

Evolution of Pervious Concrete Pavement at the Ministry of Transportation Ontario, Canada

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Abstract

As part of the Ministry of Transportation Ontario (MTO) drive to pursue innovation and have the “greenest” roads in North America, MTO is actively pursuing the use of pervious concrete pavement. Pervious concrete provides many environmental benefits and is recognized as a stormwater management best practice. There is also strong interest from the Ontario municipal sector, conservation authorities and “green” innovators in rapidly incorporating pervious concrete into their designs. The Ministry is currently investigating and trying to address concerns with pervious pavement durability, the potential for clogging, impact of traditional winter maintenance practices and users’ acceptance of surface finish.

The Ministry of Transportation Ontario (MTO) has completed two pervious concrete commuter parking lots and is currently working on a third. Field performance, construction practices and test methods are being studied for their effectiveness. Based on MTO experiences to date, an Ontario Provincial Standard Specification has been developed. This paper summarizes the construction observations, lessons learned and laboratory performance data from the Ministry’s work to date.

Introduction

Pervious concrete pavements are an emerging technology, which can help reduce the size of our ecological footprint. They offer a functional surface suitable for many applications, including parking lots and walkways, and are more harmonious with the natural environment than traditional impermeable surfaces.

Pervious concrete is typically an open graded material consisting of Portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water [ACI 2010]. The lack of fine aggregate results in a high void content in the pervious concrete; this is typically between 15-35 %. The high void content and the presence of inter-connected pores provide a free draining pavement layer.

Pervious concrete pavements provide several advantages over conventional impervious hot mix and concrete pavements. Pervious concrete pavement is recognized by the United States Environmental Protection Agency as a best management practice for stormwater management [NRMCA 2010]. Unlike conventional impervious pavements that must be sloped for proper drainage and often require expensive stormwater treatment facilities, pervious concrete pavements allow stormwater to flow through the pavement. Depending on the project design, the stormwater that enters the pervious concrete pavement can be allowed to percolate into the underlying soil, avoiding the need for a retention basin (or stormwater management pond). The benefits

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of eliminating (or reducing) stormwater management ponds include; reduced pond construction and maintenance costs, reduced property space requirements, reduced potential drowning hazards, and less standing water for mosquito-breeding sites which helps to control the spread of the West Nile virus. The reduction or elimination of surface runoff also minimizes the risk of flooding. The open, interconnected voids of pervious pavement reduce the “heat island” effect and associated heating of stormwater. Conventional paving materials can reach summertime temperatures of 50°C to 65°C, transferring excess heat to the air above them and heating stormwater as it runs across pavements. Pervious pavement allows unheated water to drain directly into the subgrade recharging groundwater tables and aquifers minimizing impact on cold-water streams, rivers and fish habitat.

MTO’s first pervious concrete commuter parking lot was constructed in 2007 along Highway 401 at the Guelph Line Interchange near the town of Milton, Ontario, approximately 50 km west of Toronto. The second project is a GO Transit commuter parking that was constructed in 2010/11 lot at the Highway 410 and Williams Parkway Interchange in Brampton, Ontario approximately 30 km northwest of downtown Toronto. A third commuter parking lot was started September 2011 along Highway 26 at the Simcoe County Road 27 Intersection in Midhurst west of Barrie Ontario approximately 100 km north of Toronto. Most of the discussions in this report are based on data and observations obtained during and after construction of the Brampton GO Transit Commuter Parking Lot.

Project Information

The Highway 410 and Williams Parkway Interchange GO Transit commuter parking in Brampton, Ontario was completed July 2011 is shown in Figure 1. This commuter carpool lot includes two parking areas along with a GO Transit bus loop. This facility is located within the Regional Municipality of Peel, and with strict stormwater runoff limits imposed is able to connect to the Region’s stormwater sewers. Permeable pavement was brought forward both as a “green alternative” and as a stormwater management solution for the project.



Figure 1. Highway 410 and Williams Parkway Brampton GO Commuter Parking

Pervious concrete was selected for the smaller of the two parking areas (30 parking spots, 919 m²) as this would limit stormwater entering the sewer system to below the Region of Peel limits. As MTO experience with the maintenance of pervious concrete is still under development the designer also elected to include supplementary stormwater drainage with the pervious concrete pavement design to provide an additional factor of safety should the pervious concrete fail to function effectively over time.

Pavement Design

The pavement design was based on both a hydrological and structural component. The hydrological design followed the guidelines of the Pervious Concrete Hydrological Design Software distributed by the Portland Cement Association (PCA 2007) and the structural design followed the guidelines of the StreetPave software distributed by the American Concrete Paving Association (ACPA 2009). As this was one of the first pervious pavement designs by MTO, the design incorporated conservative assumptions regarding material properties and time horizons. The design inputs and assumptions, taken from the respective sources are:

From the Ministry's Geotechnical Report:

- Average Daily Traffic (ADT) = 400
- 5% light commercial vehicles
- 20 year design life
- Subgrade soil resilient modulus = 20,000kPa

From Hydrologic Design Software, PCA:

- 24 hr precipitation rate 135.9mm
- Return Period = 100 year (10 years typical)
- Soil permeability exfiltration rate = 0.635 mm/hr (native silty clay subgrade)
- Porosity for Pervious Concrete = 20%
- Porosity for the Gravel Base = 30%

From StreetPave Software, PCA:

- 25% of concrete slabs crack
- 85% reliability
- 30 year design life
- 2% truck traffic growth rate per year
- 28 day flexural strength (MR) = 2.4 MPa

A hydrological design provided adequate granular base for drainage and water storage to prevent undrained water freezing in the pervious concrete layer. Select Subgrade Material (SSM), a sandy fill material, was specified where imported fill was required to prevent local clay fill from being placed under the pavement. The hydrological analysis indicated that a 200 mm granular base layer was required. Structural design inputs were based on default values provided in the design software that results in a required concrete thickness of 190 mm.

The final pervious pavement design consisted of: 190 mm of pervious concrete and 200 mm of open granular base, overlying 600 mm of select subgrade

material. This overall design thickness was compatible with the original hot mix pavement design thickness of 90 mm hot mix over 300 mm granular subbase. As MTO's experience develops with the design process and material properties, thinner pavement designs are anticipated.

Pervious Concrete Requirements

The pervious concrete specification contained a number of material requirements. The coarse aggregate was required to have a maximum nominal aggregate size less than or equal to 13.2 mm. The smaller maximum aggregate size was thought to not only improve surface texture for pedestrians but improve mix stability with smaller aggregate gradation gaps. There were no restrictions on aggregate gradation, use of fine aggregate, allowable total cementitious content or use of viscosity modifying admixtures, superplasticizers and synthetic fibres. The paste was required to be adequately air entrained to provide freeze-thaw resistance.

Successful completion of a 10 metre long trial slab was required to demonstrate the ability to produce, place, finish and cure the specific pervious concrete mix prior to proceeding with the work. In addition the contractor or sub-contractor was required to have an employee certified by the National Ready Mix Concrete Association (NRMCA) Pervious Concrete Contractor Certification Program responsible for the pervious concrete placement.

Acceptance Criteria

The in place pervious concrete was required to meet the following quality criteria, all measured on cores removed from the pavement:

1. Compressive strength minimum of 15 MPa at 28 days
2. Void Content between 15 to 25%
3. Compacted thickness not more than 6 mm less than the specified thickness

In addition, the surface of the pervious concrete pavement shall not exhibit any ravelling based on visual inspection. The contractor was responsible for designing the concrete mix and selecting the placement methods to ensure that all criteria would be met.

The contractor was required to conduct quality control testing on each load of concrete, consisting of plastic density and void content according to ASTM C1688. The plastic density was required to be within 80 kg/m³ of the plastic density of the trial section. Quality control cylinders for determination of compressive strength were requested on every third load of concrete, to be used by the ministry for information purposes only. Cylinders were cast according to CSA A23.2-3C with the exception that the rodding method of consolidation was used independent of slump.

Mix Design

Several mix designs were submitted, trial sections conducted and placement methods changed by the contractor before a preferred mix and placement method were selected. All mix designs used Type GU cement with 25% slag, superplasticizer, air entraining agent, retarder and viscosity modifier. Early trials incorporated a small amount of fine aggregate and synthetic micro-fibres.

Construction -- Trial Slab #1

The first trial slab was constructed on August 31, 2010. The contractor opted to use a vibratory steel screed running on 10 mm spacer strips placed on top of the forms followed by a hydraulically actuated rotating tube screed as shown in Figure 2. The spacer strips were removed prior to compaction with the hydraulic roller screed. The roller screed had a weight of 65-75 kg per linear metre.



Figure 2. Trial Vibratory Screed on 10 mm strips followed by Hydraulic Roller

During placement, the consistency of the concrete was found to vary throughout the load. The vibratory screed brought excessive paste to the surface and didn't appear to aid in concrete compaction. In order to improve compaction by the roller screed, an additional layer of spacer strips was utilized for part of the placement. This was unsuccessful as the roller screed was incapable of compacting 20 mm of concrete above the top of the forms to finished grade. A second mix incorporating some 20 mm aggregate was also included at the contractor's initiative in an attempt to provide better compaction.

When the hardened trial slab was cored, bands of consolidated concrete/slurry were evident in a swirled pathway throughout the extracted cores.

Hardened pervious concrete test results for 1st trial were as follows:

1. Core compressive strength at 28 days for the 13 mm maximum size aggregate averaged 3.8 MPa,
2. Core compressive strength at 28 days for the 13 mm aggregate mix with the addition of 20 mm aggregate averaged 9.1 MPa. The strength

of both mixes was significantly below the 15 MPa strength requirement.

3. Voids on cores extracted from random locations ranged from 32 % to 36%, all exceeding the 15% to 25% specification range.

Visual assessment of the trial slab conducted eight days after concrete placement, showed apparent ravelling, mortar streaking and texture variability. Based on these observations and test results, the trial slab was not accepted by MTO.

Construction -- Trial Slab #2

The second field trial slab was conducted on February 16, 2011 inside a large heated facility. The ready mix supplier in cooperation with the Contractor sponsored a NRMCA Certified Pervious Craftsman to oversee mix design and placement recommendations. Strike-off and compaction were conducted with hydraulic roller running directly on the forms. The mix design was changed to make the mix more flowable, and cohesive. Two mixes were placed using 13 mm maximum size coarse aggregate only, with no sand. Cementitious content was reduced and viscosity modifying and superplasticizing admixture dosages were increased.

Hardened pervious concrete test results for the 2nd trial were as follows:

1. Core compressive strength 28 days for the two mixes was 13.8 and 14.0 MPa, slightly below the 15 MPa specified strength requirement.
2. Void results were 32.4% and 31.1%, again exceeding the 15% to 25% specification range.
3. Splitting tensile testing at 28 days, conducted for information only was 1.1 MPa and 1.4 MPa. Typical flexural strength range for pervious concrete in general is 1.0 MPa to 3.8 MPa
4. Infiltration Rate according to ASTM C 1701, conducted for information only was 17,300 mm/h and 22,900 mm/h. Typical infiltration rate range for pervious concrete is 5,000 mm/h to 44,000 mm/h. Moderate porosity pervious concretes will usually have an infiltration rate in excess of 8500 mm/h. These results indicate the 2nd trial to be very permeable.

A visual assessment of the trial slab was carried out approximately eight days after the concrete placement. The surface of this pervious concrete trial placement exhibited a uniform surface texture, no ravelling and was able to resist mechanical abrasion without damage.

Based on field trial #2 observations and slab test results, MTO agreed to modify the pervious concrete acceptance criteria for this project. The revised acceptance criteria was: void content 15% to 35%; minimum average core compressive strength of 10 MPa with no individual compressive strength test less than 7.0 MPa; and minimum infiltration rate of 18,000 mm/hr. Acceptance incorporates a visual inspection at the end of warranty period for classification of ravelling, cracking and scaling. Any areas of moderate or severe ravelling during the warranty period are to be removed and replaced.

Construction -- Parking Lot

Placement of the pervious concrete at the commuter parking lot was carried out over three days in July 2011. The parking lot was poured in five strips each measuring approximately 3.5 m in width by 55 m in length. All site construction including landscaping was completed prior to start of the pervious concrete to avoid any potential contamination, premature plugging and or damage to the pervious concrete.

A conveyor was used to place the concrete in front of a hydraulically-actuated rotating tube (roller) screed. Prior to placing the concrete, the subgrade was pre-wetted to prevent moisture loss from the plastic pervious concrete. The roller screed was supported by fixed forms, pervious concrete pavement, or curb and gutter as shown in Figure 3. A protective flashing was placed on the edge of the pervious concrete when the roller screed was spinning on the edge of previously placed pervious sections to reduce the risk of edge ravelling.



Figure 3. Hydraulic roller screed running along pervious concrete and curb & gutter

Every load was visually inspected for consistency and tested for plastic density according to ASTM C1688 as an indicator of mix uniformity. The plastic density results ranged from a low of 1970 kg/m³ to a high of 2023 kg/m³ over the three days of pervious concrete placement. The fresh pervious concrete appeared uniform and placement was carried out with minimal delays. Concrete was evenly placed in front of the finishing equipment and struck-off to final elevation. Edges were compacted by tamping to prevent ravelling. An accumulation of paste was occasionally observed on the conveyor and beneath the conveyor tail-pulley.

Quality Assurance Testing

The acceptance criteria for the pervious concrete pavement were based on thickness, compressive strength, density and void content. Testing was carried out on cores extracted from the pervious concrete to ensure samples reflected the placement methods used and the consistency of concrete. A total of six 100 mm diameter full

depth cores were extracted evenly (i.e. not random as would be our normal practice) throughout each of the sections representing each day's production and delivered to a contracted Quality Assurance Laboratory for testing.

Hardened pervious concrete test results were as follows:

1. The thickness of the slab as measured by the length of the cores all exceeded the specified 190 mm.
2. Cores for voids extracted from various locations throughout the parking lot ranged from 15.9% to 36.5% using the CoreLok® system as incorporated into ASTM procedures ASTM D6857 and ASTM D6752 for bituminous paving mixtures
3. Core compressive strength at 28 days ranged from 6.3 MPa to 14.6 MPa. Core test results and locations are shown in Figure 4.

Acceptance Testing Core Location

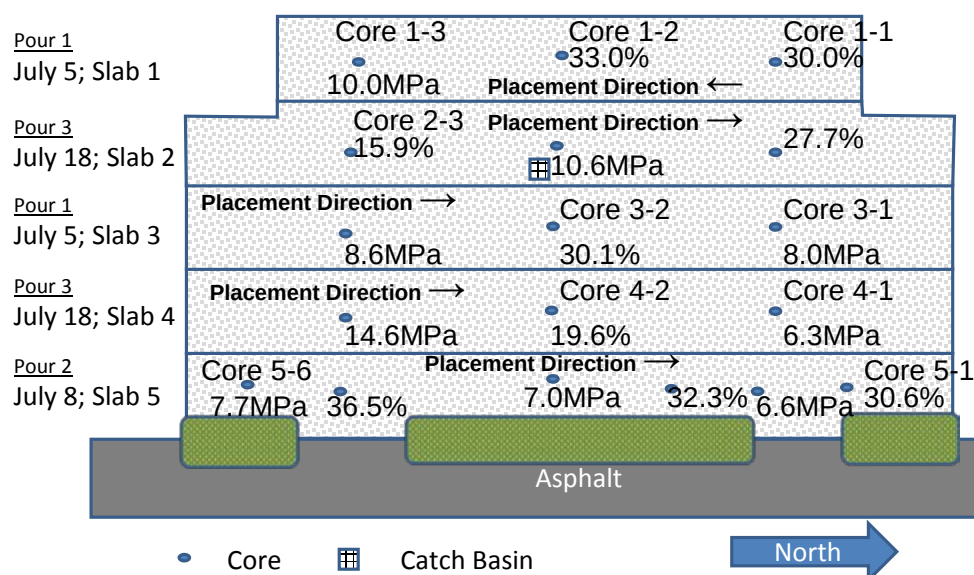


Figure 4. Acceptance Test Results by Location

Quality Acceptance Testing Discussion

The core compressive strength failed to meet the modified specified minimum average compressive strength. The average core compressive strength for July 5, 2011 placement was 8.9 MPa, July 8th placement was 7.1 MPa and July 18th placement was 10.5 MPa with an individual result of 6.3 MPa. A core examined petrographically found the cement paste to be well hydrated throughout the core.

Upon visual examination the majority of the cores were noticeably denser at the top. Compression testing cores through to destruction, showed all failures to occur in the bottom portion of the core. Core testing shows significantly less consolidation and compressive strength was achieved in the bottom portion of pavement using typical placement technology. These core test results are not an accurate strength and durability representation of the surface or top portion of the

pavement. This core testing may also not be an effective means to predict pavement ravelling performance.

Four compressive strength cylinders tests were conducted for each day's placement for information only. The average cylinder compressive strength for July 5th was 18.0 MPa, July 8th 16.9 MPa and July 18th 17.8 MPa. The cylinder results are significantly higher and more consistent than the core compressive strengths. The cylinder test results appear to demonstrate a concrete mix quality consistency between all three placements. The method of failure, and difference between core and cylinder compressive strength results, challenge the effectiveness of core compressive strength testing in assessing the anticipated performance of the pervious pavement parking lot.

The pervious pavement in the vicinity of void test results exceeding mid 30s% visually appears more likely to be susceptible to future surface ravelling.

Post Construction Inspection

A post construction inspection was carried out on August 30, 2011. Because the pervious concrete was the last construction item to be installed the finished surface was clean. The surface of the pervious concrete appeared to be in excellent condition. There was some small early evidence of slight ravelling although the parking lot has not been exposed to any significant traffic. There was a colour variation between loads of concrete and surface texture variation within loads observed. This variation of surface paste content was not obvious in the plastic concrete either at discharge from the ready mix truck, on the belt conveyor or in place after roller screeding. An uncontrolled infiltration test with a water truck clearly showed that the parking lot exceeded infiltration expectations, as was expected due to the high void contents.

Other observations included presence of paste circles. These areas are approximately 300 mm in diameter, where excessive mortar or paste has come to the surface and closed it off. These are scattered throughout the slab. Further refinements to the mix design may be needed to eliminate these.

Drying shrinkage was observed at slab edges between pour strips. Based on previous experience no control joints were included in the design of the parking lot. Upon detailed examination only one transverse drying shrinkage crack could be found forty-five days after placement. This crack was less than 1 mm in thickness, crossed one paving strip and extremely difficult to observe. Transverse drying shrinkage of 2 mm to 10 mm thickness was observed along the length between strips.

Pervious concrete pavements are typically designed only for light vehicles. As a post construction recommendation, a height restriction barrier is being installed to prevent access by heavier vehicles.

A warranty inspection will be conducted prior to the first winter and again one year after contract completion or six months of open to traffic use whichever is later. Final acceptance is based on this visual inspection for surface irregularities and ravelling.

Subsequent Visit

A subsequent visit was conducted on February 10, 2012 during a mild break in the winter weather. Aside from a few previously identified isolated construction related issues there appeared to be no unusual surface deterioration evident. There was a small amount mild ravelling and loose aggregate that may have been caused by abrasion of the snow plow. Two transverse drying shrinkage cracks

were observed propagated across all five placements. These cracks were barely noticeable but varied in width from 2 – 5 mm with no ravelling at the edges. Further inspections will be made in the spring.

Additional Investigation and Testing

The following testing was conducted to enhance the ministry's understanding of pervious concrete, these included: void correlation test program, light weight deflectometer pavement measurements and petrographic core examination.

Void Content Correlation Test Program

The method specified in this contract is MTO Laboratory Procedure LS-443 [MTO 2011] for the determination of the bulk specific gravity, maximum specific gravity and void content of hardened pervious concrete pavement using an automatic vacuum sealing method. The method references ASTM D6752 Standard Test Method for Bulk Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method and a CoreLok® vacuum chamber. This method was selected based on an evaluation of three test methods conducted as part of MTO Guelph Line pervious pavement project. The LS 443 procedure using the CoreLok® apparatus gave the most consistent results. The results of this evaluation were reported in Design and Construction of a Pervious Concrete Pavement in Ontario, Canada, MTO 2008 [Raymond 2008].

There are a limited number of laboratories capable of performing the LS-443 test method using the CoreLok® test apparatus. Working with industry revised test methods were proposed for evaluation:

- i) ASTM Draft Standard Test Method for Density and Void Content of Pervious Concrete [ASTM Item 46 2011]
- ii) Void Index of Pervious Concrete Test Method that measures the ability of a fully water saturated core to drain versus time
- iii) RMCAO Test Method for Porosity Measurement of Portland cement Pervious Concrete (Haselbach Test Method) [RMCAO 2009]
- iv) LS-443 test method using the CoreLok® test apparatus

The intent of the void correlation program is to assess the capability and consistency of the proposed test method and how they compare with the existing CoreLok® test method. Results of this program should become available in 2012.

Light Weight Deflectometer

A portable light weight deflectometer was used to observe deflection throughout the pervious parking area. It is recognized that a light weight deflectometer (LWD) was designed to measure the E-modulus of un-bonded materials in pavements; it has been shown effective for quality assurance on subgrade, subbase and thin flexible pavement construction. Because the pervious concrete was expected to exhibit similar characteristics as a light duty asphalt pavement, the LWD test was proposed. A Dynatest 3031 LWD was used to record deflection measurements at 50 locations throughout the pervious concrete parking area with comparisons to the adjacent asphalt parking area, asphalt bus loop and conventional concrete bus stop area. Significant variation in deflection was observed at five locations throughout the pervious concrete parking lot, see Figure 5.

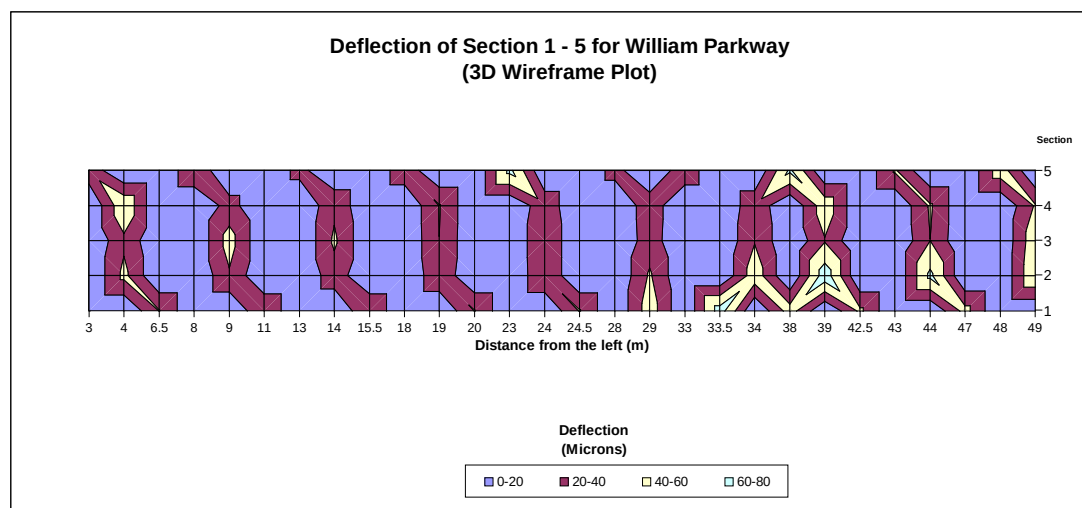


Figure 5. Lightweight Deflectometer Testing by Location

A LWD comparison to other areas of the Brampton GO commuter facility showed deflection in the conventional concrete bus area to be very low, pervious concrete moderate and asphalt bus loop to be 2 to 3 times the deflection of the pervious concrete.

There did not appear to be any correlation between high deflection pervious concrete locations and low compressive strength core test results in Figure 4. Areas of surface visual inconsistencies were frequently correlated to higher LWD deflections. It is suggested the LWD results may reflect more the strength of the compacted surface layer while the core compressive test results reflect the strength of the lower uncompacted portion of the pavement. Conducting further assessment of LWD testing as a possible predictor of pervious concrete ravelling performance is warranted.

Petrographic Examination

A Petrographic examination was conducted on a core removed from the correlation test slab. The core was sampled at eight days of age, stored wrapped in plastic, and petrographic examined at approximately 90 days of age. When the sample was unwrapped it was still moist although dried within 30 minutes of exposure. Thin sections were made from the top, middle and bottom portions of the core. The cement paste was examined microscopically in each of these thin sections with no major differences observed. The cement paste appeared relatively strong and not very absorptive when compared with other lab concrete samples. Microscopically the paste showed a good degree of hydration as shown in Figure 6. Although air entraining agent had been included in the concrete mix design, no entrained air was observed in the paste.

Cracking was present in the paste; widths were less than $20\mu\text{m}$ and generally less than $10\mu\text{m}$. The appearance of the crack pattern was typically rectilinear and there were examples where the paste was observed to bridge the crack. Some the cracks appeared to have occurred while the concrete was still plastic. This concrete was indicative of having a low water to cement ratio and some of the cracking may represent a form of drying shrinkage. Similar cracking pattern observed by other pervious concrete petrographic analyses has been attributed to drying shrinkage due to the low water cement ratio. Minnesota pervious concrete research [MnROAD 2009]

observed a majority of microcracks exhibited autogenous healing in cores taken 4 ½ months after construction.

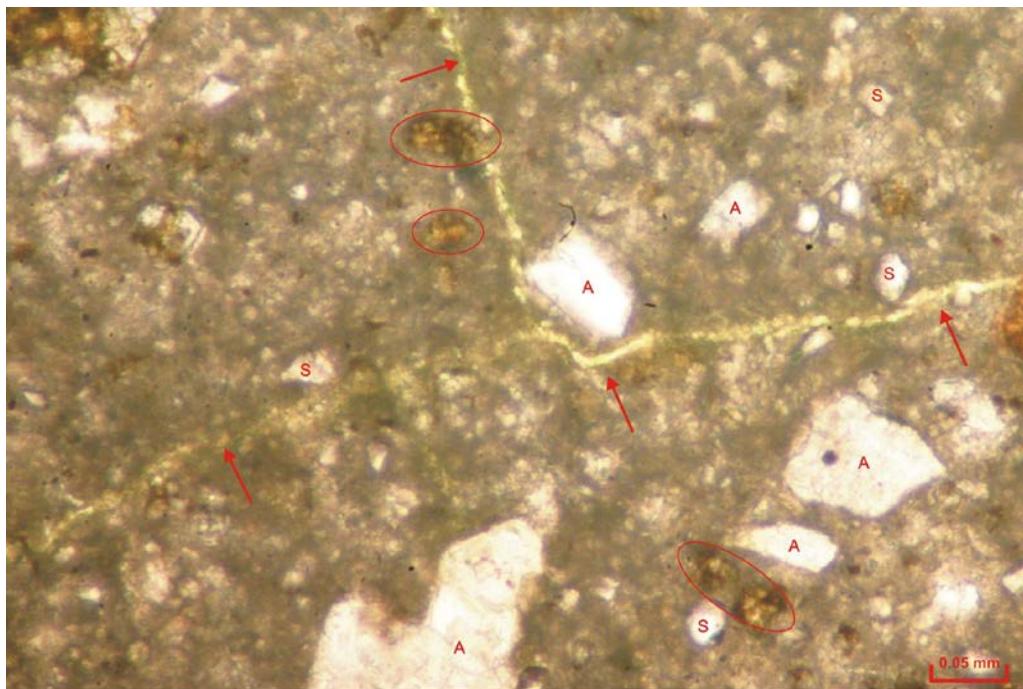


Figure 6. Microscopic view of well hydrated paste with fine cracking less than 10 µm wide (red arrows). Some relict cement grains (outlined in red circles) consisting mainly of belite, alite and interstitial brownmillerite are clearly visible as well some slag particles (S). Most of the fine aggregate (A) in this photo is <75µm in size.

Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion

Ravelling is a common failure mechanism in pervious pavements. Predicting pervious pavement resistance to surface ravelling is not well understood. A draft ASTM Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion [ASTM Ballot 26 2011] is intended to help compare resistance to degradation of proposed mix designs under standard compaction. As part of assessing the proposed test method, three cores were removed from the correlation test slab for testing in a Los Angeles Abrasion Machine following the proposed test method. A mass loss of 85.7% was obtained. Although intuitively a high loss, it was within range obtained with other specimens and laboratories.

Further work is required to assess if this test method can become an effective tool for mix design qualification or supplier product development.

Conclusions

Pervious concrete pavement is a promising emerging technology that offers a functional “green” option for light duty pavements such as parking lots. Further monitoring is needed to confirm the longer term performance, and quantify environmental benefits, of pervious concrete pavements. Development of acceptance test methods that better predict in-place pavement performance is required.

Based on MTO experience to date, the hydraulic roller screed was demonstrated to be the most successful method of screeding, consolidating and finishing the pervious concrete pavement. It provided surface compaction without vibrating fines to the surface. The ability of pervious pavement to resist ravelling is a combination of both mix design parameters and surface consolidation practices.

The ASTM C1688 Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete was not an effective enough indicator of mix uniformity. When testing for plastic density according to ASTM C1688, the contract limit of $\pm 80 \text{ kg/m}^3$ was not effective at identifying plastic concrete variation that would be visible in hardened concrete. Load to load colour variation, and variation of surface fines was observed in the hardened concrete.

Viscosity modifying agents tended to mask visual identification of plastic concrete variations. The plastic concrete appeared very uniform throughout each truckload, on the conveyor and when placed. After curing, significant variations in surface texture and colour became evident that was not seen in the plastic state throughout the parking lot.

Pervious concrete has a high susceptibility to plastic and drying shrinkage. This was evident along the longitudinal joints between paving sections and under petrographic examination. Upon close visual examination only one extremely narrow transverse shrinkage crack could be detected forty-five days after placement, and two 2-5 mm wide cracks observed mid winter with no edge ravelling evident. Drying shrinkage appears to be accommodated without the use of transverse control joints.

Curing must commence immediately behind the finishing equipment in order to reduce the risk and extent of shrinkage, loss of durability and strength. Petrographic examination of a properly cured pavement section confirmed the propensity of the pervious concrete to micro crack both in the plastic and hardened state.

Petrographic examination showed that the paste was not adequately air entrained and gives concerns about durability under freeze-thaw conditions.

More than most other concretes, pervious concrete has been seen to be more sensitive to the combination of the specific material characteristics, placement conditions and construction technologies employed.

MTO is encouraged by the performance to date, will build on the lessons learned from these projects and looks forward to continuing to support and using the technology to lessen the environmental impact of our built environment.

Recommendations

Greater emphasis on surface quality will improve anticipated lifespan and increase public acceptance of pervious concrete pavements and walkways.

Introducing additional requirements in design and at the time of construction such will increase overall pervious concrete performance. Restricting the maximum aggregate size to 13 mm or 10 mm in areas of high pedestrian traffic, and hence maximum surface void size will improve surface wearability and pedestrian walkability. Designing height restriction barriers will reduce the potential for wear and ravelling by limiting access of heavy vehicles and inappropriate winter maintenance equipment.

Development of methods to assess pervious concrete variability in the plastic state is needed. The contract and ACI recommended limit of $\pm 80 \text{ kg/m}^3$ for the ASTM C1688 test method needs to be reduced and testing continued to be conducted on every load plastic concrete to be effective. Alternatively, a new means needs to be developed to help prevent visible hardened concrete variability. This may be accomplished through changes to concrete mix design or placement methods. Until then reliance must continued to be placed on very tight batching and mixing control of all ingredients including water to ensure minimum hardened concrete variation. .

Because pervious concrete's sensitivity to placing conditions, existing environmental restrictions need to be clearly communicated upfront to all parties to prevent the placement of the pervious concrete during weather conditions that may adversely affect the quality of the work. Restrictions should be introduced and pervious concrete placement avoided during high ambient temperatures and windy conditions.

Investigation is needed to determine how to incorporate entrained air into the paste and assess its impact in providing freeze-thaw resistance.

Further investigation of test methods to predict the ravelling performance of pervious concrete is needed. Two test methods that warrant further investigation include: Deflection testing of the in-place pervious pavement using a light weight deflectometer to predict in-place resistance to ravelling; and ASTM draft "Standard Test Method for Determining Potential Resistance to Degradation of Pervious Concrete by Impact and Abrasion" to evaluate pervious concrete mix design potential ravelling performance.

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