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Pervious Concrete as a Sustainable Solution for Pavements in Urban Areas

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Abstract. In the last few years, the use of pervious concrete as a pavement material in low-volume road applications (parking lots, residential roads, pedestrian zone or sidewalks) has gained importance due to its positive environmental aspects. Pervious concrete is one of the most promising sustainable material nowadays. It is a mixture of cement, coarse aggregate, water and admixture, while contains no or little amount of fine aggregates. Comparing a conventional concrete pavement, the pervious concrete system is designed to have enhanced amount of interconnected voids allowing water to percolate through the material. Population growth, continuing urbanization and the growth of impervious urban areas lead to specific environmental and societal impacts, especially urban heat island effect, risk of flash flood, worsening quality of water in river courses and so on. Pervious concrete has remarkable potential to counteract these adverse impacts while providing necessary structural integrity, thus supporting continued urbanization. Pervious concrete is currently under serious research and development in many countries because of enhanced interest of its properties. The paper is intended to bring comprehensive information on characterization, environmental benefits, performance issues and utilization possibilities of pervious concrete.

Keywords: characterization of pervious concrete, advantages and disadvantages of pervious concrete, performance issues of pervious concrete.

Conference topic: Environmental protection.

Introduction

The natural processes of the water cycle have been fundamentally altered by human development and construction practices. In the natural state, stormwater falls to the earth and gets absorbed into the soil and vegetation where it is filtered, stored, evaporated, and redispersed into the ever flowing cycle. The current state of this cycle has reduced this process due to the vast impervious pavements which have sealed the earth's natural filter (Cahill 2003).

In the past, the principal concern about runoff from pavements has been drainage and safety, focusing primarily on draining the water off the pavement surface as quickly and efficiently as possible (Chester, James 1996). Historically, many have considered that once the stormwater was off the pavement surface and into the drainage structure the problem was solved and the "out of sight, out of mind" mentality was implored. Unfortunately, this water once drained from the pavements surface has to end up somewhere downstream and typically causes negative impacts to ecosystems resulting in habitat loss. Traditional impervious pavement is designed with sufficient cross slope and longitudinal slopes to increase the velocity of the runoff water conveying it away from the pavement before ponding can occur. The result of this increased velocity is the capacity of the stormwater to cause erosion, channel widening, sedimentation, flooding, and spreading of pollutants downstream. Furthermore, impervious pavements are designed with costly measures taken to prevent water from accumulating directly under the pavements and subsequently damaging the structure. Although many pavement designers hope that wearing courses can be kept virtually watertight with good surface seals and high-tech joint fillers, the inevitable stresses and pressures of traffic, temperature fluctuations, oxidation and weathering, and freeze thaw cycles are constantly working to open cracks that allow water to enter. Once the water is in the pavement system it becomes trapped and unable to be expelled quickly developing pore water pressures that result in piping and pumping effects that erode away sub-soils causing serious problems to the structure. The only sure way to keep water from accumulating in the structural section of the pavement is to drain it using a key feature, a layer of very high permeable (0.23 mm/s to 2.3 mm/s or even greater) material under the full width of traffic lanes which is suitable for good internal drainage of the systems to prevent this deterioration (Cedergren 1994).

Permeable pavements provide an alternative to the traditional impervious pavements and due to their porous nature; these ecological consequences can be minimized or even prevented. The advantages include reducing the volume of surface runoff, reduced need for stormwater infrastructure, less land acquisition for stormwater ponds, improved road safety by reduced surface ponding and glare, and a reduced urban heat island effect. Pervious pavements allow stormwater to flow into the soil as opposed to flowing over impervious surfaces picking up accumulated co taminants and carrying them offsite. Once an impervious pavement is replaced with a pervious pavement, stormwater is allowed to reach the soil surface where natural processes are able to break down the pollutants (Cahill 2003). Infiltrated water from pervious pavement had significantly lower levels of zinc, copper, motor oil, lead, and diesel fuel when compared to runoff from an impervious asphaltic pavement (Brattebo, Booth 2003).

Pervious concrete is a unique concrete pavement type mainly composed of rationally graded coarse aggregate and cementing materials which provide the mix with an interconnected macro-pore internal structure (Fig. 1). The limited quantity or absence of fines in pervious concrete creates highly curvaceous pores that help store stormwater within them, and reduce runoff quantity in a scientific manner. Further, the porous nature is found to reduce the urban heat island effect, and helps maintain conducive surrounding ambience (Neithalath *et al.* 2010).

Pervious concrete pavement systems act as a filter, which can retain the pollutants in the first flush of rainfall, and prevents it from entering the streams, ponds, and rivers. Up to 75% of the total urban contaminant loads can be reduced by using pervious concrete pavement. This provides a valuable stormwater management tool (Othman, Hardiman 2005). A recent study (US EPA 1999) indicates the removal efficiency of pollutants by pervious concrete pavement, the results are shown in Table 1.

Fig. 1. Cross section of pervious concrete cylinder

Table 1. Effectivness of pervious concrete pavement pollutant removal, % by mass (source: US EPA 1999)

Study locations	Total suspended solids	Total phosphorus	Total nitrogen	Chemical oxygen demand	Metals
Prince William, VA	82	65	80	–	–
Rockville, MD	95	65	85	82	98–99

Characterization of pervious concrete

Portland cement pervious concrete is a highly permeable concrete that is typically used for permeable pavements to rapidly drain and remove rainwater from the pavement surface (Fig. 2) (Kevern, Schaefer 2006). Permeability typically ranges from 0.20–0.54 cm/s and is achieved through a large interconnected void structure with a significant void content of typically 11–35%. Pervious concrete consists of cement, water, and a single-sized coarse aggregate that is used to maximize the void content. However, often a small portion of the coarse aggregate volume is replaced by fine aggregate (sand) because it improves the strength and durability significantly (Kevern *et al.* 2008). The maximum void content is achieved by designing pervious concrete to have just enough cement paste to coat the aggregates and bind them together in the contact points between the aggregates. Hence, pervious concrete may have less cement paste than conventional Portland cement concrete. The waterto-cement ratio (w/c-ratio) of pervious concrete is typically 0.27–0.34, which produces a stiff material and in many cases makes the slump test ill-suited for pervious concrete workability measurements (Tennis *et al.* 2004). The void content of pervious concrete is a function of the compaction energy, aggregate gradation, and cementitious paste content. Because of the high amount of voids, the strength of pervious concrete is usually lower than that of conventional Portland cement concrete. Strength and unit weight decrease linearly with increasing void content (Kevern, Schaefer 2006). However, addition of chemical admixtures such as air entraining admixture, high range water reducer and hydration stabilizers affect the strength properties positively, and 28-day compressive strengths of up to 28 MPa can be achieved (Kevern *et al.* 2008).

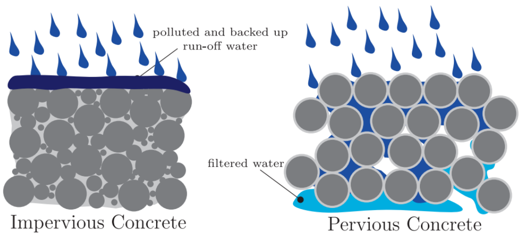

Fig. 2. Comparison of pervious concrete and impervious concrete (source: Zhong, Wille 2015)

The mix design criteria and procedure for pervious concrete are under development. In the consideration of pervious concrete function (permeable) and application (carrying traffic loads and exposed to a mild or cold weather condition), permeability, strength, and freeze thaw durability of pervious concrete should be considered simultaneously in the concrete mix design. Table 2 summarizes the related pervious concrete properties from literature.

Table 2. Selected properties of perious concrete from literature

Void content [%]	Unit weight [kg/m^3]	Permeability [cm/s]	28 day compressive strength [MPa]	Flexural strength [MPa]	Reference
15 to 25	1600–2000	0.2–0.5	5.5–20.7	1–3.8	Tennis *et al.* 2004
15 to 35	n/a	n/a	n/a	2.5–3.9	Olek *et al.* 2003
20 to 30	1890–2080	n/a	17.6–32.1	3.9–5.7	Beeldens *et al.* 2003
n/a	n/a	n/a	19	n/a	Tamai and Yoshida 2003
11 to 15	n/a	0.025–0.178	n/a	4.2–7.5	Kajio *et al.* 1998
18 to 31	n/a	n/a	11–25	n/a	Park, Tia 2004

Advantages of pervious concrete

There is no significant increase in initial cost for pervious concrete (Tennis *et al.* 2004). For pervious concrete acting as pavement and detention area or drainage facility as a part of stormwater management, this pavement technology creates more efficient land use by eliminating the need for retention ponds, other stormwater management devices or sewer system. Pervious pavement was properly counted as both a pavement structure and a part of the drainage system. By doing so, pervious concrete can save the overall project costs on a first-cost basis. Moreover, pervious concrete pavement can save up to 12% of energy consumption by reducing the heat island effect, especially in large cities that are paved with large area of impervious pavement. The life-cycle cost of pervious concrete is also much lower than normal pavement, because it can be recycled at the end of life cycle. This has been widely recognized as the lowest life-cycle cost option available for paving (Ferguson 2005). The unique surface texture of pervious concrete compared to conventional concrete pavement provides the enhanced friction for vehicles tires and skid resistance, prevent the driving hazards especially in severe weather such as snow or rainfall. The open surface of pervious concrete allows rapid infiltration and prevents water puddling, which can eliminate the spraying and skidding under freezing temperature. Experiences show that pervious concrete pavement allows rapid thawing due to the high open voids on the surface (Bean *et al.* 2007). Compared to conventional pavements, pervious concrete pavements have many other advantages as listed below (Bean *et al.* 2007; US EPA 1999; Ferguson 2005):

- The ability to drain surface water runoff faster and decrease the cost of drainage facilities, detention basins, and water supplies;
- Increase groundwater storage in urban areas and protect pristine water resources;
- Reduce the pollutants of storm water in urban areas and purify the ground water;
- Decrease effect of heat-island, decrease the surface temperature, keep the free exchange of moisture and air in underground soil and benefit for the plants to grow;
- Increase skid resistance and surface friction, which would provide the safe driving;
- Decrease tire noise, and achieve a lower noise level than normal concrete and dense asphalt pavement;
- Regarded as green and recyclable building materials.

Disadvantages of pervious concrete

Great advantages related with environmental, economic and structural issues have been the driving force of the increasing application of pervious concrete all over the world. However, there are also disadvantages and problems that have not been completely solved, and those problems impede the use and application of pervious concrete. However, its wide spread application has been limited by inconsistent information and absence of uniform standards that address the freeze-thaw durability, clogging, strength and the appropriate use and design. The disadvantages for pervious concrete as listed below are mentioned in the literature, and more research is necessary to solve these problems (Balades *et al.* 1995; Bean *et al.* 2007; US EPA 1999):

- Pervious concrete does not handle the heavy traffic loadings and vehicles due to its low compressive and flexural strength;

- The cost of maintenance and cleaning is high. The clogging effects on pervious concrete pavement decrease the initial drainage ability significantly in the short period. The drainage function may lose thoroughly if without the effective and timely cleaning;
- The resistance to freeze-thaw cycles and deicing chemicals attack are more sensitive than normal concrete;
- There are installation problems. Proper sub-grade preparation is important. With the different sub-grade materials, the compaction levels also change. A subgrade with uniform and stable surface, proper moisture content and the sufficient permeability is the key to drain the water infiltrate through the pervious concrete pavement. Over compaction may also cause the swelling of the subgrade;
- Effects on the neighboring environment and developed area. The mobile sediments from the surroundings area or construction sites must be prevented from blocking the open pores. The necessary oversight must be taken into the account in design. Particularly, the runoff from developed area is likely to contain lower levels of sediments loading to cause the clogging effects;
- Initial protection is important for lasting service life of pervious concrete pavement. For example, the pervious concrete should be finished after the adjacent area is finished and no construction traffic should be allowed onto the pervious pavement. This is normally discussed during the pre-construction meeting.

Pervious concrete sites have had a relatively high failure rate in the past, which has been attributed to poor design, inadequate construction techniques, low permeability soil, heavy construction traffic and poor maintenance. Great progresses have been made in the past few years in increasing the mechanical properties, free-thaw durability, concrete properties, and construction techniques developments (Joung, Grasley 2008).

Performance issues of pervious concrete

Environmentally friendly potential combined with enhanced traffic safety promotes pervious concrete as construction material for parking lots and road surfaces. However, broader application of pervious concrete could be achieved through mitigating the following three risks (Zhong, Wille 2015):

- Risk of clogging by organic and inorganic material and reduction the hydraulic conductivity;
- Limited bond strength between the aggregates increases the risk of surface ravelling, excessive cracking and wearing, leading to accelerated deterioration especially under high volume and heavy load traffic;
- High proportion of material surface area exposed to environmental aggressors increases the risk of loss of structural integrity due to reduced durability.

Challenges of pervious concrete

While pervious concrete has seen tremendous growth in use recently, primarily in the southern United States, challenges remain. A number of failures have occurred in use of pervious concrete (Fig. 3), thus presenting challenges to its use. Among the key challenges are strength and durability issues, maintenance – most importantly clogging, constructability issues, restrictions on heavy vehicles, and cost. Premature failures that affected the industry can often be linked to a substandard mix design – the mixes were deficient in the amount of cementitious materials in the mix. Additionally, the use of pervious concrete in northern climates was hindered by the lack of a viable freeze-thaw resistant mix design. Hence, overcoming these challenges necessitates rational approaches to development of design, construction, and maintenance strategies (Schaefer *et al.* 2016).

Failure mechanisms of pervious concrete

When subjected to loading, pervious concrete made of single-sized aggregate transfers stress through the aggregate to the cement paste. Generally, the strength of coarse aggregate is high when compared with that of the paste and the interface between the aggregate and the paste. To improve the strength of pervious concrete, the strength of the paste, and the interface between the aggregate and the paste needs to be improved. These improvements can be achieved by using lower water-to-binder ratios w/b, smaller-sized aggregates, and proper admixtures, as well as by altering the mixing process (Wang *et al.* 2006).

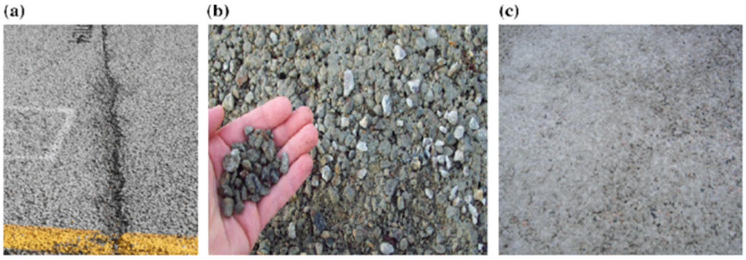

Fig. 3. Different distresses in pervious concrete pavemenent: (a) joint deterioration; (b) raveling; (c) surface sealing

Clogging of pervious concrete

The influx of storm water containing suspended solid matter such as dirt, fine sand, and debris can lead to a gradual reduction in the drainage capacity or permeability of pervious concretes used as a surface course in pavements orpark-ing lots (Fig. 4). Dirt and debris can also find their way into pervious surfaces when vehicles enter pervious concrete pavements from impervious surfaces. This reduction in permeability leads to an increase in the susceptibility of inland flooding and freeze-thaw damage along with the reduction in service life of pervious concrete pavement systems (Tan *et al.* 2003). Clogging can result from fine particles accumulating in void spaces of permeable pavements. Smaller particles trap larger particles; therefore, the rate of clogging increases as more fines are trapped. However, clogging can be limited by regular maintenance, either by a vacuum sweeper or pressure washing (Pratt *et al.* 1995).

Fig. 4. Clogging caused by surrounding unplanted area, common clogging failure caused by surface runoff (Tong 2011)

Freeze thaw durability

The void structure of pervious concrete is more complex than that of conventional Portland cement concrete because it is combined by larger water carrying voids and smaller natural and entrained air bubbles in the cement paste. The freeze-thaw durability of pervious concrete is often a major durability concern because of the larger voids; however, the open void structure is only critical if the voids become water saturated and freeze. The freeze that durability of pervious concrete is improved by creating a sufficiently fine entrained air system in the cement paste. Addition of first of all air entraining admixture but also fibers and lightweight sand have been found to improve the freeze-thaw dura-bility (Lund *et al.* 2017). American Society for Testing and Materials (ASTM) C666 is typically used to test and determine the freeze-thaw durability of pervious concrete; however, many examples show that air entrained pervious concrete performs much better in the field than in the laboratory. According to ASTM C666, the pervious concrete specimens are fully submerged in water during laboratory testing which can be considered a worstcase scenario that is not representative of field conditions where the pervious concrete drainage effect naturally occurs. In the field, pervious concrete pavements perform well over several years in areas that undergo a large number of annual freeze-thaw cycles, provided it remains unsaturated. Even though a more realistic frost test method is needed for pervious, ASTM C666 provides a consistent test method to compare different pervious concrete mix designs (Lund *et al.* 2017). Some exam-ples of freeze thaw testing of pervious concrete are given in Fig. 5. The upper samle was made of coarse aggregates without sand and the lower one was made with 7% sand of coarse aggregate weight. The sample containing sand showed better freeze thaw resistance. Samples prior freeze thaw testing are on the left.

Fig. 5. Some examples of pervious concrete freeze thaw testing (source: Kevern *et al.* 2008)

Utilization possibilities of pervious concrete

While pervious concrete can be used for a surprising number of applications, its primary use is in pavement. Pervious concrete also has been referred to as porous concrete, permeable concrete, no-fines concrete, gap-graded concrete, and enhanced-porosity concrete (Tennis *et al.* 2004). Common applications for pervious concrete are parking lots, sidewalks, pathways, tennis courts, patios, slope stabilization, swimming pool decks, greenhouse floors, zoo areas, road shoulders, drains, noise barriers, friction courses for highway pavements, permeable bases under a normal concrete pavement, and low-volume roads. Pervious concrete is generally not used solely for concrete pavements for high traffc and heavy wheel loads (Sabnis 2012). Some examples of pervious concrete utilization are given in Fig. 6 and Fig. 7.

Fig. 6. Comparison of pervious and impervious surface during winter season

Fig. 7. Square paved by colored pervious concrete (Beijing, China)

Conclusion

This paper discusses pervious concrete as a sustainable pavement solution for urban areas. Based on literature review, pervious concrete can be successfully utilized when designed, performed and maintained properly. However, pervious concrete has some performance issues mainly lower strength and durability due to its porous structure and risk of loss hydraulic conductivity due to clogging by debris and suspended solid matter. Pervious concrete in general is suitable for low – volume road applications like parking lots, driveways or sidewalks. However, this is a big space here for research of the technological aspects in order to take advantages and eliminate the disadvantages of this material, as pervious pavement seems to be a perspective construction element for sustainable urban areas.

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