ACOUSTIC PROPERTIES OF CLOGGED PERVIOUS CONCRETE PAVEMENTS

By

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Biography

Bernard Igbafen Izevbekhai is the concrete research operations engineer for the Minnesota Department of Transportation. He obtained Bachelors and Masters Degrees in civil engineering from the University of Benin in 1983 and 1987 respectively. He also obtained a Masters degree in infrastructure systems engineering from the University of Minnesota in 2004. He is currently a member of 3 committees including AFN 20 (Properties of Concrete) in the Transportation Research Board of the National Academies.

ABSTRACT

Minnesota Department of Transportation and many municipalities in Minnesota have built sidewalks city streets, low volume roads, boat ramps and parking lots with pervious concrete.

Since 2005 when the first pervious concrete initiative was constructed at the MnROAD facility, three test cells have been constructed, monitored and maintained.

Paradoxically, non pervious pavements are similar to pervious pavements in their requirements for drainability for durability. However pervious concrete requires that the voids should be connected and free of clogging agents for durability of conductive and acoustic properties. The effect of clogging and the characteristics of pervious concrete, clogged with various agents are examined. Desirable acoustic absorption and hydraulic conductivity are reduced when pervious concrete is clogged and may be restored with adequate maintenance practices.
Key Words: Pervious; Acoustic; Tortuosity; Clogging; Sound absorption.

INTRODUCTION

A pervious concrete driveway project in 2005 was the earliest in Minnesota. Eller and Izevbekhai (1) described the pervious concrete initiative that constructed a pervious concrete driveway at the MnROAD research facility in 2005. The pervious concrete driveway was subsequently monitored and according to Rohne and Izevbekhai (2) most of the driveway was clogged after 4 years of no vacuuming. Clogging resulted in early raveling as well as loss of mechanical strength properties as observed from Schmidth Hammer spot tests.

The 64 ft X 24 ft (19.2m X 7.2m) driveway was designed for 20 percent porosity. According to Sandberg and Ejsmont (3) pervious pavements can be categorized into pervious, semi pervious or non pervious according to ranges of porosity. Pervious pavements have porosity of 15% or greater. Semi-Pervious pavements are characterized 12-15% porosity and non pervious pavements have less than 12% porosity. A sustainability of porosity of pervious pavements is pivotal to their durability. In addition to compromising drainage and sound absorption, pores or cavities of pervious pavements tend to retain ice lenses during the freezing cycles but these do not thaw uniformly as would a uniform interconnected (communicating) void system when they harbor clogging agents. The non uniform freezing and thawing pressures result in early degradation of pervious pavements. Therefore clogging is regarded as one of the most undesirable that pervious pavement phenomena.

Monitoring and maintenance strategies are therefore designed to ascertain degree of clogging and restore the void system of pervious pavements. Clogging of pervious pavements is defined as the
reduction of communicating voids due to the ingress and accumulation of certain agents in the cavities. Observations made in the pervious pavements at this location indicated that most of the clogging agents resided in the upper 2 inches of the driveway pavement. A pavement is clogged when there is such an accumulation of clogging agents at the surface that it no longer conducts water or absorbs sound as expected even if cavities in the core of the structure is still open.

Quantitatively, Rohne and Izeybekhai (2, 4) showed that if the time to empty an 8 inch head of water through a dynamic head infiltrometer exceeded 2 minutes, the pavement was considered clogged. That exemplified suggested institutional limits required to trigger maintenance repair or rehabilitation activities. A report of pervious concrete for cold climate (5) optimizes porosity with respect to performance (5) at 20-25 % void content. In a closely packed aggregate system if the gravel and surrounding mortar are idealized as spherical and of a single radius r, it can be shown that the packing efficiency amounts to \( \frac{n \cdot \frac{2}{6}} \approx 0.74 \).

The maximum porosity is thus \( 1 - \frac{n \cdot \frac{2}{6}} \) which is approximately 25 %. It was also shown by Horeskenov (6), that when an acoustic surface is indented, there is a progressive increase in sound absorption of that surface up to 25 percent surface area. Thereafter, the sound absorption of the surface was equal to that of mineral wool that was used as filler for the indentation as though the entire surface was made of mineral wool. Optimum sound absorption characteristics may therefore be achieved at maximum void content but it is doubtful if above 25% void system, there is any further improvement. Additionally, Nethaliath (7) showed that beyond that optimum void content there may be a reduction in strength.

Institute for Safe Quiet and Durable (7) Highways in Purdue University recommends that for optimum noise attenuation performance, the aggregate should contain a blend of 3/8 inch or \( \frac{1}{2} \)
inch (9.5mm or 12.5mm) aggregate. Use of this aggregate size has resulted in less segregation and better void distribution in subsequent pervious concrete projects.

Unfortunately, irrespective of best design practices, pervious pavements tend to experience an accumulation of material in the voids with time. This accumulation, called clogging, forestalls the free drainage properties of the pavement thus rendering it susceptible to freeze thaw degradation.

**RESEARCH SIGNIFICANCE**

Pervious pavements are primarily designed to facilitate storm water infiltration and noise reduction. However, these benefits are constrained by clogging of the pores. It is easy to perform in-situ hydraulic conductivity and acoustic measurements to ascertain the hydrologic and acoustic health of pervious concrete. Consequently this research evaluates the effect of clogging and the efficacy of simple maintenance practices to mitigate clogging.

This paper discusses and evaluates the prevailing pervious pavements maintenance practices in Minnesota. It also discusses the impacts of clogging on hydraulic conductivity and acoustic properties. Finally it simulates by an accelerated clogging test the effect of certain clogging agents on acoustic and hydraulic conductivity properties. It also examines some intricacies of tortuosity to accentuate how the convoluted paths caused by clogging agents may reduce fluid flow rate and inhibit sound absorption.

**DESCRIPTION OF TEST SECTIONS**

Many pervious pavement construction projects have been executed in Mn/DOT. Their design and monitoring strategies are shown in table 1. Cell64 measuring (64-ft X-24 ft (19.2m x 7.2m) Driveway-Full-depth) was constructed in fall 2005 with 8 inch concrete on a 12 inch (200mm)
base made up of 1 inch (25.4mm) sized aggregate. Subsequently in 2006 a sidewalk measuring 5-ft X 100-ft (1.5m X 30m) was constructed with 8 inch concrete on a 12 inch (200mm) base made up of 1 inch (25.4mm) sized aggregate. In late summer 2008, Mn/DOT constructed a pervious concrete boat landing in Detroit Lakes Minnesota as a filtration system. It was built of eight-inch pervious concrete underlain by 2-ft (600mm) of 2-inch (50.8mm) nominal rock base on a sloped impervious geo-fabric that conducts the water to a collection point for partial treatment before release to Detroit Lakes (FIGURE1).

Experience from the earlier initiatives helped to provide new and improved designs for 3 cells (39, 85 and 89) (FIGURE2) that were built at MnROAD in fall of 2008. Cell 39 was designed as a 4-inch (100-mm) pervious overlay on a concrete substrate primarily for noise reduction. Polypropylene and cellulosic fibers enhanced bond with substrate. Cell 85 was designed as a full-depth-7-inch (175-mm) concrete on 4-inch (100-mm) railroad ballast above 8-inch (200-mm) of single grade one-inch rock base built on a sand subgrade. The layer of railroad ballast stabilized the rock base for construction traffic. Cell 89 was of a similar design to cell 85 except the former was built on a clay subgrade.

Separate projects initiated by the Cities of Minneapolis and Shoreview followed best design practices although the former was built in 2006. City of Minneapolis Cul-de-Sac consisted of a pervious concrete pavement built in 2006 at Lake Street and 12th street in Minneapolis. It consists of an 8-in (200mm) pavement built on one ft (300mm) of base over granular subgrade. Owasso Community Streets in the City of Shoreview is the single largest pervious concrete project in Minnesota. This consists of 0.6 miles (0.96km) of city streets pavement with 8-inch
(200mm) pervious concrete on 12-inch (300mm) CA 50/ rail road ballast as base course. The subgrade is made up of granular material.

MUNICIPAL MAINTENANCE STRATEGIES

Table 1 shows the maintenance strategies used by the municipalities and agencies. Ferguson (8) recommended that sanding and salting operations may clog pervious pavements and should then be excluded from snow and ice operations in pervious pavements. This section discusses the existing maintenance strategies.

All communities and agencies in Minnesota exclude sanding and salting from their winter maintenance of pervious pavements. They either plow for removal or groom the snow and ice for snowmobile recreation. The strategy of snow and ice operation in the MnROAD pervious test cells are no different from the operation conducted on other test cells at MnROAD low volume road. Activities consist of the application of salt very sparingly on the test cells in extreme cases in addition to snow plowing. When salting is performed, the Mn/DOT powdery salt is applied lightly on the surface and the melted solution or suspension flows to the shoulders. Regular snow and ice operation uses the snow plow to remove snow or ice from the surface. Due to very very low testing activities at MnROAD low volume road in winter, concern for skid resistance in the winter months is determined solely by the need for the 5-axle 80 kilo pound vehicle to safely make 80 trips a day 5 days a week. The boat ramp at Detroit Lakes provides winter recreation for the residents. The snow and ice is groomed and used as a snowmobile trail in the winter. During the spring thaw, the groomed snow and ice is allowed to melt into the pavement. At that time of the year, larger agents such as leaves and other debris are
swept off the surface and with broom-vacuum equipment, the surface is cleaned. In the non winter seasons, a monthly sweeping and vacuuming is done. In addition to monthly vacuuming City of Shoreview performs snowplowing of their pervious streets. They also perform monthly sweeping of larger debris such as leaves and a regenerative air vacuuming of the 3000-ft (900m) of pervious pavements. This City performs continuous education of the residents so that sodding and seeding and such activities that cause clogging are minimized in the vicinity of the pervious pavements.

Most Agencies have adopted pervious pavement cleaning techniques which are discussed below: They include vacuum sweepers and regenerative air sweepers.

According to Kuehl et al (9) regenerative air street sweepers move debris from the curb into the path of the sweeper head. Vacuum sweepers use gutter brooms to move debris into the path of a vacuum nozzle. There vacuum sweeper in FIGURE 3 has the vacuum nozzle located near the tire along the curb line. This allows the curb to be dry-vacuumed. Most vacuum sweepers utilize a fan that exhausts its air directly to the atmosphere. These sweepers must use water for dust suppression to forestall the obvious environmental hazard and minimize fan wear. Vacuum sweepers are known to remove fine sand and silt, but surface must be dry. The adaptation of this process to picking up entrained material within cavities under vacuum head facilitates an efficient operation. However, the tortuousity of pervious pavements poses a challenge to the efficacy of these vacuums. They are also restricted to temperatures above freezing.
FIELD EVALUATION OF MAINTENANCE STRATEGY

Maintenance strategies are evaluated by the degrees to which acoustic, hydraulic and volumetric properties are restored after a chosen maintenance practice is applied. The volumetric properties are detected with the nuclear density backscatter method, the hydraulic properties are evaluated with the infiltrometer and the acoustic properties are evaluated with the sound absorption equipment ASTM E1050, preferably measured in-situ. Core sound absorption tests are also possible but for evaluation of clogging, it is almost impossible to harvest a representative core. A maintenance strategy must improve or maintain, drainability, sound absorption and/or pore structure. Tools for evaluation are now described.

Infiltrometer

The Pervious concrete cells were monitored for flow time as an index of hydraulic conductivity. The infiltrometer is a device that facilitates measurement of the hydraulic conductivity of a pervious pavement. It is a falling head device with the water level maintained at atmospheric pressure. Its cylindrical housing accommodates a clear 8-inch (200mm) discharge head difference marked “upper” and “lower”. It differs from conventional permeameters in the sense that the velocity head is a significant part of the energy (Bernoulli) equations and is not ignored unlike the standard falling head permeameters used for infiltration of soils. The Mn/DOT infiltrometer is a modification of the ASTM (10) vessel.

FIGURE 4 shows the open ended single ring infiltrometer 24 in (600mm) long and 4 inch (100mm) diameter flanked by supporting dead-weights to enhance a hydraulic seal at the flange-pavement interface. During testing, the flow device is simply placed on the pavement and filled continuously until water is at least 2-inches above an upper mark. The discharge time from the
upper to the lower mark is noted as an indication of the hydraulic conductivity of the pavement. Some clogged portions of the driveway did not allow any vertical flow. In consequence, any thing beyond 100 seconds is regarded as clogged. In clogged spots, a record of the head difference and time taken was occasionally recorded for reference. Waiting till the 8-inch head loss is obtained in a clogged pavement is not expedient. Initially a sand cone device was used but this was replaced by a uniform cross section, varying head device. The equations for discharge were developed for the sand cone but were retained for the uniform cross section device \( \text{(3)} \) under atmospheric pressure, \[ \frac{\pi d^2}{4} \frac{dh}{dt} = v_0 A_o \] where \( h \) is small change in height of water \( A_o \) is the area at the discharge orifice, \( d \) is diameter of infiltrometer; \( v_0 \) is discharge velocity at orifice. Substituting the boundary conditions of \( h = H \) when \( T = 0 \) it can be shown that

\[ T = \frac{\pi d^2}{2 \zeta g A_o} (\bar{h} - \bar{H}) \]

where \( T \) is discharge time, \( \zeta \) is a system calibration constant, \( g \) is acceleration due to gravity. \( A \) is top open end area, \( H \) is maximum head loss, \( h \) is head loss \( d \) is diameter at orifice so derived to accommodate different open end areas else \( A_o = \pi d^2 \) in uniform area infiltrometers. The test is conducted in impervious surfaces and air during calibration. Locations on the test cells were monitored in 2008, spring 2009 and Summer 2009. Some of these locations were coincident with test spots for nuclear density and sound absorption.

**Insitu Density Evaluation**

Seamans Nuclear density gauge measures density of a pavement surface or layer by emitting radioactive rays into that layer with the “back scatter” method. Response of the media is dependent on the absorptive property of the pavement. This pulse is calibrated to known densities that facilitate true measurements.
If $\gamma$ is the bulk density of a pervious layer and $\gamma_{np}$ is density of a non-pervious layer, it can be shown that $\gamma V = \gamma_{np} (V - Vv)$ where $V$ is total volume of a pervious concrete and $Vv$ is volume of voids. $(Vv/V)$ is porosity. It is therefore evident that $(\gamma_{np} / \gamma) (1-n) = 1$

where $n$ is porosity. Therefore, Porosity $(n) = 1 - (\gamma / \gamma_{np})$.

For example cell 40 a non-pervious cell averaged 146 pcf and the outside lane of pervious cell 39 averaged 120 pcf. The average porosity is $1 - \frac{119}{148} = 0.19$

**In-Situ Sound Absorption Measurements**

The sound absorption test is a process that measures the sound absorptiveness of a pavement surface. In the sound absorption test, the sound analyzed is not generated by the interaction of the rolling tire with pavement surface but by noise source above the impedance tube (FIGURE 5). Occasionally a white noise source is used. This is a random audio signal with a flat power spectral density that contains noise at the same power at all frequencies. During the test an impedance tube is placed on the pavement surface and a set of sensitive microphones are attached to the pre-installed housing at the lower end of the tube. Microphones are connected to an analyzer. The noise source sends the incident sound energy to the surface and the incident and reflected waves are captured by the two microphones. Software windows the reflected waves and converts the data to the $3^{rd}$ octave sound absorption coefficient at 315, 400, 500, 750, 1000, 1250 and 1650 hertz. Berengier et al (7) in discussing sound absorption coefficient ($R_p$) expressed it as a function of frequency ($R_p(f)$) such that $R_p(f)^2 = \frac{1}{K_r^2} \frac{P_r(f)}{P_i(f)}^2$ where $K_r$ is the spreading factor, $P_r$ and $P_i$ are the reflected sound energy and the incident sound energy respectively. The output of a sound absorption factor is typically in the form of the sound
absorption at the seven frequencies defined above. Hence, the factor is therefore expressed as a function of frequency.

PERFORMANCE EVALUATION OF CLOGGED TEST CELLS

In the clogged cell 64 the SA at 400-Hz was 0.12 and 0.08 in the left lane and right lane respectively. An unusual local peak at 800-Hertz characterized the SA frequency plot with a spike to 0.32 and 0.14 respectively in the left and right lane. At 1000-Hz, SA was 0.12 and 0.18 respectively and at 1600-Hz the SA was at a maximum of 0.48 and 0.33 respectively. In comparison, Cell 89 SA ranges gradually and uniformly from 0.3 at 400-Hz to 0.5 at 1600-Hz (FIGURE 6a). Cell 89 being new in service shows no signs of raveling and clogging, unlike cell 64.

If cell 64 was evaluated by the infiltrometer method alone, it would be regarded as clogged but that would be from a hydraulic conductivity perspective. Most of the spots were found to be clogged as there was either no vertical movement of water into the pavement or the rate of discharge was so low that after 100 seconds the standard 8 inch head loss was not achieved. In this cell, sound absorption was lower than the new cells but was significantly higher than what was observed in the non-pervious cells.

The surface of cell 64 is in very poor condition with significant raveling and cracking. These distresses have released a high quantity of clogging agents on the pavement. The surface is loaded with the 5 axle semi trailer 2 times a day 5 days a week. After 4 years, this pavement has not been vacuumed once and it is in the path of run-off from the 100-ft X 140-ft (30m X 42m) driveway/parking lot. This contributed to its clogging. The difference in sound absorption
coefficient between cell 64 and cell 85 is a reflection of the degradation and clogging of cell 64. Nevertheless, the clogged pavement exhibits significantly higher sound absorption than non-pervious pavements. General hydraulic conductivity measurements have shown with the example of a pervious pavement left unmaintained for 4 years that clogging leads to accelerated pavement degradation as freeze thaw capitalizes on the trapped lenses of ice to damage the pavement. Before and after measurements of hydraulic conductivity of pervious pavements indicates that there is a noticeable improvement of this variable, when vacuuming is performed but when left undone for a long time, the pervious pavement falls apart and the original void content.

Various test locations in the city of Shoreview indicated differing sound absorption spectra due to the varying degrees of clogging. For instance a fairly clogged location near the curb line exhibited SA ranging from 0.15 to 0.25 between 400 and 1000Hz. Proximate unclogged location resulted in higher SA ranging from 0.3 to 0.53 between 400 and 1000-Hz (FIGURE 6b). Consequently, the clogged MnROAD cell and the Shoreview City Street, portrayed that clogging reduces sound absorption coefficient.

A QUANTITATIVE EVALUATION OF A MAINTENANCE STRATEGY

Mn/DOT demonstrated a pervious pavement vacuuming process using equipment owned and operated by a Minnesota based company at MnROAD in November 2009. Pervious concrete test cells 85 and 89 and pervious asphalt cells 86 and 88 were vacuumed. The test cells were approximately one year old at the time of the demonstration and were in good condition. The pervious concrete test cells had no surface raveling or joint distress and very few fine cracks. The pervious asphalt test cells had isolated areas of surface raveling and light rutting. The voids
in the pervious concrete and pervious asphalt test cells appeared to be clean and free of debris. It is important to note that the brush on the vacuum was not used. The contents of the vacuum were collected after vacuuming each test cell. While the test sections did not have visible debris in the voids, there was some surface material, likely from the shoulders and neighboring test cells. Flow measurements were made the day before and immediately after vacuuming. The change in time of discharge was indicated by the Mn/DOT falling head infiltrometer which has been described. The set up is shown in FIGURE 8. A test was performed in each test cell at the wheel path. It was apparent that the pervious concrete test cells (85 and 89) were very clean with no surface distress there was very little change in flow time. This improvement is likely attributable to the removal of the raveled surface aggregate. Two vacuuming activities per year were therefore recommended.

FIELD EVALUATION AND ANALYSIS

The most common clogging agents encountered in the MnROAD Cells are the “ravelings” from the pavements. Aggregate and cements and asphalt in various degrees of fragmentation were visible in the receptacle of the vacuuming equipment used in the Mn/DOT Cells. The three cities had encountered more organic as well as colloidal clogging agents than were observed at MnROAD. These organic and colloidal materials undergo volume changes in the voids, depending on their moisture content. Fwa et al (11) observed that most of the clogging agents in Singapore came from automobile tires that had picked up silty particles from other sources and transferred it to the pervious pavements. That may be applicable to city streets in which turf was established by sod application, leaving clay and silt debris that tires may pick up and disperse in the pavement surface. Additionally, during the fall, a large quality of leaves was deposited on the pavement surface. These were pulverized by traffic and washed into the pores. The city
streets were more susceptible to clogging than the MnROAD cells. In the Detroit lakes boat ramp, sand is occasionally encountered. In 2 years of service the pavement still exhibits good drainability.

To ascertain the relative long term effect of various agents, an accelerated clogging study was conducted. In this study, clogging agents are idealized into three representative groups.

Group 1: Cohesive/colloidal agents: Simulated and represented by clay

Group 2: Clean granular material: Represented by Ottawa Sand

Group 3: Granular but finer gradation than Ottawa Sand: Represented by glass beads

Pervious concrete blocks measuring 20 inches by 20 inches and 6 inches thick were all were examined to ensure that the clogging agents were retained within the test wedge. These blocks were placed on an elevated stand so that the underside of the pavement was visible. Using the BSWA impedance tube, sound absorption was measured after each stepwise application of 100-milliliters of Ottawa sand. The block was tamped with a mallet until all the sand had disappeared into the pervious pavement. The sound absorption coefficient of the surface was then measured. The test was repeated with increments of 100-milliliters until the pervious pavement could no longer absorb the Ottawa sand. The test wedge facilitated the assurance that there was no clogging agent falling freely through the wedge. Fwa et al (11) had flushed the agent through the matrix in their experiment. That method was not used in this experiment as it would lead to segregation and haphazard retention of the larger fractions of the agent. The actual clogging tests were then repeated on 3 different spots on cell 89 as shown (FIGURE 7). The results of sound absorption at 1000-Hz versus volume of clogging agent was then plotted.
There is a remarkable decrease in sound absorption factor due to the clogging agents. The three clogging agents exhibited different rates of decrease in SA with respect to volume applied. In all cases, the sound absorption coefficient decreased with respect to volume in a nonlinear trend best fitted to an exponential decay. (FIGURE 8). Initial sound absorption was not the same but the incremental volumes were 100-ml in all cases. The relationship was then normalized by determining the percentage decrease in sound absorption with respect to the volume of clogging. (FIGURE 8).

**DISCUSSION**

The three agents all exhibit reduction in acoustic absorption due to increase in the volume of clogging agent. The rate of loss of sound absorption is however different in the 3 agents and plausible reasons have been advanced for this. Total volume of agent to clog the pervious concrete was the same in each of the agents. This was not originally designed but it turned out to be 400-ml. This removed the variability of the quantity of clogging agent including the fact that core porosity values ranged from 18% to 20% which is reasonable uniformity for field evaluation.

**Loss of Sound Absorption Due to Clogging:** Loss of SA factor at full clogging of approximately 30% was observed in the Ottawa sand and clay agents. However in the glass beads a loss of 20 percent was observed. The above losses are not expressed in terms of the ratio of initial sound absorption but as actual losses in values subtracted from the original.

In terms of the actual factors, the clay lost the highest percentage of initial sound absorption as at full clogging (75%). This was followed by glass beads (52%) and by Ottawa sand (48%). The trend suggests the gravity of clogging when clogging agents are colloidal or cohesive in
comparison to granular or flocculated agents. It is therefore more hazardous to subject the pervious concrete pavement to a clay environment than to a granular environment. It is suggested that various factors influence the impact of the clogging agents. They include particle size distribution, cohesion and adhesion, effective porosity and effective tortuous. The effect of a clogging agent depends on the particle size distribution, moisture content, mineralogy and effective tortuousity. It is therefore advisable to prevent ingress of cohesive agents as much as possible.

When clogging occurs, there is a reduction in the efficiency of the void system but by volumetric reduction of the void system or by a loss of communication of voids. It can therefore be shown that the effect of clogging depends on the gravimetric properties, the particle size distribution, adhesiveness or cohesiveness of the clogging agent.

**Particle Size Distribution of Clogging Agents:** Clay particles are less than 2 µm size fraction in size while the glass beads range from 150 microns to 300 microns. The size distribution between is supposedly uniformly graded. Ottawa sand fractions range from 150 µm to 2-mm. This may explain why the percentage loss of sound absorptiveness of the clay clogged matrix was more than those of other agents.

**Adhesion and cohesion:** Clay particles cohere or are more closely packed irrespective of their moisture content. They also adhere to the tortuous cavities in the pervious matrix more than would the glass beads and Ottawa sand.

**Effective Porosity:** When clogging occurs there is a loss of volume of cavities. This volume is occupied by the clogging agent that theoretically introduces its void content.

Consider a fully clogged matrix of total volume V and pore / cavity system Vp
The clogging agent introduces a void system $Va$ into the cavities, the natural porosity of the agent is $Va/Vp$. Porosity before clogging $= Vp/V$ and porosity after clogging $(Va/V)$ is $(Va/Vp) (Vp/V)$.

Porosity after Clogging is (Natural porosity of clogging agent) X (Porosity before clogging).

The assumptions for the above to be valid are that the pervious cavities are completely clogged and neither the clogging agent nor the pervious media is segregated.

**Effective Tortuosity:**

FIGURE 8 shows the effect of gradual filling of voids with the 3 agents. Evidently clay shows a more damaging effect than the other agents. From FIGURE 9 it can be shown that the chord length for a fluid travelling vertically unaffected by lateral transmissivity is $L = 2 \frac{\sqrt{2} R}{2^2 R}$. The travel length is $S = 2 \frac{\sqrt{2} R - 2R + \pi R}{2^2 R}$. Simple tortuosity of unclogged matrix is therefore $\frac{(2 \frac{\sqrt{2} R - 2R + \pi R}{2^2 R})}{1} \approx 1.4$

If the void is clogged by stacking $n$ layers of clogging agent of radius $r$, additional path due to clogging agent is $nr (\pi - 2)$ which is always positive. Tortuosity of clogged matrix $S/L$ (clogged) is

$$\frac{(2 \frac{\sqrt{2} R - 2R + \pi R + nr (\pi - 2)}{2^2 R})}{1} = 1.4 + \frac{nr (\pi - 2)}{2^2 R}.$$  

Comparing this to previous equation, there is an increase in tortuosity when the pavement is clogged. In practice, aggregates are not rounded and they may not be consolidated to the maximum packing. Nevertheless, a clogged matrix will be more tortuous than an unclogged matrix. This validates the reduction in hydraulic conductivity and sound absorption when pervious concrete is clogged.

Due to the complexity of diffusion paths, some other tortuosity methods that are less direct than (arc length / chord length) have been proposed. Grisan et al (12) proposed another method that divides the curved path into several ($N$) parts where the chord length is $S$ and the arc length is $L$. Thus the arc-chord ratio for each part is found and the tortuosity $\tau$ is estimated by: $\tau = \frac{N-1}{L} \cdot \sum_{i=1}^{N} \frac{L_i}{S_i} - 1$
When clogging occurs, N increases tremendously, summation Li/Si increases rapidly and the path becomes more tortuous.

The accelerated clogging experiment with Ottawa sand, glass beads and clay reveals that the level of loss of sound absorption coefficient is thus related to the gravimetric, physical and natural properties of the clogging agent.

CONCLUSION AND RECOMMENDATION

Municipalities in Minnesota adhere to best practices for maintenance of pervious pavements as they commonly vacuum their pavements once every month. MnROAD test cells are not in the path of wide range of clogging agents and are vacuumed 2 or 3 times a year. Maintenance of the French drains of the pervious overlay has provided stable hydraulic conductivity to the pervious Overlay.

- The accelerated clogging experiment accentuates that fact that clogging reduces the acoustic properties of pervious pavements. It also shows that the colloidal or plastic clogging agents such as clay have the worst clogging effects. The effective void content of a clogged pavement can be deduced from the original porosity of the pavement and the natural porosity of the clogging agent.

- Clogging increases the tortuosity of pervious concrete. Clogging decreases sound absorption of pervious concrete and the original SA coefficient can be restored if effective vacuuming can be done.

- General hydraulic conductivity measurements have shown with the example of a pervious pavement left unmaintained for 4 years that clogging leads to accelerated
pavement degradation as freeze thaw capitalizes on the trapped lenses of ice to damage the pavement. Before and after measurements of hydraulic conductivity of pervious pavements indicates that there is a noticeable improvement of this variable, when vacuuming is performed but when left undone for a long time, the pervious pavement falls apart and the original void content cannot be restored.

- It is recommended that communities adopt best practices methods for maintenance of pervious pavements and adopt the continuing education strategy of City of Shoreview so that influent clogging agents can be minimized.

DISCLAIMER

This paper represents the opinions of the authors alone.

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<thead>
<tr>
<th>CITY OR AGENCY</th>
<th>PERVIOUS PROJECT</th>
<th>MAINTENANCE</th>
<th>MONITORING</th>
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<tbody>
<tr>
<td>DETROIT LAKES</td>
<td>Boat Landing &amp; Treatment System</td>
<td>None</td>
<td>Once as month</td>
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<tr>
<td>MINNEAPOLIS</td>
<td>Cul-de-sac at 10th street &amp; Lake Street</td>
<td>Plow as needed</td>
<td>Once as month</td>
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<td>SHOREVIEW</td>
<td>3000ft (900m) Of City Streets Near Lake Owasso</td>
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<tr>
<td>MINNESOTA DOT</td>
<td>Pervious Concrete Driveway Cell 64</td>
<td>Plow as needed</td>
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<tr>
<td>MINNESOTA DOT</td>
<td>Pervious Concrete Full-depth Cells 85 and 89</td>
<td>Plow as needed</td>
<td>2/3 times a year</td>
</tr>
<tr>
<td>MINNESOTA DOT</td>
<td>Pervious Concrete Overlay Cell 39 on Concrete substrate</td>
<td>Plow as needed</td>
<td>2/3 times a year</td>
</tr>
<tr>
<td>Minnesota DOT</td>
<td>Sidewalk at MnROAD</td>
<td>Plow as needed</td>
<td>2/3 times a year</td>
</tr>
<tr>
<td>Minnesota DOT</td>
<td>Driveway at MnROAD</td>
<td>Plow as needed</td>
<td>2/3 times a year</td>
</tr>
</tbody>
</table>
Table 2: Flow Times Before and After Vacuuming

<table>
<thead>
<tr>
<th>Cell #</th>
<th>Before Time (s)</th>
<th>Time After (s)</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>6.0</td>
<td>6.0</td>
<td>0</td>
</tr>
<tr>
<td>89</td>
<td>17.0</td>
<td>15.5</td>
<td>-9</td>
</tr>
</tbody>
</table>

FIGURE 1: Boat Ramp Pervious Filtration System Detroit Lakes Minnesota
Pervious cells 85 Sand Subgrade; 89 (Clay Subgrade)

Schematic Section Through the Pervious Concrete Overlay Cell 39. (French Drains at 100-ft Intervals)

FIGURE 2: General Structure of MnROAD Pervious Pavement.

a) Regenerative Air Vacuum

b) Agents Vacuumed from MnROAD Pervious Pavements

FIGURE 3: Vacuum Used on Mn/DOT Test Cells & Agents Collected at the Receptacle
Mn/DOT Infiltrometer Test

FIGURE 4: Mn/DOT’s Pervious Pavement Hydraulic Conductivity/Infiltrometer Device

a) Infiltrometer

Seamans
nuclear
Density
Gauge

BSWA 435
Impedance
Tube

FIGURE 5: Nuclear Gage and BSWA 435 Sound Absorption Impedance Tube
a) Sound Absorption Profile of Cell 64 (Unmaintained Pervious Concrete)

b) Sound absorption Profile of cell 89 (New and Maintained Cell)

FIGURE 6a: Maintained Versus Unmaintained SA Trends.
FIGURE 6 b: Sound Absorption of Clogged and Unclogged Locations in City of Shoreview

FIGURE 7: Accelerated Clogging Test
(A) Sound Absorption Versus Clogging Agent Volume

(B) Percentage Reduction in Sound Absorption Vs Clogging Volume

FIGURE 8: Results of Clogging Experiment

FIGURE 9: Section Through Idealized Closely Packed Pervious Matrix