REPORT NO. 5423

ON

PETROGRAPHIC EXAMINATION OF CONCRETE CORES TAKEN FROM THE OHIO STRATEGIC HIGHWAY RESEARCH PROGRAM (SHRP) SPECIFIC PAVEMENT STUDIES TEST ROAD

TO

THE OHIO RESEARCH INSTITUTE
FOR TRANSPORTATION AND THE ENVIRONMENT
ATHENS, OHIO

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LANKARD MATERIALS LABORATORY, INC.
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INTRODUCTION

The 3-mile long SHRP pavement project is located on US 23, 25-miles north of Columbus, Ohio, in Delaware County. Northbound lanes were constructed of portland cement concrete (PCC), while southbound lanes were constructed of asphalt concrete (AC). Construction of the mainline pavement was completed in 1996.

The main variables for the PCC pavement were pavement thickness (8-inches and 11-inches), and the base material and design (lean concrete base, dense graded aggregate base, asphalt treated base, permeable asphalt treated base, and permeable cement treated base). Six-inch and 8-inch thick bases were used, and some were designed to drain, while others were not.

During 1999, longitudinal cracking was observed in two of the PCC pavement sections. These included Section 390205 and Section 390206. Since then, cracking has continued to progress in these sections and has developed in other sections. Currently, all of the 8-inch PCC sections show some cracking, and the 11-inch thick PCC on the lean concrete base has developed cracking.

A number of cores were taken from Sections 390205 and 390206 in October 1999. The cores were not examined until recently when they were provided to Lankard Materials Laboratory (LML) for a petrographic examination. One of the main items of concern here is whether or not material deficiencies or shortcomings have played a role in the pavement cracking distress. Beyond this, it is desired to determine, if possible, the origin of the cracking distress. The remainder of this report describes the procedures used in this examination, and the results/ findings that were obtained.

DESCRIPTION OF CORES

Six-inch diameter cores were taken at four locations including (1) Test Section 390205, (2) Test Section 390206, (3) Test Section 390809, and (4) Test Section 390810. (In subsequent text, reference to the "390" prefix will be eliminated for simplification.)

Test Sections 205 and 206 are both mainline concrete pavement with 8-inches of portland cement concrete (PCC) on 6-inches of lean concrete base (LCB). The LCB for both sections was placed on August 19, 1995. The PCC for Section 205 was placed on September 11, 1995; that for Section 206 on September 18, 1995. Cores taken in these sections were taken through both the PCC and the LCB slabs.

Test Sections 809 and 810 are in the PCC sections of the southbound ramp lanes. A specific experiment connected with the southbound ramp lane is Experiment SPS-8, "A Study of Environmental Effects in the Absence of Heavy Traffic".

More detailed information on these cores follows:

PCC Test Section 206

This test section, which has a lane width of 14-feet, is at the south end of the project. The concrete for this test section is identified as "Mix 900", which is shown in Table 1. This is an air-entrained concrete containing 750 pounds of portland cement and 113 pounds of fly ash per cubic yard. The "900" refers to a target 28-day flexural strength of 900 psi for this concrete. Some of the project documents refer to this concrete as the "Plan B Concrete Mix Design".

Three cores were provided to LML from Test Section 206 (identified as Cores 1, 2, and 3). The coring sites for these cores are identified in Table 2. Table 2 also shows the length of the PCC core and the LCB core at each coring site. The PCC target thickness value of 8-inches was met or slightly exceeded for all three PCC cores, and the LCB target thickness of 6-inches was met or slightly exceeded by all three of the LCB cores. Comments on the condition of the cores as-received at LML are also provided in Table 2.

Photographs of Cores PCC 1, 2, and 3, are shown in Figures 1, 2, and 3. Photographs of Cores LCB 1, 2, and 3, are shown in Figures 4, 5, and 6. One end surface of the PCC cores is the grooved wearing surface of the test section pavement. The other end surface of the PCC cores is the bottom of the pavement slab cast on the LCB base. The bottom end surface of the LCB cores represents the bottom of these slabs cast on the sub-base.

All of these cores were received intact, with the exception of Core PCC-1. This core was received in two pieces, separated along a full-width, full-depth crack fracture plane. This is a longitudinal crack (slightly skewed) in this pavement section.

The mix design for the LCB is shown in Table 3. This mix design is the one reported by Bowser-Morner, Inc. (Dayton, Ohio), in the trial mix work.. The lean concrete base actually used on the project shows a reduced sand content and the use of fly ash as a portion of the cementitious phase. This information, taken from an ODOT Concrete Inspector's Report, shows a sand content of 1762 pounds and the use of Class C fly ash at 48 pounds per cubic yard.

PCC Test Section 205

This test section, which has a lane width of 12-feet, is on the south end of the mainline PCC pavement, located just north of Section 206. Test Section 205 is 8-inches of ODOT Class C, Option 1 Concrete on 6-inches of LCB.

The mix design for ODOT Class C, Option 1 Concrete is shown in Table 4. This is an air-entrained concrete containing 510 pounds of portland cement and 90 pounds of fly ash per cubic yard. The "normal" Class C, Option 1 Concrete has a maximum water to cementitious material ratio (w/cm) of 0.5. The concrete placed in Section 205 had a target w/cm of 0.40.

There is only a single coring site in Test Section 205. The PCC core (PCC-4) meets the target thickness of 8-inches, while the LCB core (LCB-4) is slightly under the target thickness of 6-inches, at 5¾-inches. Data for these cores are shown in Table 2. Photographs of Core PCC-4 are shown in Figure 7, and photographs of Core LCB-4 are shown in Figure 8. Core PCC-4 was taken through a transverse crack (slightly skewed) in Pavement Section 205, but the core was

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received intact. Core LCB-4 was received in two pieces, separated by a full-width, full-depth crack. The wearing surface in both Core PCC-4 and Core LCB-4 is grooved. The grooved surface in Core LCB-4 was sawcut into the surface.

In none of the cores provided from the mainline PCC pavement (Sections 205 and 206), was the portland cement concrete bonded to the lean concrete base.

PCC Test Sections 809 And 810

These test sections are at the south end of the southbound ramp. Both test sections have a lane width of 11-feet. The same concrete, identified as "Mix 550", was used in both of these test sections and is shown in Table 5. This is an air-entrained concrete containing 350 pounds of portland cement and 120 pounds of Class F fly ash per cubic yard. The target thickness of Test Section 809 is 8-inches; the target thickness of Test Section 810 is 11-inches. Both of these test slabs were cast on 6-inches of dense graded aggregate base (DGAB).

One full-depth core was taken from each of these test sections and are identified in this report as Core 809 and Core 810. The coring site for the 8-inch core taken from Test Section 809 is identified as "Station 26 + 40". The coring site for the 11-inch core from Test Section 810 is identified as "Station 26 + 90". The pavement target thickness values were met by both of these cores. Photographs of the cores are shown in Figure 9. Both of these cores were receive intact, and neither was taken through a crack in the ramp pavement. One end surface of the cores is the existing grooved wearing surface of the test pavement slabs. The other end surface is the bottom of the cores cast on the DGAB.

CONCRETE TEST DATA

Property measurements were made on core and cylinder specimens through a one-year period following construction of the pavements. Twenty-eight day and one-year measurements made of compressive strength, splitting tensile strength, and flexural strength of the portland cement concretes are shown in Table 6. These data were provided to LML by Roger Green in the ODOT Office of Pavement Engineering. Modulus of elasticity data was also reported for the concrete in Test Section 205, and the concrete in Test Sections 809 and 810.

Twenty-eight day and one-year compressive strength data were also provided for the lean concrete base from Test Sections 205 and 206. These values ranged from 1080 psi to 1880 psi at 28-days, and from 1390 psi to 2490 psi at 1-year.

PETROGRAPHIC EXAMINATION PROCEDURES

All ten of the cores were given a detailed preliminary visual and stereomicroscopic examination. This examination was made on as-cored surfaces, on end surfaces, and on existing fracture surfaces.

All of the PCC cores were then sectioned (diamond saw) as shown in Figure 10. The initial cut on the cores was made at their midpoint (relative to length) to provide samples of a length suitable for subsequent sample preparation steps. Immediately following the sawcutting step, an indicating solution was applied to the fresh sawcut surfaces to identify the extent of carbonation of the concrete. The indicating solution in this case is phenolphthalein, which shows a distinctive color change at a pH of about 9.8.

The sections identified as "T2" and "B2" in Figure 10 were used to prepare lapped surfaces for

the petrographic examination. The petrographic examination was conducted on all of the cores following the guidelines of ASTM C 856, "The Standard Practice for Petrographic Examination of Hardened Concrete" (Optical Microscopy Procedures). Examinations were made on the lapped surfaces of Core Sections T2 and B2 and on fresh fracture surfaces of Core Sections T1 and B1.

The examination of lapped surfaces provided (1) identification of the cementitious and aggregate constituents of the concrete, (2) an estimate of the water to cementitious material ratio (w/cm) of the concrete, (3) an assessment of the cement paste/aggregate bond, (4) an opportunity to observe any cracking, delamination, softening, or other forms of microstructural distress, (5) an assessment of the consolidation features of the concrete, and (6) an assessment of the extent of moisture cycling in the concrete.

Further opportunities to identify distress features were obtained by subjecting Core Sections T1 and B1 to loading in a 400,000-pound Universal Testing Machine using a modification of ASTM C 496, "The Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens". Here, the loading was done on the partial core sections identified as T1 and B1 in Figure 10. When tested to complete failure, using this procedure, numerous fracture surfaces are created. It is anticipated that if the concrete contains distress in the form of microcracking, freeze/thaw damage, or cement-aggregate reactions, that the fracture will occur preferentially through these planes of weakness. Subsequent microscopic examination of these fracture surfaces will reveal these distress features if they exist. Conversely, fractures which reflect principally fresh cement paste and aggregate fractures, will help to confirm that no hidden defects are present in the concrete.

In all of the cores, a measurement was made of the cement paste content and the air content (entrained and entrapped) using the procedure of ASTM C 457, "The Standard Practice for Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete" (Modified Point Count Method). This measurement was made on both the top sections and bottom sections of the cores (Figure 10).

A density measurement was made on Core Sections T3 and B3 (Figure 10) following a 48-hour water soaking period. This measurement was made following the guidelines of ASTM C 642, "The Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete" (Water Immersion Procedure). A density measurement made on water saturated concrete is expected to correlate with the original unit weight of the concrete.

The salient observations and findings of the examinations/tests are discussed below. For clarity, the results are presented separately for each of the four concretes represented by the cores examined here. These are identified as (1) Mix 900 (Table 1); (2) Lean Concrete Base (Table 3); (3) ODOT Class C, Option 1 Concrete (Table 4); and (4) Mix 550 (Table 5).

One feature of the concretes that will not be reported separately, is the description of the fine and coarse aggregates. The coarse aggregate in all of the concretes is identified as "Carey Stone", produced by National Lime, and the fine aggregate in all of the concretes is "Prospect Sand".

The coarse aggregate is a crushed dolomitic limestone with a nominal maximum particle size of 1-inch. The angular particles are compact to platy in shape. The dolomitic limestone particles are typically very light gray to medium light gray in color. Relative to other regional sources of limestones/dolomitic limestones, this rock is quite hard and typically shows a low rate of water

absorption. The presence of irregularly shaped porosity is a common feature in these aggregate particles. The pores typically range from 0.1-mm to 2-mm in size. The presence of this macro porosity provides an excellent surface for bonding to the cementitious phase in concretes.

The fine aggregate in the concretes represented by these cores is a natural sand composed of both carbonate and siliceous rock/mineral types. Carbonate rocks include both limestones and dolomitic limestones. Siliceous rock/minerals include quartz, sandstones, siltstones, shale, igneous lithics, and chert. Chert is a very finely crystalline form of silica (SiO_2) which can, under some conditions, be involved in alkali-silica reactions (ASR). In the cores examined here, the chert content of the fine aggregate phase is estimated at less than 1%.

In all of the cores examined here, including the LCB cores, the coarse aggregate particles are uniformly distributed from top to bottom in the core.

RESULTS: MIX 900

This concrete was used in Section 206 of the mainline PCC pavement. Cores provided to LML from this section include Cores PCC-1, PCC-2, and PCC-3.

Unless otherwise stated, the observations and features described here pertain to the concrete represented by all three cores.

Cementitious Phase

The cementitious phase in this concrete is composed of both well hydrated portland cement and fly ash. The cement paste phase is medium gray in color and is very hard. When probed, the cement paste shows a high degree of luster and is difficult to scratch.

The target water to cementitious material ratio (w/cm) for this concrete is 0.31. The color, texture, hardness, and fracture characteristics of the cement paste in these cores indicates that the w/cm of this concrete is in conformance with the target value.

The measured (ASTM C 457) cement paste content ranges from 35.0% to 35.5% in these cores (see Table 7).

Air Content

Although it is judged that an air-entraining agent was used in the concrete represented by all three of these cores, the total air content falls well below the target value of 6% in Cores PCC-1 and PCC-2 (2.5% and 2.2%). Indications that the concrete did contain an air-entraining admixture is based on the size range of the air voids that are present, which fall mostly well within the entrained air void size category.

The total air void content in Core PCC-3 is 6.6%, which is very close to the target value of 6%.

In all of these cores, the entrained air voids are uniformly distributed from top to bottom in the cores (including the wearing surface layer).

Density

The density of the concrete represented by these cores was measured following a 48-hour water soaking period. The density measurement made in this manner is expected to correlate with the original unit weight of the concrete.

The density of the concretes represented by Cores PCC-1 and PCC-2 is 146.7 lb/ft^3 and 147.8 lb/ft^3. In Core PCC-3, which has an air content of 6.6%, the saturated density is

140.4 lb/ft^3. The lower density of Core PCC-3 reflects the higher air content relative to Cores PCC-1 and PCC-2.

Carbonation

The depth of carbonation of the wearing surface was measured by applying an indicating solution (phenolphthalein) to fresh sawcut surfaces.

In all three of the cores examined here, there is virtually no carbonation of the wearing surface, reflecting the low w/cm of the cementitious phase.

Cement Paste/Aggregate Bond

In all three of these cores, a tight, uninterrupted bond persists between the cementitious phase and the coarse aggregate particles. In the present investigation, split tensile test fractures made on portions of these cores show 100% coarse aggregate fracture as the failure mode, reflecting the excellent quality of the cementitious phase, as well as the good bonding qualities of the coarse aggregate particles. Compressive strength measurements made at an age of 1-year on cores taken from Pavement Section 206 were close to 8000 psi. (Table 6).

Moisture Migration

As water moves into and out of concrete, soluble constituents derived from the cementitious phases can be deposited on free surfaces such as air void surfaces and crack surfaces. These deposits are referred to as "secondary deposits", and they are not typically viewed as a distress feature.

Secondary deposits are common in the cores examined here, indicating that there has been a

considerable amount of moisture cycling in these concretes. Many of the entrained air voids that are under 50-μm in size, are completely filled with secondary deposits in these cores.

Cement-Aggregate Reactions

The fine aggregate phase in these concretes contains a small amount of chert, a very finely crystalline form of silica that is known to participate in cement-aggregate reactions. In rocks and minerals containing silica, this cement-aggregate reaction is referred to as alkali-silica reaction (ASR).

Historically, ASR activity is indicated by a number of microstructural features which include (1) reaction rims around reacting aggregate particles, (2) distinctive internal cracking in reacting aggregate particles, (3) cracking in cement paste adjacent to reacting aggregate particles, and (4) the presence of ASR reaction product, typically referred to as "gel".

In the three cores examined here, there is evidence of ASR activity. Water is used to carry the abrasive grains used to lap/polish the sawcut surfaces of concretes for reflected light microscope examination. Following this lapping operation, water that was absorbed is evaporated. In some cases, soluble constituents in the concrete are deposited on the lapped surfaces following this drying step. In the present case, all three cores showed surface deposits following the lapping operation. These deposits were analyzed chemically using energy dispersive x-ray spectroscopy (EDS) procedures. An EDS spectrum obtained on material deposited on the surface of Core PCC-1 is shown in Figure 11. This analysis indicates that the material is an alkali-silica reaction product containing calcium (Ca), potassium (K), and sodium (Na) as the cation species.

From a microstructural point of view, the only physical evidence of ASR activity is the presence

of rims on chert aggregate particles. However, neither these particles or any other siliceous aggregate particles in these concretes show any evidence of cracking either within the aggregate particles themselves, or in the adjacent cement paste phase. Portions of these cores were fractured in the split tensile test and the surfaces carefully examined for any evidence of reacted aggregate particles or ASR gel. Following extensive examinations, no evidence of this type was found.

It is concluded that the ASR activity in these concretes has been very mild and is not of a destructive form. There is no indication that the activity has had any adverse effect on the strength of the concrete, which still shows 100% coarse aggregate fracture as the failure mode.

Distress Features

The concrete pavement from which these cores were taken (Section 206) currently shows longitudinal cracks, the plane of which is oriented perpendicular to the plane of the wearing surface of the slabs. One of the cores examined here (PCC-1) was taken through one of these cracks. A plan view of the wearing surface of Core PCC-1 is shown in Figure 1. This shows that, in addition to the main full-width longitudinal crack, there is a second full-width crack about 1½-inches from the main crack.. Figure 12 shows section views, perpendicular to the plane of the wearing surface, of Core PCC-1. The left-hand photograph in Figure 12 shows the as-lapped surface, while in the right-hand photograph, cracks in the concrete have been delineated with a black marking pen. An examination of the crack fracture plane shows coarse aggregate fracture predominating, indicating that the concrete had a high degree of its strength at the time the cracking occurred. As shown in Figure 12, the main fracture shows a considerable amount of branching, indicating that the cracking took place gradually rather than as a single

catastrophic event.

In addition to the main fractures in Core PCC-1, there are a few crazing cracks oriented perpendicular to the plane of the wearing surface, and a few microcracks randomly oriented in the cementitious matrix. The microcracks are very tight, typically less than ¼-inch long when measured in two dimensions.

Beyond the macro and microcracking shown in Figure 12, there is no other form of cracking distress in the concrete represented by Core PCC-1. This, despite the fact that the concrete is inadequately air-entrained, having a total air void content of only 2.5%. There is no evidence of any freeze/thaw cracking distress in either the cementitious phase or aggregate particles in this core.

As shown in Figures 2 and 3, Cores PCC-2 and PCC-3 both show the presence of crazing cracks in the pavement wearing surface. These cracks, however, are tight and shallow (less than 1-inch deep), and are not viewed as a distress feature. Both of these cores do show a small amount of microcracking such as was seen in Core PCC-1. Figure 13 shows an example of the extent of microcracking in Core PCC-2. Beyond these examples, there is no evidence of any other form of cracking or distress in the concretes represented by Cores PCC-2 and PCC-3.

Mix 900 Summary

Property data and observations made on Cores PCC-1, PCC-2, and PCC-3, are summarized in Table 7. The concrete is judged to be in reasonable compliance with the target values of the mix design for this concrete (Table 1), with the exception of the air content. The target air content is 6% ±2%. Two of the cores examined here have air contents of 2.2% and 2.5%.

The main consequence of an inadequate level of air-entrainment is an increase in the risk of freeze/thaw-related damage. However, none of the cores examined here show any freeze/thaw cracking distress either in the cementitious phase or in the coarse aggregate particles.

Core PCC-1 was taken through an existing longitudinal crack in the Section 206 pavement. In both plan view (Figure 1) and section view (Figure 12), this cracking reflects a branching nature. This condition indicates that the pavement slab received repeated stress loadings at this site prior to complete failure, which is characteristic of a fatigue failure.

Beyond the cracking just described, the three cores examined here show a very small amount of microcracking within the cementitious phase, which is not uncommon for concretes with a high cementitious phase content. These microcracks are not viewed as a distress feature in these concretes.

Although there is evidence of ASR activity in these concretes, it has been of a mild form and has not resulted in any degradation or distress in the concretes.

RESULTS: ODOT CLASS C, OPTION 1 CONCRETE

This concrete, shown in Table 4, was placed in Section 205 in the mainline PCC pavement. Core PCC-4 (Figure 7) is the only core from this pavement section that was examined here.

Cementitious Phase

The cementitious phase in this concrete is composed of well hydrated portland cement and fly ash. The cementitious phase is medium gray in color and shows a good hardness. It is difficult to score the paste when probed with a steel point, and the probe impact area shows good luster.

Paste fracture surfaces are clean and sharp.

The target w/cm for this concrete is 0.40. Features of the paste examined in Core PCC-4 indicate that this target value was met. The measured (ASTM C 457) cement paste content of this concrete is 27.0%.

Air Content

Although the concrete is air-entrained, the total air void content at 2.5% is well below the target value of 6%. Despite the low total air void content, the majority of air voids are well within the entrained air void size category. Air voids are present from top to bottom in the core, although the top ¼-inch of the core shows a deficiency of air voids relative to the concrete at lower depths.

Density

The water saturated density of the concrete represented by Core PCC-4 is 147.3 lb/ft3. This relatively high value reflects the low total air void content of this concrete.

Carbonation

There is virtually no carbonation of the wearing surface in this core.

Cement Paste/Aggregate Bond

A tight, uninterrupted bond persists between the coarse aggregate particles and the cementitious phase in this concrete. Intentional fracturing of portions of this core (split tensile test) show 100% coarse aggregate fracture as the failure mode.

Moisture Migration

The presence and extent of secondary deposits in this core indicate a moderate amount of moisture cycling in this pavement section. As was observed in cores taken from Pavement Section 206, many of the air voids smaller than 50 μm are completely filled with secondary deposits.

Cement-Aggregate Reactions

As observed in the concretes from Pavement Section 206, this core from Pavement Section 205 also contains a small amount of chert in the fine aggregate phase (less than 1%). These chert particles also show a reaction rim. Despite this there is no cracking associated with these chert aggregate particles, and no cracking in the cement paste adjacent to these aggregate particles. In addition, post-lapping drying of the lapped surface of Core PCC-4 did not yield any ASR reaction product.

Distress Features

As shown in Figure 7, Core PCC-4 was taken through a crack in the pavement that can be seen with the unaided eye (although it is tight). As expressed on this core, this crack is partially a transverse crack (oriented parallel to the groove lines) and then skews slightly to the diagonal of this orientation. Figure 14 shows section views, perpendicular to the plane of the wearing surface, of Core PCC-4. Two section views are shown, which are separated from each other by a distance of ⅞-inch. One section shows two fractures penetrating a distance of about 3¼-inches into this 8-inch long core, while less than an inch away, there is only one fracture penetrating a distance of about 4¼-inches. These fracture planes are wider at the top of the core relative to

their bottom end termination (0.13-mm versus 0.03-mm). The fractures typically pass through, rather than around, coarse aggregate particles. Unlike the longitudinal fractures shown in Core PCC-1, these cracks show virtually no branching. In addition to these main fractures, there are a number of shallow crazing cracks in this core as well (also shown in Figure 14).

The cracks shown in Figure 14 is the only cracking observed in Core PCC-4. No microcracking was observed, and no cracking that could be traced to the effects of freeze/thaw cycling of this inadequately air-entrained concrete was observed either.

ODOT Class C, Option 1 Concrete Summary

Property measurements and observations made on Core PCC-4 are summarized in Table 7. Based on these measurements made on Core PCC-4, the in-place concrete in Test Section 205 is in compliance with the target mix design values (Table 4) with the exception of the air content. The target air content is 6% ±2%, while the actual air content is 2.5%. Although the maximum w/cm of ODOT Class C, Option 1 Concrete is 0.50, the target w/cm of this concrete on this project was 0.40. The in-place concrete is in compliance with this target value.

The core from Section 205 shows tight transverse cracking which originates at the wearing surface and penetrates to about half of the depth of this 8-inch thick slab. The nature of this cracking indicates that it is primarily related to restrained drying shrinkage strain. The cracking occurred at a time that the concrete had achieved a considerable strength level.

Beyond this cracking, and the presence of minor craze cracking, the concrete represented by the core examined here shows no other cracking or distress of any type. Despite having a total air void content well below the target value, there is no evidence of freeze/thaw-related damage in

either the cementitious phase or the coarse aggregate phase.

RESULTS: LEAN CONCRETE BASE (LCB)

In each of the three coring sites in Test Section 206 (Cores 1, 2, and 3), and at the coring site in Test Section 205 (Core 4), the core was taken through the 8-inch PCC slab and through the 6-inch LCB base material. In all cases the LCB cores examined here represent the base material directly under the PCC cores. Photographs of Cores LCB-1, LCB-2, and LCB-3 are shown in Figures 4, 5, and 6, while photographs of Core LCB-4 are shown in Figure 8.

The mix design for the lean concrete base material is shown in Table 3. As discussed in the "Note" section of Table 3, the concrete as-placed contains fly ash as a constituent of the cementitious phase. Unless otherwise stated, the observations discussed below are common to all four of the LCB cores examined here.

Cementitious Phase

The cementitious phase in these cores is comprised solely of well hydrated portland cement and fly ash. The cement paste is light in color, is soft and porous, and shows an earthy texture when fractured or probed. As shown in Table 3, the water-cement ratio (w/c) for this concrete is 1.5. Features of the cement paste examined here indicate that the w/c is in excess of 1.0.

The cement paste content in these cores ranges from 16.3% to 19.2% (see Table 8), with an average value of 18.3%.

Air Content

The target air content in the lean concrete base is 6% ±2%. The measured air content in these

cores ranges from 7.3% to 11.0%. As shown in Table 8, around half of the total air void content in Cores LCB-1, LCB-2, and LCB-3 (Section 205) is entrapped air (air void diameter greater than 1-mm). In Core LCB-4 (Section 205), 70% of the total air void content represents entrapped air voids.

Incomplete consolidation of this concrete has left irregularly shaped voids ranging from 1-mm up to 6-mm or so. These voids frequently occur along the boundaries of fine or coarse aggregate particles. Figure 15 shows enlarged (10X) section views of LCB cores showing examples of these voids.

The target entrained air value in the LCB material was 6%. The entrained air content in the LCB cores from Section 206 ranges from 4% to 5%. In Core LCB-4, taken from Section 205, the entrained air content is only 2.2%.

Density

The saturated density values measured on the four cores of LCB range from 139.3 lb/ft^3 to 143.8 lb/ft^3, with an average of 141.2 lb/ft^3 (Table 8). The lower density values occur in the cores containing the highest total air contents.

Carbonation

The LCB cores showed complete carbonation except for the geometric center of the core. These measurements, however, are very likely not reflective of the actual carbonation situation of these cores in service. The reason for this is that the cores were taken almost four years ago, and most of the carbonation is likely due to the exposure of these highly porous concretes to atmospheric carbon dioxide (which would not occur in service).

Cement Paste/Aggregate Bond

Despite the high w/c in these concretes, a tight, uninterrupted bond persists between the cement paste and the coarse aggregate particles. Intentional fracturing (split tensile test) of portions of these cores in the present investigation actually showed that 10% to 20% of the coarse aggregate particles fracture. This reflects, in large part, the excellent bonding surfaces of the coarse aggregate particles.

Moisture Migration

Despite the highly porous nature of this lean concrete, there is very little evidence of secondary deposits in these concrete microstructures. This is true even for Core LCB-1, which in service is located directly under Core PCC-1, which contains a full-depth crack.

The indications that there has been very little moisture cycling in the lean concrete base suggests one of two possible conditions that could account for this. Either the concrete has been relatively dry over its 8-year exposure time, or it has remained relatively saturated. Observations made in the present investigation, as well as moisture measurements made at the project site, suggest that the latter condition (ongoing saturation) has been in effect.

Cement-Aggregate Reactions

The only indication of ASR activity in the concrete represented by these cores is the presence of reaction rims on chert aggregate particles. There is, however, no cracking distress associated with these aggregate particles, and no ASR reaction product was expelled from these cores during their preparation for the microscopic examination.

Distress Features

Portland cement concrete Core PCC-1, from Test Section 206, was taken through a full-depth, longitudinal crack in the pavement. Despite this, the lean concrete base material directly under this pavement core shows no cracking distress of any type. Cores LCB-2 and LCB-3, also from Test Section 206, show no distress of any type.

As shown in Figure 8, Core LCB-4, taken from Test Section 205, had a full-depth crack in service. The portland cement concrete overlying Core LCB-4 also shows a crack perpendicular to the wearing surface (Core PCC-4, Figure 7). However, in Core PCC-4, the crack does not pass through the full thickness of the core (see Figure 14). The fracture surface in Core LCB-4 shows mainly coarse aggregate pullout.

In Core LCB-4, the wearing surface was grooved after the concrete had hardened and prior to the placement of the PCC pavement slab. This treatment of the wearing surface of the LCB was not done in Test Section 206.

Lean Concrete Base (LCB) Summary

The concrete evaluated in the trial mix design work contained only portland cement as the cementitious phase. The in-place concrete contained both portland cement and fly ash as the cementitious phase. ODOT Concrete Inspection Reports indicate that the lean concrete base was placed with 160 pounds of portland cement and 48 pounds of Class C fly ash. It is judged that the in-place concrete is in reasonable compliance to these values of cementitious ingredients.

The target air content of the lean concrete base is 6% ±2%. When considering only the entrained air content (air voids less than 1-mm in diameter), the three cores representing LCB from the

Section 206 pavement meet the target value, while the single core from Section 205 has an entrained air void content below the target value (2.2%). The four LCB cores showed relatively high levels of air voids larger than 1-mm, ranging from 3.7% to 6.2%. These large voids represent both entrapped air voids and incomplete consolidation of the concrete.

The incomplete consolidation of the lean concrete base, combined with the high w/cm, indicates that this concrete has a high permeability. This condition is in keeping with the observation that this base material in service was saturated much of the time. Despite this condition, the LCB cores examined here do not show any cracking distress that could be attributed to freeze/thaw cycling. The LCB core from Section 205 contains a full-depth fracture, the plane of which is oriented perpendicular to the plane of the wearing surface. This is a longitudinal crack (slightly skewed) in the base material that may be due to structural failure.

RESULTS: SOUTHBOUND RAMP CONCRETE

Cores 809 and 810, shown in Figure 9, were taken from the 8-inch section and 11-section of the ramp, respectively. Concrete for the ramp was intended to be an air-entrained concrete containing both portland cement and fly ash as cementitious ingredients. As shown in Table 5, the target cement content is 350 pounds per cubic yard, and the target fly ash content is 120 pounds per cubic yard. These values reflect the mix design evaluated as the "trial mix". The ODOT Concrete Inspector's Report indicates that the fly ash content actually used was 52 pounds per cubic yard, with a w/cm of 0.58.

Cementitious Phase

The cementitious phase in Core 809 is composed of well hydrated portland cement and fly ash.

The cementitious phase shows a moderate degree of hardness with a water to cementitious material ratio (w/cm) estimated at 0.55 to 0.58.

In Core 810, the cementitious phase is also composed of both well hydrated portland cement and fly ash, with the bulk of the top 8-inches of the core having a w/cm estimated at 0.52. In the bottom 3-inches of this 11-inch core, the w/cm is considerably lower estimated at 0.45.

The measured cement paste content in Core 809 is 20.4%. The measured cement paste content in Core 810 is 20.7%.

Air Content

The concrete represented by both cores is air-entrained. The total air void content in Core 809 is 7.4%; the total air void content in Core 810 is 7.0%. As shown in Table 9, about 35% of the total air void content is represented by entrapped air voids having a diameter greater than 1-mm.

In Core 810, which is 11-inches long, the air content is not uniform from top to bottom in the core. In the top half of the core, the total air void content is 5.7%, while in the bottom half of the core the total air void content is 8.2%.

Density

Density measurements were made following a 48-hour water soaking period. The water saturated density of Core 809 is 140.5 lb/ft^3, while that of Core 810 is 140.8 lb/ft^3.

Carbonation

The depth of carbonation of the wearing surface of Core 809 is a maximum of 6-mm with a typical carbonation depth of 3-mm to 4-mm. The wearing surface of Core 810 shows a carbonation depth of 3-mm to 5-mm.

Cement Paste/Aggregate Bond

As was observed in all of the other cores examined on this project, a tight, uninterrupted bond has persisted between the coarse aggregate particles and the cementitious phase over the 7-year service life of the ramp pavement slabs.

In both cores, the mode of failure of the concrete in the split tensile test was 100% coarse aggregate fracture.

Moisture Migration

In Core 809, the top 5-inch thickness of this 8-inch long core shows very light secondary deposits. In the bottom 3-inches of the core, secondary deposits are light to moderate.

The condition just described for Core 809 also holds for Core 810, with the greatest accumulation of secondary deposits in the bottom third of the core.

Cement-Aggregate Reactions

There is no indication of any ASR activity in the concrete represented by these cores.

Distress Features

The wearing surface in both cores retains the original grooved texture. However, in both cores, although not necessarily viewed as a distress feature, a thin (less than 0.5-mm) layer of cement paste has been lost revealing the surfaces of fine aggregate particles over the entire wearing surface.

Neither of these cores shows any evidence of cracking distress or any other type of distress.

Ramp Concrete Summary

Measurements made on two cores in the present investigation indicate reasonable compliance of the in-place concrete with the concrete mix design as reflected in the ODOT Concrete Inspector's Report for this concrete. The latter shows a portland cement content of 350 pounds per cubic yard and a fly ash content of 52 pounds per cubic yard with a w/cm of 0.58.

The concrete is air-entrained and the target air content value of 6% ±2% was met.

Neither of the two cores examined here show cracking distress or distress of any other type.

SUMMARY AND CONCLUSIONS

The SHRP Specific Pavement Studies Test Road near Delaware, Ohio, was constructed during 1995, and completed in 1996. Longitudinal cracking developed in two of the PCC test sections in 1999. These test sections (390205 and 390206) are constructed of 8-inches of portland cement concrete (PCC) on 6-inches of lean concrete base (LCB). Subsequent to 1999, cracking has developed in all of the other 8-inch thick PCC sections on the test road, as well as in the 11-inch PCC section over the lean concrete base.

The present petrographic examination was conducted to learn the effect of the portland cement concrete proportioning and properties on this cracking distress. Beyond this issue, there is an interest in learning what factors are involved in the cracking.

The petrographic examination was conducted on ten, 6-inch diameter cores taken from three of the PCC test sections. All of the cores were taken in October 1999. The cores were taken from the two mainline PCC pavement sections that showed the early longitudinal cracking (Section 390205 and Section 390206), as well as the southbound entrance ramp to the mainline PCC

pavement, which also showed early deterioration (390809 and 390810). Four full-depth cores were taken in the mainline pavement sections, which include an 8-inch thickness of the PCC and a 6-inch thickness of the LCB. One 8-inch core and one 11-inch core was taken in the south-bound ramp pavement.

The significant observations and the conclusions derived from the present examination are summarized below.

LONGITUDINAL CRACKING ISSUE

Only one of the four mainline PCC pavement cores examined here was taken through a longitudinal crack (Core PCC-1). However, observations made on this core provide insights into the nature of the crack development and propagation.

The fracture plane in Core PCC-1 is oriented perpendicular to the plane of the wearing surface. This is not a single, simple crack. There is actually more than one crack involved, and these cracks exhibit a significant amount of branching. The cracks pass through, rather than around, coarse aggregate particles. These features are shown in Figures 1 and 12. The nature of this cracking indicates that it occurred as a result of repeated stress applications over a period of time. This pattern suggests that it is a fatigue failure.

A failure of this type would require either a failure of the LCB base material, or curling in the PCC slab itself. Observations made in the present investigation, as well as data generated on the project site itself, suggests that the latter (PCC slab curling) is most likely to be involved. There is no evidence indicating that either the lean concrete base or the sub-base has failed.

The curling of portland cement concrete slabs occurs as a result of differential movement

(strains) in the top of the slab relative to the bottom. These strains can be a result of either differential temperatures in the top and bottom of the slab, as well as differential moisture contents in the top and bottom of the slab. Both of these features are operative here.

The overall orientation of the test road is north/south. Transverse construction joints in the PCC pavements, the lines of which follow an east/west axis, are doweled. The distance between construction joints is 14-feet. The presence of the dowels is expected to restrict curling along the north/south axis, but would have little effect on curling along the east/west axis. With respect to vehicle wheel loads, curling along this axis would be expected to result in live loads that could produce a longitudinal crack. Fatigue failures can occur at stress levels well below those required to fail the concrete under static loading conditions.

One factor that may be involved in exaggerating the amount of curl in the PCC slabs over the lean concrete base, is the likelihood of a high degree of water saturation in the LCB on an ongoing basis. Due to this condition, the bottom of the PCC slab would also experience a relatively high degree of water saturation over time. The top of the PCC slab would experience dimensional changes in response to the loss and gain of surface water. During periods of drying, the curling strains in the top of the slab would be expected to be high relative to the moisture-saturated bottom of the slab.

As discussed earlier, although the 8-inch thick PCC slabs on the lean concrete base were the first to show longitudinal cracking, subsequent longitudinal cracking in the 11-inch PCC concrete sections has only occurred to date in those slabs placed on the lean concrete base. It is expected that the magnitude of curling will decrease as a function of a an increase in slab thickness. All four of the PCC cores examined here achieved, or slightly exceeded the target pavement

thickness of 8-inches.

Role Of Concrete Composition And Proportioning In The Cracking Problem

The ten cores examined here represent four different air-entrained concretes. They include:

1. a high strength concrete containing 750 pounds of portland cement and 113 pounds of Class C fly ash per cubic yard, with a w/cm of 0.31. This concrete is the PCC wearing course in Test Section 390206
2. ODOT Class C, Option 1 Concrete which contains 510 pounds of portland cement and 90 pounds of Class C fly ash per cubic yard, with a w/cm of 0.4 (This concrete is the PCC wearing course in Test Section 390205.)
3. concrete for the lean concrete base (LCB), which contains 160 pounds of portland cement and 48 pounds of Class C fly ash per cubic yard, with a w/cm around 1.5 (This concrete was used as the lean concrete base under Test Sections 390205 and 390206.)
4. concrete used in the southbound ramp to the mainline PCC sections, which had 350 pounds of portland cement and 120 pounds of Class F fly ash per cubic yard, with a w/cm of 0.5

All of the concretes were intended to be air-entrained with a total air void content of 6% ±2%.

The coarse aggregate was the same in all of the concretes (Carey-National Lime). The fine aggregate was also the same in all of the concretes (Prospect Sand). Issues relating to compliance of the in-place concretes with the compositional requirements and the proportioning target values are summarized below:

1. All of the concretes contain the same fine and coarse aggregates.
2. The cementitious phase in all of the concretes is composed of both well hydrated portland cement and fly ash. Fly ash was an intended ingredient in all of the concretes except the lean concrete base. Trial mix work done on the lean concrete base showed only portland cement as the cementitious phase.
3. The w/cm of all of the concretes is in reasonable compliance with the mix design target values.
4. All of the concretes are air-entrained. Two of the three cores taken from Section 390206, and the one core taken from Section 390205, show a total air void content well

below the specified minimum value of 4% (2.2% to 2.5%). Two of the LCB cores had total air void contents in excess of the target maximum value of 8% (9.4% and 11.0%).

5. The cementitious materials content is judged to be in reasonable compliance with the target values in all four of the concretes.

Based on the above assessments, the major noncompliance issues include (1) the use of fly ash in the lean concrete base, (2) the lower than desired air content in the mainline PCC concretes, and (3) the higher than desired air content in the lean concrete base.

The use of fly ash in the lean concrete base is not expected to have had an adverse effect on the structural performance of the base inasmuch as the fly ash was added in addition to the same amount of portland cement that was used in the trial mixes for this concrete.

The low air void content in the mainline PCC concrete would not be expected to have contributed to the longitudinal cracking problem. As a variable, air content is expected to have little or no effect on the magnitude of curling strains, and decreases in air content are expected to increase both flexural and compressive strength.

The high total air void content in some of the LCB cores appears, in part, as a result of incomplete consolidation of these concretes, resulting in pockets of gross porosity. This may have had the effect of increasing the permeability of these concretes, and contributing to the high moisture levels of the base concrete in service.

Overall Performance Of The Concretes In Service

The principal concern with the PCC mainline concretes on the test road is the occurrence of longitudinal cracking. Only one of the four mainline PCC cores examined here was taken through a longitudinal crack. The only other occurrence of cracking distress in these four cores is

a tight, partial-depth crack in Core PCC-4 that is attributed to restrained drying shrinkage strain. Beyond these issues, all of the PCC concretes represented by the cores examined here show no evidence of any other major distress or degradation issues.

Three of the four lean concrete base (LCB) cores examined here show no evidence of distress of any type. One of the LCB cores contains a full-depth fracture oriented perpendicular to the plane of the wearing surface of the core.

Despite the fact that portions of the mainline portland cement concrete wearing courses had a low level of air-entrainment, there is no evidence of any freeze/thaw related cracking in these concretes. This result is attributed to the fact that the concretes have some level of air-entrainment and to the good quality (low w/cm) of the cementitious phase. None of the LCB cores show any evidence of freeze/thaw-related cracking.

The coarse aggregate in all of the concretes is a hard dolomitic limestone with a low rate of water absorption. This aggregate has shown excellent durability over the 7-year service life of these pavements. In all four of the concretes examined here, the quality of the bond between the cement paste phase and the aggregate particles is judged to be excellent.

As discussed in the body of this report, there is an indication of alkali-silica reaction activity in the high strength concrete in Test Section 390206. This activity is characterized as being very mild and has resulted in no distress or degradation of this concrete. The absence of this activity in the other concretes suggests that it is the high level of cementitious phase in this concrete that has contributed to this result (high alkali level).

Compressive strength measurements made on cores taken from Test Sections 390205 and 390206 at 1-year showed values around 8000 psi. Observations made on PCC cores taken from these sections indicate that these strength levels are currently being maintained. This assessment is based on the observed mode of failure for portions of the cores intentionally fractured in the present investigation, along with an assessment of the quality of the cementitious phase and on the absence of any degradation/distress features in these concretes. Beyond the longitudinal cracking issue, which is the subject of the present investigation, the mainline PCC cores examined here have shown excellent durability over their 7-year service life.

Dr. David R. Lankard, President & Petrographer
Lankard Materials Laboratory, Inc.

DRL/pl

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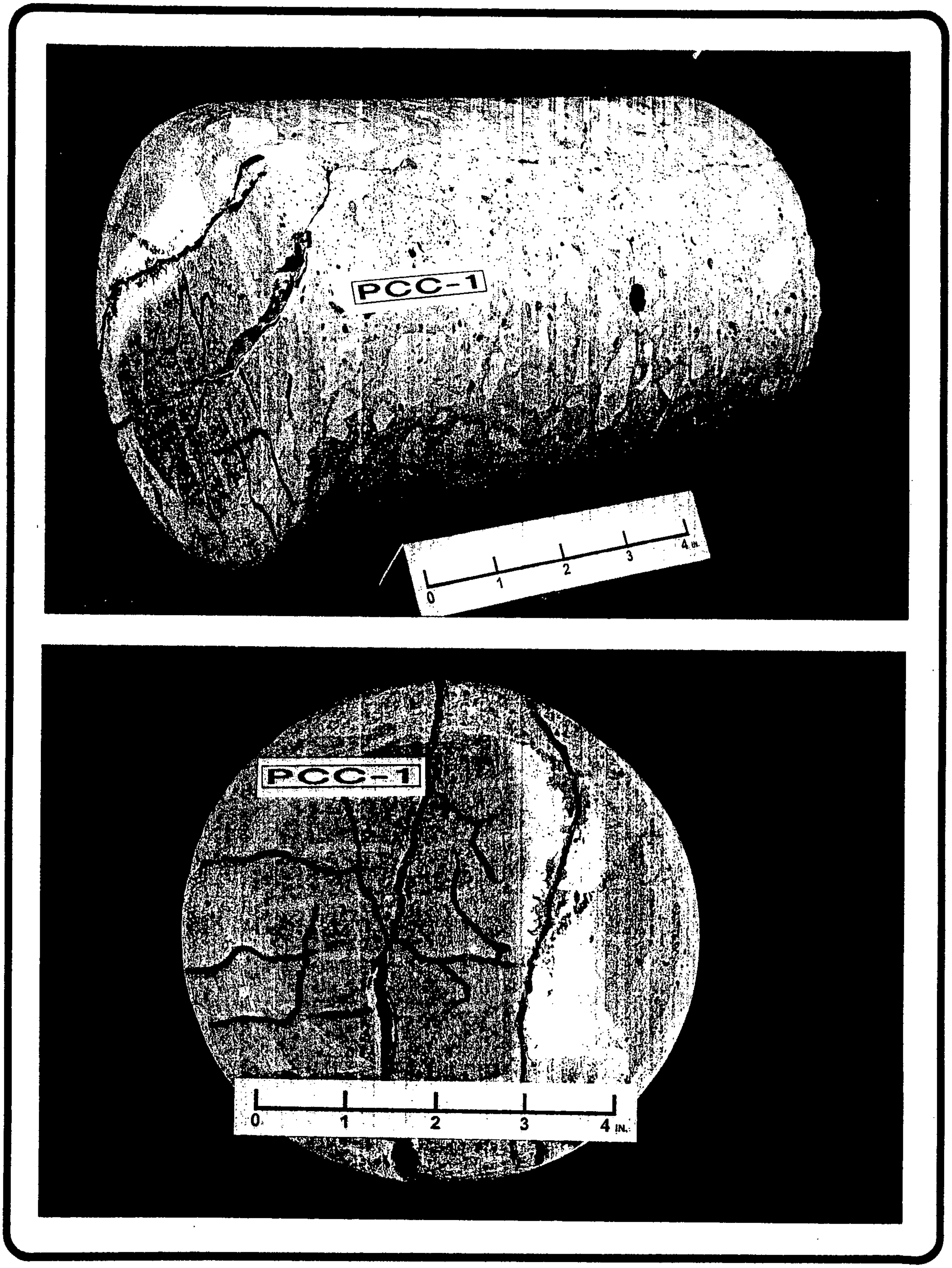


Figure 1. Core PCC-1 As-Received at LML

This is a portland cement concrete core from the Mainline Pavement Section 390206. This full-depth core has a diameter of 6-inches and a length of 8½-inches. This core was taken through a full-depth longitudinal crack in the pavement. This crack, as well as crazing cracks in the wearing surface are delineated with a black marking pen.

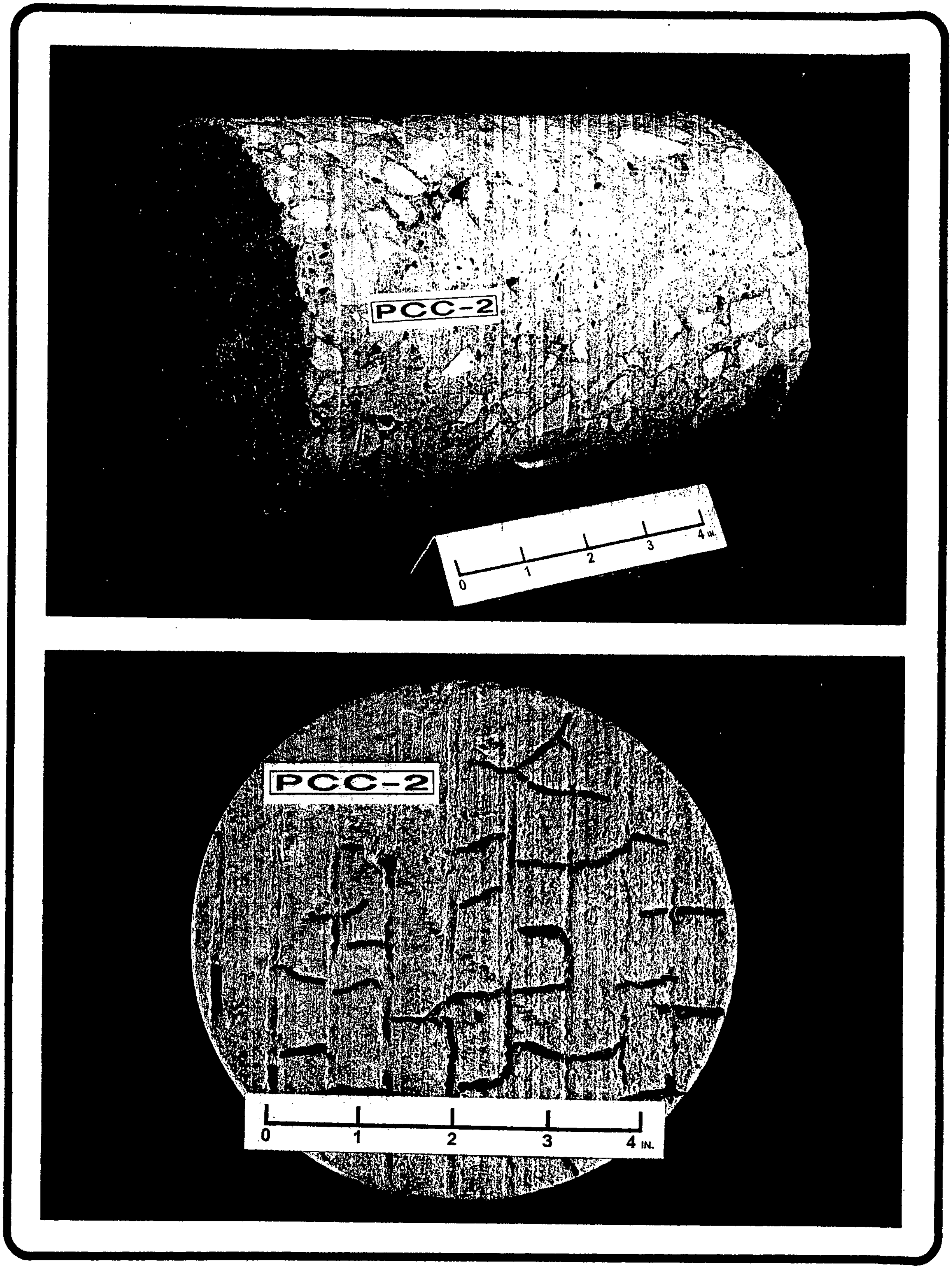


Figure 2. Core PCC-2 As-Received at LML

This is a portland cement concrete core from the Mainline Pavement Section 390206. This full-depth core has a diameter of 6-inches and a length of 8⅛-inches. Crazing cracks in the wearing surface are delineated with a black marking pen.

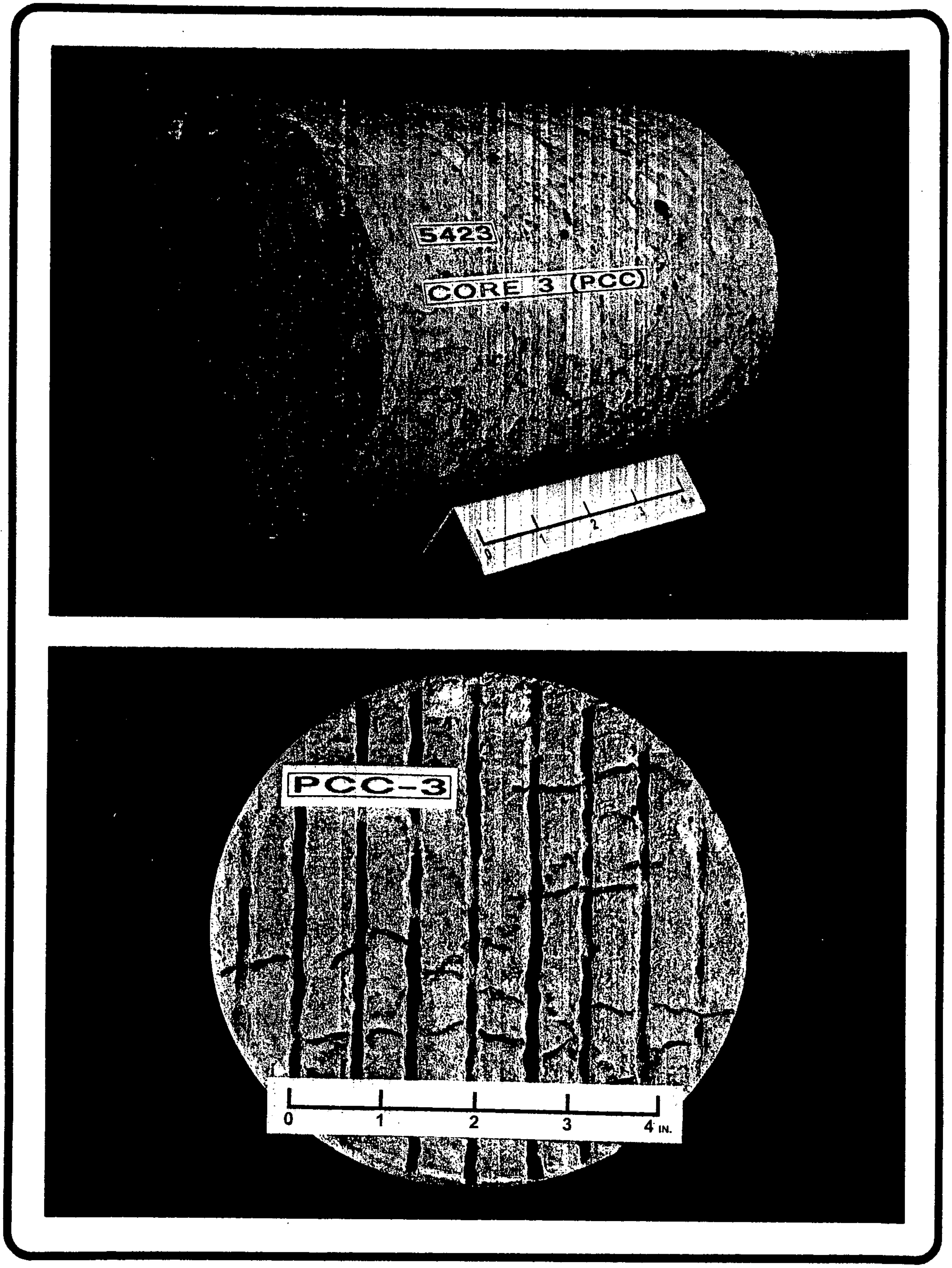


Figure 3. Core PCC-3 As-Received at LML

This is a portland cement concrete core from the Mainline Pavement Section 390206. This full-depth core has a diameter of 6-inches and a length of 8⅛-inches. Crazing cracks in the wearing surface are delineated with a black marking pen.

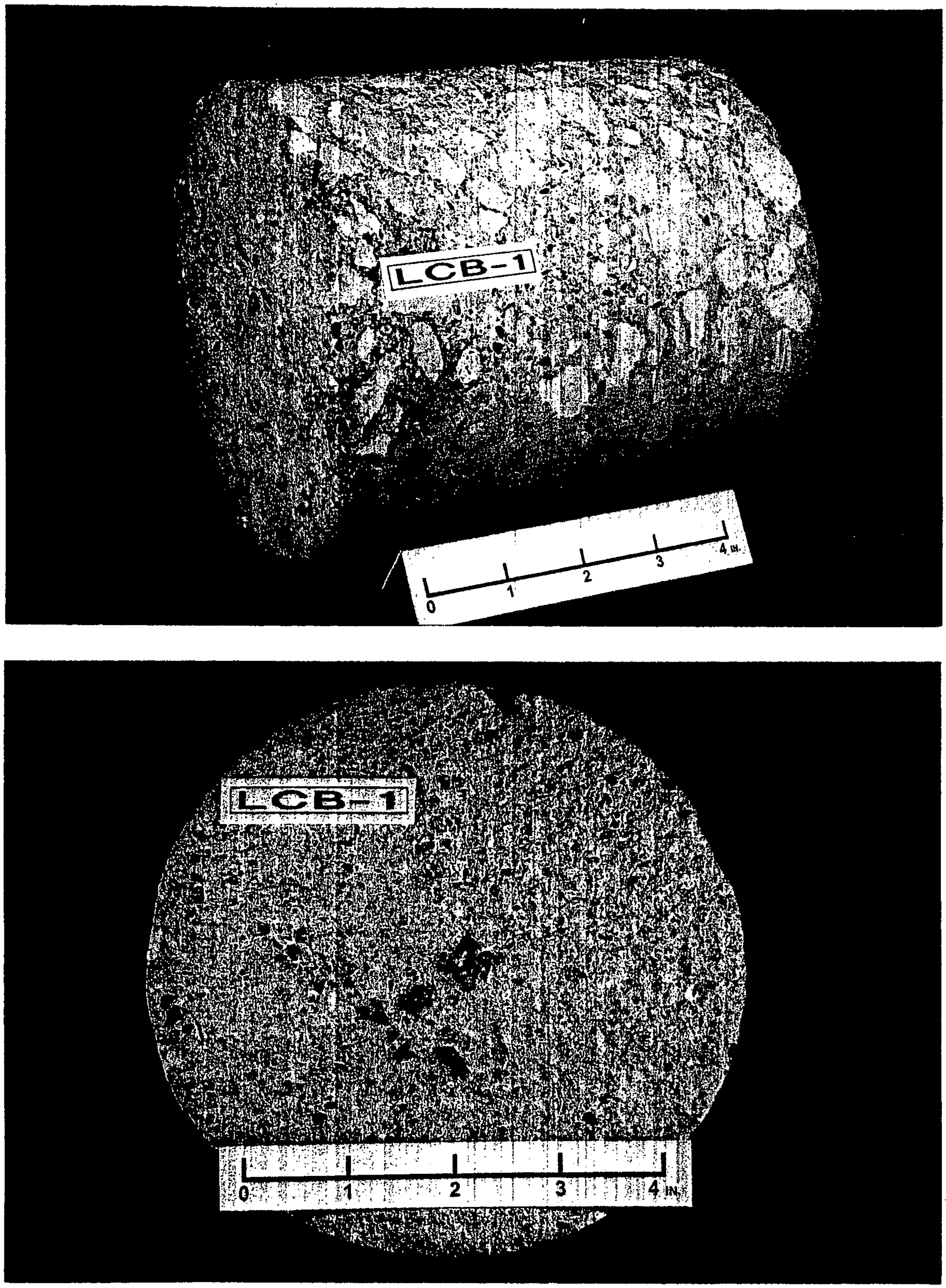


Figure 4. Core LCB-1 As-Received at LML

This is the lean concrete base (LCB) directly under Core PCC-1. This full-depth core has a diameter of 6-inches and a length of 6-inches.

Figure 4

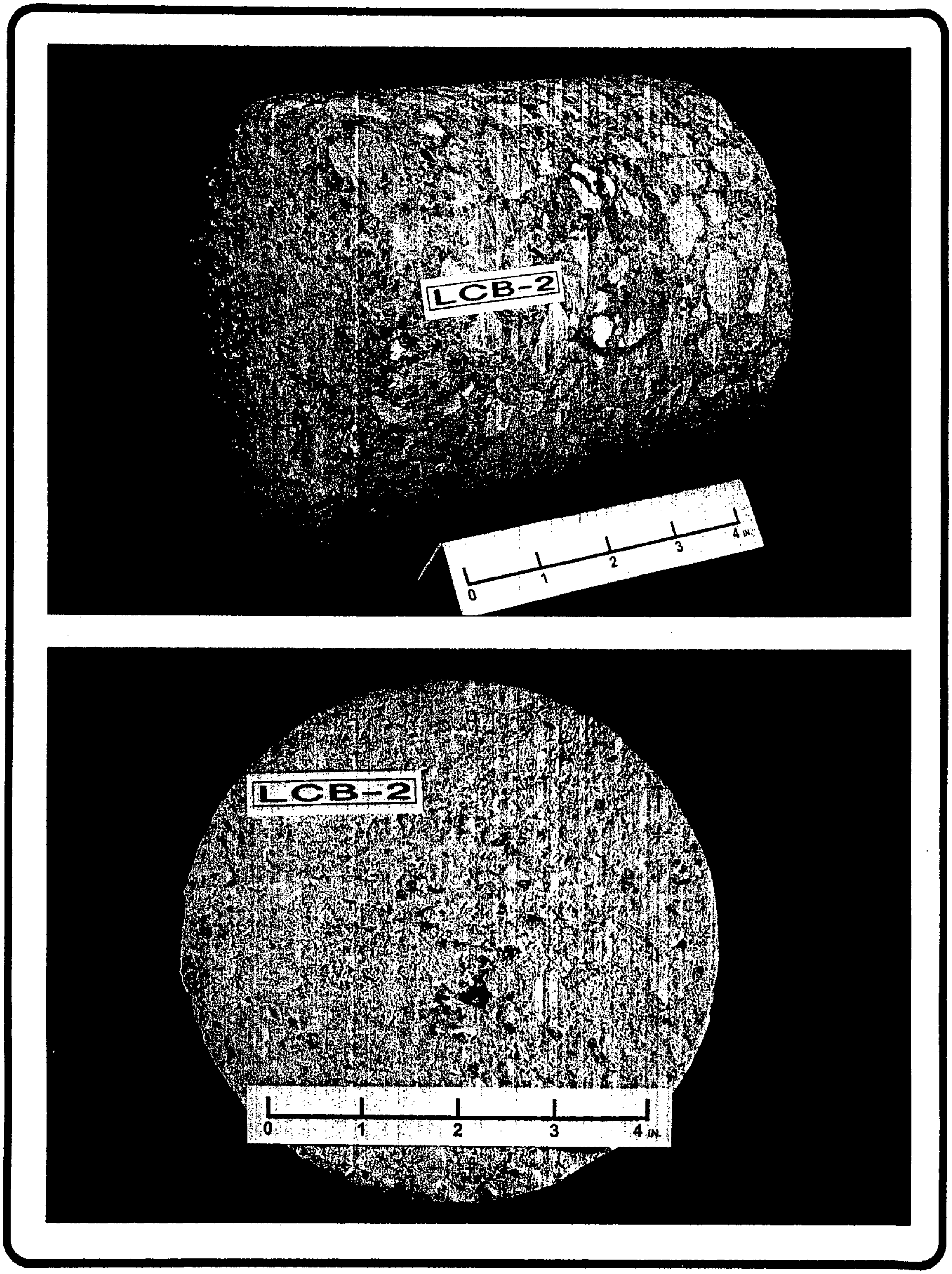


Figure 5. Core LCB-2 As-Received at LML

This is the lean concrete base (LCB) directly under Core PCC-2. This full-depth core has a diameter of 6-inches and a length of 6⅛-inches.

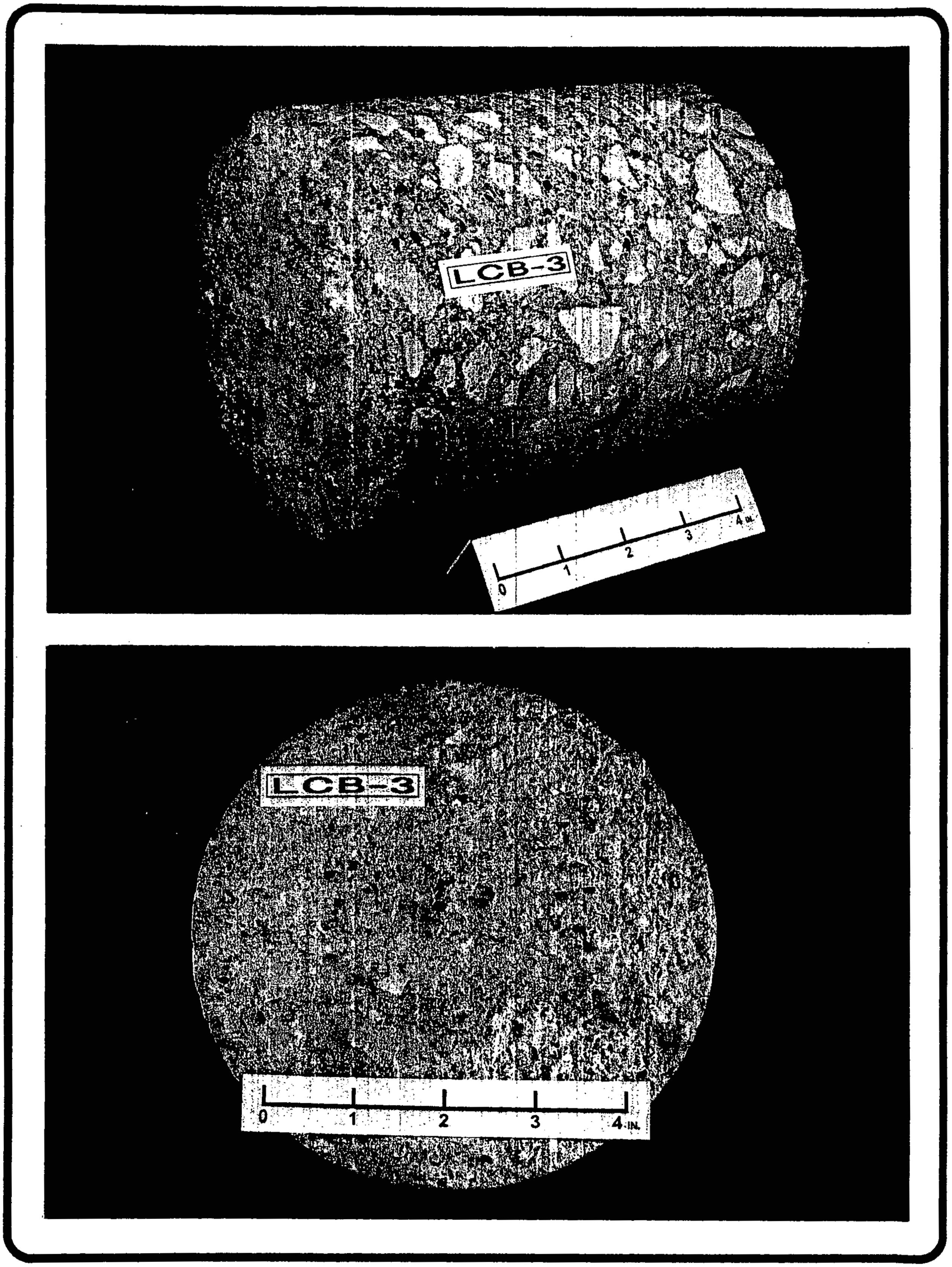


Figure 6. Core LCB-3 As-Received at LML

This is the lean concrete base (LCB) directly under Core PCC-3. This full-depth core has a diameter of 6-inches and a length of 6½-inches.

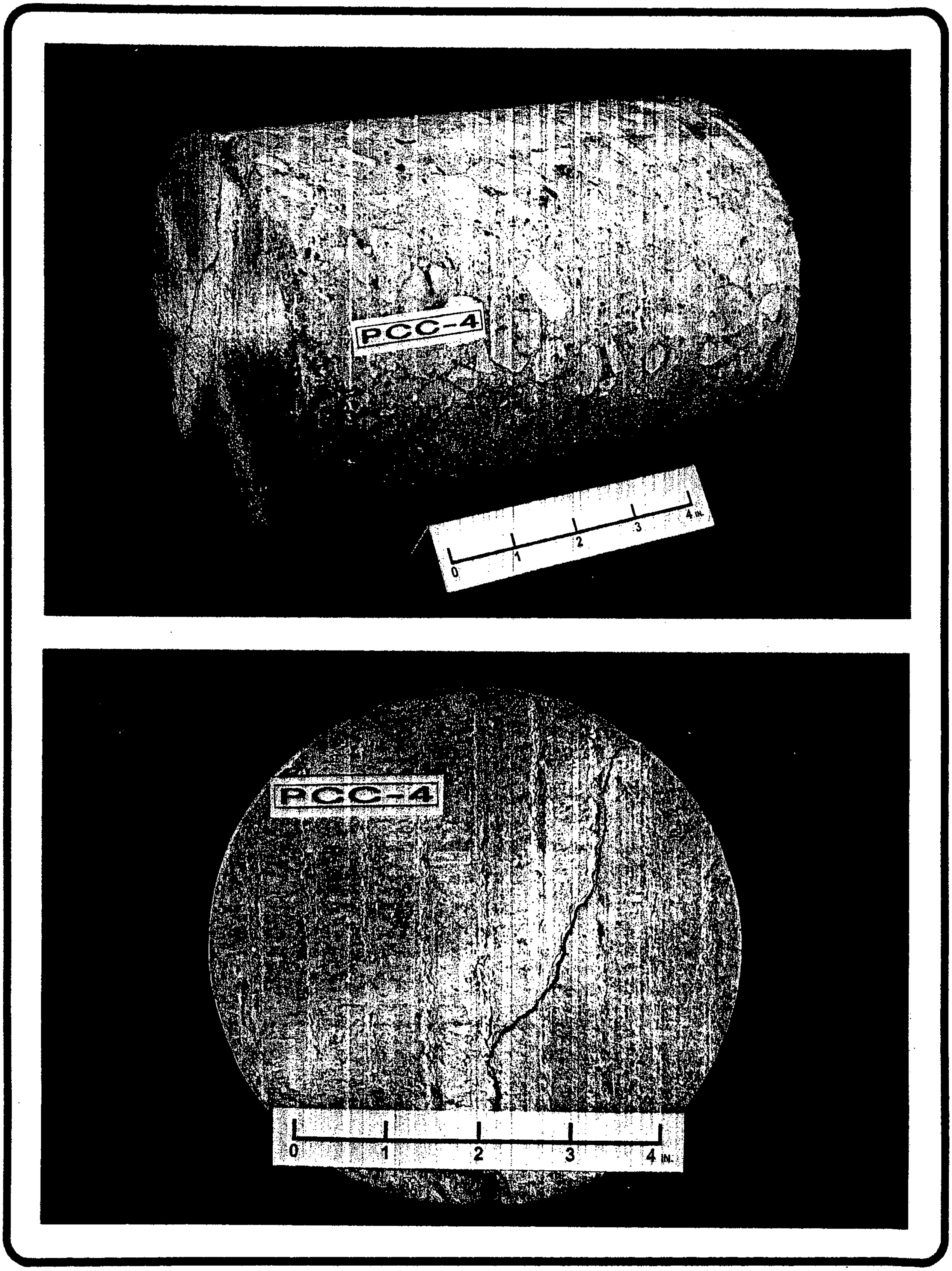


Figure 7. Core PCC-4 As-Received at LML

This is a portland cement concrete core from the Mainline Pavement Section 390205. This full-depth core has a diameter of 6-inches and a length of 8-inches. This core was taken through a crack in the pavement that is 4-inches deep. This crack is delineated in the photos with a black marking pen.

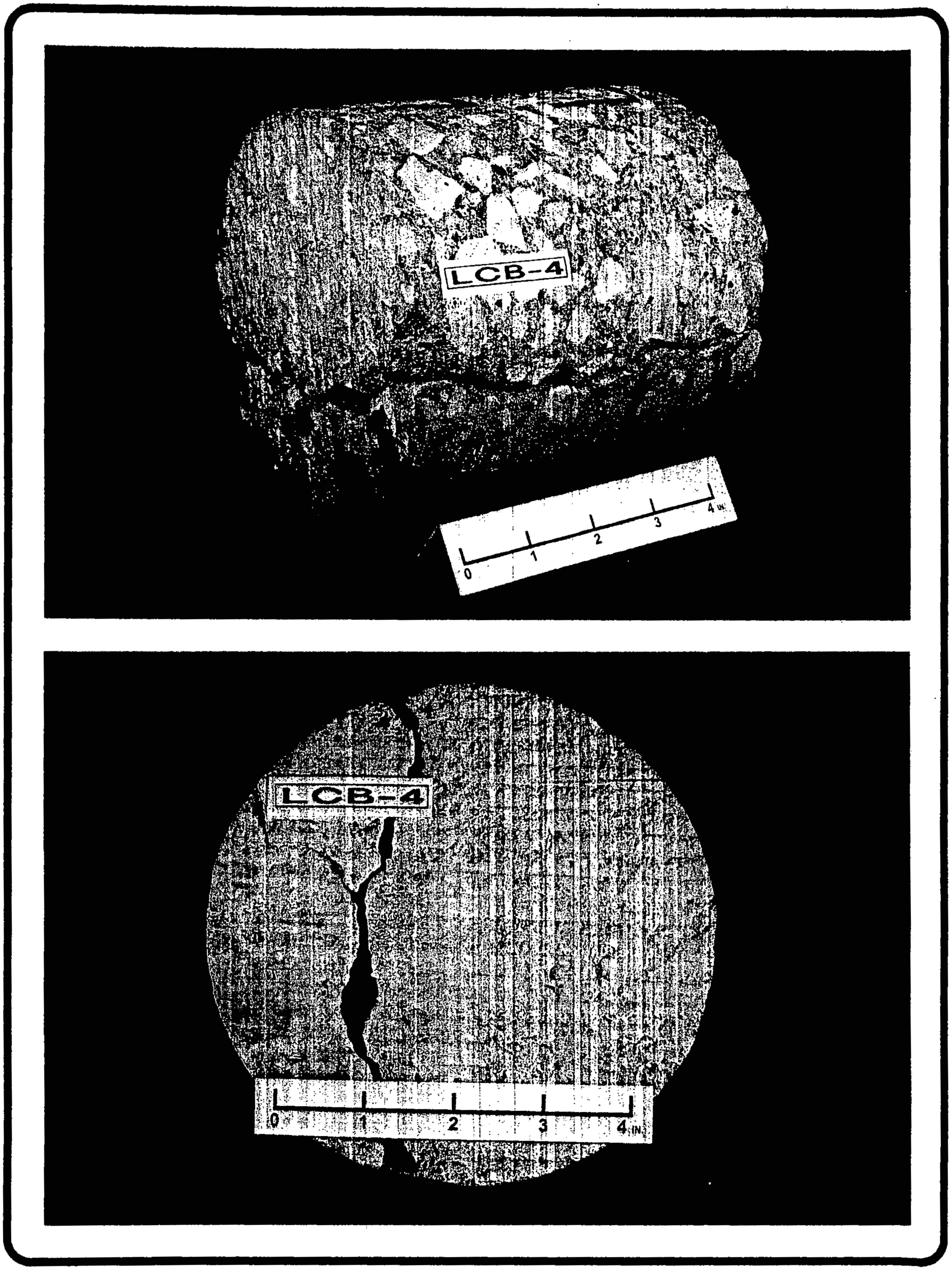


Figure 8. Core LCB-4 As-Received at LML

This is the lean concrete base (LCB) directly under Core PCC-4. This full-depth core has a diameter of 6-inches and a length of 5¾-inches. This core was received in two pieces, separated by a full-depth crack. Note that the wearing surface of this core is grooved.

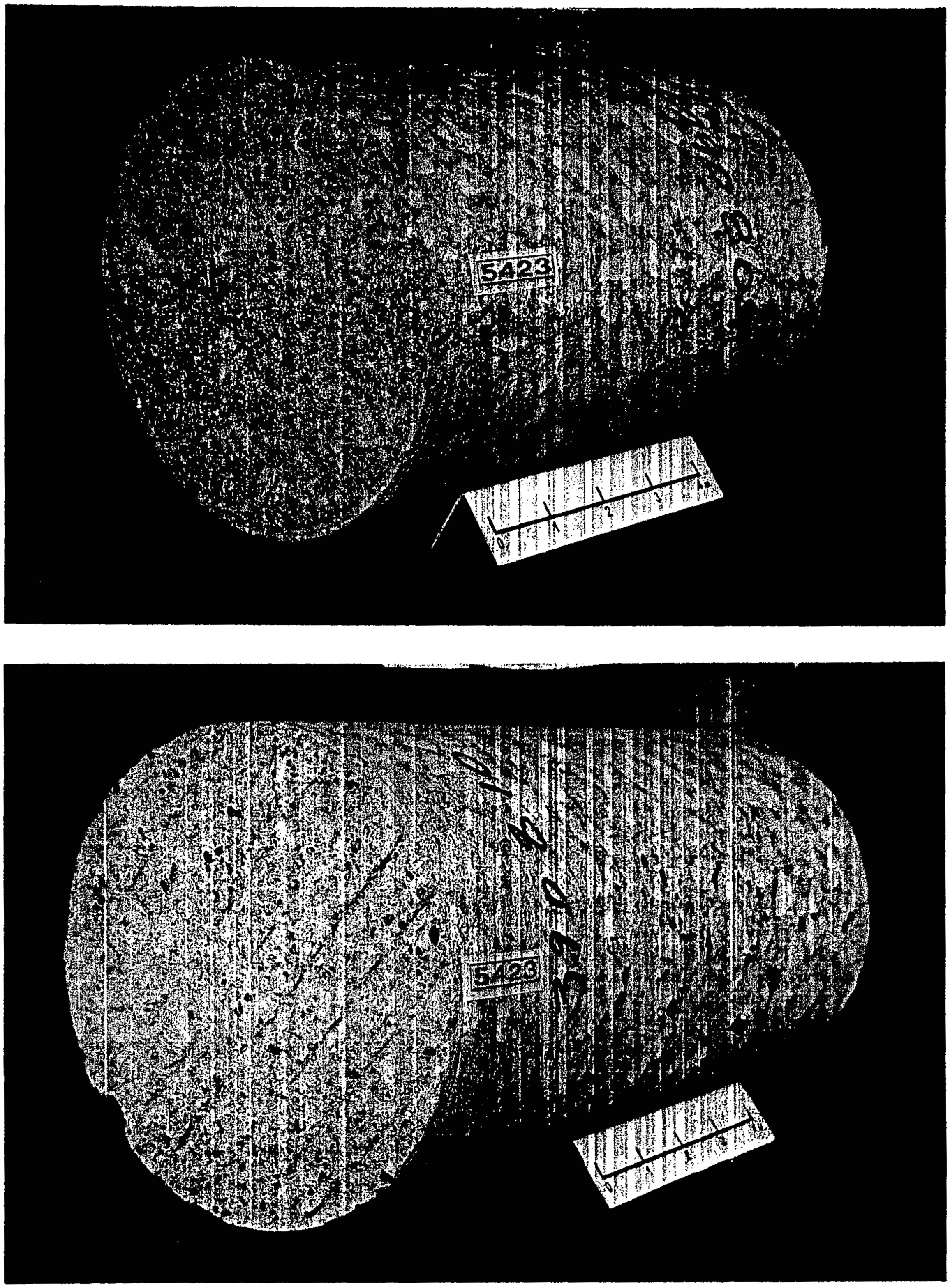


Figure 9. Cores 809 and 810 Representing PCC Pavement from the Southbound Ramp Section (Experiment SPS-8): Test Sections 390809 and 390810

Both cores have a diameter of 6-inches. Core 809 has a length of 8-inches. Core 810 has a length of 11-inches.

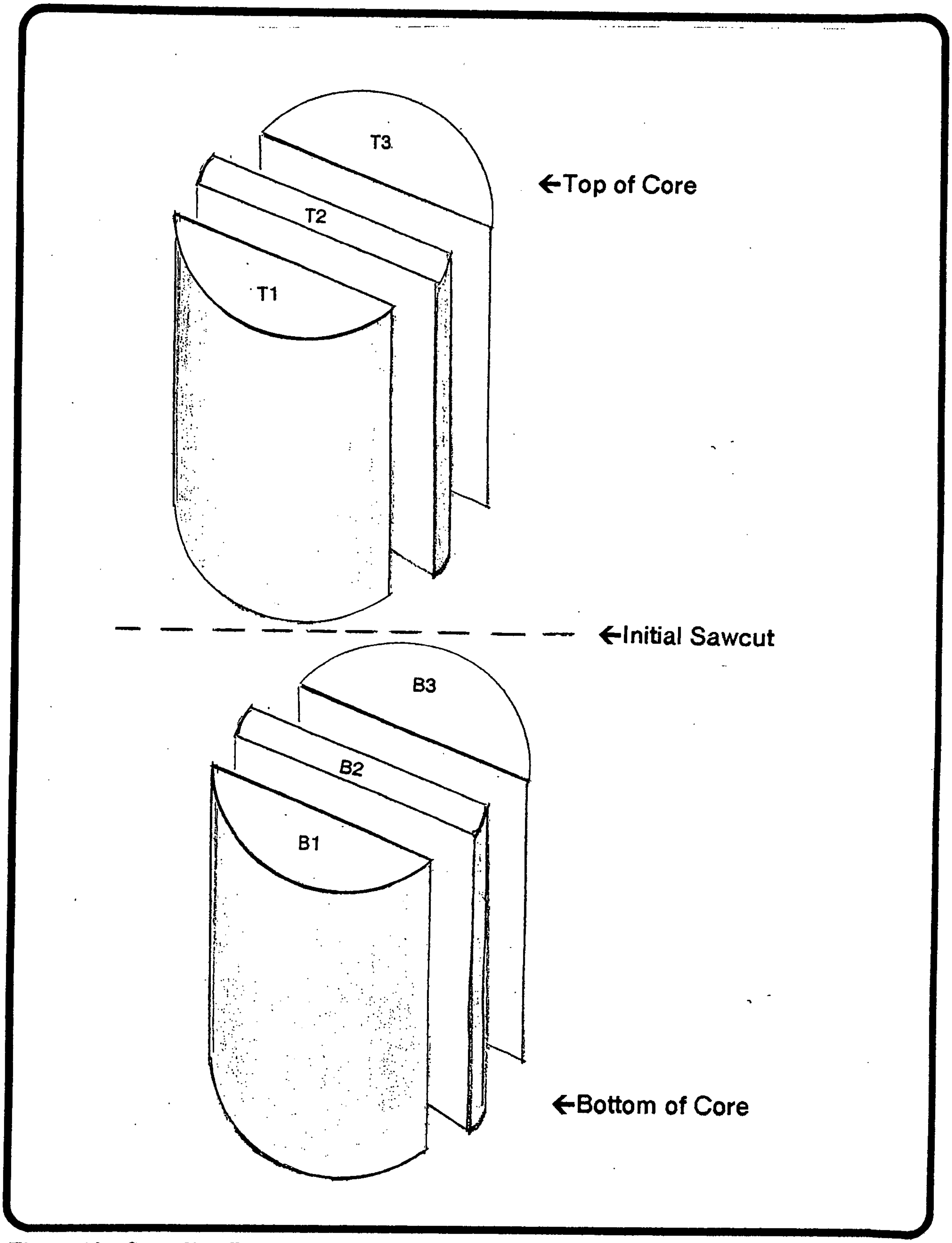
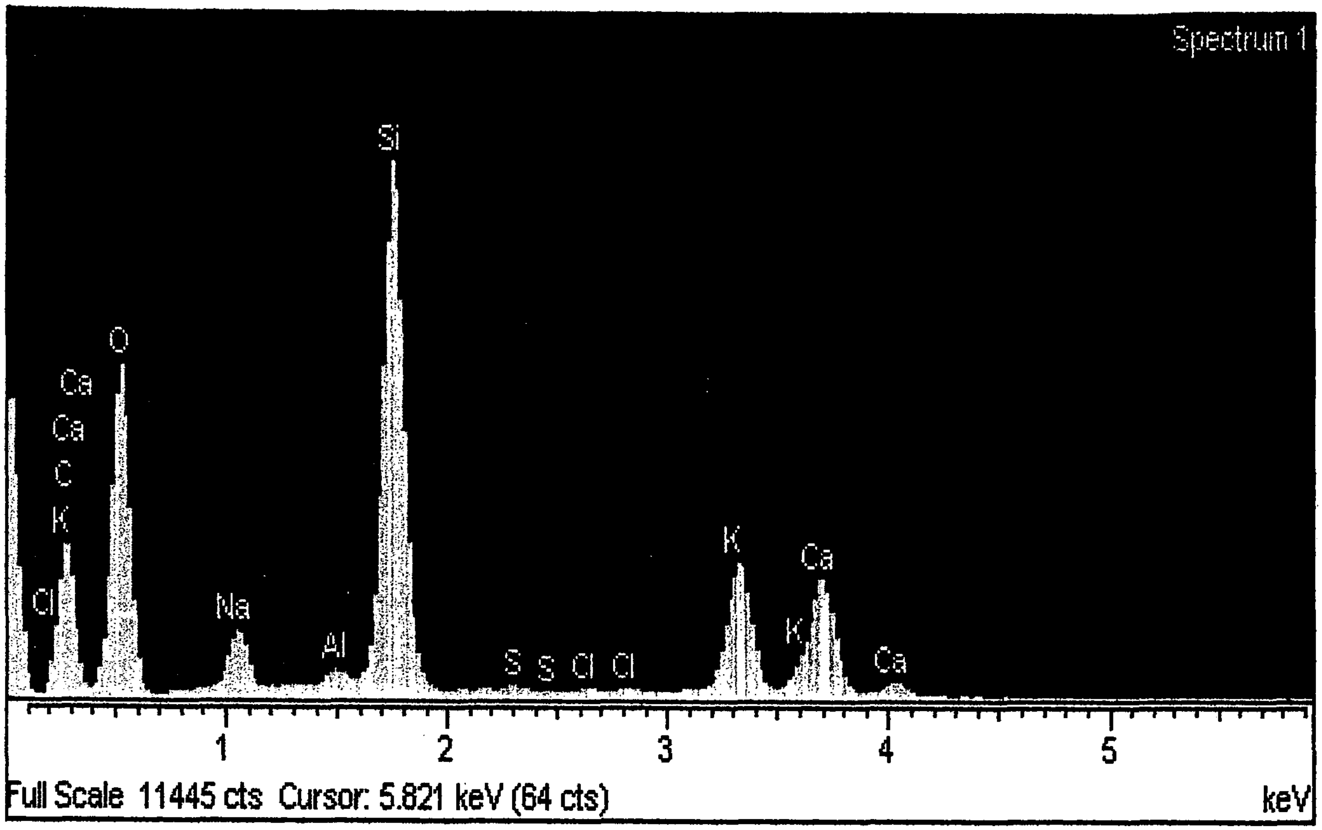


Figure 10. Sampling Diagram for Examination of the PCC Concrete Cores in the Present Investigation

The core samples, originally in the shape of a right circular cylinder, are sawcut using a diamond saw to yield the indicated sections. The initial sawcut was not needed for the LCB cores.

Figure 10



Element	Weight%	Atomic%	Compd%	Formula	Number of ions
Na K	4.56	4.48	6.15	Na2O	0.61
Al K	0.64	0.53	1.21	Al2O3	0.07
Si K	26.96	21.65	57.68	SiO2	2.97
S K	0.31	0.22	0.77	SO3	0.03
Cl K	0.17	0.11	0.00		0.01
K K	13.04	7.52	15.70	K2O	1.03
Ca K	13.09	7.37	18.31	CaO	1.01
O	41.23	58.13			7.99
Totals	100.00				
				Cation sum	5.74

Figure 11. Energy Dispersive X-ray Spectroscopy (EDS) Spectrum of Material Deposited as Efflorescence on Lapped Surfaces of PCC Cores from Test Section 390206

The material is reaction product from alkali-silica reaction activity in these concretes.

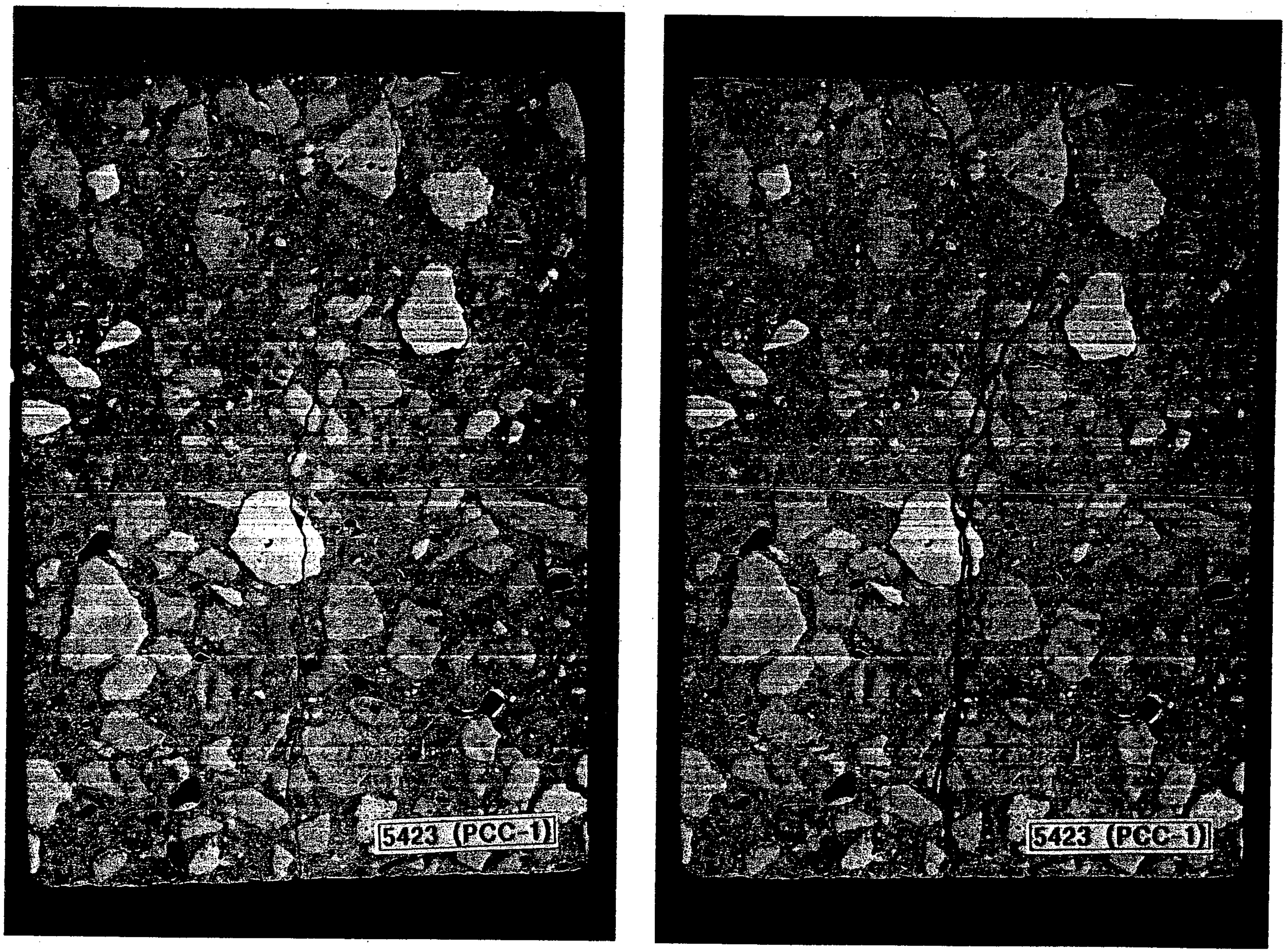


Figure 12. Section View (Perpendicular to the Wearing Surface) of Core PCC-1 (Test Section 390206)

The wearing surface is at the top in the photographs. The left-hand photograph shows the as-lapped surface. In the right-hand photograph, cracks in the concrete are delineated with a black marking pen (including wearing surface crazing cracks and short, discontinuous microcracks at lower depths in the core).

Figure 12

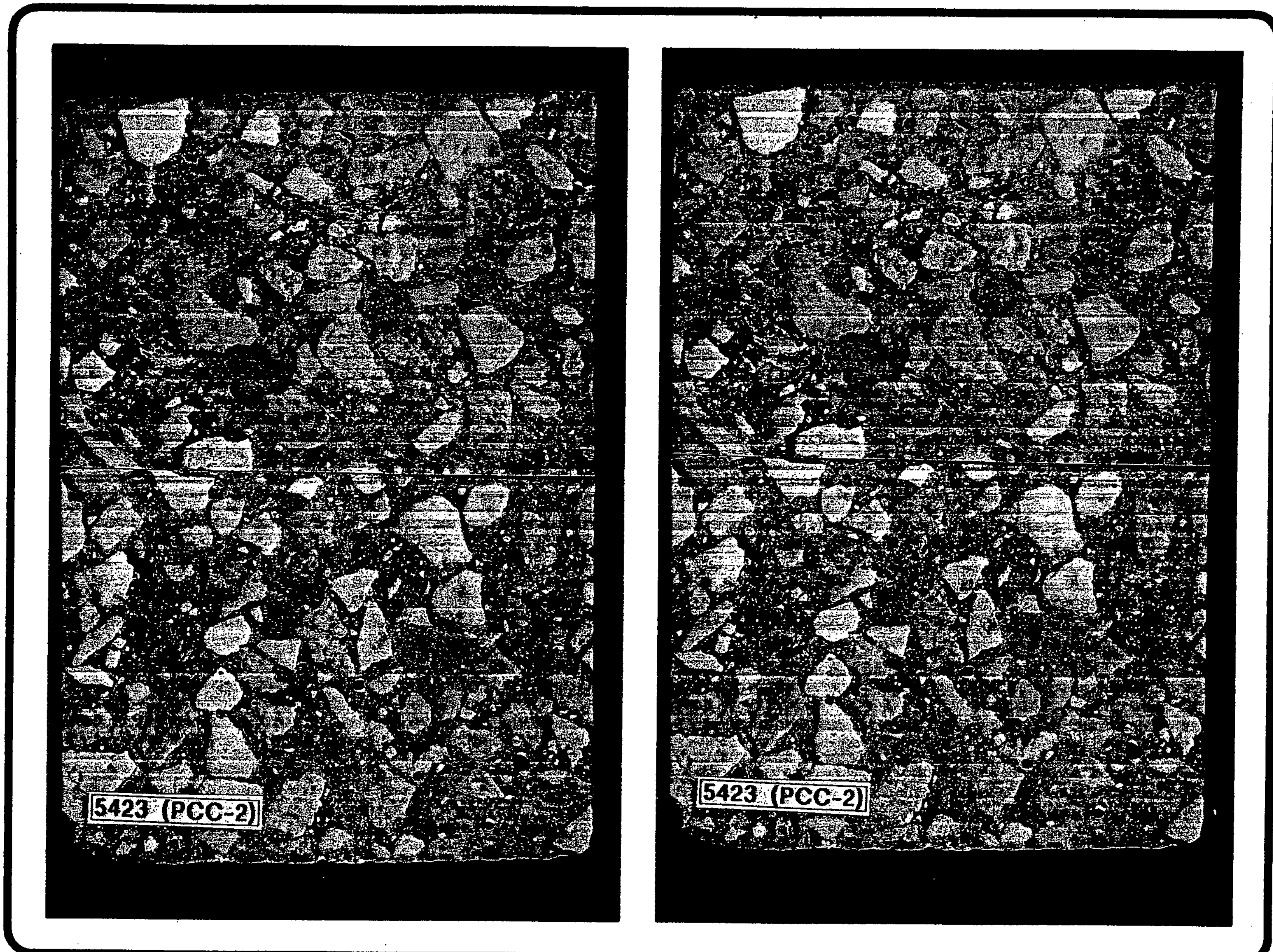


Figure 13. Section View (Perpendicular to the Wearing Surface) of Core PCC-2 (Test Section 390206)

The wearing surface is at the top in the photographs. The left-hand photograph shows the as-lapped surface. In the right-hand photograph, crazing cracks and microcracks in the concrete are delineated with a black marking pen.

Figure 13

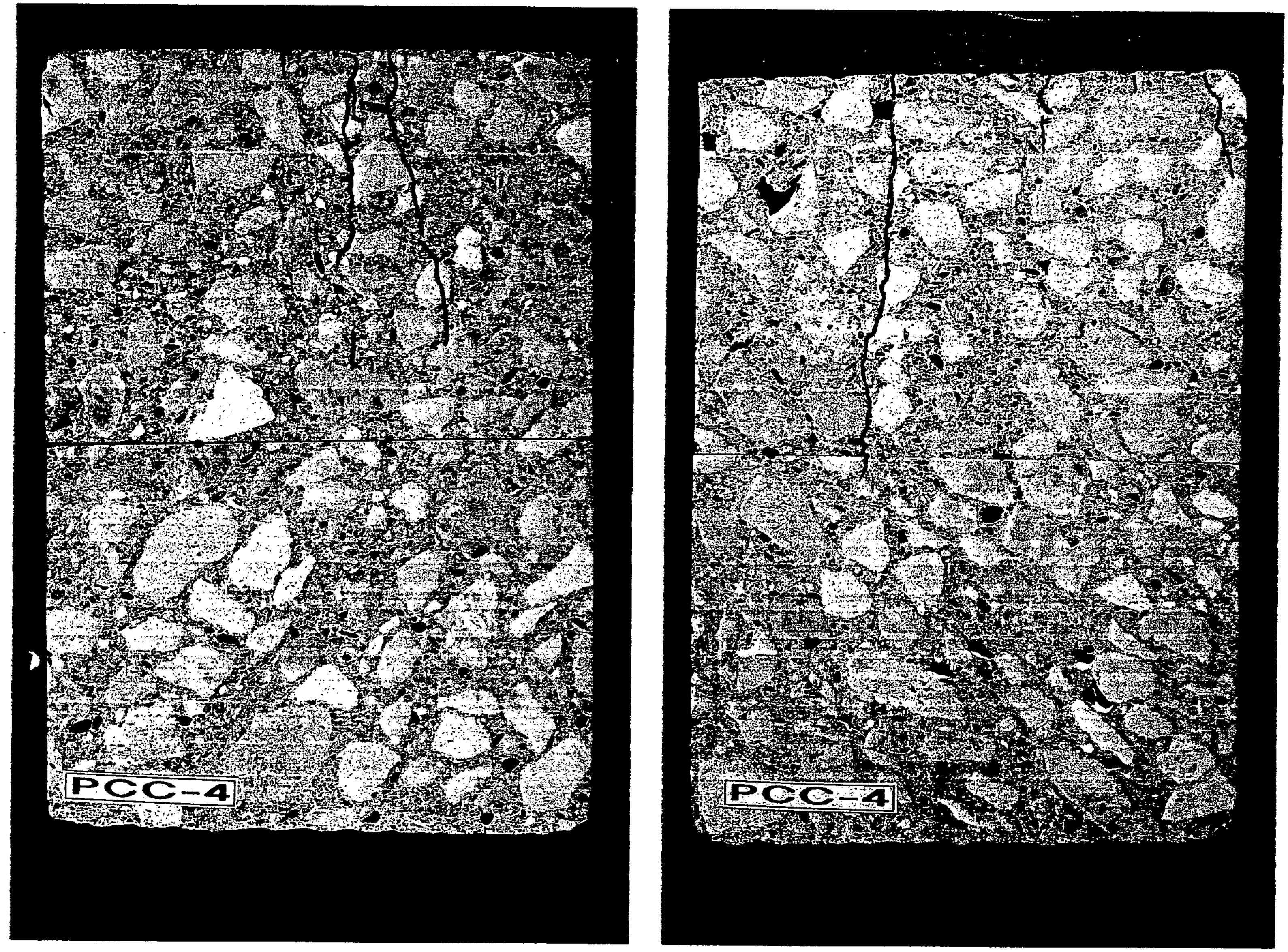


Figure 14. Section View (Perpendicular to the Wearing Surface) of Core PCC-4 (Test Section 390205)

The wearing surface is at the top in the photographs. The left-hand photograph shows the as-lapped surface. Cracks in the concrete are delineated with a black marking pen (including cracks originating at the wearing surface that are 3-inches to 4-inches deep, as well as shallow crazing cracks in the wearing surface).

Figure 14

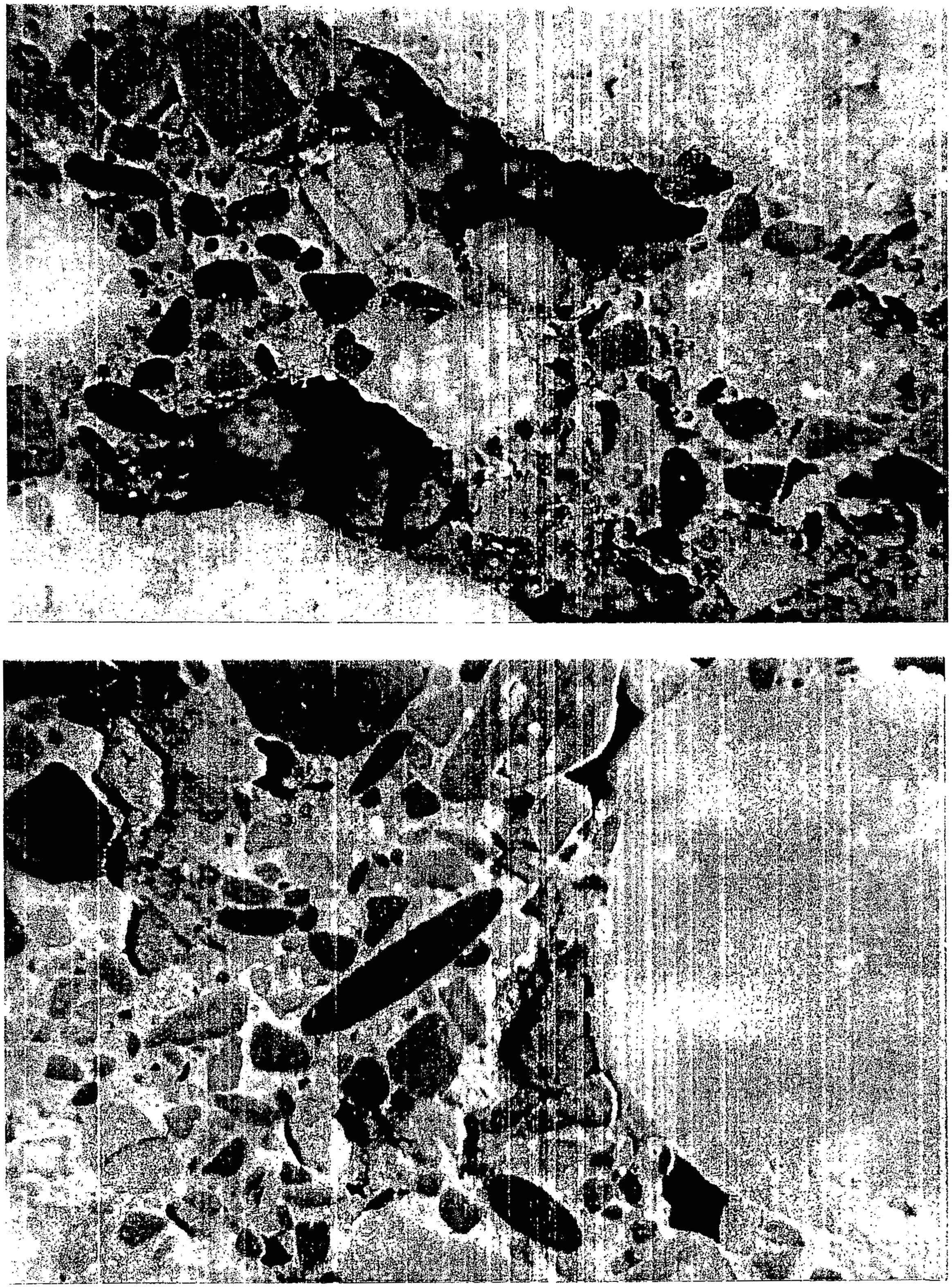


Figure 15. Enlarged Section Views (10X) Showing Gross Porosity in Lean Concrete Base (LCB) Cores, a Common Microstructural Feature in These Concretes

Table 1. Concrete Used in the Construction of the Wearing Course for Section 390206 of the Test Pavement

Concrete Constituent	Pounds Constituent Per Cubic Yard
Portland Cement	750
Fly Ash	113
Sand	950
#57 Limestone	1850
Water	270
Air (6%)	---
	3933

NOTE: The mix design shown here is identified in Bowser-Morner, Inc. (Dayton, Ohio), Report No. 303901, dated April 7, 1995. The concrete is identified in this report as "Plan B Concrete Mix Design ODOT DEL 23-17.48". The aggregate weights shown are saturated surface dry (SSD) weights. At 6% air, the theoretical unit weight of this concrete is 145.7 lb/ft^3. The theoretical water to cementitious material ratio is 0.31.

Table 2. Core Retrieval Data for Cores Taken from Sections 390206 and 390205 of Mainline Pavement on the Test Road

Coring Site #	Test Section	Coring Site	Core Length, (inches)		Comments
			PCC	LCB	
1	390206	STA. 334+00, 1-foot west of edge line, mid panel	8¼	6	Core PCC-1 was received in two pieces. It contains a full-width, full-depth crack.
2	390206	2-feet north and 1-foot east of Core 1, 6-inches west of edge line, 1-foot from joint	8⅛	6⅛	Both cores were received intact.
3	390206	17-feet north and 1½-feet west of Core 2, 2-feet from joint and 2-feet west of edge line	8⅛	6½	Both cores were received intact.
4	390205	STA. 5+15-OL 5-feet from center line	8	5¾	Core LCB-4 was received in two pieces. It contains a full-width, full-depth crack. The wearing surface of the core is grooved.

NOTE: Two cores were taken at each coring site, including the portland cement concrete (PCC) wearing course, and the lean concrete base (LCB) base course.

Table 3. Concrete Used in the Construction of the Lean Concrete Base (LCB) for Sections 390205 and 390206 of the Test Pavement

Concrete Constituent	Pounds Constituent Per Cubic Yard
Portland Cement	160
Sand	1465
#57 Limestone	2000
Water	235
Air (6%)	---
	3860

NOTE: The mix design shown here is taken from Bowser-Morner, Inc. (Dayton, Ohio), Laboratory Report No. 303842, dated March 8, 1995. The concrete is described as "lean concrete base (LCB) Project DEL 23-17.48". An ODOT Concrete Inspector's Daily Report dated 8/19/95, shows a reduced sand content (1762 pounds) and the use of Class C fly ash at 48 pounds per cubic yard. The mix design shown above has a theoretical unit weight of 143.0 lb/ft3, and a theoretical water-cement ratio greater than 1.0.

Table 4. Concrete Used in the Construction of the Wearing Course for Section 390205 of the Test Pavement

Concrete Constituent	Pounds Constituent Per Cubic Yard
Portland Cement	510
Fly Ash	90
Fine Aggregate	1260
Limestone	1595
Water	300
Air (6%)	---
	3755

NOTE: This mix design is taken from the Ohio Department of Transportation Construction and Materials Specification Document. Trial batches made at Bowser-Morner (Dayton, Ohio) show a water-cement ratio of 0.40 for the concrete intended for use on the Test Pavement Project. To accommodate this change, the ODOT Concrete Inspector's Daily Report for 09/11/95 shows an increase in coarse aggregate content.

Table 5. Concrete Used in the Construction of the Wearing Course for Sections 390809 and 390810 of the Test Pavement

Concrete Constituent	Pounds Constituent Per Cubic Yard
Portland Cement	350
Class F Fly Ash	120
Fine Aggregate	1335
Coarse Aggregate	1800
Water	235
Air (6%)	---
	3840

NOTE: The mix design shown here is reported on Bowser-Morner, Inc. (Dayton, Ohio) Laboratory Report No. 226390 dated 09/14/94. It is identified as "Concrete Mix Design ODOT DEL 23-17.48 (350 Plan A)". The theoretical unit weight of this concrete is 142.2 lb/ft^3, and the theoretical water to cementitious material ratio is 0.50. ODOT Concrete Inspector's Daily Report dated, 10/07/94, shows a reduced fly ash content for the concrete as-placed, with a water to cementitious material ratio of 0.58.

Table 6. Ohio Department of Transportation (ODOT) Data on Concretes used in the Construction of Test Sections 390205, 390206, 390809, and 390810

Test Section	Compressive Strength, psi		Split Tensile Strength Or Flexural Strength, psi		Modulus Of Elasticity, (times 10^6 psi)
	28-day	1-year	28-day	1-year	
205	8165[a]	8120[a]	545	750	7.3[b]
206	5930[c]	7915[a]	425	620	---
809 & 810	2910[d]	4880[d]	755[c]	795[c]	3.4 to 3.8

[a] Average of data obtained on three cores
[b] 1-year
[c] Flexural strength
[d] Average of data obtained on six cores and cylinders

Table 7. Characterization Data Obtained on Mainline Pavement Portland Cement Concrete Cores 1, 2 3, and 4

Core #	Estimated Water to Cementitious Material Ratio	Air[a] Content, %	Saturated Density lb/ft^3	Cement Paste[a] Content %	Depth of Carbonation of the Wearing Surface, mm
PCC-1	0.30	2.5	146.7	35.5	0
PCC-2	0.30	2.2	147.8	35.1	0
PCC-3	0.30	6.6	140.4	35.0	0
PCC-4	0.40	2.5	147.3	27.0	0

[a] ASTM C 457

Table 8. Characterization Data Obtained on Mainline Pavement Lean Concrete Base (LCB) Cores 1, 2, 3, and 4

Core #	Air Content[a], %			Cement Paste Content[a], %	Density, lb/ft^3	Depth of Carbonation, mm
	< 1-mm	> 1-mm	Total			
LCB-1	3.9	3.7	7.6	18.8	141.8	Complete carbonation except for the geometric center of the core
LCB-2	4.9	4.5	9.4	19.0	139.7	Complete carbonation except for the geometric center of the core
LCB-3	4.8	6.2	11.0	16.3	139.3	Complete carbonation except for the geometric center of the core
LCB-4	2.2	5.1	7.3	19.2	143.8	Complete carbonation except for the geometric center of the core

[a] ASTM C 457

Table 9. Characterization Data for Portland Cement Concrete Cores 809 and 810 (Southbound Ramp Wearing Course)

Core #	Estimated Water To Cementitious Material Ratio, %	Air Content[a], %			Cement Paste Content[a], %	Density, lb/ft^3	Depth Of Carbonation Of The Wearing Surface, mm
		< 1-mm	> 1-mm	Total			
809	0.55 to 0.58	4.6	2.8	7.4	20.4	140.5	3 to 6
810	0.45 to 0.52	4.5	2.5	7.0	20.7	140.8	3 to 5

[a] ASTM C 457

Appendix A

ASTM C 457 Data

Table A-1. Cement and Air Content Measurements for Cores PCC-1, LCB-1, PCC-2, and LCB-2 (ASTM C 457)

Coring Site 1	PCC-1							LCB-1
	Top (PCC-1-B_T)			Bottom (PCC-1-B_B)			Whole Core	
	Side 1	Side 2	Both Sides	Side 1	Side 2	Both Sides		
Stops	1048	1080	2128	1010	1044	2054	4182	1909
Total Air Void Content, %	2.10	2.22	2.16	2.87	2.78	2.82	2.49	7.60
Air Void Content > 1 mm, %	0.67	0.74	0.70	1.29	1.44	1.36	1.03	3.67
Cement Paste Content, %	37.31	30.65	33.93	35.35	38.89	37.15	35.51	18.75
Paste/Air Ratio	17.77	13.79	15.70	12.31	14.00	13.16	14.28	2.47
Traverse Length, in.	52.4	54.0	106.4	50.5	52.2	102.7	209.1	95.45
Traverse Area, in^2	18.0	18.0	36.0	23.0	23.0	46.0	82.0	33.0

Coring Site 2	PCC-2							LCB-2
	Top (PCC-2-B_T)			Bottom (PCC-2-B_B)			Whole Core	
	Side 1	Side 2	Both Sides	Side 1	Side 2	Both Sides		
Stops	993	984	1977	1001	1004	2005	3982	1878
Total Air Void Content, %	3.53	2.34	2.93	1.20	1.59	1.40	2.16	9.37
Air Void Content > 1 mm, %	1.61	1.42	1.52	0.50	0.60	0.55	1.03	4.47
Cement Paste Content, %	35.79	37.80	36.77	31.27	35.46	33.37	35.06	19.01
Paste/Air Ratio	10.14	16.17	12.53	26.08	22.25	23.89	16.23	2.03
Traverse Length, in.	49.6	49.2	98.9	50.1	50.2	100.3	199.1	93.9
Traverse Area, in^2	23.0	23.0	46.0	23.0	23.0	46.0	92.0	30.0

Table A-2. Cement and Air Content Measurements for Cores PCC-3, LCB-3, PCC-4, and LCB-4 (ASTM C 457)

Coring Site 3	PCC-3							LCB-3
	Top (PCC-3-B_T)			Bottom (PCC-3-B_B)			Whole Core	
	Side 1	Side 2	Both Sides	Side 1	Side 2	Both Sides		
Stops	1031	1028	2059	1034	1036	2070	4129	1859
Total Air Void Content, %	7.86	5.35	6.61	6.67	6.47	6.57	6.59	10.97
Air Void Content > 1 mm, %	3.01	0.97	1.99	1.55	2.41	1.98	1.99	6.19
Cement Paste Content, %	33.75	36.96	35.36	36.46	32.82	34.64	35.00	16.25
Paste/Air Ratio	4.30	6.91	5.35	5.46	5.07	5.27	5.31	1.48
Traverse Length, in.	51.6	51.4	103.0	51.7	51.8	103.5	206.5	92.95
Traverse Area, in^2	23.0	23.0	46.0	23.0	23.0	46.0	92.0	33.0

Coring Site 4	PCC-4							LCB-4
	Top (PCC-4-B_T)			Bottom (PCC-4-B_B)			Whole Core	
	Side 1	Side 2	Both Sides	Side 1	Side 2	Both Sides		
Stops	1041	1046	2047	1047	1037	2084	4131	1863
Total Air Void Content, %	2.11	2.68	2.44	2.58	2.60	2.59	2.52	7.30
Air Void Content > 1 mm, %	0.58	1.05	0.83	1.72	1.64	1.68	1.26	5.05
Cement Paste Content, %	29.59	24.19	27.41	27.60	25.75	26.68	27.04	19.22
Paste/Air Ratio	14.00	9.04	11.22	10.70	9.89	10.30	10.74	2.63
Traverse Length, in.	52.1	52.3	102.4	52.4	51.9	104.2	206.6	93.15
Traverse Area, in^2	23.0	23.0	46.0	23.0	23.0	46.0	92.0	27.5

Table A-3. Cement Paste Content and Air Content Measurements for Cores 809 & 810 (ASTM C 457)

Parameter	Core 809	Core 810 (Top)	Core 809 (Bottom)
Stops	1912	1824	1844
Total Air Void Content, %	7.37	5.70	8.19
Air Void Content > 1-mm, %	2.82	2.14	2.77
Cement Paste Content	20.40	20.72	20.66
Paste/Air Ratio	2.77	3.63	2.52
Traverse Length, in.	95.6	91.2	92.2
Traverse Area, in^2	31.6	28.8	31.6