CONSTRUCTION MATERIALS CONSULTANTS, INC.

Laboratory Investigation of Delamination of a Concrete Slab

Project Address

Prepared for:
ABC Engineering
Project No.

Date
CMC Project#

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Date

ABC
ABC Engineering
Address

RE: DELAMINATION OF CONCRETE SLAB

Dear Mr. ABC:

Construction Materials Consultants, Inc. (CMC) is pleased to provide the enclosed comprehensive report on 'Laboratory Investigation of Delamination of a Concrete Slab' for a concrete core, which was, reportedly, retrieved from an indoor concrete slab at the above-referenced project location that is exhibiting delamination of the finished surface at a depth of $^{1}/_{2}$ to $^{3}/_{8}$ in.

Results, opinions, and conclusions presented herein are based on the information and sample provided at the time of this investigation. We reserve the right to modify the report as additional information becomes available. Neither CMC nor its employees assume any obligation or liability for damages, including, but not limited to, consequential damages arising out of, or in conjunction with the use, or inability to use this resulting information.

Sample will be discarded two weeks after submission of the report unless otherwise requested in writing. All reports are the confidential property of clients, and information contained herein may not be published or reproduced pending our written approval.

Please feel free to contact us with any additional questions. We look forward to providing our service again for your future projects.

Sincerely Yours,

CONSTRUCTION MATERIALS CONSULTANTS, INC.

Dipayan Jana, PG
President, Petrographer

DJ:jlh

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EXECUTIVE SUMMARY

Severe delamination of an indoor concrete slab in a new automobile facility has prompted this investigation. A dense, hard trowel-finished slab has, reportedly, delaminated to a depth of $^{3}/_{8}$ to $^{1}/_{2}$ in. within days of placement. Compressive strength of core showed a low 28-day strength of 2540-psi, as opposed to the desired strength of 3500-psi. Therefore, slab surface delamination, and, lower-than-desired compressive strength – both problems are investigated here by petrographic examinations of a concrete core (No. 3) *a la* ASTM C 856.

The concrete in the examined core contained: (i) crushed granite coarse aggregate having a nominal maximum size of $^{1}/_{2}$ in. (13 mm), (ii) natural siliceous-calcareous sand fine aggregate having a nominal maximum size of $^{3}/_{8}$ in. and containing quartz, quartzite, limestone-dolomite, feldspar, sandstone, siltstone, etc., (iii) a hardened Portland cement paste having a cement content estimated to be $6^{1}/_{2}$ to 7 bags per cubic yard and a water-cement ratio estimated to be 0.45 to 0.50 in the interior body but noticeably less than 0.40 at the top $^{1}/_{16}$ to $^{1}/_{8}$ in., (iv) fine, hair-like polypropylene-type synthetic fibers, and (v) an excessive air entrainment in the concrete judged to be from accidental over dosage of air entraining chemicals to the mix - to the point of having more than 20 percent total air in the interior body; but, again, significantly lower air content to almost no air at the top $^{1}/_{16}$ to $^{1}/_{8}$ in. Compared to the body, lower air and *w/c* at the top $^{1}/_{8}$ in. is judged to be due to dense hard trowel finishing operations that have washed air and water out of the surface.

The reported "stickiness" of freshly placed concrete is determined to be due to having too much air in the mix for an indoor slab let alone to receive a smooth, flat, dense, hard trowel-finished surface, air entrainment was not at all needed, as common industry-recommendation for such a slab is to have a maximum 3 percent air, and the slab is not needed to be air-entrained. The present concrete is determined to have at least 15 to 20 percent air, and when measured by image analysis it showed an alarmingly high 21.8 percent air.

The very first detrimental effect of having such a high air content is on the compressive strength of concrete. Such an excessive air entrainment has reduced the compressive strength of concrete significantly, as the reported 28-day strength of a core was only 2540-psi as opposed to the specified strength of 3500-psi. Even that 2540-psi strength is judged to be too high for a concrete that contains 20+ percent air. Loss of strength from high air has occurred both: (i) by having too much air (for every one percent point increase in air above the design air content at a given workability can reduce the strength by 3 to 5 percent), and, (ii) by having clustering of air voids along aggregate-paste interfaces to weaken the interfaces, and, thereby further reduce the strength.

Besides severe strength loss, the more serious problem of high air is the reported delamination of the slab after this high-air, sticky concrete was hard trowel-finished to achieve an acceptable flatness, hardness, density, and smoothness of the industrial floor. The reported severe delamination of the slab (although the core provided and examined here does not contain one for drilling apparently from an area were finished surface is still adhered to the main body) is determined to be due to having air in the concrete let alone in excess of 20 percent where the slab was intended to receive a hard trowel finish.

A 20 percent air in a concrete is a testament of a very poor quality control of the concrete irrespective of its intended indoor versus outdoor applications for structural purposes. For an indoor slab, air entrainment is not at all needed, especially when the slab is to be hard toweled; for an outdoor slab exposed to freezing, maximum air content should not exceed $7^{1}/_{2}$ percent. In no circumstances can a concrete provide its intended service if it contains as high as 20 percent air.

The purpose of proper field testing of plastic concrete during placement is to identify such serious problems with the mix, as the reported "stickiness" of concrete, understand the cause for such stickiness, call for a plastic air test to confirm the suspicion of high air, and reject the concrete altogether rather than continue proceeding with hard trowel finishing the 'sticky' concrete to the point of severely densifying the finished surface to achieve the desirable dense hard trowel finished appearance, and, in the process increase the potential for delamination. A high-air concrete cannot be hard trowel finished without escaping the potential for delamination.

INTRODUCTION

Reported herein are the results of detailed laboratory studies of a hardened concrete core received from Mr. ABC n of ABC Engineering. The concrete core was, reportedly, taken from an indoor concrete slab. At the location of the core for this study, the concrete slab, reportedly, showed signs of surface delamination within a few days of placement.

Background Information

The following background information was received with the core:

i. Slab is delaminated at a depth of $^{1}/_{2}$ in. to $^{3}/_{8}$ in.
ii. Fresh concrete was not tested, interior slab, poly and wire mesh, contractor said mix was very "sticky" and remarked about lack of bleed water. Slab was first cored for compressive strength, attained 2540 psi in 28-days, 3500 psi required.
iii. Surface delamination within a few days after placement.
iv. Placement date was January of 2016, inside heated structure.
v. No detrimental environmental factors, indoor, heated, showroom floor.
vi. Core had been prepped for compressive strength testing so core had been saw-cut and capped with sulfur capping compound. Subject slab had been removed prior to the decision being made to do petrographic analysis so an un-tampered core was not available.

Figure 1 shows the project location in a Google Map, as well as the 'street-view' from the Google Map.

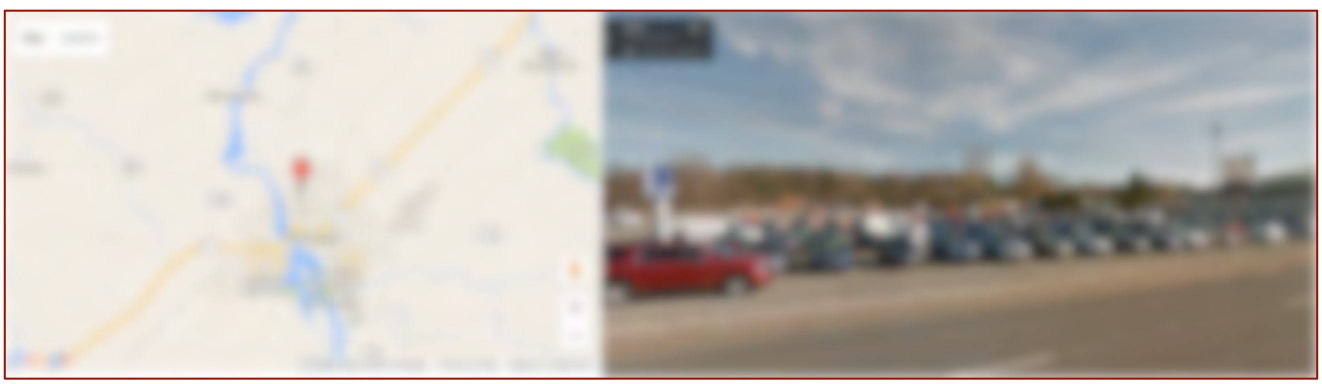


Figure 1: Google map showing the project location.

Results of Compressive Strength & Field Testing of Concrete

As stated previously, no "field testing" was completed during placement. Compressive strength testing of cores from the slab have, reportedly, showed a low strength of 2540 psi in 28-days, as opposed to the required strength of 3500 psi. Therefore, in addition to the reported delamination issue, the concrete, reportedly, also has a lower-than-required strength issue.

METHODOLOGIES

The core was tested and examined by following the methods of ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete." Details of petrographic examinations and sample preparation techniques are described in Jana (1997a, b, 2001, 2004a, b, 2005a, b, 2006, 2007).

The steps of petrographic examinations include (Jana 2006):

i. Visual examinations of sample, as received;
ii. Low-power stereomicroscopical examinations of as-received, saw-cut and freshly fractured sections, and lapped cross section of core for evaluation of textures, and composition;
iii. Low-power stereomicroscopical examinations of air content and air-void system of concrete in the core;
iv. Examinations of oil immersion mounts in a petrographic microscope for mineralogical compositions of specific areas of interest;
v. Examinations of blue dye-mixed (to highlight open spaces, cracks, etc.) epoxy-impregnated large area (50 mm × 75 mm) thin section of concrete in a petrographic microscope for detailed compositional and microstructural analyses;
vi. Photographing sample, as received and at various stages of preparation with a digital camera and a flatbed scanner; and,
vii. Photomicrographs of lapped cross section and thin section of sample taken from stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information of concrete.
viii. A Jenoptik Progres GRYPHAX camera attached to a Nikon Eclipse 600 POL petrographic microscope (equipped with reflected, transmitted, polarized and fluorescent-light facilities), a Jenoptik Progres C14 camera attached to an Olympus SZH reflected and transmitted-light stereomicroscope, and an OMAX digital camera attached to a Nikon SMZ-10A low-power stereomicroscope were used together for detailed optical microscopical examinations and associated digital photomicrography.
ix. Additionally, an air-void analysis of the lapped cross section of core was done by using the flatbed scanner method (Peterson et al., 2002), where air voids are highlighted in white against everything else in the black background in a black-and-white binary image of the lapped section. The lapped cross section was first darkened with a black Sharpie permanent marker pen, and then all voids were filled with a fine wollastonite ($CaSiO_3$) white powder; then scanned at a high resolution on a flatbed office scanner. The scanned image was then used for calculation of air-void parameters according to the procedures described in Peterson et al., 2002, and Jana 2007.

SAMPLE

Photographs, Identification, Integrity, and Dimensions

Figure 2 shows the core requested for the present study, identified as No. 3. The core is 4 in. (102 mm) in nominal diameter, and has a nominal length of $6^{1}/_{2}$ in. (165 mm). The core was received in intact condition, and prepared for compressive strength testing, i.e. the ends were sulfur-capped, but was not tested.

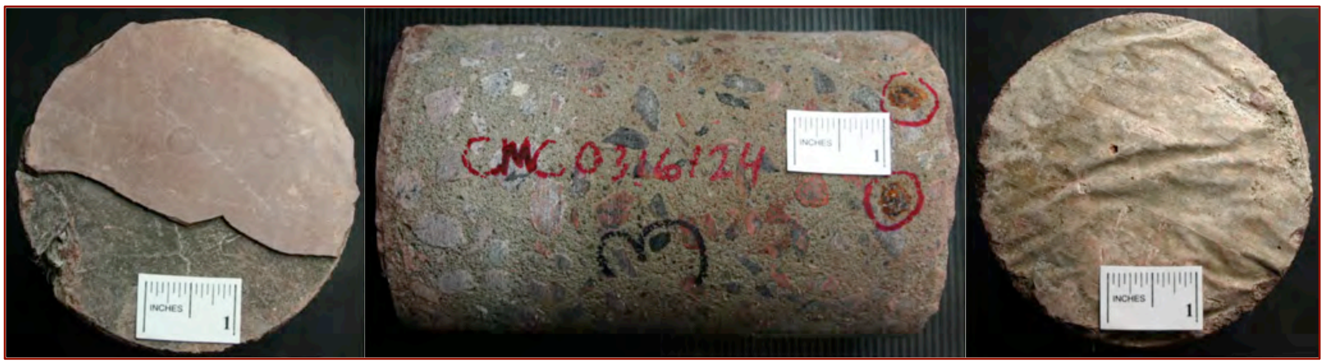


Figure 2: The top surface with remains of sulfur cap over a machine trowel-finished surface (left photo), the side view with identification (center photo), and the bottom surface (right photo) of Core No. 3 with impression of placement on a plastic vapor retarder, as received.

End Surfaces

The top exposed surface (beneath sulfur capping) of Core No. 3 is a smooth, flat, hard, dense, shiny, machine trowel-finished surface with remains of sulfur capping. The bottom surface is smooth, formed, and wavy with impression of placement of slab on a plastic vapor retarder, which indicates that the core represents the full thickness of the slab at this location.

Cracking & Other Visible Distress, If Any

There is no evidence of any distress or cracking of concrete found in the interior body of the core.

Embedded Items

Distributed throughout the concrete are fine hair-like, polypropylene-type synthetic fibers in the paste. The core also contains a No. 2 reinforcing steel at a depth of $5^{3}/_{4}$ in. from the top surface, which is present in sound condition with no evidence of corrosion.

Resonance

The core has a ringing resonance, when hammered.

PETROGRAPHIC EXAMINATIONS

Coarse Aggregate

Coarse aggregate is crushed granite having a nominal maximum size of $^{1}/_{2}$ in. (13 mm). Particles are angular, dense, hard, medium to dark gray, massive textured, equidimensional to elongated, unaltered, uncoated, and uncracked. Coarse aggregate particles are well-graded and well-distributed (Figure 5). There is no evidence of alkali-aggregate reactions of coarse aggregate particles in the core. Coarse aggregate particles have been sound during their service in the concrete, and are judged not to have contributed to the observed distress of the concrete.

Fine Aggregate

Fine aggregate is natural siliceous-calcareous sand having a nominal maximum size of 4 mm (Figures 3 and 4). Particles contain major amounts of quartz, moderate amounts of limestone-dolomite and feldspar, and subordinate amounts of sandstone, siltstone, shale, mica, mafic minerals, and ferruginous rocks. Particles are variably colored, angular to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and uncracked. Fine aggregate particles are well-graded and well-distributed (Figures 4 and 5). There is no evidence of alkali-aggregate reaction of fine aggregate particles. Fine aggregate particles have been sound during their service in the concrete. The following photomicrographs of blue dye-mixed epoxy-impregnated thin section of the core show the crushed stone coarse aggregate and natural siliceous-calcareous sand fine aggregate particles in Core No. 3.

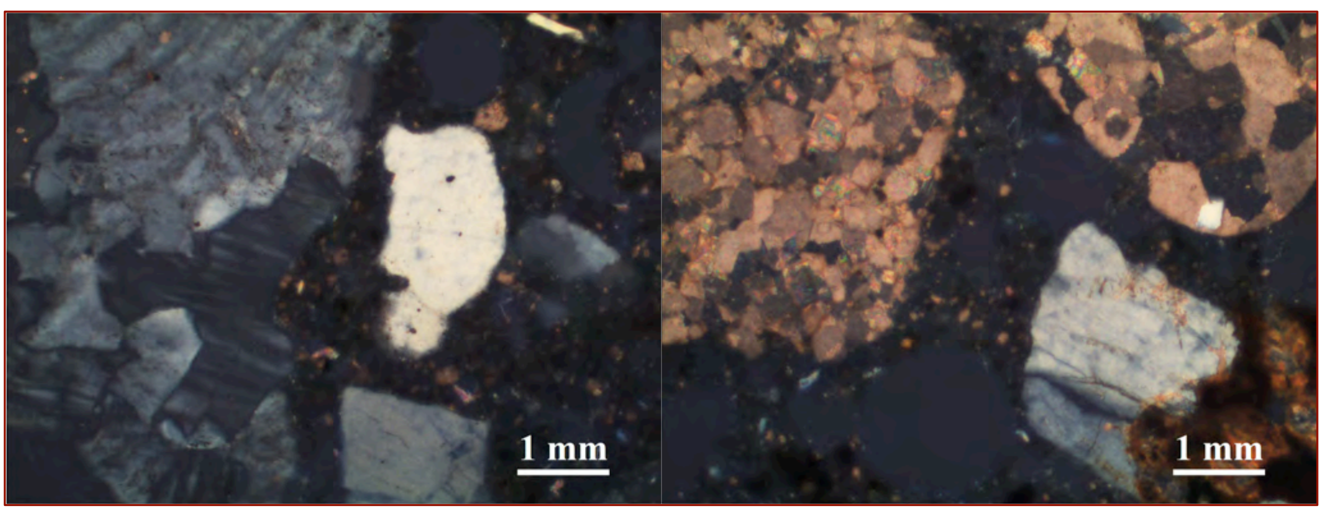


Figure 3: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of concrete in Core No. 3 showing: (i) crushed granite coarse aggregate particles that are dense, hard, and massive textured, and, (ii) siliceous-calcareous sand fine aggregate particles.

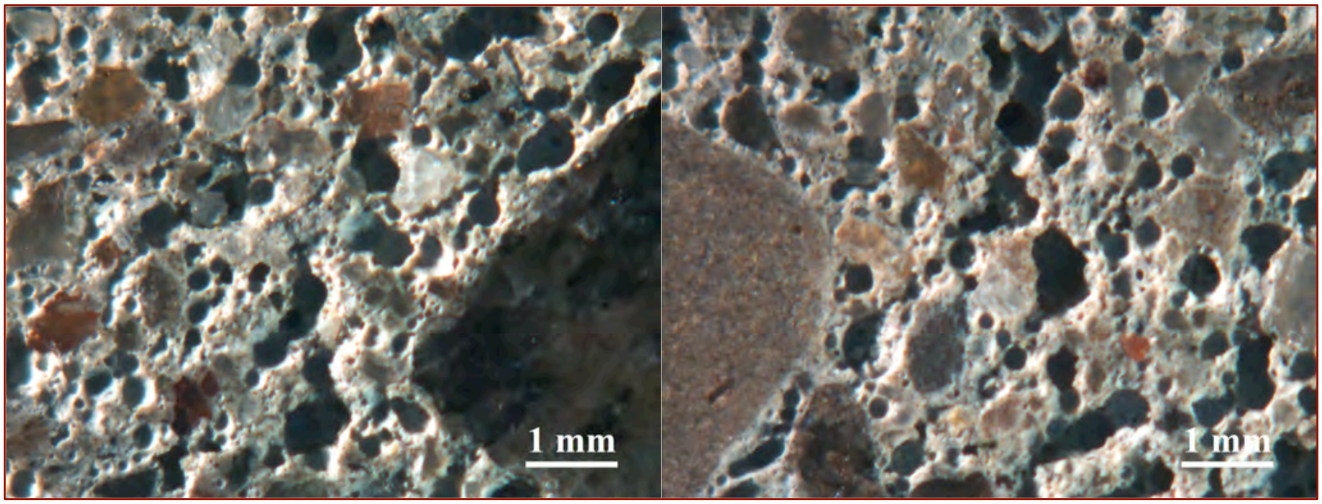


Figure 4: Photomicrographs of lapped cross section of Core No. 3 showing size, shape, grading, and distribution of fine aggregate particles in the core. Notice excessive air entrainment in the concrete (discussed later).

The following Table summarizes properties of coarse and fine aggregates determined from the core.

Properties and Compositions of Aggregates	Core 3
Coarse Aggregate	
Types	Crushed granite
Nominal maximum size	$^{1}/_{2}$ in. (13 mm)
Rock Type	Granite
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dense, hard, medium to dark gray, massive textured, equidimensional to elongated
Cracking, Alteration, Coating	Unaltered, Uncoated, and Uncracked
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None
Fine Aggregates	
Types	Natural siliceous-calcareous sand
Nominal maximum size	4 mm
Rock Types	Major amounts of quartz, moderate amounts of limestone-dolomite and feldspar, and subordinate amounts of sandstone, siltstone, shale, mica, mafic minerals, and ferruginous rock
Cracking, Alteration, Coating	Variably colored, subangular to subrounded, dense, hard, equidimensional to elongated
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None

Table 1: Properties of coarse and fine aggregates of concrete in the core.

In summary, both coarse and fine aggregates are found to be sound, of good quality, and did not contribute to the reported delamination.

Figure 5 shows the overall good grading and well-distribution of coarse and fine aggregates on a lapped cross section of the core. The boxed area in the left photo is enlarged in the right to show an uplifted appearance of the crushed granite coarse aggregate particles relative to the mortar fraction – due to excessive air-entrainment in the mortar fraction that has reduced the density of mortar fraction significantly from too much air and gave a frothy-texture to the mortar fraction (discussed later).

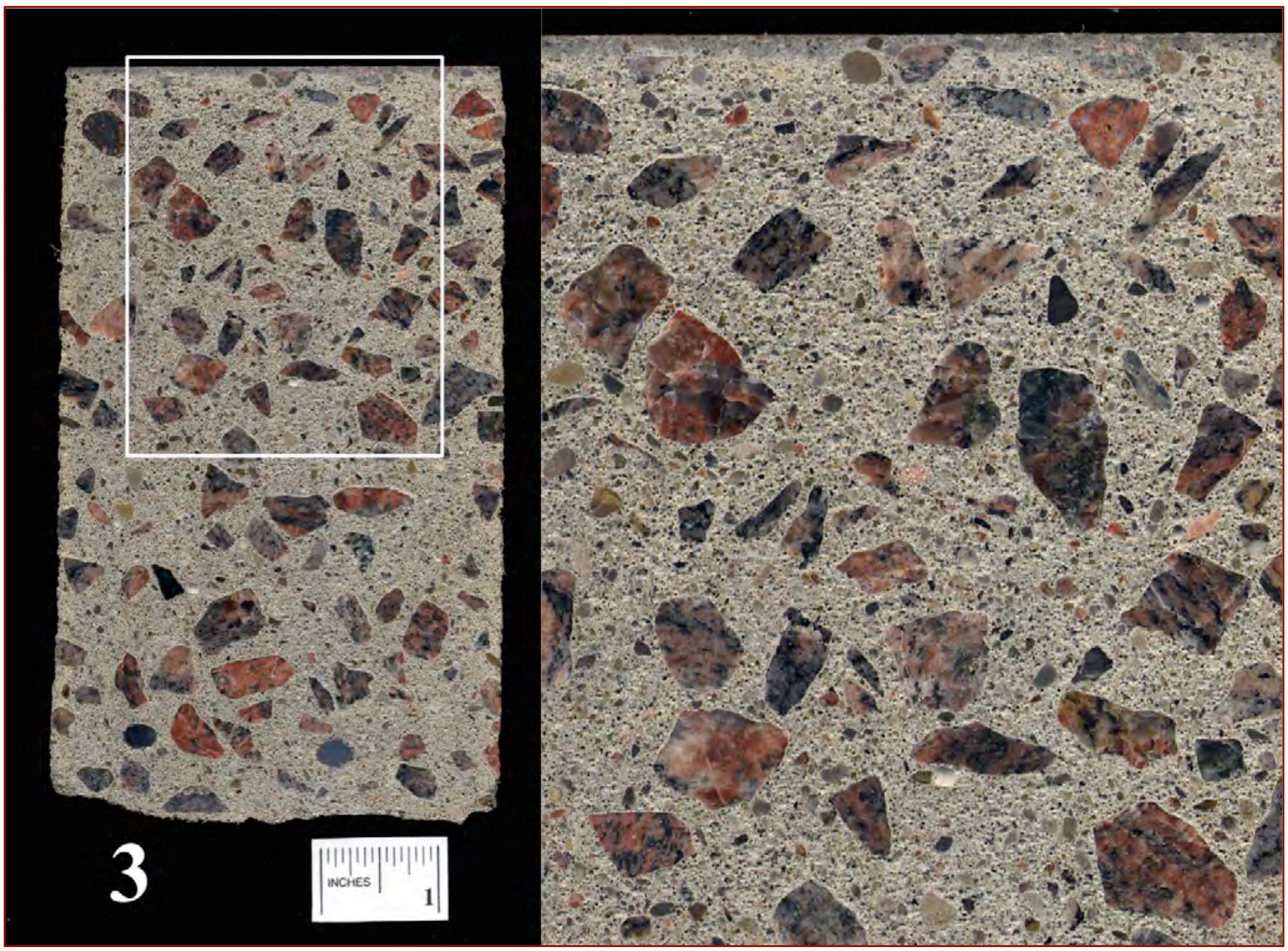


Figure 5: Lapped cross section (left) and an enlarged view of the boxed area of lapped cross section (right) showing the overall good grading and well-distribution of coarse and fine aggregates and frothy nature of mortar-fraction of the concrete from excessive air entrainment.

In summary, both coarse and fine aggregates are found to be sound, of good quality, and did not contribute to the reported delamination, or the low strength problems.

Paste

Properties and composition of hardened cement paste are summarized in Table 2. Paste is medium to light gray, moderately dense and moderately hard. Freshly fractured surfaces have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 6 to 8 percent of the paste volume. Hydration of Portland cement is normal in the interior body but restricted due to very low *w/c* at the very top, immediately beneath the finished surface due to hard trowel finishing operations. In addition to Portland cement, distributed throughout the paste are limestone fines having the fineness of Portland cement that are judged to be from the dusts of calcareous component of fine aggregate.

The following photomicrographs of blue dye-mixed epoxy-impregnated thin section of the core showing residual Portland cement particles and limestone fines in the overall moderately dense microstructure of paste.

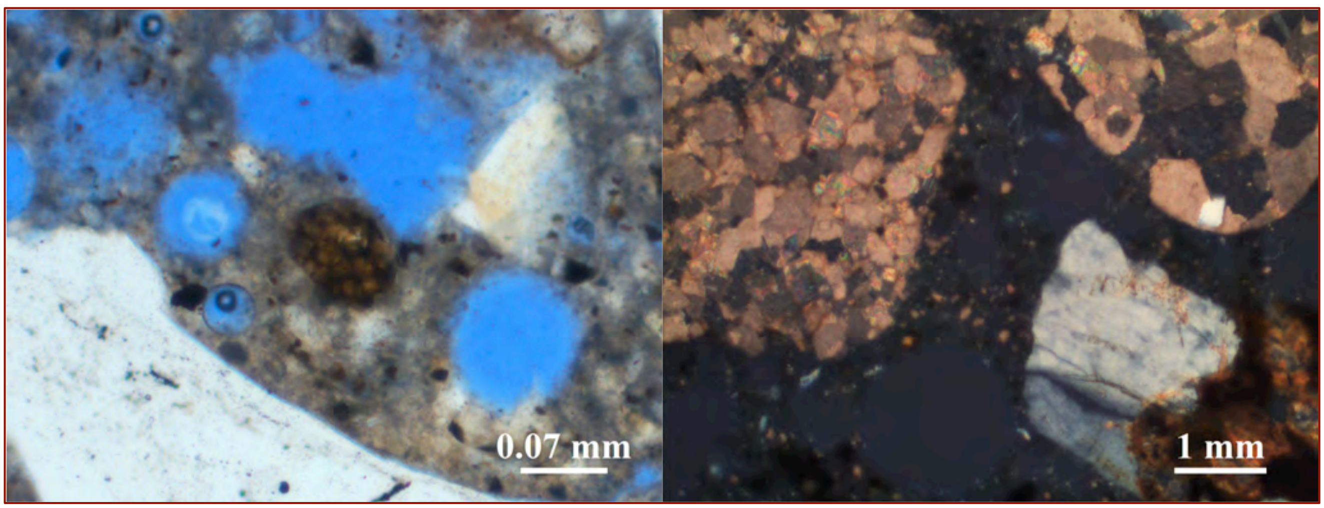


Figure 6: Photomicrographs of thin section of concrete in Core No. 3 showing residual Portland cement particles and limestone fines in the overall moderately dense microstructure of paste.

Properties and Compositions of Paste	Core 3
Color, Hardness, Porosity, Luster	Med. to Light Gray, Moderately Hard, Moderately Dense, Subvitreous
Residual Portland Cement Particles	Normal, 6 to 8 percent by paste volume
Calcium hydroxide from cement hydration	Normal, 10 to 14 percent by paste volume
Pozzolans, Slag, etc.	Limestone Fines
Water-cementitious materials ratio (*w/c*), estimated	0.45 to 0.50; lower within the top $^1/_{16}$ to $^1/_8$ in.
Cement contents, estimated (bags of portland cement per cubic yard)	$6^1/_2$ to 7
Secondary Deposits	Calcium Carbonate in voids
Depth of Carbonation, mm	0 mm due to dense hard trowel finishing
Microcracking	None
Aggregate-paste Bond	Moderately Tight to weak due to clustering of air

Properties and Compositions of Paste	Core 3
	voids along aggregate-paste interfaces
Bleeding, Tempering	None
Chemical deterioration	None

Table 2: Proportions and composition of hardened cement paste in Core No. 3.

The textural and compositional features of the paste are indicative of a Portland cement content estimated to be 6½ to 7 bags per cubic yard. The core has a water-cement ratio (*w/c)* estimated to be from 0.45 to 0.50 in the main body, and a lower *w/c* at the very top surface-region (top 1/16 to 1/8 in.) of concrete immediately beneath the trowel-finished surface, where concrete has a densified mortar fraction compared to the less dense (excessively air-entrained) interior body.

The following photomicrographs of lapped cross section (on left) and corresponding thin section (on right) of the top surface region of Core No. 5 show: (i) 'normal' *w/c* in the interior body, and, (ii) noticeably lower *w/c* at the very top near-surface region immediately beneath the finished surface where paste is denser, darker gray and harder compared to normal less dense paste in the interior body (which is seen in both lapped section and thin section photomicrographs, latter by less absorption of dyed epoxy at the very top denser near-surface concrete).

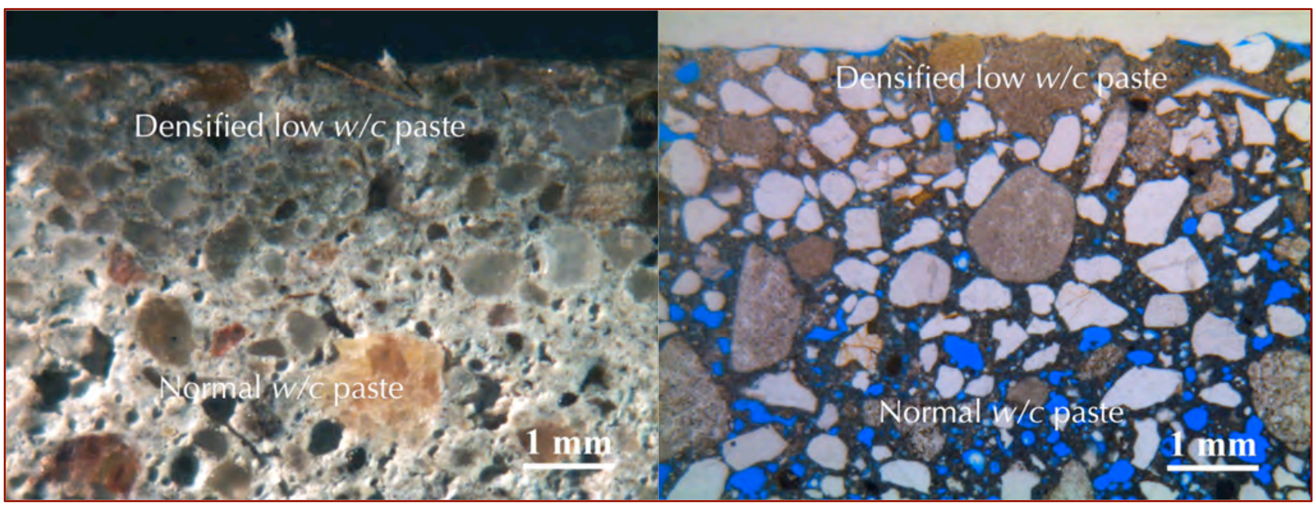


Figure 7: Normal *w/c* (0.45-0.50) paste in the interior concrete but noticeably denser, harder, darker gray paste immediately beneath the finished surface where *w/c* is lower (<0.40) than that in the interior.

There is no evidence of any deleterious secondary deposits found in the core. Carbonation was undetectable at the top finished surface of the concrete due to dense trowel-finished surface at the top. Bonds between the coarse and fine aggregate particles and paste are moderately tight, except at locations of air-void clustering along aggregate-paste interfaces that has weakened the bond, as discussed later. There is no evidence of microcracking due to deleterious reactions.

Air

Air occurs as: (i) numerous fine discrete, spherical and near-spherical voids having sizes of up to 1 mm, and (ii) a few coarse, near-spherical and irregularly shaped voids of sizes coarser than 1 mm. The former voids are characteristic of entrained air and the latter ones are entrapped air.

Air-void system of concrete in Core No. 3 is suggestive of intentional addition of an air-entraining agent in the mix. The total air content is estimated to be at least 15 to 20 percent, which is significantly higher than the ACI-recommended maximum air content of 3 percent for an indoor slab intended to receive a hard trowel-finish.

The very top surface region, i.e. the top $^{1}/_{16}$ to $^{1}/_{8}$ in. (1.59 mm), however, shows a significantly reduced air content (estimated to be less than 2 percent) compared to the main body due to hard trowel-finishing and finishing-induced densification of surface. The following photomicrographs of lapped cross section of the core show the excessively air-entrained nature of the interior concrete in the right photo, as well as noticeably reduced air content within the top surface region compared to the main body in the left photo:

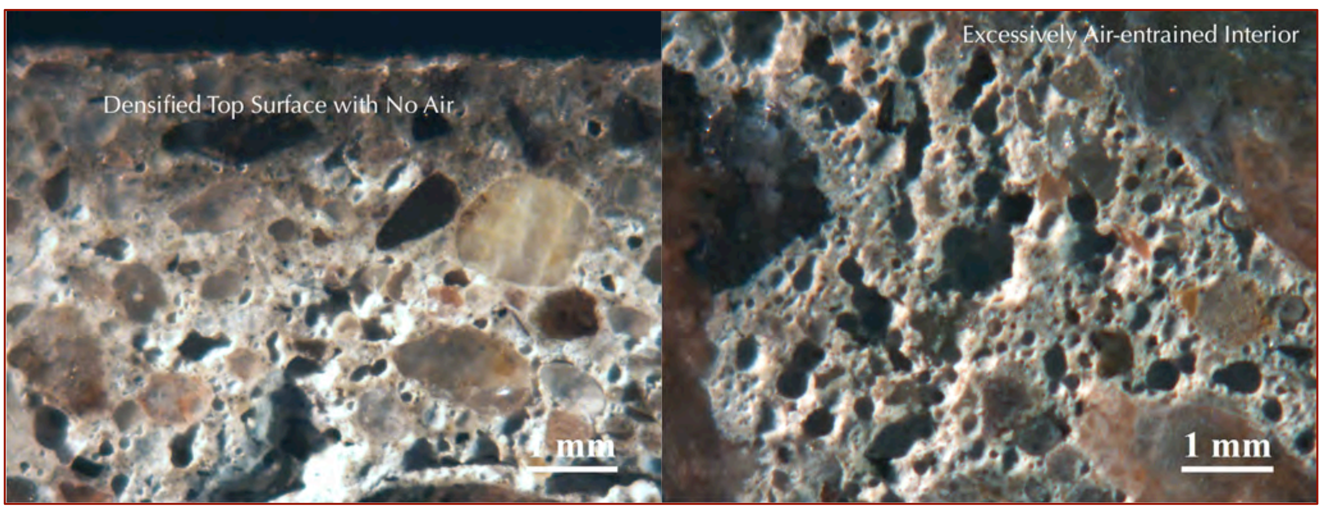


Figure 8: Photomicrographs of lapped cross section of Core No. 3 showing the densified top surface region with little to no air voids (left photo), and the excessively air-entrained nature of the concrete in the main body (right photo).

The following blue dye-mixed epoxy-impregnated thin section of concrete shows excessive air-entrainment as air bubbles that are highlighted by the dyed epoxy – notice excessive air entrainment in the left photomicrograph in Figure 9.

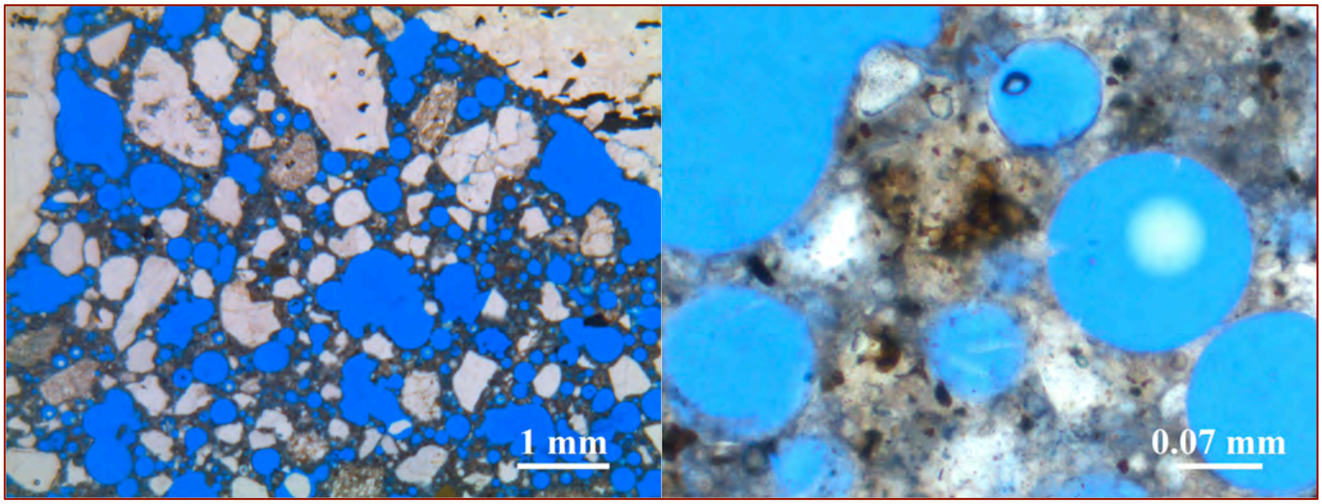


Figure 9: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of Core No. 3 showing the excessively air-entrained nature of the concrete.

In order to explain how excessive air content is compared to common industry-recommended maximum air content of 3 percent for an indoor slab to receive a hard trowel finish, the following two photomicrographs of two different concrete from this project (on left) and an entirely different project (on right) show 20+ percent air in the concrete in this project versus 2.5 percent air in a concrete from a different project, which should been the air for the present indoor concrete slab to receive a hard trowel finish.

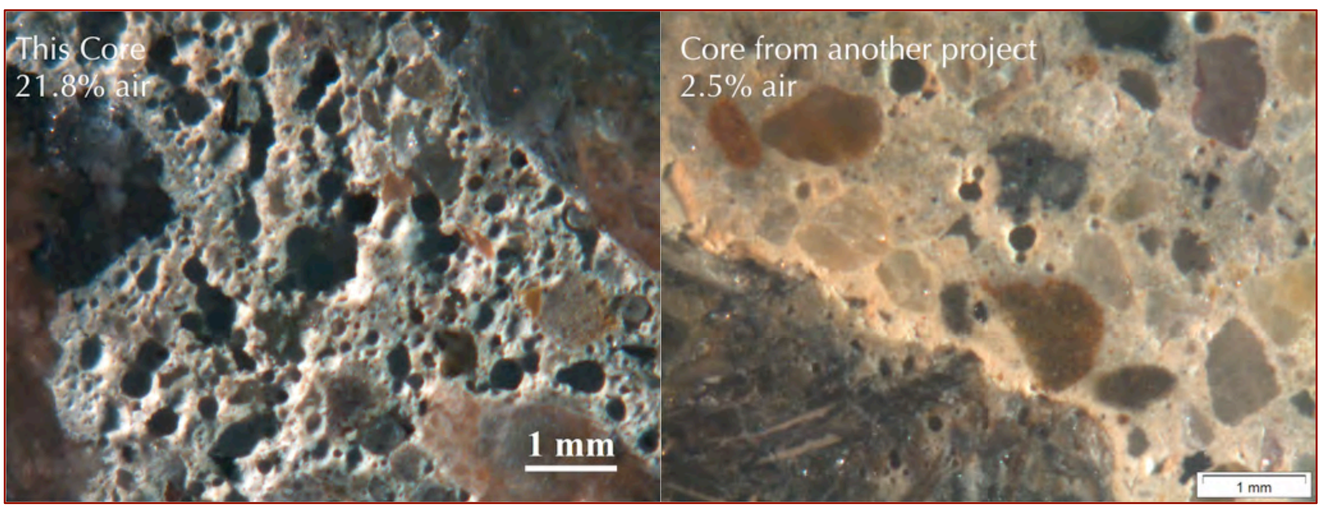


Figure 10: Another view of the right photo of Figure 8 shown here again in the left, showing excessive air entrainment in the interior concrete i.e. from a depth of approximately 5 mm from the top surface through the rest of the core. This left photo clearly shows an air content of at least 20 percent, far higher than the recommended maximum air content of 3 percent. For a comparison, also shown on right is another concrete from a different project where air content was measured by ASTM C 457 to be 2.5 percent i.e. to show how less than 3 percent air concrete looks like. These two comparison photos of air contents clearly show the inherent high air problem of this concrete, which should have been questioned during plastic air measurements, or from the reported "stickiness" of concrete during placement and finishing, which was from this too much air, and is also the cause of the reported low strength results of companion cores.

Figure 11 clearly shows excessive air entrainment in the interior concrete beyond 5 mm depth from the top, as opposed to almost no air at the very top 5 mm due to finishing-induced loss of air from the surface. The following photomicrographs, thereby, show two distinct microstructural zones –

i. Finished-induced densified low to no-air, low *w/c* near-surface densified zone; and
ii. Interior excessively air-entrained concrete.

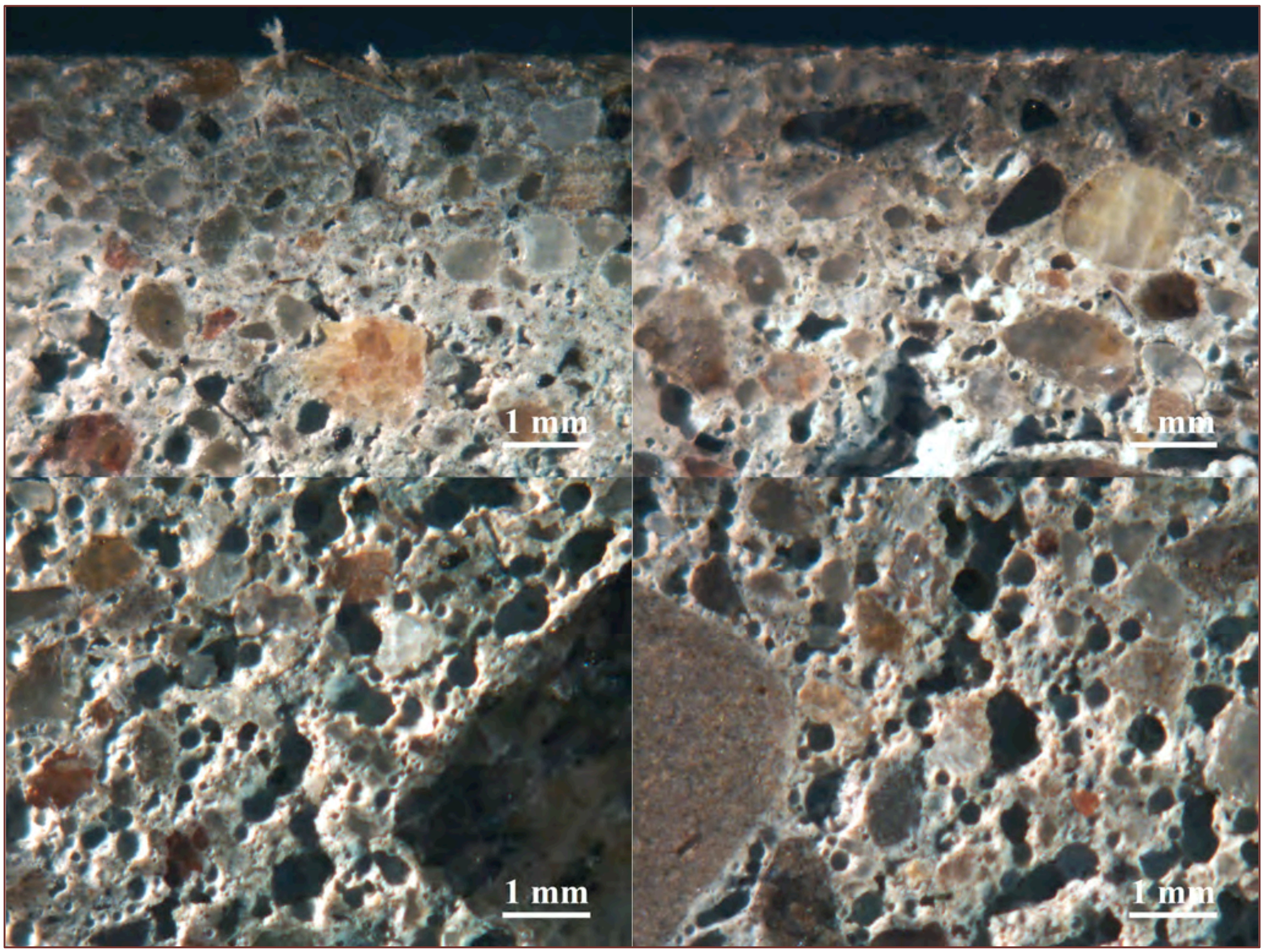
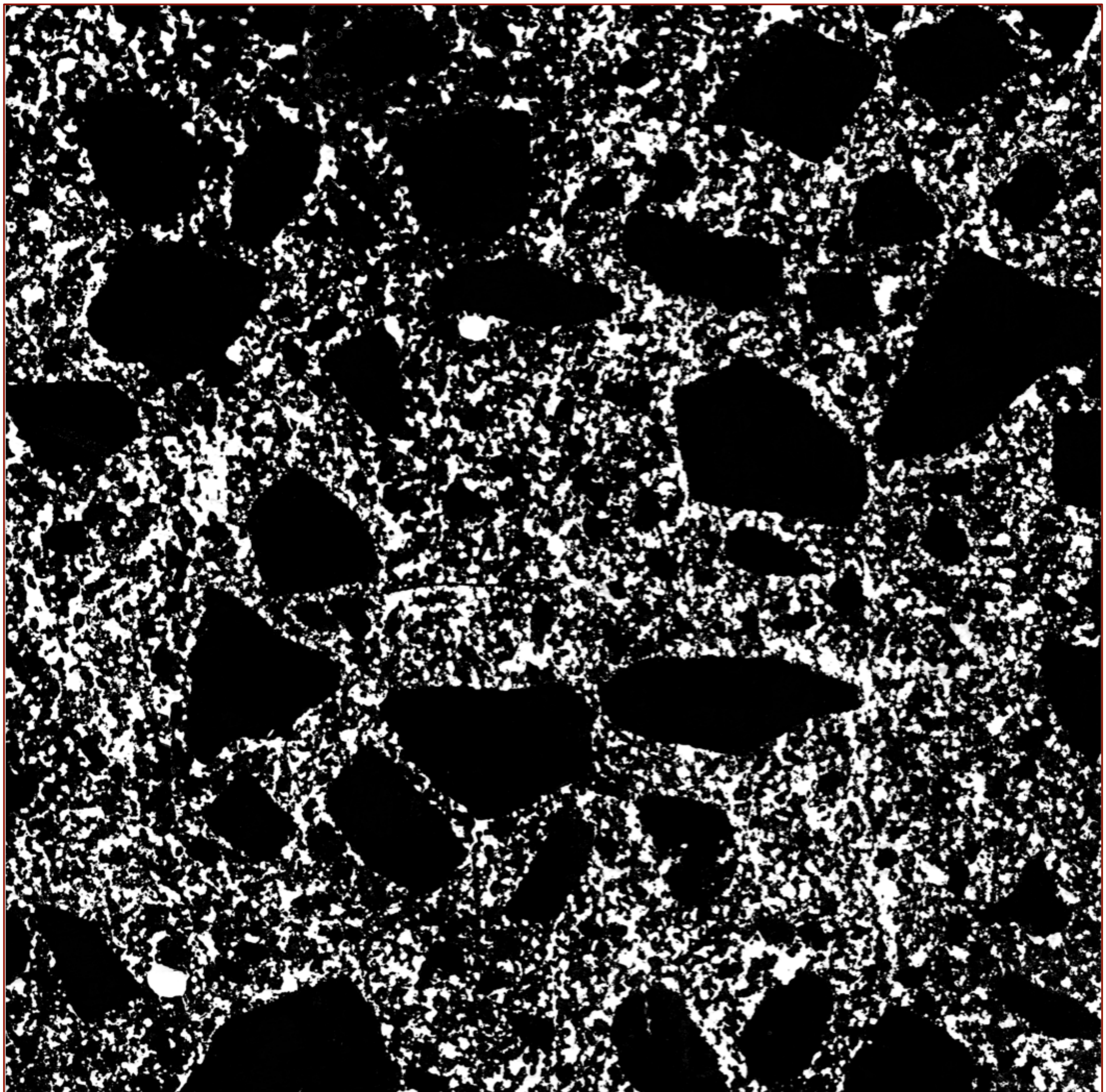


Figure 11: Photomicrographs of lapped cross section of core showing two distinct microstructural zones – (i) finished-induced densified low to no-air, low *w/c* near-surface densified zone, and (ii) interior excessively air-entrained concrete.

The following black-and-white photograph of lapped cross section of the core shows excessive air voids in white against everything else in black, which was prepared to scan on a flatbed office scanner and do an actual air measurement by using the flatbed scanner method for determining air-void parameters according to Peterson et al. 2002.



Calculated Air Content (%):	21.8
Given Paste Content (%):	27.7
Paste/Air Ratio:	1.27
Void Frequency (Voids/mm):	0.78
Specific Surface (mm^2/mm^3) (Recommended >25 mm^2/mm^3):	14.34
Powers Spacing Factor (mm) (Recommended < 0.2 mm):	0.09

Figure 12: Measurements of air contents and air-void parameters in the core by flatbed scanner method of Peterson et al. 2002. The core shows excessive air entrainment, as high as almost 22 percent air.

The overall quality and condition of concrete in the body of the core is found to be free of any cracking or any other evidence of physical or chemical deterioration. The interior concrete is reasonably well-consolidated (despite excessive air).

Too much air and fibers – both have created a "sticky" concrete, as reported, and increased difficulties in finishing operations to achieve a desired smoothness and flatness of the floor, as a result of which finishing was judged to have been continued for a prolonged period i.e. beyond the final set of concrete, and, subsequently developed a finishing-induced low to no air, very low *w/c* densified near-surface zone having a marked difference in properties than the interior concrete - and reported development of delamination between these contrasting skin and body within a few days of placement.

DISCUSSIONS

Potential for Near-Surface Delamination of an Air-Entrained Concrete Slab that has been Trowel-Finished

Trowel finishing of an air-entrained concrete slab can potentially develop near-surface delamination, i.e. a plane of separation between the trowel-densified surface region, and the interior concrete.

Background information provided with the core indicated that the slab surface was delaminated within days of placement. Its formation is judged to be due to hard trowel-finishing operations on an excessively air-entrained concrete that has an estimated air content of 20+ percent. Hard finishing operations on an air-entrained concrete can lead to such near-surface separations and eventually to long continuous delamination of the top thin sheet of the finished surface region.

To avoid any potential for slab delamination, ACI recommends the total air content of a concrete to be maximum 3 percent if the slab is intended to receive a hard trowel finish and preferably not be air-entrained[1]. The present concrete has as much as 20+ percent air in the interior concrete (i.e. beneath the densified low or no-air near-surface zone of 1/16 in. due to trowel finishing) that has the potential for development of near-surface delamination.

Although the present core was taken from an area where the slab surface is still adhered to the interior concrete and hence the core does not show any incipient or complete delamination, but background information provided with the core indicated occurrence of delamination within days of placement to the point to warrant this investigation.

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[1] Jana, D., and Erlin, B., Delamination: A sometime curse of entrained air, Concrete Construction, January 2005, pp. 101-107.

What Went Wrong?

The problem was initiated, as mentioned with excessive air entrainment in the concrete from introduction of an air-entraining agent in the original concrete mix. A 20+ percent air in the interior body of a concrete cannot be generated by any other method except from accidental over-dosage during addition of an air-entraining agent in the mix. Possible scenario of such over-dosage is malfunction of admixture dispensing unit at the batch plant or by other means. Air being beneficial in an outdoor concrete by virtue of its proven effect on improved workability and freeze-thaw durability has accidentally turned into the air being the main detrimental agent in causing surface delamination for an indoor concrete, where besides workability benefit air is not at all needed. This detrimental effect of air was introduced from having too much air, i.e. well above the maximum recommended air content of 3 percent by the ACI, and hard troweling a concrete having so much air let alone an air-entrained concrete has eventually caused the reported delamination.

Why it went wrong? What are the detrimental effects of having too much air in the concrete?

Entrained air, let alone too much air in a concrete makes the whole concrete mass sticky, and increases the difficulty in finishing, and in achieving a desirable/acceptable finish (despite giving better workability from a ball-bearing effect of entrained air)[2].

Excessive entrained air slows down bleeding of concrete (upward rising of mix water and fines) significantly, and hence, increases the potential for accumulation of bleed water beneath the finished surface region, if finishing were initiated prior to the cessation of bleeding. Therefore, too much entrained air may give a false impression of no bleed water at the surface and hence finishing can be initiated, while the concrete inside may still be bleeding, rather slowly, and bleed water will still slowly accumulate beneath the finished surface region – to eventually crate a plane of weakness and then a plane of separation between the early finished surface and concrete body.

Finishing operations to achieve a desirable finish is difficult for a sticky concrete having a high amount of air. Finishers tend to extend finishing operations, and prolonged finishing further densifies the surface region by washing out most of the entrained air and mix water from the top, thus creating a thin densified surface mortar rich in cement and fines and lacks air or water, having low to no entrained air and very low *w/c* compared to the main body of the concrete that is not so much affected by finishing. Such a difference in density, hardness, air, *w/c*, etc. between the thin sheet of finishing-densified surface mortar of low to no air and very low *w/c* and the normal finishing-unaffected main concrete body creates the seed for potential future delamination between the

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[2] Jana, D., Delamination – A State-of-the-Art Review. Proceedings of the 29th Conference on Cement Microscopy, ICMA, Quebec City, Canada, 2007, pp. 135-167.

two – (i) either by accumulation of bleed water beneath the thin sheet of densified surface mortar, as explained, and/or (ii) by simply from shearing action of the thin dense surface crust over a less dense high *w/c* and high air interior body, especially during the prolonged finishing.

Even though the above paragraph sounds like finishing operations, or rather prolonged finishing operations might have been the 'cause' of the delamination, finishing is NOT the cause, at least here – having air-entrainment with as much as 10 percent estimated air, i.e. excessive air entrainment in a concrete that was intended to be trowel-finished is the root cause, which had required finishing to be prolonged to achieve a desirable finish, no extended finishing, if any, is an 'effect' of excessive air entrainment – in eventually causing the surface deamination and cracking. *Request of hard trowel finishing operations on an air-entrained concrete, or, request for an air-entrained concrete to be hard-trowelled almost guarantee development of surface delamination.*

Without excessive air, finishing on a normal concrete could still cause delamination – simply by initiation of finishing operations prior to the cessation of bleeding, but in this case finishing has not caused the delamination, excessive air entrainment did, which has forced the bleeding to slow down and hence increased the potential for bleed water accumulation beneath the finished surface, and prolonged finishing of high air sticky concrete to further densify the surface.

Excessive Air Entrainment (+ Fiber) = Sticky Concrete Too Difficult To Finish = Prolonged Finishing = Delamination, Cracking

Too much air – Concrete in Core No. 3 has a total air content that is estimated from petrography to be 15 to 20 percent and determined from image analysis (Peterson et al., 2002) to be 21.8 percent. This air content is excessive, significantly higher than the recommended maximum air content of 3 percent.

Excessive Dosage of AEA – This excessive air entrainment is judged to be due to accidental over-dosage of air entraining chemical to the mix at the batch plant and cannot be produced by any other means to this extent. Such extreme air content can only be produced from excessive dosage of air entraining chemical. A possible scenario where such can happen is during malfunction of admixture dispensing unit at the batch plant.

Plus Fibers – Placement, consolidation, and finishing of such a high-air concrete would be a serious challenge for any finisher. Not only the concrete has excessive air but also has fine, hair-like polypropylene-type synthetic fibers throughout the mass, which will further increase the difficulty in placement, consolidation and finishing process.

Reasons for "Sticky" Concrete – Too much air and fibers – both have made the concrete too sticky to work with.

Finishing-induced densification of surface – In the process of prolonged finishing, the top few millimeters of the finished surface has been densified significantly compared to excessively air-entrained interior concrete.

Prolonged finishing has washed some mix water and air out of the surface and created a very dense hard darker gray low to no air skin, which is significantly different in compositions and proportions (air, *w/c*) than the interior concrete. This densified finished surface is the direct result of having too much air in the concrete, which made the concrete sticky, increased difficulty in finishing, and forced the finisher to finish for long to achieve an acceptable finish.

Slowed bleeding, Densification of Surface, Bleed-Water Accumulation – Two problems can come from such densified finished surface from excess air. First, excess air slowed down bleeding or upward migration of water significantly. An advantage of bleeding is to hydrate the cement particles at the top surface region by the bleed water. Concrete has its own ability to create a well-hydrated finished surface, which cannot be achieved simply by adequate curing. Too much air slowed down bleeding to such an extent that the finished surface was not hydrated adequately before evaporation might have taken place to remove some water out of the surface after placement, which could have prompted development of shrinkage-related cracking at the surface. Secondly, accumulation of bleed water beneath the densified finished surface can develop a weak zone immediately beneath the densified finished surface mortar, which is susceptible to delamination.

Prolonged Finishing – Delamination – The other problem of excessive air and hence "sticky" nature of concrete is subsequent prolonged finishing of high-air sticky concrete to achieve the desired flatness and smoothness of the floor, which could, thus, develop delamination as fine elongated discontinuous (and eventual continuous) separation as elongated voids between the finishing-induced densified low to no air, low *w/c* surface skin and the interior excessively air-entrained less-dense concrete.

A delaminated slab surface can further develop cracking of the delaminated 'sheet' from traffic load.

Excessive Air Entrainment + Air-Void Clustering = Low Strength Concrete

Another detrimental side effect of having too much air is clustering of air voids giving a frothy texture to the paste, and especially along aggregate-paste interfaces, which can weaken the interfacial bonds, and, thereby further reduce the compressive strength. Figure 13 shows such clustering of voids along coarse aggregate-paste interfaces that has significantly weakened the interfaces. Strength of concrete depends strongly on the strength of interfacial bonds (since concrete is week in tension). The lapped surface and thin section examined show many such clustering, especially along coarse aggregate-paste interfaces.

High air, therefore, reduced the overall compressive strength both by: (i) increased porosity (for every one percent point increase in air above the design air content, at a given workability, can reduce compressive strength by 3 to 5 percent point), and (ii) by weakened aggregate-paste bond from clustering of excess air along the interfaces.

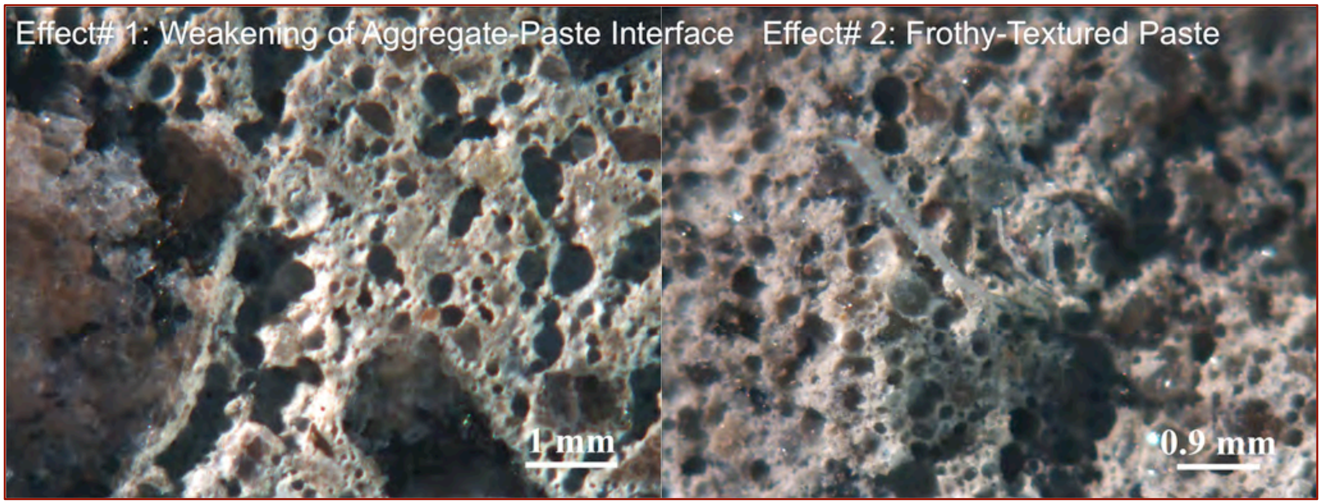

Figure 13: Two undesirable effects of excessive air entrainment that leads to loss of strength of concrete – weakening of aggregate-paste bond by air void clustering along the interface (left photo), and, frothy-textured paste from having too much air (right photo). Also note some fibers in the fresh fractured surface in the right photo.

Prolonged Finishing

The evidence of densified near-surface region of concrete having very low *w/c* and low to no air at all to a depth of 5 mm from the very top finished surface, in stark contrast to high-air interior concrete is the direct evidence of prolonged finishing, which is understandable given such a high air in the concrete where finishing was needed to continue to handle such a high-air sticky concrete so that an acceptable broom finish can be achieved. Therefore, finisher had no choice but to continue finishing to achieve the durable floor flatness and smoothness.

Finisher, however, could have suspected such a high air in the fresh concrete especially from the reported "stickiness" of concrete, or the need to finish long enough to the point of densifying the surface all of which should have given clues to the high air in the concrete, which should have been enough to waive all liabilities from potential future delamination of the slab – as finishing on an excessively air-entrained concrete would inevitably lead to the problem of delamination – as happened in this project.

Compressive Strengths

The reported 2540-psi 28-day compressive strength of core from the slab, which is significantly less than the required 3500 psi strength is the testament of such a high air of concrete as seen in the present core.

CONCLUSIONS

The reported delamination is judged to be due to use of an excessively air-entrained concrete in the original concrete mix delivered that was intended to receive hard trowel finishing operations to generate a smooth, flat, dense, hard, shiny industrial finished surface to receive heavy traffic. The total air content for the slab to receive hard trowel finishing (for the densified surface) should have been restricted to 3 percent air maximum (as per common ACI recommendations). Trowel-finishing operations on an air-entrained concrete is the root cause, let alone having as much as 15 to 20 percent air, where having so much air was judged not according to the industry recommendations for a slab intended to receive a trowel finish.

Therefore, in this situation the finisher is judged not responsible to cause delamination since trowel finishing was intended for the desired dense hard shiny finished surface result for industrial applications, and, the finisher cannot introduce so much air in the concrete. Finishing, however, can cause development of delamination by bleed water accumulation beneath the prematurely finished surface (where finishing was initiated prior to the cessation of bleeding), which, again, would be a secondary cause of delamination since it is having too much entrained air in the first place which would increase the potential for late bleed water accumulation by reduced bleeding rate. Finisher, however, should have rejected the concrete from his reported "stickiness" of concrete, hence asked for a plastic air check to confirm the high-air problem, and inform the proper personnel the potential for delamination if that high-air concrete were to be hard towel finished.

Concrete designer can be waived from the responsibility if the designer was not aware of the fact that the slab was intended to receive a hard trowel finishing operation, even though putting 20 percent in a concrete cannot be forgiven for any structural applications. In that case, it would be the lack of communications between the designer, supplier, finisher, and other individuals responsible for the project, i.e. not knowing NOT to use an air-entrained concrete having more than 3 percent total air for an indoor slab, which will receive a hard trowel finish, which would cause this unfortunate delamination of the slab by troweling-finishing operations on an air-entrained concrete. The concrete should not have been designed to be air-entrained in the first place for an indoor slab let alone having as much as 15 to 20 percent air in the first place, when it was intended to receive a hard trowel finish.

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✪ ✪ ✪ END OF TEXT ✪ ✪ ✪

APPENDIX

Figure A1: Shown are: (a) the smooth, flat, dense, hard, shiny, trowel-finished top surface with remains of sulfur capping (top left photo); (b) the smooth, formed, and wavy bottom surface with impression of placement of slab on a plastic vapor retarder (top right photo); and (c) side view of Core No. 3 (bottom photo), as received. Within the red circles in the bottom photo are No. 2 reinforcing steels at a depth of $5^3/_4$ in. from the top surface.

Figure A2: Lapped cross section of Core No. 3 showing: (a) the good grading and well-distribution of the aggregate particles; (b) the densified top surface region; and (c) the moderately dense nature of the interior concrete. Notice a lifting appearance of crushed granite coarse aggregate particles due to frothy texture of the mortar fraction from excessive air entrainment. Also notice the densified surface skin at the top 1/8 in. from trowel finishing.

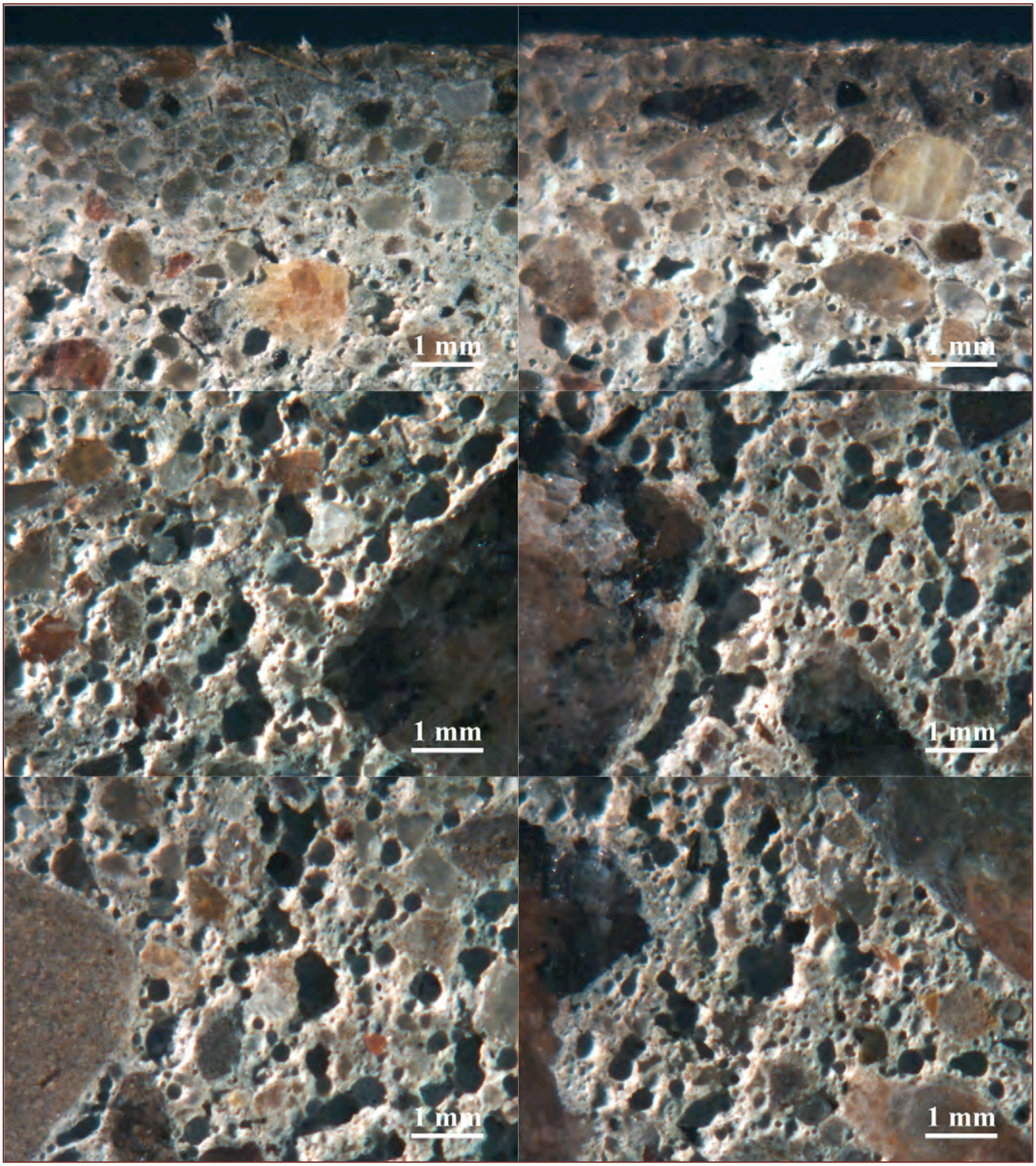

Figure A3: Photomicrographs of lapped cross section of Core No. 3 showing: (a) the densified top surface region with no air and a lower *w/c* denser and darker paste at the top few millimeters compared to the main body (top photos); and (b) the excessively air-entrained nature of the interior concrete with clustering of voids (middle and bottom photos).

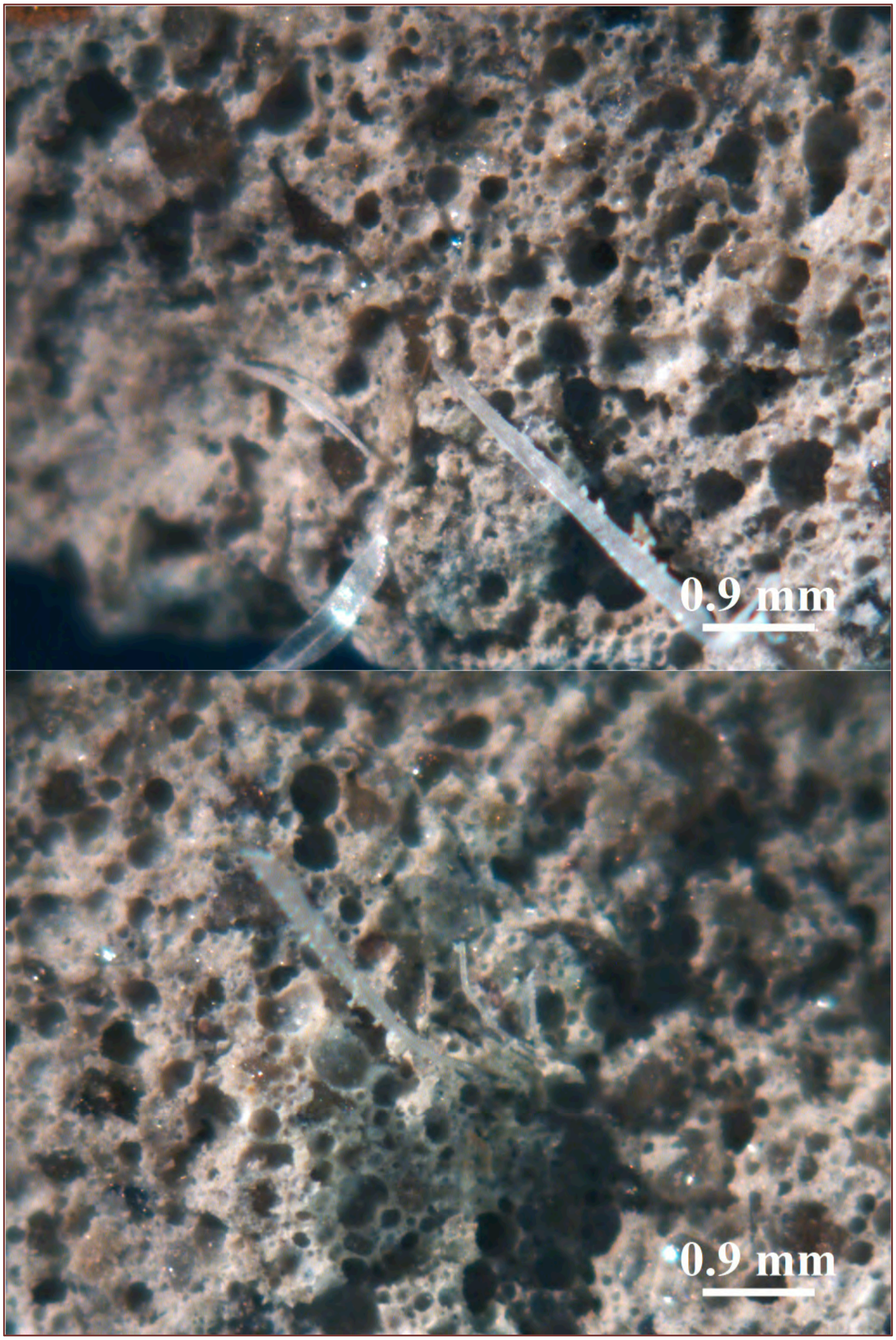

Figure A4: Photomicrographs of fresh fractured sections of the core showing: (a) the presence of fine polypropylene type fibers distributed throughout the concrete; and (c) the frothy texture of the paste due to excessive air entrainment.

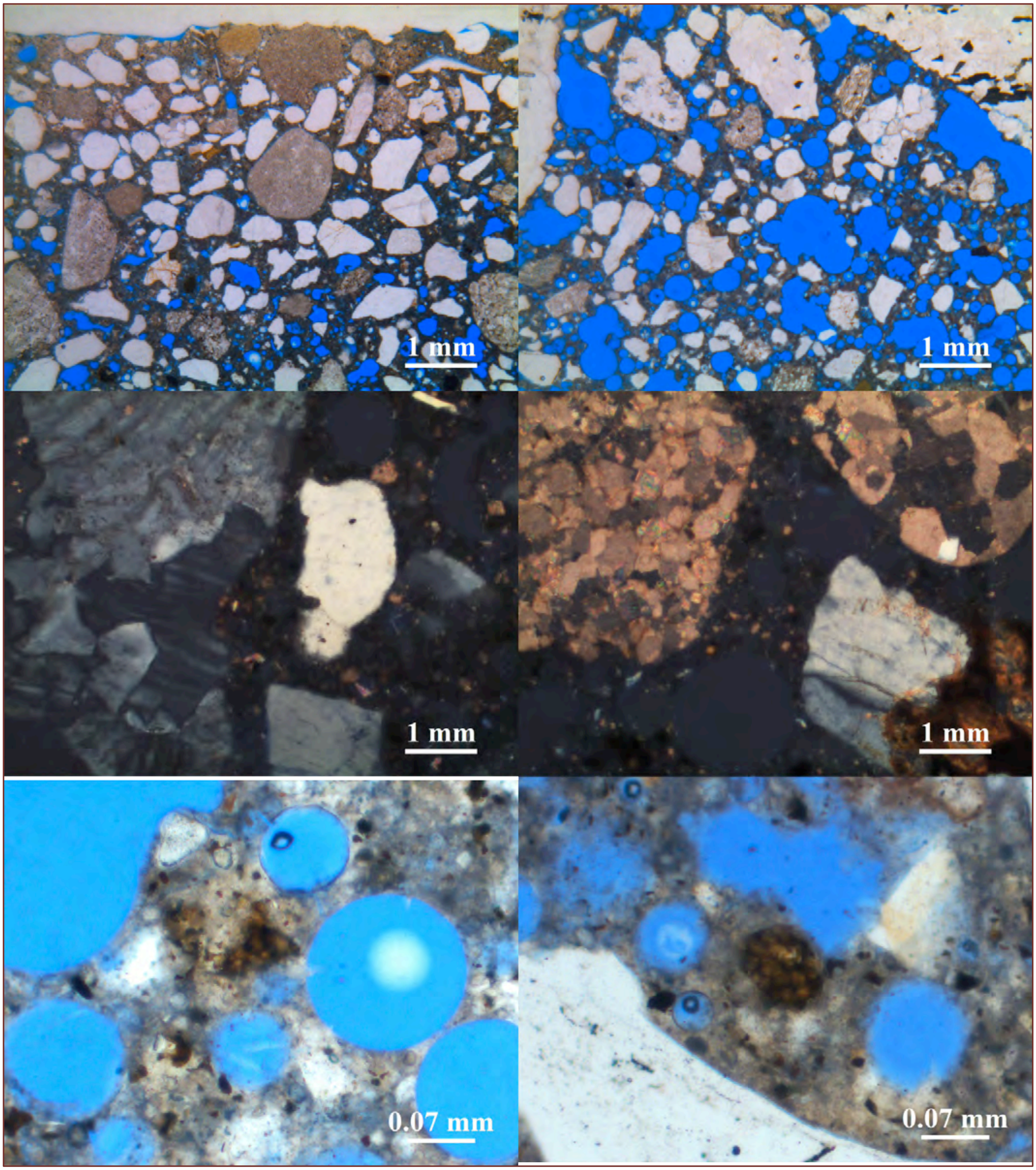

Figure A5: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of Core No. 3 showing: (a) the excessively air entrained nature of the concrete (top photos); (b) the crushed granite coarse aggregate particles and natural siliceous-calcareous sand fine aggregate particles (middle photos); and (c) residual Portland cement particles in the paste (bottom photos).

END OF REPORT[3]

[3] The CMC logo is made using a lapped polished section of a 1930's concrete from an underground tunnel in the U.S. Capitol.