Laboratory Investigations of the Oldest Concrete Pavement in America – Applied Geology in Civil Engineering

Blake Lemcke, PG
Senior Petrographer/Geologist
American Engineering Testing, Inc.
550 Cleveland Ave. North
St. Paul, MN 55114
651-659-9001
blemcke@amengtest.com

Prepared for the 69th Highway Geology Symposium, September 2018

Acknowledgements

I would like to thank several of my colleagues, mentors, and co-workers who have exhibited patience, guidance, and a sense of humor not only in the writing of this paper but in my adventure through the tiny world of concrete petrography and concrete technology. My accomplishments were possible because of the time they've invested in me:

Gerard Moulzolf, PG – American Engineering Testing, Inc.
Lawrence Sutter, PhD, PE, FACI – Michigan Technological University
Terrance Swor, PG – American Engineering Testing, Inc.
Scott Wolter, PG – American Petrographic Services, Inc.
Richard Stehly, PE – American Engineering Testing, Inc.
Karl Peterson, PhD – University of Toronto
Dan Frentress, PE – Frentress Enterprises LLC

...and finally, all my fellow lab-workers

Disclaimer

Statements and views presented in this paper are strictly those of the author(s), and do not necessarily reflect positions held by their affiliations, the Highway Geology Symposium (HGS), or others acknowledged above. The mention of trade names for commercial products does not imply the approval or endorsement by HGS.

Copyright

ABSTRACT

In summer of 2016, American Engineering Testing (AET) was contacted by the American Concrete Paving Association (ACPA) to investigate concrete from Court Avenue in Bellefontaine, Ohio – the oldest concrete pavement in the United States (ACPA, 2016). The study involved several collaborating parties in both the private and academic sectors to assess the physical, chemical, and geologic properties of the historic pavement, which is still in service. The goals of the investigation were to understand how a concrete pavement placed in 1893 is still performing and what implications can be drawn to modern portland cement concrete pavements (PCCP's) used in highway construction.

AET received two pavement sections from the ACPA for the laboratory study. Representative sub-samples were procured by AET and sent to four separate laboratories to perform analysis of their choosing. Techniques utilized in the study included: petrography (optical microscopy), air void system analysis, scanning electron microscopy, electrical resistivity, neutron imaging, thermogravimetric analysis, and low-temperature differential scanning calorimetry.

These combined studies revealed the nature of the pavement's construction, the properties and attributes of the raw materials utilized, and led to an understanding of the pavement's durability and longevity. Specific material properties obtained by the study were as follows: aggregate characteristics which included lithology/type/size/grading, hardened paste properties which included air void system parameters/water-cement ratio/cement clinker chemistry and morphology. Physical concrete characteristics obtained included permeability, volume of permeable pores, and sorptivity. Petrography in-particular has proven a beneficial tool in the assessment of concrete (both young and old) and is a testament to the power of applied geology in highway engineering and construction.

INTRODUCTION

This paper primarily presents data and results of petrographic analysis performed by AET on historic concrete pavement from Bellefontaine, Ohio. The pavement from Court Avenue was placed in 1893 and is the oldest known example of portland cement concrete pavement (PCCP) in the United States (Figure 1, a). The laboratory study was envisaged by the ACPA and involved three other entities, including: Braun Intertec Corp., Oregon State University, and the University of Toronto. Bellefontaine, located in west-central Ohio, lies directly in a severe freeze-thaw environment according to the American Concrete Institute (ACI). The longevity of the pavement in such an environment is a testament to the material's durability and the ACPA felt it warranted an in-depth study. The obvious question to be answered: what characteristics allowed the concrete to last 125 years? The paper also draws comparisons between the historic pavement and modern PCCP's, which are widely used in highway construction.

BACKGROUND

George W. Bartholomew (Figure 1, b) has been attributed with the vision, mix-design, and financial backing of this pavement – including the production of the cement used in the mixture (Sutter, 2017). During this time in the United States portland cement was in its infancy, and many preferred the more reliable German-produced portland cements or the American 'Rock/Natural Cements'. Bartholomew learned of the cement making process while visiting Germany and later at the Alamo Cement Company in San Antonio (Snell, 2002). He began experimenting with local marl deposits in an area north of the city upon returning to the area in 1886. Upon developing the correct materials for cement production, he founded the Buckeye Cement Company in 1889. They first used vertical-style kilns which utilized a continuous feed which reportedly improved production rates. Ground marl and 'blue clay' (raw-feed) was fed into the top of the kilns and raked into the underlying combustion chamber (Sutter, 2017). Clinker was eventually removed from the base of the kiln. Information regarding the clinker grinding process is sparse, however; the clinker was apparently milled with rounded imported 'flint stones' from Iceland (Pardi, 2017). The fuel utilized in the kilns at that time was petroleum crude.

(a) (b)

Figure 1 – recent photograph of Court Avenue (a) and photograph of George Bartholomew, date unknown (b) (photos accessed from http://explorer.acpa.org/explorer/places/united-states/ohio/bellefontaine/street/old-us-30-lincoln-highway/)

Historical accounts say that the streets of Bellefontaine were a sea of deep mud in the spring and fall of each year (Pardi, 2017). During drier months the streets were hard and very dusty. George Bartholomew saw this as an opportunity to increase commerce in the city, as horses and buggies experienced great difficulties on the earthen thoroughfares. Having previously placed a driveway for a local lumberyard, the City Council was impressed and commissioned a 220-foot-long test strip in 1891. W.T.G. Snyder, a local cement contractor, was hired to place the test strip.

The installation followed a similar technique to sidewalk construction, the slabs were formed in 5-foot square sections (Snell, 2002). Tar paper was placed between adjacent slabs and a 'two-lift' system was utilized. The base coarse contained coarser rock and a higher water to cement ratio (w/c) while the upper lift or wear-course contained smaller aggregate and a lower w/c. Concrete mixing was done without heavy equipment; the sand, stone, and cement were unloaded into a pile and mixed by hand and tamped into the forms. The pavement was cured by placing a few inches of wetted sand over its surface for one week. The original surface finish of the pavement was tined to aid in horseshoe traction. In 1893, portions of the pavement were sent to the International Exposition in Chicago (World's Fair) where Bartholomew won first prize for Engineering Technology Advancement in Paving Materials (Snell, 2002).

Sampling

Two large segments of full-depth pavement were received by AET in summer of 2016. One of the segments was unadulterated (Figure 2, a) and one had been previously core sampled and exhibited several cylindrical core hollows (Figure 2, b). Both pavement segments were fairly large; the intact sample measured approximately 12" x 12" and the previously-cored segment slightly smaller. Both segments represented a nearly 'full-depth' cross-section of the pavement and were about 6" to 8" thick. The larger non-cored segment was wet saw-cut into several 'slabs' for the laboratory analysis and as display pieces. The slab sections were flattened and polished with loose grit abrasives on a lapidary wheel using water as a lubricant. The slabs were worked from a coarse 80 grit up through progressively finer grits and eventually finished on 600 to produce a matte finish suitable for microscopic observations. The smaller pavement segment was treated in a similar fashion, with smaller slabs and sections sub-sampled.

(a) (b)

Figure 2 – pre-submittal photos of intact concrete pavement segment (a) and previously-cored segment (b) (photos supplied by the ACPA)

Sub-samples and polished slabs were distributed to the University of Toronto, Oregon State University, and Braun Intertec for analyses of their choosing. Upon slab preparation, the distinct layers or 'two-lift' construction of the pavement was obvious (Figure 3). Thin sections of the pavement were produced by AET from the denser wear-course, porous base-course, and the interface between the two concrete placements.

Figure 3 – saw cut and lapped cross-sectional profile of Bellefontaine pavement sample. Note the two-layer construction is evident by both paste coloration and aggregate sizing

PETROGRAPHIC FINDINGS

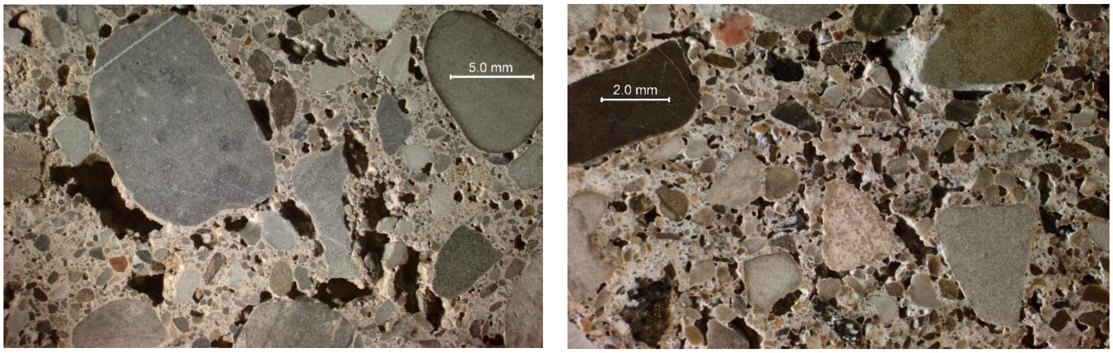
The base concrete of the examined pavement section ranged from 44 mm (1-3/4") to 102 mm (4") in thickness, contained a 38 mm (1-1/2") nominal-sized carbonate-rich gravel coarse aggregate, was placed at a moderately high w/c, and was fully carbonated throughout its thickness (Figure 4). The concrete topping ranged from 32 mm (1-1/4") to 70 mm (2-3/4") in thickness, contained a mixture of natural 'pea gravel' and crushed granite coarse aggregate, was placed at a moderately low w/c, and exhibited an overall negligible carbonation profile measured from the top surface of the pavement. The two concretes appeared to be very well bonded to each other. The total thickness of the base layer in the examined section was likely not full-depth, as much of its bottom surface exhibited a fractured rather than formed appearance. The base concrete of the pavement contained a measured 7.9% total air void content and the top or wear-course contained 7.5% total air.

Figure 4 – saw cut and lapped cross section of pavement after application of pH indicator. Magenta stain represents pH levels over 8.3. Note the base concrete exhibited lower pH associated with paste carbonation.

Air Void Analysis

Air void system analysis (ASTM C457, Procedure A) were performed individually on both layers of the concrete pavement section. This testing involves a 'linear traverse' of the lapped section under high magnification in which individual void spaces are measured (chord lengths) and tallied. This test method was developed by ASTM for modern concrete mixes in which air entraining admixtures are utilized to create a system of microscopic bubbles (voids) which protect the paste from frost damage. Air entrainment has been widely utilized since the middle of the 20th century in high performance concretes. The American Concrete Institute (ACI) has developed a series of air void system parameters which they consider necessary for freeze/thaw durability. These parameters are the total volume of entrained air, spacing factor (average distance of the air voids), and specific surface value (essentially a ratio of void diameters to void volumes).

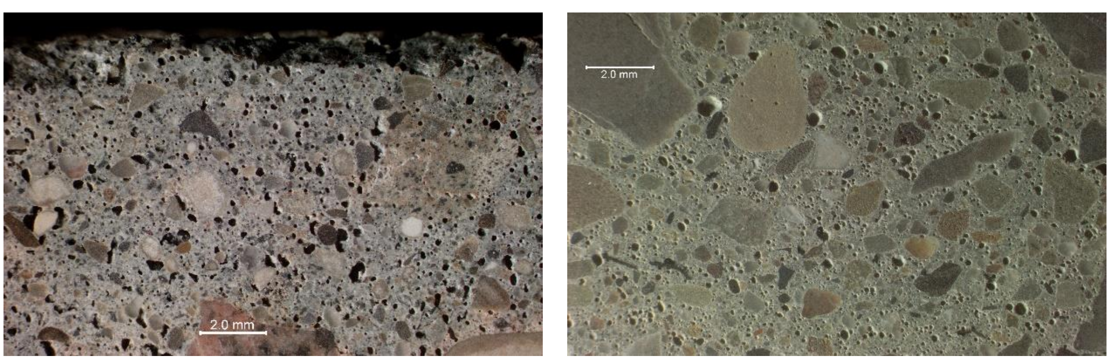
The base concrete layer contained a measured air void content of 7.9% with a spacing factor of 0.012" and specific surface value of 240. Approximately 4.3% of the measured air was 'entrained-sized' or less than 1 mm (1/32") chord length and 3.6% of the air was considered 'entrapped-sized' or greater than 1 mm chord length. The vast majority of the air in the base layer consisted of coarse, irregular-shaped, consolidation-like voids (Figure 5, a) which resulted from incomplete tamping or packing of the mixture. Some areas of the base layer even exhibited a 'honeycomb' appearance from the under consolidation of the mixture (Figure 5, b). This type of 'coarse' air is generally not beneficial to protecting the paste in a freeze/thaw environment, but is however ideal for drainage.



(a) (b)

Figure 5 – saw cut and lapped surfaces of the base concrete layer showing coarse irregular-shaped voids under 5x mag (a) and abundant voids producing a honeycomb' texture under 10x mag (b)

The concrete topping layer or wear-course contained a measured air void content of 7.5% with a spacing factor of 0.008" and specific surface value of 660. Remarkably, these air void system parameters were consistent with the modern recommendations for freeze/thaw durability outlined in ACI 212.3R: "The cement paste in concrete normally is protected against the effects of freezing and thawing if the spacing factor does not exceed 0.008", as determined in accordance with ASTM C457. Additional requirements are that the surface area of the air voids should be greater than 600 in^2/in^3…" The air void system of the wear-course closely resembled those observed in modern concretes produced with intentional air entraining admixtures (Figure 6, a & b). The top layer or wear-course concrete would be particularly susceptible to saturation from meteoric water and freeze/thaw cycling; the air void system (and low w/c, discussed later) certainly played an important role in the topping's durability/longevity. The possible origins of such an air void system in this historic concrete which was produced prior to the discovery of air entrainment is discussed later.



(a) (b)

Figure 6 – lapped section of top layer or wear-course concrete showing abundant (sub) spherical air voids within its paste under 10x mag (a) and comparison to a modern concrete with purposeful air entrainment under 10x mag (b)

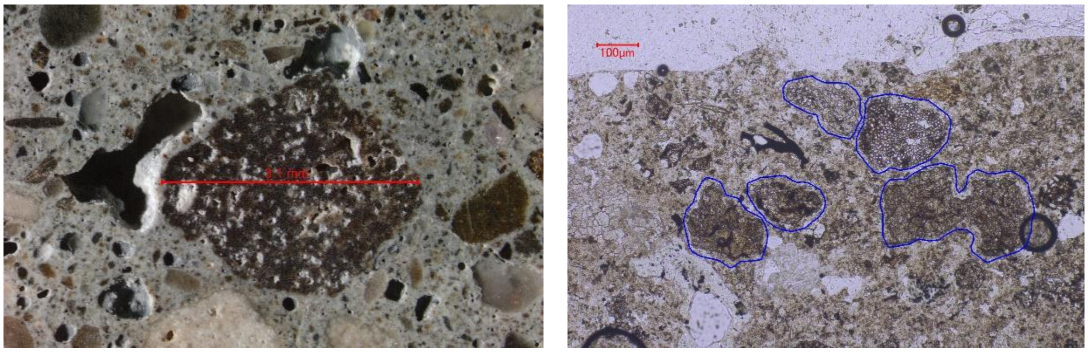
Paste Characteristics

A controllable parameter in designing concrete for durability is the water to cement ratio (or w/c). Concrete is a porous material often likened to a 'hard sponge' and contains three different types of voids or pores. The smallest of these are the pores present within the gel of the amorphous cement hydration products (calcium-silicate hydrates, CSH). These pores are present on a nano-scale (0.5 to 10 nm) and their role regarding durability is relatively insignificant. In contrast, the capillary or interstitial pores of the paste are of great importance regarding the overall strength and freeze/thaw durability of any concrete. This porosity is typically on the range of 10 nm to 10 µm and results from the residual spaces between cement hydration products, residual cement grains, and aggregates. The nature of this porosity is a direct result of the concrete's w/c as it is placed, representing spaces which were originally filled with mix water. The largest of the pores in concrete are the coarse voids which become incorporated during mixing or consolidation, whose importance was covered in the previous Air Void Analysis section.

Water to Cement Ratio (w/c)

Just as variation was noted in the total air void content of the two pavement 'lifts', a variance in w/c between the two layers was equally evident from the analysis. Simple physical characteristics such as paste color and paste hardness can be used to qualitatively assess the w/c of any concrete mixture. The paste coloration of the upper concrete placement was light to medium gray (Munsell® Rock Colors N7 to N5). In contrast, the base concrete placement exhibited a much lighter paste coloration which ranged from yellowish gray to very pale orange (Munsell® Rock Colors 5Y 8/1 to 10YR 8/2). These coloration differences are quite clear in Figure 3. The gray or general dark coloration of the concrete topping layer was consistent with placement at a moderately low w/c and the lighter overall color of the base with placement at a moderately high c/m. Although paste carbonation (discussed later) can also influence coloration. Paste hardness, as one might guess, is also directly related to w/c. In general, harder pastes are indicative of lower w/c (being less porous) while softer paste indicate higher w/c. The paste of the wear-course exhibited variable hardness, but was generally considered to be moderately hard overall (Mohs 3.5 – 4). The paste of the base concrete was judged to be moderately soft (Mohs 2.5 – 3).

A more detailed and quantitative estimate of w/c can be drawn from thin section analysis. Aged or historic concretes add an extra challenge to the petrographer, as portland cement manufacturing and grinding technology has changed drastically in the last 60 years. Both layers of the concrete pavement exhibited abundant residual cement clinker grains for observation, many of which were coarsely-ground (up to 3 mm) and even visible in hand sample (Figure 7, a). Additionally, the clinker morphology was somewhat inconsistent, with many grains being of unique composition (Figure 7, b). For example, some unhydrated particles within the wear-course contained very fine and well-rounded belite particles with interstitial alite, and many particles were free of the ferrite and aluminate cement phases. Additionally, several of the residual calcium silicate grains (alite and belite) were a moderately dark tan to brown coloration – not a common feature of modern cements. The abundance of residual cement clinker was not surprising given the very coarse grind of the cement. The topping or wear-course contained a visually estimated 8 to 10% residual cement and an approximate w/c of 0.30 to 0.45, depending on exact location. The base concrete was estimated to contain between 4 and 6% residual cement particles and w/c between 0.55 and 0.65. Interestingly, a historical marker placed at the site in Bellefontaine claims the bottom course of the concrete pavement *had 18 sacks of cement, 104 cubic feet of aggregate, and water; making a 1:2:4 ratio of materials. Then a 2 inch 1:2 mortar top was spread on the base and tamped.* (Sutter, 2017). Petrographic estimates were generally in-line with these figures from the historical marker.



(a) (b)

Figure 7 – a very coarse dark-colored remnant clinker particle with a max. dimension of 3 mm in the wear-course concrete under 25x mag (a) and variable clinker morphology (blue outlines) as viewed in thin section of the wear-course under plane polarized light at 100x mag (b)

Residual Cement Characteristics

Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were performed at the University of Toronto. The work revealed many of the residual clinker particles to be of compositions quite like modern portland cements. Figure 8 shows one such residual particle and details its elemental composition based on emitted x-ray energy upon electron-beam stimulation. The phases documented in the particle include the four main phases of modern portland cements, which include: alite (tricalcium silicate), belite (dicalcium silicate), aluminate (calcium-aluminate), and ferrite (calcium-iron-aluminate). Euhedral grains of tabular alite are arranged with sub to anhedral grains of belite within the particle. Filling in the interstices are the aluminate and ferrite phases. Of interest, the presence of a Mg-rich phase was also noted in the interstitial material and was attributed to the presence of periclase (MgO) (Avdyllari, 2017). Periclase is not commonly found in modern cements as Mg contents of raw-feed are now kept to a minimum as periclase hydration can lead to soundness issues. Its presence in this historic material is consistent with the use of relatively 'impure' raw ingredients. Although the manufacture of this historic cement in a vertical-style kiln would now be considered crude; the resulting material was very similar to modern cements produced in rotary-style kilns.

Also of interest regarding the cement and cement hydration is the lack of gypsum utilized in the ground clinker. Gypsum is currently inter-ground with cement in order to control its setting time. The discovery of gypsum addition was not realized until several years after the Court Avenue pavement had been placed. Portland cements which lack a source of sulfate will 'flash' set, reducing workability and disallowing longer placement times. Further, long-term storage of ground cement is problematic without gypsum as it will prematurely hydrate from atmospheric humidity, leading to clumping of the gray powder.

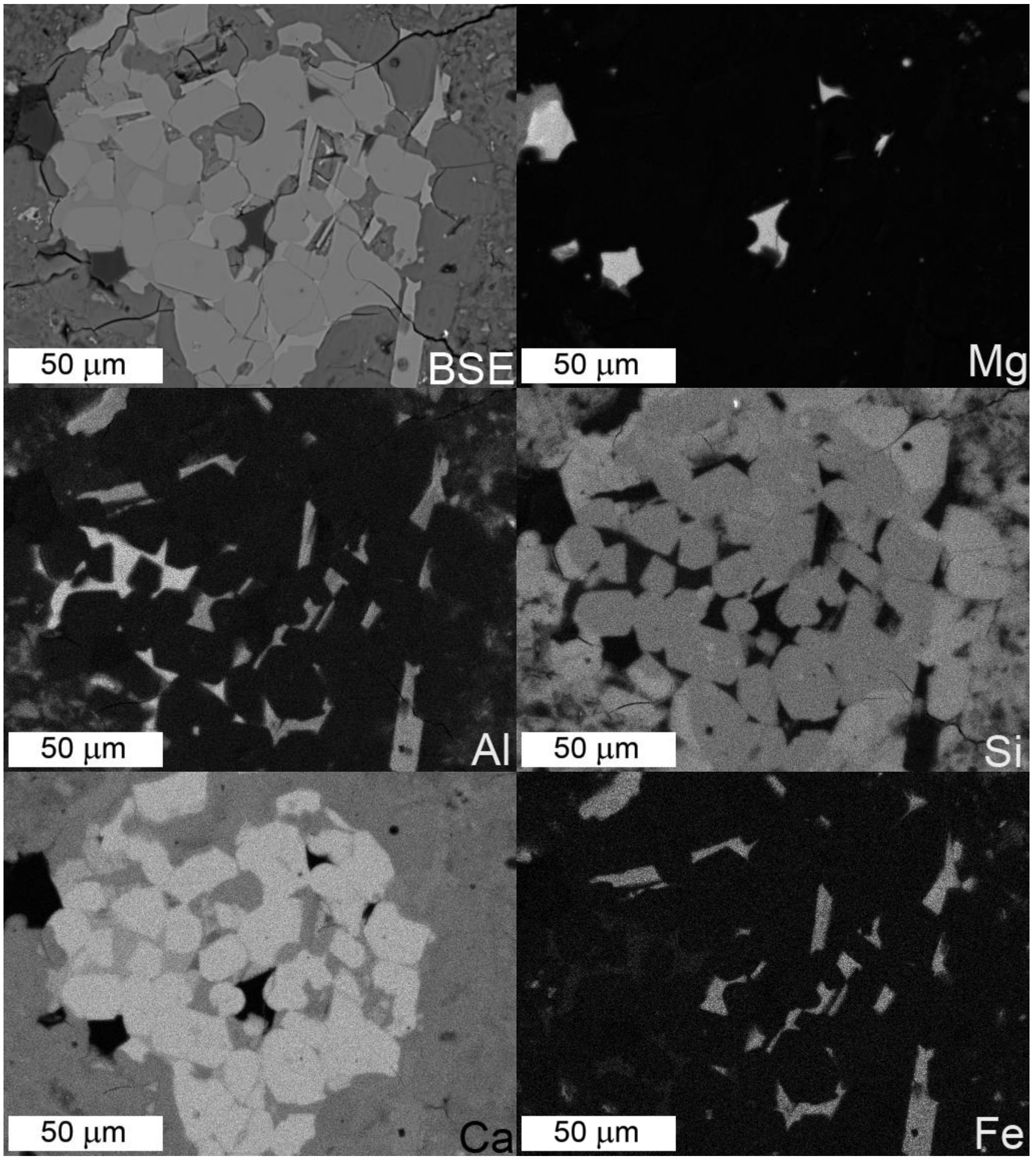


Figure 8 – series of images consisting of a back-scattered electron (BSE) image (upper left) and subsequent elemental maps obtained from the same region. The element listed in the bottom right corner of the images denotes its presence as brightly-lit areas. Note the few brightly-lit areas in the Mg map which are attributed to the presence of magnesium oxide or periclase (MgO). Images from (Avdyllari, 2017).

Carbonation

The carbonation of portland cement paste involves the reaction of carbonic gases (carbon di/monoxide) in the air or dissolved in moisture and the cement hydration products. The hydration products altered from this reaction include the crystalline portlandite phase ($CaOH_2$) and the amorphous CSH gel. As concrete is exposed to the atmosphere, the reaction slowly converts the portlandite and CSH into the more stable calcium carbonate phases of calcite and/or vaterite. The rate of this reaction is dependent upon several factors, with the most influential being paste porosity and permeability (a function of w/c) and the exposure conditions of the concrete. With the carbonation reaction comes a drop in the pH level due to the consumption of alkalis. Concrete is a very alkaline or basic material and when freshly mixed typically exhibits pH levels in the 12 to 13 range. Phenolphthalein is an ideal indicator for the drop in pH that occurs from the carbonation reaction, being a bright magenta at pH levels between approximately 8.2 and 13.0. The indicator is colorless below 8.2, and as can be readily seen in Figure 3, which shows the base concrete of the Bellefontaine pavement to exhibit nearly complete carbonation. This is a direct result of the base concrete's porosity/permeability which was the product of both its higher w/c and abundant coarse consolidation voids, readily allowing the passage of moisture. The high w/c and permeance of the base layer may at first seem like a negative attribute; however, this design produced relatively strong base material which also allowed for adequate drainage to ensure the passage of moisture/meteoric water. The negligible level of carbonation of the wear-course after over 100 years of service is a direct result of this layer's density or low porosity/permeability. This strong surface, the result of low w/c, has proven very durable to overhead traffic (both horses and automobiles) and general exposure.

It is important to note that once the carbonation reaction begins, the hydration reaction is halted. This is paramount in the curing of modern portland cement concretes as adequate cement hydration (or curing) is needed to realize the full-strength potential of the material, which establishes its long-term durability. Tying this into the residual cement observed in the wear-course, one could assume that the concrete of the wear-course is still undergoing the hydration reaction and is slowly gaining strength after over 100 years of service!

Aggregate Characteristics

It has been said that you can make poor concrete from good materials, but never make good concrete from poor materials. As demonstrated, the paste/cement portions of the Bellefontaine pavement were of great quality for their time, and so, the aggregates also deserve some credit for the longevity of Court Avenue.

The aggregates of the base concrete layer were of a coarser gradation and of slightly different composition than those of the wear-course topping. Aggregate in the base layer consisted of 38 mm (1-1/2") to 51 mm (2") nominal-sized natural carbonate-rich gravel. Lithologies documented primarily included: micritic, argillaceous, and sandy dolostones. The base layer also contained many pea-gravel sized particles of similar composition. The coarse aggregates were mostly rounded to sub-rounded with only a few sub-angular particles present. This aggregate property likely made for easier workability when hand mixing the plastic concrete mixture in its formwork. Additionally, the predominant carbonate lithology of the aggregates lent itself to a very good bond with the surrounding paste, aiding strength. It has been well-documented in concrete literature that carbonate lithologies exhibit exceptional bonding properties with portland cement pastes. Overall, the coarse aggregates of the base concrete were considered hard and durable; however, some aggregate deterioration was noted in the examined pavement and are discussed later. The finer, sand-sized particles of the mixture comprised quartz, feldspar, carbonate, and other lithic particles (including chert).

The wear-course topping concrete visually contained a lesser amount and finer coarse aggregate relative to the base concrete. This was consistent with the general paste-rich appearance of the topping compared to the more paste-lean base layer. The topping layer contained a 12 mm (1/2") nominal sized coarse aggregate that appeared to be a mixture of natural carbonate-rich pea gravel and crushed (?) or angular igneous rock. The pea gravel was of similar lithologic composition to that documented in the base concrete. The abundant angular igneous particles consisted primarily of a dark-colored amphibole-bearing gabbro and lighter-colored granitic lithology. It is not known if the igneous material was a natural feature of local gravel deposits at that time or was intentionally added to the topping mixture to add durability. As can be seen in Figure 9, the dark igneous particles were primarily present within the topping concrete, and a few also residing within the base layer. Like the base concrete aggregates, the coarse aggregate in the wear-course was considered very hard and durable. Without question, the harder siliceous aggregates in the topping would provide an abrasion resistant surface that could withstand the impacts of overhead traffic.

Figure 9 – saw cut and lapped pavement section showing many dark and angular igneous rock particles within the wear-course topping, a few were also noted in the base layer.

Deterioration Mechanisms and Secondary Features

Some wear-and-tear would be expected from any material exposed to the forces of nature for over 100 years. And although still in service, the Bellefontaine pavement exhibits some evidence of deterioration driven by the universal solvent – water. As in with modern concretes, the primary culprit in most deterioration is water or moisture. Perhaps the most mundane deterioration documented in the pavement is the wearing of its top surface. While some of this surface erosion was likely derived from physical wear or impacts from traffic, much of it was likely due to paste denudation from slightly acidic meteoric water. Similar to the acid erosion of ancient marble statues, acid rain will slowly dissolve both the carbonate aggregate and surrounding cement paste binder. While the degree of this weathering was not directly measurable in the examined specimens, much of the paste on the exposed top surface of the material was recessed and surrounding siliceous aggregates 'stood proud' from the surface – good evidence of chemical weathering.

While not a direct deterioration mechanism, the topping material exhibited several deep drying-shrinkage cracks. These cracks were apparent on the top surface of the pavement and reflected sub-vertically through the full-depth of the wear-course. The shrinkage results from both the long-term drying of the paste and from the progression of cement hydration. This cracking, while not necessarily detrimental itself, act as conduits for water/moisture to infiltrate the pavement system. Shrinkage in modern concretes is expected, and engineers typically plan for this in the design of pavement and floor slabs.

Freeze-Thaw Deterioration

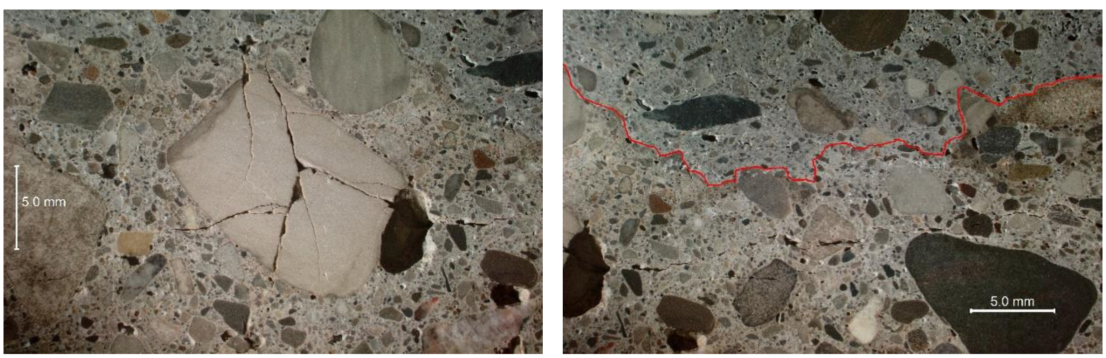
Some evidence of freeze-thaw deterioration was documented in both concrete layers, within both the paste and aggregates. Freeze-thaw deterioration is essentially the overcoming of the tensile strength of the concrete by the expansive force of freezing (expanding) water. Of course, the water in concrete would be present within the voids and capillary porosity of the paste. A good entrained air void system typically alleviates these internal pressures by allowing the freezing water to expand into the small spherical voids of the air void system. As previously discussed, the wear-course topping contained an air void system which meets the current recommendations to resist frost damage. However, the paste of the wear-course contained several anomalies which consisted of pebble-sized paste nodules or 'agglomerations' which did not contain any of the observed sub-spherical air voids (Figure 10, a). This is where deterioration was noted, most commonly occurring within these anomalous zones present near the top surface of the pavement. These areas of paste were noted to contain abundant sub-horizontal microcracks – consistent with damage from cyclic freezing and thawing (Figure 10, b).

The origin of these anomalous 'void-free nodules' was not entirely clear, as was the origins of the sub-spherical voids themselves. One hypothesis is that the nodules represent cement which had prematurely hydrated due to the lack of gypsum or sulfate in the cement, as previously discussed. These pre-hydrated paste clumps were not broken up during the mixing/placement of the pavement when the air voids were apparently incorporated or 'entrained' into the mixture. It is plausible though somewhat unlikely, that the mixing alone led to the formation of the entrained-like air voids. Some have speculated that the residues of the crude petroleum used to fire the vertical cement kilns was present in the final ground cement product. Upon mixing with water, the residue acted as a surfactant similar to modern air entraining admixtures, and produced the abundance of microscopic 'bubbles' within the paste. The pre-hydrated 'clumps' would be protected from this mixing and thus contain no bubbles or voids. Despite the origins of the anomalous paste nodules and the voids themselves, the air void system of the wear-course has clearly been essential in protecting the paste from freeze-thaw damage.

(a) (b)

Figure 10 – anomalous paste 'nodule' (red outline) near the pavement surface which lacks fine air voids under 5x mag (a) fine sub-horizontal microcracking within the nodule highlighted by white secondary deposits under 25x mag (b)

It can be seen in Figure 10b that much of the horizontal microcracking (and some surrounding pores) are filled with white-colored secondary deposits. The deposits primarily consisted of portlandite and calcite with some minor ettringite. This 'self-healing' was possible from paste leaching and transport of hydration products within the concrete system. Overall, this freeze-thaw damage within the wear-course was very minor and had little effect on the bulk condition of the examined pavement samples.



(a) (b)

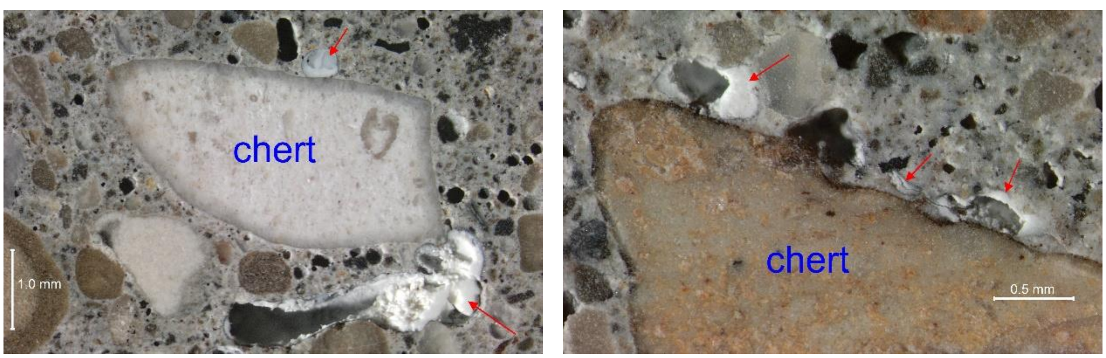
Figure 11 – cracking within soft dolostone coarse aggregate particle within base layer concrete under 5x mag (a) and sub-horizontal cracking within base concrete paste near the contact with the wear-course (red line) under 5x mag (b)

Freeze-thaw damage within the base concrete was more extensive than that observed in the wear-course topping. Although the base layer lacked entrained air and was more porous, most of the frost damage was documented within softer dolostone coarse aggregate particles (Figure 11, a). Currently, this type of aggregate deterioration in pavements is termed 'D-cracking' as it usually manifests near control or construction joints where the infiltration of water leads to saturation. The subsequent damage results in cracking that reflects towards the pavement surface and creates a 'D' shaped crack along the pavement's edge. Relatively few of the carbonate gravel particles exhibited this cracking, and of those that did, most was relatively minor. The cracking was observed propagating into the surrounding paste, though typically not far. Some minor freeze-thaw damage was also observed within the paste itself and consisted of sub-horizontal microcracking, mostly present near the interface between the base layer and overlying wear-course (Figure 11, b).

Alkali-Silica Reactivity (ASR)

Alkali-silica reactivity was documented within the wear-course topping concrete of the examined samples. ASR can be a destructive force which is caused by the swelling of an expansive gel byproduct. The reaction occurs between unstable forms of silica within aggregate particles and alkalis present within the paste (typically Na and K). Unstable silica is essentially 'attacked' by alkaline-rich pore solutions and dissolved to form a gel. The gel is extremely hygroscopic and at relative humidity greater than 80-90% it will absorb water and expand – initiating cracking and destroying concrete from the inside-out. Another water-driven deterioration mechanism, ASR was discovered in the 1930's and first written about in 1940 by Thomas E. Stanton while studying concrete expansion in California. ASR has affected infrastructure throughout the world, in worst-case-scenarios leading to structural deficiencies and demolition. It is important to note that ASR typically takes many years to fully manifest and lead to this destruction.

The level of reactivity in the Bellefontaine pavement was considered innocuous and had not induced any bulk deterioration. Several chert particles within the sand and pea gravel of the wear-course exhibited proximal deposits of ASR gel (Figure 12, a & b). Only a few of the particles exhibited the associated expansive cracking, which was very minor and did not extend far into the surrounding paste.



(a) (b)

Figure 12 – chert fine aggregate particles undergoing minor ASR within the wear-course concrete, red arrows indicate proximal deposits of secondary bright white ASR gel under 25x mag (a) and 50x mag (b)

ANCILLARY LABORATORY TECHNIQUES

As mentioned, several sub-samples of the pavement were distributed to various laboratories/Universities for study and testing. The primary tests applied were physical in nature and involved those associated with fluid transport which have been developed for modern concretes. The most striking results from these analyses were the data obtained from the electrical resistivity testing. This testing relates to the connectivity and tortuosity of the pore structure of the paste. The resistivity testing was performed at Oregon State University and relates a number, called the formation factor, to the microstructure of the paste. The base layer had a measured formation factor of 137 and the wear-course a measured value of 987. For example, modern concretes which are low in permeability (as determined by ASTM C1202) have a typical formation factor between 140 and 150. The measured value for the wear-course indicates a permeability much lower than modern high-performance concretes at 28 or 56 days of age.

The results for other physical testing (porosity, sorptivity, calcium hydroxide content) produced variable results from which not much further information could be drawn. The direct measurement and modern test procedures applied to small fragments of historic material is a likely cause for this. Several of these tests require large specimens, for example 6" diameter x 12" long cast cylinders, and their application was not ideally-suited for the pavement sections. Further, paste alterations (carbonation, secondary deposits, etc.) likely influenced the outcome of physical testing results.

CONCLUSIONS

The concrete pavement from Court Avenue in Bellefontaine, Ohio is the oldest known concrete pavement in the United States and is still in service today. The longevity of the pavement is a product of the raw materials and processes used in cement production and in the manufacture of the concrete itself. The pavement also owes its longevity to its 'two-lift' design, now commonly referred to as granitoid-type construction (Lemcke, 2017). The upper wear-course was very dense and impermeable due to placement with a low w/c, keeping moisture out and providing a hard and solid wearing surface. The base layer was less dense and more permeable, but still somewhat hard and durable, providing a solid yet permeable sub-base for the protective wear-course topping. Apparently incidental microscopic air bubbles were incorporated into the paste of the wear-course and have kept keep freeze-thaw deterioration to a minimum. The 'air void system' of the wear-course closely resembles those produced in modern concretes with specialized air entraining admixtures. While trying to understand the pavement's longevity through modern physical testing; petrography proved the most powerful and beneficial tool in determining its general properties and overall success as a pavement. Petrography is also applied to modern concretes of any construction type to determine the cause(s) of performance issues or to aid in condition assessments, for quality control and material screening purposes.

REFERENCES:

American Concrete Pavement Association. Historical Concrete Pavement Explorer. *First and Oldest Concrete Pavements in U.S. – Main Street and Court Avenue, City Square in Bellefontaine, OH.* ACPA. http://explorer.acpa.org/explorer/places/united-states/ohio/bellefontaine/street/old-us-30-lincoln-highway/#post_profile. Accessed May 4, 2018

Avdyllari, K. Avdyllari, S. Chan, C. Rahman, T. *Report on 1891 Concrete from Bellefontaine Ohio*. Department of Civil Engineering, University of Toronto, 2017

Lemcke, B. Moulzolf, G. *Report of Concrete Analysis.* American Engineering Testing, Inc. St. Paul, MN, 2017.

Pardi, M. What Does Bellefontaine's 125-Year Old Concrete Tell Us About Pavement Performance. *American Concrete Pavement Association*, ACPA, San Francisco, CA, 2017.

Snell, L. Snell, B. Oldest Concrete Street in the United States. *Concrete International* March 2002, pp. 72-74.

Suraneni, P. Qiao, C. Khanzadeh Moradllo, M. Weiss, J. *Progress Report of the Tests on Concrete from the Bellefontaine Pavement*. School of Civil and Construction Engineering, Oregon State University, Corvallis, 2017.

Sutter, L. *A Laboratory Examination of Court Avenue, Bellefontaine Ohio: The Oldest Concrete Pavement in the United States.* Department of Materials Science and Engineering, Michigan Technological University, Houghton, MI, 2017.