Technical Note

Transport and Retention of Water and Salt within Pervious Concrete Pavements Subjected to Freezing and Sand Application

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Abstract: Pervious concrete pavement can effectively reduce both the volume of water and the concentration of many sediment-associated contaminants in urban runoff. However, chloride from road salt is recognized as a threat to surface and groundwater resources because it is a conservative ion and does not readily bind to soil particles. To better understand and manage water resources in urban environments experiencing annual freeze-thaw cycles, this study examines the impact of road salt (sodium chloride) and sand applications on water and chloride movement in pervious concrete structures in a laboratory setting. Water movement and salt retention were characterized within pervious concrete slabs under frozen and thawed conditions. Laboratory experiments were repeated using both brine (23% salt solution) and fresh water as well as varying additions of sand (typical of winter sand application rates in Canada) to provide a range of temperatures experienced in cold-climate urban environments. Performance testing (via infiltration capacity) was conducted to assess the suitability of pervious concrete in climates where road sand and salt application is necessary. For all experimental conditions studied, chloride was rapidly transported through the pervious concrete. The complete freezing of pore water throughout the concrete slab reduced water and salt movement within the concrete matrix, while sand application reduced water movement through pores and delayed peak flow. The infiltration capacity of the pervious concrete structures, as tested, exceeds the probable maximum water loading rate that will be encountered in Southern Ontario, Canada, with or without sand, frozen or unfrozen. From a groundwater management and source water protection perspective, the data indicate that pervious concrete pavement structures may contribute to chloride contamination of groundwater if used in salt vulnerable areas and groundwater recharge zones. **DOI: 10.1061/(ASCE)HE.1943-5584.0001036.**

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Introduction

Increased flow volumes and degraded water quality of urban runoff can have significant impacts on stream morphology and ecosystem health (Paul and Meyer 2001; Schueler 1994, 2000; Wang et al. 2001). Accordingly, a wide range of structural and nonstructural best management practices (BMPs) are typically used to reduce runoff and enhance water quality in urban areas (McCuen and Moglen 1988; Ministry of the Environment 2003). Pervious concrete surfaces are increasingly being used as a BMP, primarily to moderate storm-water runoff, with additional benefits such as reduced tire pavement interaction noise (Shao et al. 1994) and limited transfer of some pollutants to groundwater (Tennis et al. 2004; Toronto and Region Conservation Authority 2008). However, winter road maintenance practices in cold regions typically include the application of road salt (sodium chloride) and sand to keep highways safe and fully operational (Stone and Marsalek 2011). While the use of pervious concrete as a BMP in urban areas may be appropriate for use in regions where road salt application is not necessary, the environmental risks of chloride-laden runoff entering environmentally sensitive areas such as groundwater recharge zones in cold climates is of concern and needs to be reduced. This risk is addressed in the current study, specifically as it pertains to the use of pervious concrete structures; however, it is a common concern for many stormwater BMPs, and it is not unique to pervious concrete.

Kwiatkowski et al. (2007) reported that Cl^- levels entering soils underlying a pervious concrete infiltration basin were not significant enough to impact groundwater; however the Cl^- concentrations reported were highly variable and reached more than 1,000 mg/L Cl^- during a winter runoff event. This level greatly exceeds the current Canadian water quality guidelines (CWQG) for the protection of aquatic life that report long-term exposure limits of 120 mg/L Cl^- (CCME 2011). Considering the high permeability design of pervious concrete structures (Tennis et al. 2004), areas with shallow groundwater aquifers are potentially vulnerable to contamination by pollutants in urban runoff via short-circuit infiltration through the highly porous concrete structures. Chloride transport through shallow groundwater aquifers in urban watersheds is directly linked to high Cl^- concentrations in the base flow of urban streams, with an increased risk of densimetric stratification and poor vertical mixing of ponds in urban areas (Marsalek 2003). Houle (2008) examined the effectiveness of reduced salting strategies on a porous asphalt parking lot compared to a standard dense-mix asphalt lot. The study demonstrated that the

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frequency and mass of salt applications required during winter precipitation or freeze-thaw periods was reduced on the porous asphalt due to low amounts of snow and ice cover on the porous asphalt surface and subsequently high skid resistance. Snow and ice formation on the porous asphalt was constrained in part by the high permeability of the porous asphalt causing a reduction in the occurrence of standing water on the surface. In cold climates, winter road maintenance programs conventionally involve a combination of snow and ice clearing activities including salt and sand application (Andrey et al. 2001). However, no attempt was made by Houle (2008) to assess the impact of sand application (i.e., surface clogging) on the ability of the porous pavement to limit standing water. Thus, the implications for salt application requirements under varying degrees of sand applications remain unaddressed.

The emerging literature indicates that pervious concrete surfaces promote infiltration and generally perform well under high-flow (i.e., storm flow) conditions to reduce overland flow (Marsalek and Schreier 2009). However, much less is known about the water quality impacts of pervious concrete, specifically with regard to road salt applications. Knowledge of Cl^- transport and retention in pervious concrete has implications for safety and water resources management in freeze-thaw environments. Pervious concrete pavement performs well when properly designed and constructed for both the traffic loading and environmental conditions, namely freeze-thaw cycling and precipitation (Henderson 2012; Henderson and Tighe 2011). However, the usage of pervious pavement needs to consider groundwater interactions and the potential implications on groundwater quality in sensitive groundwater recharge zones where road salt and/or sand application might be required. The objectives of this study are to (1) determine the effect of sand application on the performance of pervious concrete, under both frozen and thawed conditions in a laboratory setting; (2) characterize the transport and retention of chloride within the pervious matrix; and (3) discuss the implications of pervious concrete use on groundwater quality, especially with regard to source water protection in salt vulnerable areas.

Methods

Construction and Determination of Pore Volume

Pervious concrete pavement slabs ($30 \times 30 \times 15$ cm) were constructed with an optimized mix that would provide sufficient durability for proper field placement (Henderson 2012), following the standard method CSA A23.2-3C [Canadian Standards Association (CSA) 1984]. Water and salt retention in four pervious concrete slabs were assessed in the Centre for Paving and Transportation Technology (CPATT) lab at the University of Waterloo. Volumetric water content of each slab was determined using Campbell Scientific CS-605 time domain reflectometry (TDR) probes, positioned at 5 and 15 cm from the surface of the slab. Slabs were paired for testing (Table 1); two slabs were used for salt (as a surrogate for chloride) characterization (herein referred to as CS 1 and CS 2) and two slabs were used to characterize the hydrologic performance of the pervious concrete (HS 1 and HS 2).

The pore volume of each slab was determined prior to conducting the laboratory experiments. Each dry slab was preweighed and the pore volume was determined through displacement, where the concrete slab was slowly and carefully lowered into a tub full of tap water. The volume of the concrete matrix is responsible for the water being displaced from the tub, thus the pore volume is the residual of the total volume of the slab. The slabs were allowed to drain then reweighed to determine the volume of water retained in the pervious concrete (Table 1). Porosity was calculated as the ratio of the void space volume to the volume of the concrete slab. The void space volume is a measure of the larger pores within the pervious matrix that readily fill with water and does not include small air spaces that exist within the structure of the concrete matrix.

Table 1. Pore Volume of Pervious Concrete Slabs

	Salt slabs (CS)		Hydrology slabs (HS)	
Characteristic	CS 1	CS 2	HS 1	HS 2
Dry weight (kg)	37.30	36.98	35.38	34.76
Wet weight (kg)	38.08	37.76	36.26	35.56
Pore volume (L)	3.44	5.59	4.06	4.40
Porosity	0.19	0.31	0.23	0.24

Note: Wet weight measured after gravitational drainage ceased.

Experimental Design

Fresh water and a 23% brine (sodium chloride) solution were applied at a constant rate to the surface of the HS and CS pervious concrete slabs, respectively. A rain simulator and a Mariotte device were used to provide a constant flow rate and even distribution on the surface of the slabs. The slabs were subjected to varying additions of sand (Table 2), under both frozen and thawed conditions, with both salt and fresh water. Accordingly, there were a total of 12 quasi-independent experimental designs, with two repetitions of each (Table 3). Note that, since the repetitions of the experiment are conducted on the same slabs, this is not a truly independent experimental design. It was anticipated that variations in internal pore structure, pore volumes, etc. would confuse comparisons of different experimental tests analyzed on different concrete slabs. The intention of the experimental design, as outlined above, was to minimize the effect of variable slab properties. Between tests, the slabs return close to baseline conditions, which allows for independent sequential testing on the same set of slabs. For the low temperature experiments, the slab was placed in a walk-in freezer at −15°C for 24 h. The water or brine solution to be applied to the frozen slab was placed in the same freezer for at least two hours prior to application, and ice cubes composed of water or brine, whichever was appropriate, were placed in the reservoir of the Mariotte system to maintain a temperature near to 0°C. Slabs were tested initially under controlled conditions (i.e., no sand applied), with sand applications increasing incrementally, according to a "heavy" sand loading rate of 40 g/m^2 sand, and 0, 10, and 50 individual sand applications (Tables 2 and 3). Sand was applied evenly to the surface of the slabs by hand. These application rates were established based on discussion with several municipal and provincial maintenance operators (S. Tighe, personal communication, 2013). The sand that was used in the experiment was donated by a regional maintenance contractor for Southwestern Ontario and is a standard material that is used for winter maintenance in

Table 2. Sand Application Treatment

Clogging level	Number of applications	Sand added (g) (cumulative total)
0	0	0
1	10	36
2	50	180

Note: Clogging levels 1 and 2 represent 10 and 50 sand applications at the "heavy" sand application rate (40 $g\,sand\,m^{-2}$).

Table 3. Experimental Treatments and the Time Required to Reach Steady State Flow (When Water Flowing Out of Base of Slab Remained Relatively Constant Over Time)

Treatment (number of sand applications)	Time required to reach steady state flow (min)			
	Salt slabs		Water slabs	
	CS 1	CS 2	HS 1	HS 2
Thaw (0)	4.0	5.2	14.1	25.3
Frozen (0)	6.0	10.0	31.0	4.0
Thaw (10)	9.0	7.0	14.0	10.5
Frozen (10)	7.0	17.0	8.0	8.0
Thaw (50)	—	11.0	15.0	6.0
Frozen (50)	9.0	13.0	22.3	30.6

Note: Longer times indicate slower movement of water through the slab; thaw (50) sand slab (CS 1) was omitted due to experimental inconsistencies.

Canada. According to the Ontario provincial standard specification developed for the Ontario ministry of transportation (OPSS.PROV 1004, 2012), the gradation requirements for winter sand are such that 90–100% of particles are <4.75 mm (pass through a 4.75 mm sieve size) and <15% of particles are <0.15 mm. There was no further sorting of the sand used in the experiment.

The Mariotte system is designed to provide a constant flow rate, regardless of the level of water (or brine) in the delivery system. The flow rate from this system can be altered by changing the height of the vent tube by sliding it up and down for increased and decreased flow rates, respectively. A flow rate of 45 mL/min was used for each run to simulate a precipitation intensity of 30 mm/h. According to the 31-year (1971–2003) rainfall intensity-duration frequency data from the Waterloo-Wellington Airport, this flow rate is equivalent to the two-hour duration of a 10-year storm event. Two independent rainfall simulation devices (one each for the CS and the HS slabs) were used to run the experiments simultaneously. Water samples were collected beneath the slabs at regular time intervals to measure the volume of the water flowing through each slab.

Instrumentation Details

The volumetric water content (VWC) is defined as the ratio of the volume of water per unit volume, expressed herein as a percentage. VWC was measured every 10 min with a Campbell Scientific TDR-100 system and a SMDX-50 multiplexer controlled by a CS1000 data logger. The empirical calibration function reported by Topp et al. (1980) was used to convert the dielectric number from the TDR to the volumetric water content within the pervious concrete slab. TDR measurements can be limited by the negative effect of increased salinity on the resolution of the TDR signal (Wyseure et al. 1997; Or et al. 2004). However, this phenomenon is only observed when electrical conductivity (EC) exceeds 0.2 S/m (Wyseure et al. 1997) to 0.6 S/m (Sun et al. 2000), which is two orders of magnitude greater than the EC of the brine solution used in this experiment. Janoo et al. (1999) identified that TDR measurements consistently predicted a lower moisture content for traditional concrete and mortar (not pervious concrete) than for a soil of equal dielectric constant. However, this appeared to be a systematic error, which would affect the volumetric water content measurements in the slabs in this study equally, hence comparisons of TDR measurements between slabs is still valid. Further, using the Topp et al. (1980) calibration function to compare the volumetric water content of soils with a wide range of bulk densities can lead to unacceptable errors (Malicki et al. 1996); however, the comparisons of TDR measurements within this study are all on the same material (i.e., pervious concrete) with a similar bulk density, which will constrain errors associated with applying the Topp et al. (1980) calibration function. For the CS slabs, the movement of salt was monitored through measurement of the EC of the water flowing from the bottom of the slab at regular time intervals using a Thermo Scientific EC probe (±1%). All EC measurements were corrected to 25°C standard conductivity values. The tests were repeated under frozen and thawed conditions with three levels of sand clogging for a total of 12 experiments repeated in duplicate.

Results and Discussion

Moisture Dynamics

The VWC in the two HS slabs ranged from 8% (under dry conditions) to 22% (under wet conditions). Slight differences in VWC between slabs under dry conditions (data not shown) are related to compaction differences causing variability in pore volume (Table 1) and porosity during slab construction. After each experiment, the slabs drained (i.e., returned to their pretest VWC value) within two days. The time required to drain water from frozen slabs was greater than for thawed slabs (Fig. 1). Under frozen conditions, less water drained from the slabs, which caused the VWC to stabilize at higher residual water content (time to residual water content identified by vertical lines in Fig. 1). Paradoxically, VWC did not decline while the slab thawed after the experimental run and consistently stabilized at a slightly lower residual water content following thawed experimental runs (Fig. 2). This could be an artifact of hysteresis-derived inconsistencies in pore drainage under frozen conditions, whereby drainage pathways are constricted under frozen conditions and, upon thawing, a small volume of residual water (that would have drained under thawed conditions) is held by capillarity within the block. Further, it is generally assumed that TDR measurements of the VWC of frozen soils does not include the ice content (Patterson and Smith 1980), which implies that the residual water content under frozen conditions is bound water held by tension that remains in the liquid state (Drotz et al. 2009). Sand application minimally impacted water retention within the pervious

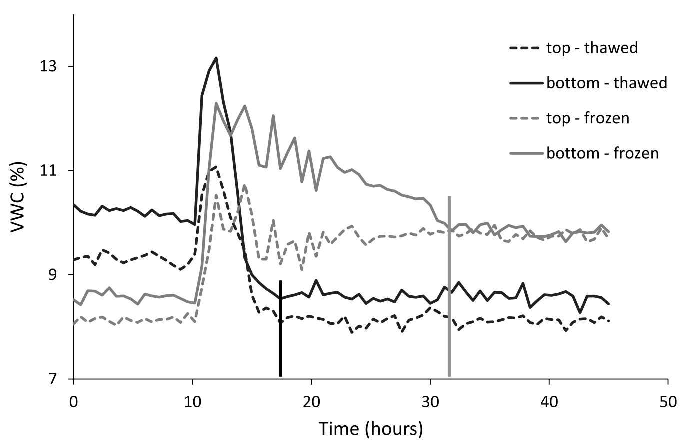

Fig. 1. VWC for the HS 2 slab during two experimental runs (black line = thawed; gray line = frozen), both at control conditions (i.e., no sand application); vertical lines indicate the time that residual water content was reached; note: "top" denotes the probe located 5 cm from the slab surface, while "bottom" denotes the probe located 15 cm from the slab surface; experimental runs began at 10 h

concrete, as indicated by consistent residual VWC values with increased sand applications (Fig. 2). In a field setting, grinding of sand particles by vehicle traffic can cause sand material to be broken down into smaller pieces (van Duin et al. 2008), which would cause increased water retention and higher residual VWC values than observed in the laboratory. However, the clogging process for pervious concrete is often constrained to the upper layers of the porous structure (Balades et al. 1995), which would limit the changes in water retention and residual VWC in the lower layers of the concrete where fine particles are less likely to accumulate. Frozen residual VWC was greater than thawed residual VWC for all experiments, regardless of the amount of sand applied (Fig. 2). The multiple spikes in VWC shown in Fig. 2 indicate the start of an experimental run (addition of water to the slab) under differing experimental conditions. Changes in the observed height of VWC spikes were due to slight variation in the rate at which water was applied to the surface of the slab during the experiments. A test run conducted prior to the commencement of experimental runs (Fig. 2) did not have a substantial impact on subsequent experimental results. The VWC at the slab bottom was consistently higher than at the top of the slab, which is due to the preferential draining of the upper portion of the slab by gravity. As a consequence of this preferential drainage, water remained in the lower portion of the slab for longer periods as it continued to drain from above. This phenomenon is magnified under frozen conditions. The drainage from the bottom of the slab (and to this area from the upper portion of the slab) was slower than in unfrozen slabs because water films frozen within the matrix constricted pore size, which caused a reduction in the rate of downward flow.

The residual VWC within the slab following drainage was comparable across the entire range of sand applications. It is hypothesized that excessive addition of sand to the slab surface (and infiltration into the upper portion of the concrete) will reduce the average pore size in the slabs within the pervious concrete and increase water retention. This could have negative implications on the performance of the pervious concrete under extreme conditions (i.e., very clogged and frozen) because there is potential for the pervious concrete to have its drainage efficiency reduced.

Sand Application and Water Movement

Experiments were conducted to determine the effect of sand application and temperature (frozen versus thawed conditions) on water movement through the pervious concrete slabs. The timing of the initial water pulse was measured until the flow rate from the bottom of the slab reached steady-state (when the water flowing out of the base of the slab remained relatively constant over time). In some experiments, an average steady-state flow rate was used. It is prudent to note that the viscosity of water is temperature-dependent; hence differences in the water temperature between the frozen (~0°C) and thawed (~20°C) experimental test runs can influence the movement of water through the pervious concrete slabs. In general, the influence of temperature-induced viscosity differences of groundwater (hydraulic conductivity) measurements made in the field (relatively cold) and in the lab (room temperature) is usually small, so correction factors are seldom introduced (Freeze and Cherry 1977). Here, the influence of viscosity differences between experimental runs is minimized by the high flow rate (45 mL/ min) and large water-conducting pore spaces. Slight differences are likely well within the measurement error associated with the experimental measurements themselves and is, thus, not accounted for.

The time to reach steady-state flow conditions is proportional to the ability of the slab to transmit water. There were some inconsistencies in the data that are likely due to a combination of measurement error and experimental design (i.e., variation in the rain simulator flow rates). In general, the time to reach steady-state flow increased with decreasing temperature and increasing water content (Table 3). Slab CS 1 exhibited a generally shorter time to steady-state flow than slab CS 2 despite having a lower porosity (Table 1). This implies that bulk concrete porosity might not be a good indicator of vertical permeability. Haselbach and Freeman (2006) identified that vertical variation of porosity within pervious concrete can affect the overall permeability. Quantification of the vertical distribution of porosity within the concrete slabs was not completed in this study; however, these findings suggest that the connectivity of vertical pore spaces within the concrete can influence the transmission of water. The application of sand generally reduced water flow when pores near the surface were filled with sand. These observations are reflected in the slope of the line relating the flow rate from the base of the slab to the time elapsed since the start of the experimental run (i.e., initiation of water flow onto the surface of the slab, Fig. 3). A steeper slope indicates that steady-state flow conditions were reached more rapidly than a gentler slope, which would indicate that water movement is being impeded within the slab. The steepest slope was observed for the experiment under thawed conditions and no sand application. For each consecutive

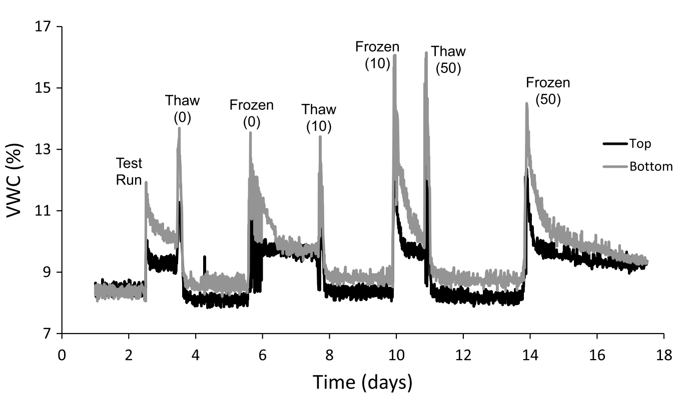

Fig. 2. VWC of the HS 2 slab during each different experimental run (the number of sand applications is indicated in parentheses)

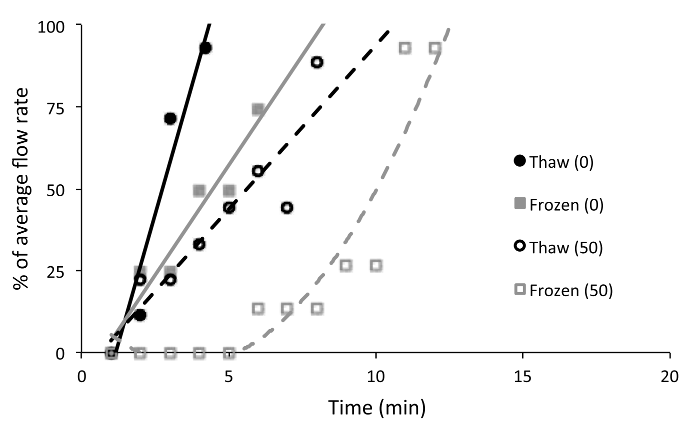

Fig. 3. Average flow rate versus time for CS slab CS 2, illustrating the variation in the time required to reach steady-state flow conditions as a consequence of sand application (number of applications indicated in parentheses) and freeze/thaw conditions; solid trend lines represent conditions with no sand applied and dashed trend lines represent 50 sand applications; flow rate is expressed as a percent of the average flow rate for each experimental test independently

experimental run, the slope became more gradual until the frozen and 50 sand applications experiment, which was best represented by a curve (Fig. 3). This indicates that the greatest delay in the movement of water through the slab was during the early stage portion of the experiment when surface and near-surface clogging constrained the movement of water through the slab. This was likely related to the presence of ice within the pore spaces, since the early stages of the experiment correspond with the peak ice content (due to some ice melt during the experiment) as well as the early occurrence of the largest difference between the thawed and frozen experimental runs at 50 sand applications (Fig. 3). Nevertheless, these conditions (i.e., frozen, 50 sand applications) exhibited the longest time required to reach steady-state flow and demonstrates that the movement of water through the slab was reduced under frozen conditions and heavy sand loading. The flow rate is expressed as a percent of the average flow rate for each experimental test independently, in an attempt to normalize for differences in flow rates between tests. However, trends in the data are not consistent among all slabs. The presence of salt was expected to enhance water movement through the slab under frozen conditions, as a consequence of the reduced frozen water content within the CS slabs; however, the data do not support this hypothesis.

Salt Transport

Electrical conductivity measurements of the brine solution recovered from the bottom of the CS slabs (denoted as C) were compared to the EC of the initial brine solution (C_o) applied (Fig. 4). Under all experimental conditions, EC of the water collected from the bottom of the slab reached the EC of the initial brine solution quickly (<10 min). In the thawed and frozen slabs only, 50–200 mL of brine, respectively, was required to achieve $C/C_o = 0.5$ (median concentration). This is an order of magnitude less than the pore volume of this slab, so it is evident that the solute is bypassing most of the empty pore space and tracking in a preferred flow-path. This was delayed more in the frozen slab, and freezing may have blocked some of the preferential flow-paths. Accordingly, only a small portion of the total volume available for flow was being used. The frozen breakthrough curve [Fig. 4(a)] exhibits greater dispersion (curve more spread out), because freezing likely increased flow-path tortuosity. A similar breakthrough pattern was observed under heavy sanding conditions [Fig. 4(b)] and suggests that a higher flow rate could have been sustained under all sand loading and frozen-thawed conditions tested.

Applicability in Field Settings

The laboratory-based design of this study facilitates characterization of some of the processes that occur in a field-based application; however, this approach introduces some limitations. For example, the hydrological design of pervious concrete includes a substructure that was not included in the laboratory experimental setup. The substructure is designed with a sufficiently high percolation rate to promote drainage (Tennis et al. 2004), which indicates that the pervious concrete should remain in a drained or unsaturated state under normal operation. This would minimize differences in hydraulic conditions between the laboratory (water drains freely at the base of the pervious concrete slab) and field (pervious concrete drains into an unsaturated substructure) conditions. Thermodynamically, pervious concrete structures have a demonstrated sensitivity to variations in atmospheric temperatures, attributed to their void structure (Shao et al. 1994). Also, since pervious concrete in a field setting is relatively thin ($< \sim 30$ cm; Tennis et al. 2004), it would remain fully encompassed within a shallow soil frost zone in cold climates (Penner and Crawford 1983). Considering the strong coupling between ambient atmospheric temperatures and the temperature of pervious concrete, as well as the shallow and relatively thin pervious concrete layer design, simulation of freezing conditions in a lab setting is not an unrealistic representation of thermodynamic (and, thus, hydrologic) conditions encountered in a field setting. Chloride is a conservative ion, so any differences in hydraulic and thermodynamic conditions as a result of the laboratory setting will not affect the transport and/or retention of the chloride. Lastly, the design of the laboratory-based experiment did not account for the effect of traffic-induced grinding of sand and pavement particles, as observed in other studies (van Duin et al. 2008; Kresin et al. 1997). These structures are most typically used in areas both with minimal traffic and traffic that runs at lower speeds, such as in parking lots and driveways, which should constrain the amount of grinding in most field applications. Nonetheless, reduction of sand particle size via grinding would likely result in more severe clogging in a field setting than was observed in the laboratory. In an effort to replicate field conditions, the sand used in the experiment was not sieved nor sorted and, thus, is representative of the sand applied operationally in the field.

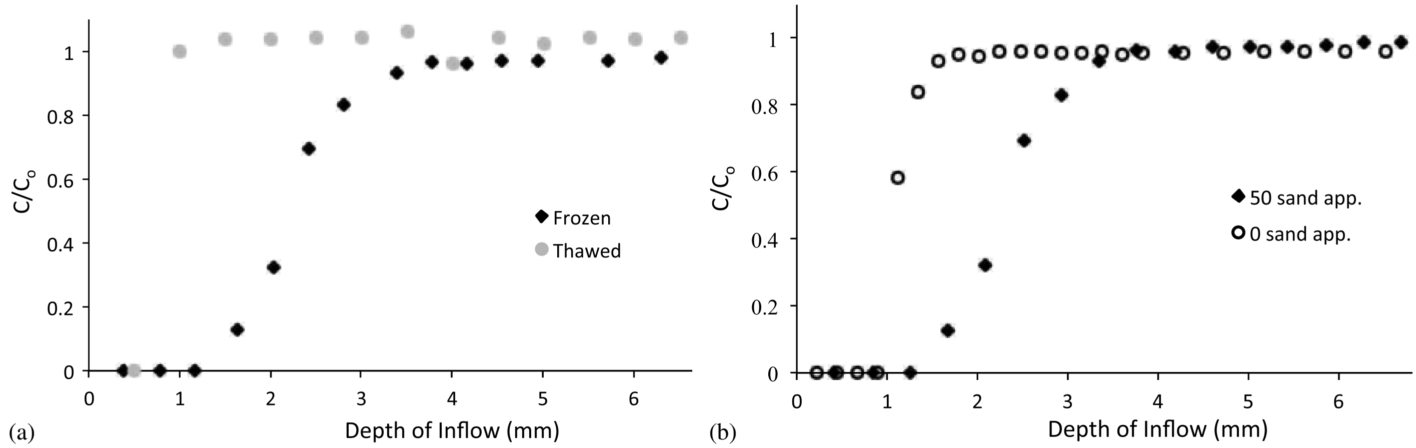

Fig. 4. Breakthrough curves for EC values: (a) breakthrough curve for frozen and thawed conditions with 50 sand applications, which demonstrates differences between frozen and thawed conditions; (b) breakthrough curve for 0 and 50 sand applications under frozen conditions, which demonstrates differences caused by sand application

Implications for Ground Water Management and Recommendations

The intention of the Ontario clean water act is to reduce significant risks to drinking water by identifying vulnerable areas (wellhead protection areas, intake protection areas, and other highly vulnerable areas) and developing source water protection plans to reduce significant risks to acceptable levels and prevent future significant risks. Chloride is listed as a potential threat to drinking water as indicated in Section 1.1 of Ontario Regulation 287/07. Implications of the Ontario Clean Water Act for road salt management include: (1) improved design and delivery of parking lot winter maintenance programs; (2) increased adoption of new technology; (3) improved delineation of salt vulnerable areas and refined winter maintenance procedures in intake protection zones (IPZs); (4) increased level of training (certification) for road authorities and private contractors; (5) integration of salt management plans with source water protection committees (SPCs) objectives to delineate source waters, identify threats, and develop and implement an SWP plan; and (6) improved stormwater management practices.

Pervious concrete technologies can be used to effectively reduce urban runoff (Tennis et al. 2004) and may delay the delivery of Cl^- to receiving surface waters relative to conventional pavements (Kwiatkowski et al. 2007). However, when these technologies are improperly located and/or poorly designed they can negatively impact groundwater quality. To meet the future requirements of the Clean Water Act, improved planning and design guidance (see below for design modification recommendations) is required for the use of this material for parking lots located in salt vulnerable areas (Stone and Marsalek 2011). In order to reduce chloride transfer from road salt applications in salt vulnerable areas, it will be necessary for source protection committees in coordination with city and municipal officials to consider the use and design of pervious pavement structures (parking lots, roads, laneways) within their respective jurisdictions and hydrogeological environments. Pervious concrete structures are generally implemented as a BMP to moderate stormwater runoff (Toronto and Region Conservation Authority 2008) and are not necessarily designed nor intended to reduce or remove contaminants (including Cl^-) from infiltrating water. However, some research has demonstrated reduced concentrations of contaminants in stormwater after percolating through pervious concrete structures (Kwiatkowski et al. 2007). In the present study, chloride was quickly transported through the pervious concrete slabs. However, in practice under field conditions some of the salt may be partially detained in structural layers below the pavement. Currently, there is limited knowledge related to chloride transport mechanisms associated with the underlying structural layers, and more research is required under field conditions in order to design and test the use of pervious pavement installation in a range of hydrogeological environments. Specifically, in salt vulnerable areas we recommend that pervious concrete be installed on porous materials underlain with impermeable barriers in order to collect and treat runoff to minimize its impact on groundwater quality.

Conclusions

Laboratory experiments were conducted on pervious concrete slabs to determine the effect of sand application and temperature (frozen and thawed conditions) on flow dynamics and salt retention/transport. In all experiments, salt was transported through the pervious concrete very quickly. Slight dispersion of salt was observed in EC breakthrough curves; however, there is a strong potential for rapid flushing of salt through the highly permeable matrix of pervious concrete structures. Dispersion increased slightly under frozen conditions and with increased sand application, due to the more tortuous flow paths. Application of sand to the surface of pervious concrete reduced the movement of water through the pores. This caused a delay in peak flow measured at the base of the slab. Since the sand is unlikely to penetrate into the pore space at depth within the concrete these impacts are limited to the near-surface portion of the concrete. The study demonstrated that sanding and freezing did not significantly impair the ability of the slabs to transmit flow. Under extreme sand applications and low temperature, the drainage efficiency of the concrete is only moderately reduced. Our observations indicate that the infiltration capacity of the pervious concrete structures, as tested, exceeds the probable maximum water loading rate that will be encountered in Southern Ontario, Canada.

The future development, improvement, and application of pervious concrete technologies as a stormwater management measure to reduce runoff will have important implications in the context of the Clean Water Act. While current pervious concrete technologies can be used in stormwater control structures to reduce runoff volume, when either improperly located or poorly designed they can negatively impact groundwater quality. Improved design guidance for pervious concrete applications for stormwater management is required.

Acknowledgments

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