Some Recent Environmental Pavement Technologies – Fact or Fiction

Art Johnston, C.E.T.,
Principal Consultant, Transportation, Tetra Tech Canada

Martina Riessner, E.I.T.,
Pavements Engineer, Transportation, Tetra Tech Canada

Cong Luo, E.I.T.,
Pavements Engineer, Transportation, Tetra Tech Canada

Paper prepared for presentation
at the Emerging Environmental Technologies Session
of the 2017 Conference of the
Transportation Association of Canada
St. John's, NL

ABSTRACT

The roadbuilding industry has been working towards environmental stewardship in many aspects of pavement construction. As an example, almost 100% of reclaimed asphalt pavement is recycled and used in pavement construction. In fact the amount of recycled asphalt pavement used exceeds that of glass, paper, aluminum and plastic combined. Warm mix asphalt represents another advancement with significant environmental advantages, such as reduced fossil fuel costs and less emissions. More recently, two pavement technologies have come to the forefront; permeable pavements and solar pavements.

Permeable pavements offer an enhanced method for managing stormwater. These pavements, generally used for parking lots or other low traffic applications, allow stormwater to drain through the pavement surface into a stone recharge bed (or reservoir) and infiltrate into the soils below the pavement. The surface of a permeable pavement can be specially designed asphalt concrete or Portland cement concrete, or permeable pavers. Advantages include purifying stormwater runoff, and replenishing water tables and aquifers rather than forcing rainfall into storm sewers.

Solar pavements are even a more recent environmental development. Solar pavements (or surfacing) is a modular system of specially engineered solar panels that can be walked and driven upon. In some cases the panels contain LED lights to create lines and signage without paint. They can contain heating elements to prevent snow and ice accumulation. The Netherlands built the first solar road, a bike path, in 2014. France announced a bolder move recently that over the next five years, it plans to install 1,000 kilometres of solar roads. Installations in North America are likely "just around the corner".

This paper will have the objective of providing a fair, but critical review of these two pavement technologies, specific to the Canadian context. There can be no denying that these innovations have a significant environmental upside; but does that upside come at a cost, a cost that may or may not make good sense?

INTRODUCTION

A fair amount of publications have discussed the feasibility of using roads to harvest solar energy through fluid-filled piping networks embedded in the pavement structure. An innovative method of harvesting solar energy using pavement structures has recently been introduced in which photovoltaic panels are applied to the surface of the road to generate electricity. This technology potentially allows us to take advantage of the vast network of existing pavement while collecting renewable energy. This paper will provide some background information regarding the development of photovoltaic paneled roads, examine the current state of the practice, and discuss the future outlook for this emerging technology.

Traditional pavements are built with dense graded mixes, which is impermeable and allow surface water to flow along the pavement surface. Then the storm runoff is captured through extensive pipe network to nearby watercourses or sewer systems. However, since the late 1800s, an increased runoff from urban areas has become a problem (Kuichling 1989) and it continues to be a leading cause of impairment in the nation's waterways with increasing urbanization (EPA 2002). Therefore, an emerging pavement technology, permeable pavements, is constructed for low volume road and parking lots as a sustainable stormwater management technique. In addition to the benefits of stormwater management, this paper will provide the findings of performance/economical benefits and the challenges/concerns, especially the winter performance, from review of recent research papers and specifications.

PERMEABLE PAVEMENTS

Background Information

Permeable pavements, which permit surface water to pass freely through the pavement structure, are an alternative technology for stormwater management by reducing or controlling the amount of runoff and reduce the potential groundwater contamination through the infiltrating system. The other benefits include both environmental and safety benefits. However, the permeable pavement systems could not perform as intended over long periods of time. Clogging of the pavement can reduce its infiltration capabilities. It is also a challenge for permeable pavement to perform in cold climates.

Nowadays, permeable pavements are available with a variety of designs. Based on the difference in the structures and materials, permeable pavements are divided into three categories: permeable asphalt pavement, permeable concrete pavement, and permeable concrete paver pavements.

Permeable Asphalt Pavement

Permeable asphalt pavement looks similar to conventional asphalt pavement, but consist of an inter-connected open-graded asphalt and concrete over an open-graded coarse aggregate base located above free-draining soil (Scholz 2006).

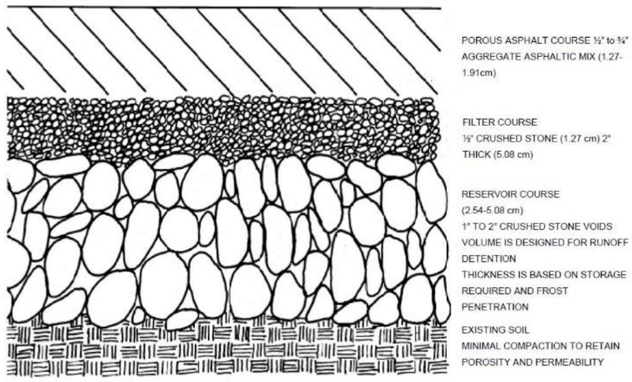


Figure 1: Typical schematic layout of permeable asphalt pavement (Diniz 1980)

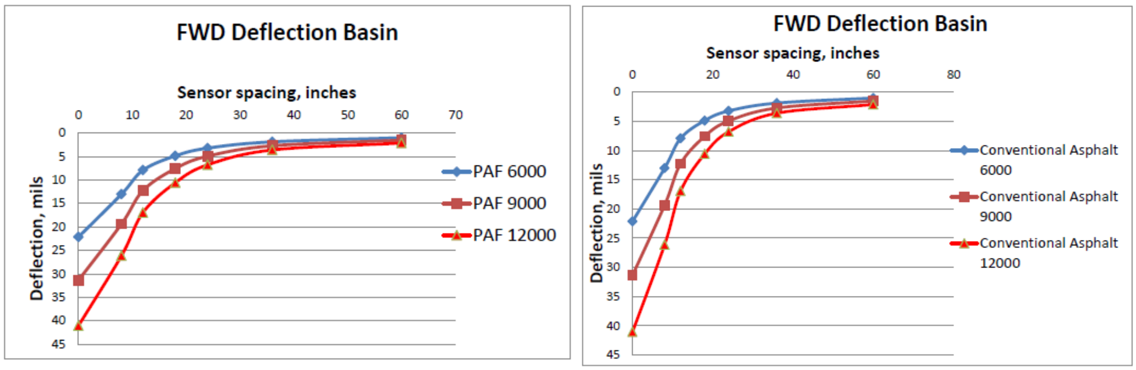
Figure 1 presents an example of a typical permeable asphalt pavement from an Environmental Protection Agency study (EPA 1999) with significantly higher percentages of air voids in the asphalt mix in order to provide permeability or infiltration capability. An average 16% to 22% (or greater) air void percentage is recommended from the recent studies (NAPA 2003, Backstrom 200, FHWA 2004 and V.Heystraeten 1990).

A well-known advantage of permeable asphalt pavement over traditional pavement is the potential to reduce the rate of runoff as the pavement is able to store and infiltrate stormwater. Research from Europe shows an average 96.7% of the stormwater can be infiltrated in the soil below the reservoir structure (Legret 1999). In a permeable asphalt road section with swales, between 30% and 40% of precipitation ran off the site (Stenmark 1995).

Since the surface liquid infiltrates through the entire pavement layer, the permeable pavement system can provide an excellent system for removal of pollutants. The studies in Maryland and Virginia show that 82% to 95% of sediment, 65% of total phosphorus, and 80% to 85% of total nitrogen are removed (EPA 1999). The recent field research in Florida also shows the permeable asphalt pavement would have a total nitrogen mass reduction of 19% and a total phosphorus mass reduction of 20% (Chopra 2011A). The recent field research in Florida also shows the permeable asphalt pavement would have a total nitrogen mass reduction of 22% and a total phosphorus mass reduction of 22% (Chopra 2011B). Metal load reductions (Cu, Fe, Pb, Mn, Zn) were all greater than 75% (Rushton 2001).

The open-graded friction course is able to dampen road noise and tire spray, and remove water from the road surface, which reduces the risk of hydroplaning, especially during wet night conditions (Fitts 2002). It is also potential for improved skid resistance when there is heavy precipitation and excess runoff conditions (EPA 1999). Permeable asphalt pavement is also recycled material friendly. A study shows that recycled materials have geotechnical and hydraulic properties equivalent or superior to that of typical granular materials (Rahman 2015).

Based on the study from University of Waterloo, the porous asphalts exhibited lower dynamic modulus values as compared to the traditional mixes (Schaus 2007). However, FWD testing was done by FDOT to identify the permeable pavement strengthen. It is interesting that the deflection of the conventional asphalt pavement is greater than that of permeable asphalt pavement. When load is dropped on permeable asphalt surface, the response in each sensor is not that of the pavement system but instead it is the rebound displacement when rubber loading plate rebounds from the flexible pavement surface (Chopra 2011A).



FWD Deflection basins for porous asphalt

FWD deflection basins for conventional asphalt

Figure 2: FWD testing results permeable vs. conventional asphalt pavement (Chopra **2011A)**

In most regions of North America, porous aggregate used alone without binding or reinforcement is the least expensive of all paving materials, including conventional dense asphalt. Even though in the places where the porous materials are expensive, the construction cost could still be reduced because of no additional cost of pipes and reservoirs (Ferguson 2005).

Permeable Concrete Pavement

Permeable concrete pavement structure is similar to permeable asphalt pavement with little to no fine aggregates and the slurry is tamped or rolled in placed, rather than the tradition floating (Tennis 2004).

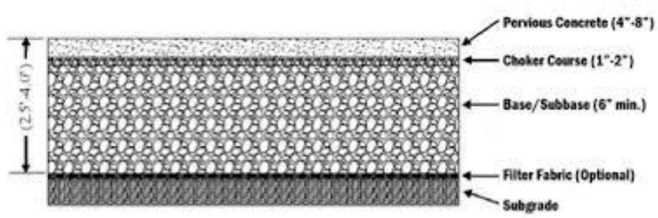


Figure 3: Typical schematic layout of permeable concrete pavement (figure from US EPA)

A permeable concrete pavement shows dramatic reduction in surface runoff volumes. Figure 4 details peak flow rates from several storm events in the study in North Carolina (Collins 2006).

DATE	RAINFALL (in.)	Asphalt (l/s)	Flow Rate (l/s)	% Reduced
			----------PC--------	
5-Jun	0.29	0.245	0.019	92.2
21-Jun	0.24	0.343	0.016	95.3
25-Jun	1.08	0.998	0.314	68.4
3-Jul	0.37	0.656	0.068	89.6
4-Jul	0.92	1.140	0.637	44.2
6-Jul	0.56	0.735	0.074	89.9
15-Jul	0.52	1.725	0.366	78.8
23-Jul	0.58	1.784	0.357	80.0
25-Jul	0.22	0.151	0.002	98.7
27-Jul	0.22	0.136	0.009	93.4
5-Aug	0.52	0.575	0.121	78.9
11-Aug	0.42	0.328	0.114	65.2
21-Aug	0.68	1.043	0.428	59.0
22-Aug	0.49	1.036	0.182	82.4
			AVG	**79.7**

PC – porous concrete exfiltrate

Figure 4: Peak flow rates for asphalt runoff and permeable pavement exfiltration (Collins 2006)

FWD testing was done by FDOT to identify the permeable pavement strength. The deflection of the conventional concrete pavement is much less than that of permeable asphalt pavement (Chopra 2011B) which indicates permeable concrete pavement could be appropriate for high volume or heavy load road.

Pavement Type	Back-calculated Elastic Moduli (psi)	
	Test	Literature
Pervious Concrete	740 – 1350	725 - 2900
Conventional Concrete	3000 - 7700	2000 - 6000

Figure 5: Comparison of back-calculated in-situ elastic moduli (Chopra **2011B)**

Permeable Concrete Paver Pavement

Permeable pavers consist of infiltration trenches with a paving material over top to support vehicle and pedestrian loads (Burak 2004). Figure 6 illustrates a typical permeable paver structure.

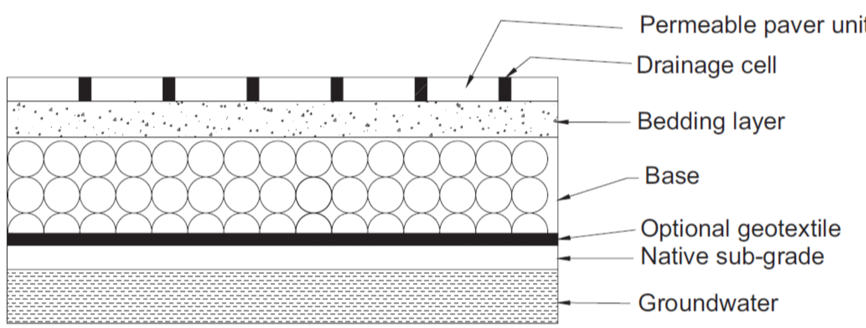


Figure 6: Typical schematic layout of permeable concrete paver pavement (figure from Scholz 2006)

Permeable concrete paver pavements have the same benefits as the other permeable pavements, such as reduce the runoff and remove the pollutants, hydrocarbons contamination and metals from the surface runoff (Scholz 2006).

Current Challenges

A frequent concern with permeable pavements is the clogging of the surface over time. The functionality of permeable pavements is related to the degree to which the pavement is clogged with silt and/or other fine debris. Excessive clogging of the pavement can inhibit its infiltration capabilities and therefore the system will not provide the desired service (Brown 2003).

Another concern is the ability of the system to perform in the winter. Water is frozen in cold areas in winter, which could prevent drainage through the pavement (NRMCA 2004). The infiltration capacity of at freezing point was approximately 40% of the infiltration capacity at 20 °C; the infiltration capacity could be reduced by approximately 90% after melting and freezing cycles for 2 days (Backstrom 2000). During the cold weather like in Canada, salt and sand applied to the surface may gather in the air voids in the pavement (Henderson 2011). The surface can be plowed during winter, but care should be taken to avoid plowed material clogging the pores in the system (Dietz 2007).

Field research on bacteria and virus removal in bio-retention or pervious paving systems is lacking (Pitt 1999). Chlorides may be present in stormwater and it is also very mobile in soil, and can easily travel to shallow groundwater (Kaushal 2005), threatening aquatic life. Preferential infiltration of potentially contaminated runoff at discrete points may eventually exceed the contaminant retardation capacity of the underlying sediment. Hence, a possible contaminant breakthrough along the infiltration points may cause groundwater contamination problems (Boving 2007).

The initial installation cost is much higher than the conventional asphalt pavement. Plus, based on the annual maintenance cost of 1% of the installation cost and relatively shorter service life, the porous asphalt pavement could be much more expensive in the life-cycle cost analysis (Montalto 2007).

Renewal Maintenance Methods

The permeable pavement systems will not perform as intended over long periods of time. The vacuum suction strength is sufficient in improving capability to infiltrate for permeable concrete pavement but it doesn't work well for permeable asphalt pavement (Chopra 2011A&B).

The study from University of Waterloo conducted several concrete maintenance methods at field sites in Ontario. The results show that power washing can push debris deeper into voids and decrease permeability rather than improve it. Sweeping of the surface can be effective in removing debris only off the surface and not from deep voids, therefore not necessarily significantly improving permeability. Washing the surface with a large diameter hose can dislodge debris deep in voids and renew permeability, in some cases, to near initial permeability values (Henderson 2011).

SOLAR ROADS

Background Information

Three solar roadway projects have received significant public attention in the past several years. This represents a very recent environmental pavement development. The ability to harvest solar power from pavements appears very attractive. The following sections provide further information regarding several versions of this technology and other related information.

SolaRoad

SolaRoad, the world's first solar bike path, was built using a prefabricated panel technology developed by a consortium of Netherlands Organisation for Applied Scientific Research (TNO), Imtech (Dynniq) and Ooms Civiel. This pilot project was constructed in Krommenie, Netherlands.

Figure 7: SolaRoad, the world's first solar bike path, in Normandy

Solar Roadways®

Solar Roadways® was started by a couple in Idaho who gained public attention after a very successful crowdfunding campaign on Indiegogo in which they raised $2.25 million USD. Solar Roadways technology consists of hexagonal panels containing microprocessors that can be programmed and can interact with one another and their environment.

Figure 8: Solar Roadways® has developed interlocking hexagonal panels

Wattway

Colas partnered with the French National Solar Energy Institute (INES) to develop Wattway, a solar road technology based on crystalline silicon. Wattway's panels are only a few millimeters thick and can be applied to existing pavement. The world's first solar paneled road was constructed in Normandy, France.

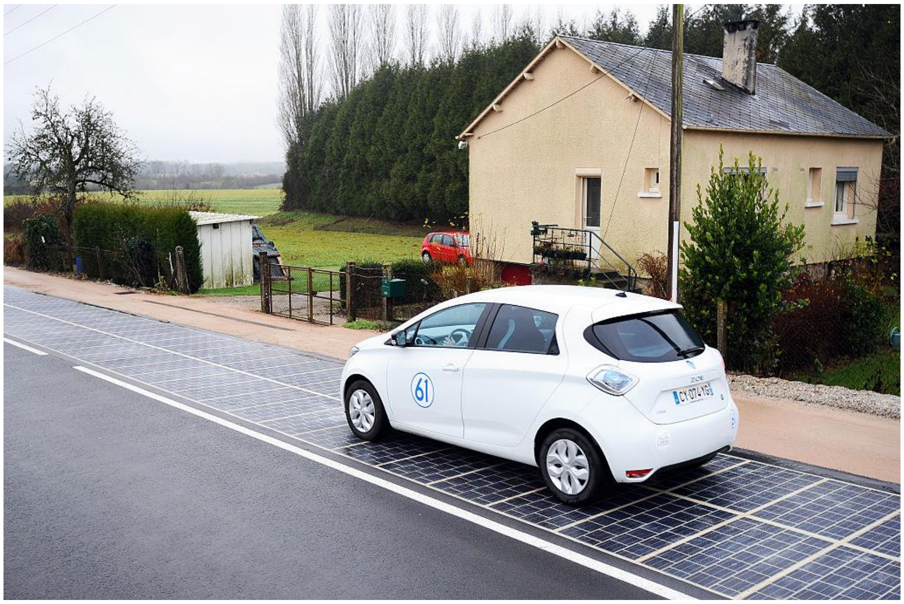


Figure 9: Wattway is the world's first solar paneled road

Solar Paneled Roads: Timeline

Although surfacing roads with solar panels is a very recent innovation, the technology has gained a lot of momentum in recent years. The timeline below summarizes the key milestones for the projects discussed above.

Figure 10: Timeline showing milestones in solar paneled road technology

Applications

Advocates of solar paneled roads are optimistic that this technology can revolutionize the way we view transportation infrastructure. The hope is that solar energy can be collected from the vast network of road and walkways to power street lights, charge electric vehicles, and heat the roads in order to prevent snow and ice accumulation.

Solar Roadways introduces an even higher level of sophistication because the panels are programmable and can interact with each other and their surroundings. For example, they have been designed to increase road safety by flashing warnings when there are pedestrians or animals on the roadway as illustrated in Figure 1 below. The LED lights can be programmed to change lane or parking lot configurations, eliminating the need for paint lines. The possibilities introduced by solar paneled roadways is encouraging us to consider how roads can be used as more than just a surface to drive on.

Figure 11: This conceptual image illustrates how Solar Roadways technology is designed to warn drivers of wildlife on the highway

Technological Challenges

A significant challenge in the development of solar paneled roads is that they need to be strong enough to withstand traffic loading. There is no doubt that this technology is still in the early testing stages. SolaRoad encountered problems with a section of the coating delaminating on the bike path as a result of temperature fluctuations. The Solar Roadways® test strip in Idaho encountered malfunctions with the electrical system, manufacturing problems, and drainage problems.

As with any new technology, research and development can be a very iterative process. It will take years to evaluate how prototype roadways perform under repeated loading, and how the solar panels will be affected as the surface below settles and cracks with age. Although tire grip has been considered in the design of these solar road technologies, it is also important to continue analyzing the prototypes to ensure that the road surface doesn't become slippery after repeated traffic loading.

Economic Feasibility

Making solar paneled roads economically feasible is one of the biggest challenges facing this new technology.

Solar paneled roads are extremely expensive to build. The prototypes constructed for SolaRoad, Solar Roads® and Wattway were all multi-million dollar projects. For comparison, the current cost of conventional electricity and solar electricity in the United States is approximately $0.12/ kWh.

SolaRoad spent €3.5 million for a 70 meter long bike path which generates approximately 70 kWh per sq.m. per year. Although the power output exceeded expectations, it is still only enough to power three households annually. Electricity in the Netherlands costs approximately €0.2/kWh, so this is equivalent to less than €1500 of conventional electricity annually.

Solar Roadways® constructed a 12 sq.m. test pavement in Idaho for $4.3 million USD. The prototype currently generates an average of 0.62 kWh / day, which is an annual equivalent of about $23 through conventional electricity (which costs about $0.10/kWh in Idaho).

A 50 sq.m. section of Wattway solar panels at the Georgia Visitor Information center is expected to have an annual output of 7,000 kWh. At an electricity cost of $0.12/kWh, this is equivalent to about $840 USD worth of power.

Although solar power is becoming more and more affordable, solar paneled roads will have to be able to compete with conventional solar panels on roofs and in green-fields before the industry shifts towards this technology. The price tag associated with solar paneled road technology is expected to decrease as the manufacturing and installation process becomes more streamlined and economies of scale come into play. However, the abuse that these solar panels will take from traffic loading require them to be constructed much more robustly than traditional solar panels, and likely have a shorter design life and more repairs. Therefore, the high capital cost and maintenance costs will likely continue to be higher than that of conventional solar panels.

Dirt and roadway traffic will also reduce the time that the road surface is exposed to sunlight. Furthermore, panels on roads produce energy less efficiently than conventional panels because they cannot be angled in order to take full advantage of the sun.

Solar paneled roads may prove useful in specific instances in order to meet aesthetic or space constraints. However, because of the higher cost and lower efficiency, solar paneled roads will have a hard time competing with the more conventional practices of installing solar panels on roofs or in fields.

DISCUSSION AND FUTURE OUTLOOK

Permeable Pavements

It is clear that the benefits of permeable pavements can be significant including:

- Eliminating surface runoff and groundwater recharging;
- Reducing runoff water suspended solids and pollutants; and
- Reducing the need for catch basins, underground piping and/or retention areas.

Some of these benefits have not only environmental but financial as well.

Permeable pavements do have limitations. The strength characteristics of these pavement materials are likely not appropriate for higher loading applications. Permeable pavements are typically more costly that traditional pavements (typically 2 to 3 times that of conventional pavement) and likely have a somewhat reduced service life. The reduced service life can, in some circumstances be addressed with good maintenance practices but the specialized equipment to undertake “vacuuming” or “flushing” is not currently common.

Production, placement and compaction of permeable asphalt or concrete has proven to be a challenge. These materials are very "design and workmanship sensitive" which often can significantly reduce the porosity of the surfacing, resulting in a reduction in serviceability. Porous pavers can be used to avoid these challenges but at a cost premium.

As with many pavement related technologies the Canadian climate poses significant challenges. The potential for clogging of the surfacing layer is significant and designers must use materials and construction strategies that address this. The higher void content of both asphalt and concrete permeable pavements may make them susceptible to mechanical degradation (e.g., raveling) due to multiple freeze thaw cycles. The clogging may also be exasperated by winter sanding in many regions of Canada. If used, road salt contains chlorides that could migrate through the porous pavement into groundwater. Infiltrating runoff may freeze below the pavement, causing frost heave, though design modifications can reduce this risk. Again, porous pavers may prove to be the most reliable surfacing type for cold climate regions. That said, snow plow blades could catch block edges and damage surfaces.

Solar Roads

Although some people have expressed skepticism regarding the feasibility of solar paneled roadways, the developers behind this technology have big plans for the coming year. Wattway will continue in its development phase through the implementation of over 100 trials worldwide by the end of 2017, including a test strip in Calgary, Alberta. One of the potential applications of this technology will be evaluated in Roche-sur-Yon, France, where 50 sq.m. of Wattway panels in a parking lot will be used to charge electric vehicles. Wattway technology is worth keeping an eye on over the next few years as they work towards an objective of being price competitive with traditional solar farms by 2020.

Figure 12: Wattway technology will be tested worldwide in the coming year

Solar Roadways® is planning to install 50 more hexagonal panels at a rest stop in Conway, Missouri. If this pilot project is successful, it may be applied to parts of Route 66 in collaboration with the Missouri Department of Transportation.

The popularity of the crowdfunding campaign for Solar Roadways® indicates that recent innovations in alternative energy are capturing the public interest. It will be a challenge for solar roads to compete with traditional solar panels on roofs or in fields. They are less efficient and more costly, since they need to be able to withstand traffic loading. Solar paneled roads may be useful in specific instances where there are space or aesthetic constraints preventing installation on the roof. The research and development currently being conducted on solar roadways may pave the way for future innovations that are both sustainable and cost-effective.

CLOSURE

The objective of this paper was to provide a synopsis of the state-of-the-practice with respect to these two relatively recent environment friendly pavement technologies. The appropriateness of these technologies for Canadian applications has been examined with a "real world" perspective. The opinions provided are those of the authors only.

REFERENCES

1. Bäckström, M. and Bergström, A., 2000. Draining function of porous asphalt during snowmelt and temporary freezing. Canadian Journal of Civil Engineering, 27(3), pp.594-598.
2. Bean, E.Z., Hunt, W.F. and Bidelspach, D.A., 2007. Field survey of permeable pavement surface infiltration rates. Journal of Irrigation and Drainage Engineering, 133(3), pp.249-255.
3. Boving, T.B., Stolt, M.H., Augenstern, J. and Brosnan, B., 2008. Potential for localized groundwater contamination in a porous pavement parking lot setting in Rhode Island. Environmental Geology, 55(3), pp.571-582.
4. Brown, D., 2003. Thinking green with porous asphalt. Hot Mix Asphalt Technology Issue: MAY/JUNE, http://www. asphaltalliance. com.
5. Chopra, M., Stuart, E., Hardin, M., Uju, I. and Wanielista, M., 2011A. Pervious Pavements-Installation, Operations and Strength Part 1: Pervious Concrete Systems.
6. Chopra, M., Wanielista, M., Stuart, E., Hardin, M. and Uju, I., 2011B. Pervious Pavements-Installation, Operations and Strength Part 2: Porous Asphalt Systems.
7. Collins, K.A., Hunt, W.F. and Hathaway, J.M., 2009. Evaluation of various types of permeable pavement with respect to water quality improvement and flood control. In Low Impact Development: New and Continuing Applications (pp. 275-289).
8. Dietz, M.E., 2007. Low impact development practices: A review of current research and recommendations for future directions. Water, air, and soil pollution, 186(1-4), pp.351-363.
9. Dunn, C., Brown, S., Young, G., Stein, S. and Mistichelli, M.P., 1995. Current water quality best management practices design guidance. Transportation research record, 1483, pp.80-88.
10. Diniz, E.V., 1980. Porous pavement. Phase 1: Design and operational criteria. NASA STI/Recon Technical Report N, 81.
11. EPA, S., 1999. Stormwater Technology Fact Sheet: Porous Pavement.
12. EPA, A., 2002. National Water Quality Inventory 2000 Report. EPA-841-R-02-001.
13. Fitts, G., 2002. The new and improved open graded friction course mixes. Asphalt, 17(2).
14. Ferguson, B.K., 2005. Porous pavements. CRC Press.
15. Henderson, V. and Tighe, S.L., 2011. Evaluation of pervious concrete pavement permeability renewal maintenance methods at field sites in Canada. Canadian Journal of Civil Engineering, 38(12), pp.1404-1413.
16. Kuichling, E., 1889. The relation between the rainfall and the discharge of sewers in populous districts. Transactions of the American Society of Civil Engineers, 20(1), pp.1-56.
17. Legret, M. and Colandini, V., 1999. Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals. Water Science and Technology, 39(2), pp.111-117.
18. Montalto, F., Behr, C., Alfredo, K., Wolf, M., Arye, M. and Walsh, M., 2007. Rapid assessment of the cost-effectiveness of low impact development for CSO control. Landscape and urban planning, 82(3), pp.117-131.

19. National Asphalt Pavement Association ed., 2003. Porous asphalt pavements. National Asphalt Pavement Association.

20. National Ready Mixed Concrete Association, 2004. Freeze Thaw Resistance of Pervious Concrete. Silver Spring, MD. http://www. rmcfoundation. org/images/PCRC% 20Files/Durability% 20&% 20Maintenance/Freeze-Thaw% 20Resistance% 20of% 20Pervious% 20Concrete. pdf. Accessed January, 25, p.2013.

21. Pitt, R., Clark, S. and Parmer, K., 1994. Protection of Groundwater from Intentional and nonintentional stormwater infiltration. US Environ. Prot. Agency. EPA/600/SR-94/051. PB94-165354AS, Storm and Combined Sewer Program, Cincinnati, OH, p 187.

22. Rahman, M.A., Imteaz, M.A., Arulrajah, A., Piratheepan, J. and Disfani, M.M., 2015. Recycled construction and demolition materials in permeable pavement systems: geotechnical and hydraulic characteristics. Journal of Cleaner Production, 90, pp.183-194.

23. Schaus, L.K., 2007. Porous asphalt pavement designs: Proactive design for cold climate use.

24. Scholz, M. and Grabowiecki, P., 2007. Review of permeable pavement systems. Building and Environment, 42(11), pp.3830-3836.

25. Solar Roadways. *Transportation Asset Management Case Studies Life-Cycle Cost Analysis: The Pennsylvania Experience* [online]. Updated: 10/23/2013. [Viewed 28 April 2017.] http://www.solarroadways.com/

26. Stenmark, C., 1995. An alternative road construction for stormwater management in cold climates. Water Science and Technology, 32(1), pp.79-84.

27. Tennis, P.D., Leming, M.L. and Akers, D.J., 2004. Pervious concrete pavements (No. PCA Serial No. 2828). Skokie, IL: Portland Cement Association.

28. Van Heystraeten, G. and Moraux, C., 1990. TEN YEARS'EXPERIENCE OF POROUS ASPHALT IN BELGIUM. Transportation Research Record, (1265).

29. Wattway by Colas. *Transportation Asset Management Case Studies Life-Cycle Cost Analysis: The Pennsylvania Experience* [online]. Updated: 10/23/2013. [Viewed 28 April 2017.] http://www.wattwaybycolas.com/en/