) | 10.3 | 90.4 | 45.0 | 1808 | 554 | 0.0073 | 7.47 | 141.3 |

**Table E-3. Total Air Void Content for Average and Excellent Pavement Projects (5536)**

| Pavement Performance Ranking | Average Value of Total Air Void Content of the Concretes, % | Range of Values of Total Air Void Content of the Concretes, % |
|---|---|---|
| **Excellent (10)** | 6.0 | 3.4 to 9.2 |
| **Average (10)** | 6.8 | 1.9 to 8.4 |



**EXCELLENT**

**GAL-7 (CR) = 3.4**
**GRE-35 (CR) =4.2**
**HAM-126 (CR) = 5.0**
**ALL-30 (CR) = 5.2**
**JEF-7 (JT) = 6.1**
**CUY-82 (CR) = 6.9**
**CUY-322 (CR) = 9.2**
**SUM-76-15-W (CR) = 7.0**
**MOT-35 (CR) = 5.0**
**MOT-202 (CR) = 8.3**

**AVG = 60.3/10 = 6.0**

**AVERAGE**

**ATH-682 (CR) = 7.6**
**ATH-33 (CR) = 6.6**
**JEF-22 (CR) = 5.2**
**TUS-39 (CR) = 7.6**
**CUY-176-10-S = 1.9**
**CUY-176-11-S = 8.4**
**CUY-176-12-S = 8.4**
**CUY-252 (CR) = 8.2**
**SUM-75-15-E (CR) = 6.30**
**LOG-33 (JT) = 7.5**

**AVG = 66.7/10 = 6.77**

# APPENDIX F

## TABLES F-1 through F-5

## CONCRETE STRENGTH AND ELASTIC PROPERTIES

**LML PROJECT NO. 5536**
**STATE JOB NO. 134280(0)**

**Table F-1. Compressive Strength of Average and Excellent Pavement Projects (5536)**

| Pavement Performance Ranking | Compressive Strength, psi | |
|---|---|---|
| | Average | Range |
| **Excellent (10)** | 6180 | 4880-8410 |
| **Average (10)** | 6310 | 3760-8720 |



**EXCELLENT**

**GAL-7 (CR) = 7850**
**GRE-35 (CR) =6110**
**HAM-126 (CR) = 6490**
**ALL-30 (CR) = 8410**
**JEF-7 (JT) = 6830**
**CUY-82 (CR) = 5740**
**CUY-322 (CR) = 5050**
**SUM-76-15-W (CR) = 5490**
**MOT-35 (CR) = 4880**
**MOT-202 (CR) = 4930**

**AVG =61780/10 = 6180**

**AVERAGE**

**ATH-682 (CR) =7990**
**ATH-33 (CR) = 6850**
**JEF-22 (CR) = 7340**
**TUS-39 (CR) = 6860**
**CUY-176-10-S = 6260**
**CUY-176-11-S = 3760**
**CUY-176-12-S = 3820**
**CUY-252 (CR) = 5850**
**LOG-33 (JT) = 8720**
**SUM-76-15-E (CR) = 5650**

**AVG = 63100/10 = 6310**

**Table F-2. Split Tensile Strength of Average and Excellent Pavement Projects (5536)**

| Pavement Performance Ranking | Split Tensile Strength, psi | |
|---|---|---|
| | Average | Range |
| **Excellent (10)** | 630 | 515-830 |
| **Average (10)** | 600 | 490-630 |



**EXCELLENT**

**GAL-7 (CR) = 660**
**GRE-35 (CR) =570**
**HAM-126 (CR) = 640**
**ALL-30 (CR) = 710**
**JEF-7 (JT) = 540**
**CUY-82 (CR) = 515**
**CUY-322 (CR) = 600**
**SUM-76-15-W (CR) = 620**
**MOT-35 (CR) = 830**
**MOT-202 (CR) = 610**

**AVG = 6295/10 = 630**

**AVERAGE**

**ATH-682 (CR) =630**
**ATH-33 (CR) = 620**
**JEF-22 (CR) = 490**
**TUS-39 (CR) = 640**
**CUY-176-10-S = 610**
**CUY-176-11-S = 600**
**CUY-176-12-S = 540**
**CUY-252 (CR) = 570**
**LOG-33 (JT) = 710**
**SUM-76-15-E (CR) = 630**

**AVG = 6040/10 = 600**

**Table F-3. Static Modulus of Elasticity (4 in. Diameter Cores) of Average and Excellent Pavement Projects (5536)**

| Pavement Performance Ranking | Static Modulus of Elasticity, x $10^6$ psi | |
|---|---|---|
| | Average | Range |
| **Excellent (10)** | 5.52 | 3.96-7.16 |
| **Average (10)** | 4.33 | 2.72-5.76 |



**EXCELLENT**

**GAL-7 (CR) = 3.96**
**GRE-35 (CR) =5.89**
**HAM-126 (CR) = 6.90**
**ALL-30 (CR) = 5.54**
**JEF-7 (JT) = 5.32**
**CUY-82 (CR) = 5.25**
**CUY-322 (CR) = 4.37**
**SUM-76-15-W (CR) = 5.71**
**MOT-35 (CR) = 7.16**
**MOT-202 (CR) = 5.08**

**AVG = 55.18/10 = 5.52**

**AVERAGE**

**ATH-682 (CR) =4.29**
**ATH-33 (CR) = 4.10**
**JEF-22 (CR) = 5.76**
**TUS-39 (CR) = 4.17**
**CUY-176-10-S = 4.43**
**CUY-176-11-S = 3.83**
**CUY-176-12-S = 3.60**
**CUY-252 (CR) = 2.72**
**LOG-33 (JT) = 4.99**
**SUM-76-15-E (CR) = 5.44**

**AVG = 43.33/10 = 4.33**

Table F-4. STRENGTH AND ELASTIC PROPERTY CORRELATION WITH MATERIAL PROPERTIES: (LML PROJECT 5536)

| LML Core Number | Core I.D. Number | w/cm | Type of Coarse Aggregate | Total Aggregate Content, v/o | Total Air Void Content, % | Quality of CementPaste/ Aggregate Bond | Compressive Strength, psi | Split Tensile Strength, psi | Static Modulus of Elasticity, psi x $10^6$ |
|---|---|---|---|---|---|---|---|---|---|
| 1/2 | GAL-7 | 0.48 | Gravel (2) | 76.3 | 3.4 | Good | No Test | 660 | 3.96 |
| 3/4 | ATH-682 | 0.45 | Gravel ($^3/_8$) | 65.3 | 7.6 | Excellent | 7990 | 630 | 4.29 |
| 5/6 | ATH-33 | 0.45 | Limestone (1) | 63.1 | 6.6 | Fair | 6850 | 620 | 4.10 |
| 7/8 | GRE-35 | 0.48 | Limestone ($^3/_4$) | 69.0 | 4.2 | Good | 6110 | 570 | 5.89 |
| 9/10 | HAM-126 | 0.45 | Gravel (1) | 69.1 | 5.0 | Good | 6490 | 640 | 6.90 |
| 11/12 | ALL-30 | 0.42 | Limestone ($^3/_4$) | 66.7 | 5.2 | Fair | No Test | No Test | 5.54 |
| 13/14 | JEF-22 | 0.42 | Slag (1) | 66.9 | 5.2 | Good | 7340 | 490 | 5.76 |
| 15/16 | JEF-7 | 0.46 | Slag ($^3/_4$) | 67.5 | 6.1 | Good | 6830 | 540 | 5.32 |
| 17/18 | TUS-39 | 0.43 | Gravel ($^3/_4$) | 70.4 | 7.6 | Good | 6860 | 640 | 4.17 |
| 19/20 | CUY-82 | 0.48 | Limestone ($^3/_8$) | 66.2 | 6.9 | Good | 5740 | 515 | 5.25 |

Green = Excellent Performance Red = Average Performance

Table F-4 (Cont'd). STRENGTH AND ELASTIC PROPERTY CORRELATION WITH MATERIAL PROPERTIES: (LML PROJECT 5536)

| LML Core Number | Core I.D. Number | w/cm | Type of Coarse Aggregate | Total Aggregate Content, v/o | Total Air Void Content, % | Quality of CementPaste/ Aggregate Bond | Compressive Strength, psi | Split Tensile Strength, psi | Static Modulus of Elasticity, psi x $10^6$ |
|---|---|---|---|---|---|---|---|---|---|
| 21/22 | CUY-176-10-S | 0.44 | Slag (1) | 67.1 | 1.9 | Good | 6260 | 610 | 4.43 |
| 23/24 | CUY-176-11-S | 0.43 | Limestone ($^3/_8$) | 63.3 | 8.4 | Poor | 3760 | 600 | 3.83 |
| 25/26 | CUY-76-12-S | 0.43 | Limestone ($^3/_8$) | 64.0 | 8.4 | Fair | 3820 | 540 | 3.60 |
| 29/30 | CUY-322 | 0.46 | Limestone ($^3/_8$) | 61.7 | 9.2 | Poor | No Test | 600 | 4.37 |
| 31/32 | CUY-252 | 0.45 | Limestone ($^3/_8$) | 62.4 | 8.2 | Low | No Test | 570 | 2.72 |
| 33/34 | SUM-76-15-W | 0.44 | Limestone ($^3/_8$) | 63.5 | 7.0 | Good | 5490 | 620 | 5.71 |
| 37/38 | SUM-76-15-E | 0.44 | Limestone ($^3/_8$) | 66.0 | 6.3 | Fair | 5650 | 630 | 5.44 |
| 39/40 | MOT-35 | 0.45 | Gravel ($^3/_8$) | 66.9 | 5.0 | Fair | 4880 | 830 | 7.16 |
| 41/42 | MOT-202 | - | Gravel ($^3/_8$) | 65.0 | 8.3 | Fair | 4930 | 610 | 5.08 |
| 43 | LOG-33 | -0.48 | Limestone ($^3/_8$) | 62.2 | 7.5- | Fair | 8720 | 710 | 4.99 |

Green = Excellent Performance Red = Average Performance

## Table F-5. RANKED STRENGTH/ELASTIC PROPERTIES CORRELATION (LML PROJECT 5536)

| Ohio University Core I.D. Number | Pavement Performance Rating | Average Compressive Strength, psi | Average Split Tensile Strength, psi | Average Modulus of Elasticity, psi x $10^6$ | Coarse Aggregate Type | Total Air Void Content, % | Air Void Specific Surface Area, $in^2/in^3$ | Paste-Aggregate Bond |
|---|---|---|---|---|---|---|---|---|
| LOG-33 | Average | 8720 | 710 | 4.99 | 3/8 LS | 7.5 | 554 | FAIR |
| ALL-30 | Excellent | 8410 | 710 | 5.54 | ¾ LS | 5.2 | 637 | FAIR |
| ATH-682 | Excellent | 7990 | 630 | 4.29 | 3/8 GRAVEL | 7.6 | 561 | EXCELLENT |
| JEF-22 | Average | 7340 | 490 | 5.76 | 1 SLAG | 5.2 | 658 | GOOD |
| TUS-39 | Average | 6860 | 640 | 4.17 | ¾ GRAVEL | 7.6 | 529 | GOOD |
| ATH-33 | Average | 6850 | 620 | 4.10 | 1 LS | 6.6 | 869 | FAIR |
| JEF-7 | Excellent | 6830 | 540 | 5.32 | ¾ SLAG | 6.1 | 611 | GOOD |
| HAM-126 | Excellent | 6490 | 640 | 6.90 | 1 GRAVEL | 5.0 | 589 | GOOD |
| CUY-176-10-S | Average | 6260 | 610 | 4.43 | 1 SLAG | 1.9 | 708 | GOOD |
| GRE-35 | Excellent | 6110 | 570 | 5.89 | ¾ LS | 4.2 | 878 | GOOD |
| CUY-252 | Average | 5850 | 570 | 2.72 | 3/8 LS | 8.2 | 755 | LOW |

Table F-5 (Cont'd). RANKED STRENGTH/ELASTIC PROPERTIES CORRELATION (LML PROJECT 5536)

| Ohio University Core I.D. Number | Pavement Performance Rating | Average Compressive Strength, psi | Average Split Tensile Strength, psi | Average Modulus of Elasticity, psi x $10^6$ | Coarse Aggregate Type | Total Air Void Content, % | Air Void Specific Surface Area, $in^2/in^3$ | Paste-Aggregate Bond |
|---|---|---|---|---|---|---|---|---|
| CUY-82 | Excellent | 5740 | 515 | 5.25 | 3/8 LS | 6.9 | 946 | GOOD |
| SUM-76-15-E | Average | 5650 | 630 | 5.44 | 3/8 LS | 6.3 | 877 | FAIR |
| SUM-76-15-W | Excellent | 5490 | 620 | 5.71 | 3/8 LS | 7.0 | 975 | GOOD |
| CUY-322 | Excellent | 5050 | 600 | 4.37 | 3/8 LS | 9.2 | 629 | POOR |
| MOT-202 | Excellent | 4930 | 610 | 5.08 | 3/8 GRAVEL | 8.3 | 590 | FAIR |
| MOT-35 | Excellent | 4880 | 830 | 7.16 | 3/8 GRAVEL | 5.0 | 1339 | FAIR |
| CUY-176-12-S | Average | 3820 | 540 | 3.60 | 3/8 LS | 8.4 | 821 | FAIR |
| CUY-176-11-S | Average | 3760 | 600 | 3.83 | 3/8 LS | 8.4 | 802 | POOR |

# APPENDIX G

# SUMMARY OF DATA FOR RESEARCH STUDY PAVEMENTS HAVING NO MID-SLAB CRACKS

## LML PROJECT NO. 5536
## STATE JOB NO. 134280(0)

### Table G-1. DATA COMPARISON FOR RESEARCH STUDY PROJECTS WITH NO MID-SLAB CRACK

| LML Core Number | Core Identification Number | Design Pavement Thickness, in. | Joint Spacing, ft. | Base Material (Base Material Still Adhered to Concrete? ) | Joint crack is Single or Multiple Cracks? | Material Loss Along Joint Fracture Plane % | Coarse Aggregate | Secondary Deposits |
|---|---|---|---|---|---|---|---|---|
| 7/8 | GRE-35 (JT) (1997) | 10 | 21 | NSDB/304 (Drainable) | Single Crack- Minor material loss along crack | 4 | ¾ in. Dolomitic Limestone | Moderate |
| 11/12 | ALL-30 (JT) (1997) | 11 | 21 | ATFDB/304 (Drainable) | Single Crack- Minor material loss along crack | 2 | ¾ in. Dolomitic Limestone | Low |
| 23/24 | CUY-176 -11-S (JT) (1996) | 12 | 21 | 310 T2 (Yes/Slag) | Single | 3 | 3/8 in. Dolomitic Limestone | Abundant |
| 29/30 | CUY-322 (JT) (1993) | 10 | 21 | 310 T2 | Single (very tight) crack0 | 0 | 3/8 in. Limestone | Moderate |
| 33/34 | SUM-76-15-W (JT) (1992) | 11 | 21 | 403/301/304 (AC Base) (Yes) | Multiple –Top to Bottom, Small Cone | 7 | 3/8 in. Dolomitic Limestone | Low |
| 43 | LOG-33 (JT) (1994) | 12 | 15 | NSDB/ACT1 (Drainable) Not AC | Single | 0 | 3/8 in. Limestone | Moderate |

Green = Excellent Performance
**Red = Average Performance**

Blue = Reinforced PCC Pavement
Plum = Unreinforced Pavement

Table G-2. DATA COMPARISON FOR PROJECTS WITH NO MID-SLAB CRACK

| LML Core Number | Core Identification Number | Cement Paste Content, % | Total Aggregate Content, v/o | Air Content, % | Coarse Aggregate Freeze/Thaw Rating | Compressive Strength, psi | Split Tensile, psi | Modulus Elasticity, x $10^6$ psi |
|---|---|---|---|---|---|---|---|---|
| 7/8 | GRE-35 (JT) (451) | 26.8 | 69.0 | 4.2 | None | 6110 | 570 | 5.89 |
| 11/12 | ALL-30 (JT) (451) | 28.1 | 66.7 | 5.2 | None | 8410 | 710 | 5.54 |
| 23/24 | CUY-176 -11-S (JT) (451) | 28.3 | 63.3 | 8.4 | None | 3760 | 600 | 3.83 |
| 29/30 | CUY-322 (JT) (451) | 29.1 | 61.7 | 9.2 | None | 5050 | 600 | 4.37 |
| 33/34 | SUM-76-15-W (JT) (451) | 29.5 | 63.5 | 7.0 | None | 5490 | 620 | 5.71 |
| 43 | LOG-33 (JT) (452) | 30.3 | 62.2 | 7.5 | None | 8720 | 710 | 4.99 |

Green = Excellent Performance
**Red = Average Performance**

Blue = Reinforced PCC Pavement
Plum = Unreinforced Pavement

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