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CLOGGING IN PERMEABLE CONCRETE: A REVIEW

Alalea Kia, Hong S. Wong, Christopher R. Cheeseman*

Department of Civil and Environmental Engineering, Imperial College London, SW7 2BU, UK

*Corresponding author: c.cheeseman@imperial.ac.uk

ABSTRACT

Permeable concrete (or "pervious concrete" in North America) is used to reduce local flooding in urban areas and is an important sustainable urban drainage system. However, permeable concrete exhibits reduction in permeability due to clogging by particulates, which severely limits service life. This paper reviews the clogging mechanism and current mitigating strategies in order to inform future research needs. The pore structure of permeable concrete and characteristics of flowing particulates influence clogging, which occurs when particles build-up and block connected porosity. Permeable concrete requires regular maintenance by vacuum sweeping and pressure washing, but the effectiveness and viability of these methods is questionable. The potential for clogging is related to the tortuosity of the connected porosity, with greater tortuosity resulting in increased potential for clogging. Research is required to develop permeable concrete that can be poured on-site, which produces a pore structure with significantly reduced tortuosity.

Keywords: permeable concrete; pervious concrete; sustainable urban drainage; infiltration; flooding; permeability; clogging

1. Introduction

Urban areas are associated with hard impervious infrastructure that increases surface water run-off during heavy rain and the potential for localised flash flooding. Permeable concrete shown in Fig. 1, is widely-regarded as an important cost effective sustainable urban drainage system that can reduce storm-water run-off to alleviate the problem of localised urban flooding (EPA, 2004). It is made by omitting most or all of the fine aggregate from normal concrete and by careful control of the cement paste fraction. This produces a highly porous material with typically 15-35% volume of interconnected voids that allow very rapid water percolation.

A typical permeable pavement system consists of a top permeable concrete layer placed above a sub-base coarse aggregate layer and subgrade soil (Fig. 2). In practice, there are many variations in the number, thickness and composition of each layer, but all with the purpose of storing stormwater runoff until it infiltrates into the existing soil or is drained. Permeable pavement systems can be designed for full, partial or zero exfiltration depending on site soil conditions. Partial and zero exfiltration systems contain sub-drains or an impermeable liner to prevent water reaching the underlying soil. These systems are best suited for sites with poorly draining soils, contaminated soils or in groundwater sensitive areas (Drake et al., 2013; Crookes, 2015).

Permeable concrete is primarily used in car parks, pedestrian footpaths, cycle paths and other low-traffic areas. The hydrologic benefits of permeable pavements for reducing run-off volume and peak flow rates are well-documented (Abbott and Comino-Mateos, 2003). For example, annual run-off volume reductions of 50 to 100% have been observed (Stenmark, 1995; Legret and Colandini, 1999; Dempsey and Swisher, 2003). Even if the underlying soil is poor draining, permeable pavement systems can reduce peak flows by over 90% and surface run-off volumes by 43% (Drake et al., 2014). As such, permeable concrete pavements are well suited to existing urban areas that lack conventional storm-water management facilities. In new urban areas, they can decrease development costs by limiting the need for other storm-water management infrastructure (ACI, 2010; Ferguson, 2005; Tennis et al., 2004).

It has also been reported that permeable concrete captures suspended solids, P, N, Zn, Cu and motor oil, improving stormwater and groundwater quality (Schueler, 1987; Brattebo and Booth, 2003; Scholz and Grabowiecki, 2007; Calkins et al., 2010; Welker et al., 2013; Sansalone et al., 2008). It is also reported to improve skid resistance and minimise heat island effects in cities (Tennis et al., 2004; Amde and Rogge, 2013; Schaefer et al., 2006). However, the latter is probably due to a change in pavement colour (black asphalt to grey concrete), rather than the high permeability of permeable concrete.

While permeable concrete clearly has many benefits, it is inevitably susceptible to clogging that leads to serviceability problems and premature degradation (Deo et al., 2010; Yong et al., 2013; Mata and Leming, 2012; Coughlin et al., 2012; Tong, 2011). Physical clogging is caused by debris build-up on the surface and in the pore structure; this is likely to be the most common mechanism. Biological clogging caused by algae and bacteria, and penetration of plant roots can also occur (Ye et al., 2010; Mishra et al., 2013). Addressing this problem will substantially improve the durability of permeable concrete and optimise its application as a sustainable urban drainage system. Yet, this is not well-understood and limited information is available on factors influencing clogging (Tong, 2011; Mishra et al., 2013; Radlinska et al., 2012).

The objective of this paper is to critically review available studies on clogging, summarise current understanding of the problem and mitigating strategies. We aim to identify knowledge gaps and highlight research needs. A major challenge is that such research requires a range of expertise including cement and concrete materials science, pavement design, mass transport phenomena, structural, environmental and water resources engineering. Also, the amount of related studies has increased significantly in recent years. Therefore, a review that summarizes work from across these expertise is much needed. The structure of this paper is as follows. Properties of permeable concrete and factors influencing performance are first reviewed. Then, research related to understanding clogging and methods to unclog permeable concrete are addressed. Finally, future research needs are discussed.

2. Properties of permeable concrete

2.1. Composition and mix design

Materials used in permeable concrete are the same as in normal concrete, but the mix proportioning is different. The aim in permeable concrete mix design is to achieve a balance between voids, strength, paste content and workability. Fine aggregate content is significantly reduced (Tennis et al., 2004; Obla 2007). Various mix proportioning methods have been recommended, and the most important requirement is to provide sufficient cement paste to bind aggregates to achieve the required strength and high void content. Absolute volume method is often used in mix design (ACI, 2010; NRMCA, 2009; Deo and Neithalath, 2011; and Sumanasooriya and Neithalath, 2011). Other approaches have been suggested. Nguyen et al. (2014) developed a mix proportioning method based on excess paste theory. Yahia and Kabagire (2014) proposed a method based on volumetric ratio of paste to inter-particle voids. ACI (2010) recommends a repeated trial-and-error approach to mix design and field testing until the desired properties are achieved. The range of permeable concrete mix proportions are summarised in Table 1 compiled from literature (Montes and Haselbach, 2006; Wang et al., 2006; Sumanasooriya et al., 2012; NRMCA, 2009; Ibrahim et al., 2014; Crouch et al., 2006; Mata and Leming, 2012; Sonebi and Bassuoni, 2013; Meininger, 1998; Ghafoori and Dutta, 1995). This shows a huge variation in the mix composition of permeable concrete. This is partly due to the fact that permeable concrete can have different performance requirements and that no single universally accepted mix design method exists.

2.2. Compressive strength

Compressive strength of permeable concrete at 28-day can range from 1 to 28 MPa, increasing to 46 MPa with addition of silica fume, fine aggregate content and super-plasticisers (Ibrahim et al., 2014; Tennis et al., 2004; Lian and Zhuge, 2010). A design strength of 13.8 MPa would be required for pavements and footpaths not exposed to vehicles (Crouch et al., 2006; ACI, 2010). Pavements exposed to traffic require strengths greater than 20.7 MPa, and these are usually limited to low speed and/or infrequent usage (Hager, 2009). The strength of permeable concrete is mainly determined by total porosity, which in turn is influenced by a host of factors such as cement content, water/cement ratio, aggregate characteristics and extent of compaction during placement. Fig. 3 plots strength against porosity for a wide range of permeable concrete mixes compiled from literature (Wang et al., 2006; Sumanasooriya and Neithalath, 2011; Sumanasooriya et al., 2012; NRMCA, 2009; Kevern et al., 2010; Ibrahim et al., 2014; Lian and Zhuge, 2010; Sonebi and Bassuoni, 2013; Meininger, 1998). As expected, a strong correlation is observed. On average, strength decreased by about 3% for every 1% increase in void content.

2.3. Pore structure

The pore structure of permeable concrete consists of large interconnected voids with sizes ranging from 2 to 8 mm depending on mix proportion, aggregate used and degree of compaction (Tennis et al., 2004; Neithalath et al., 2008). These are the pores of interest because they control the performance of permeable concrete (Meininger, 1988; Ghafoori and Dutta, 1995). The volume fraction, size distribution and topological structure of the pores are the critical parameters controlling permeable concrete behaviour (Sansalone et al., 2008). Permeable concrete also contains very fine capillary and gel pores that are inherent features of the cement paste, with characteristic size ranging from several microns to nanometres. However, these pores make insignificant contribution to water percolation and so are of less interest. As noted earlier, the void content of permeable concrete is typically 15-35%, depending on a host of variables such as cement paste fraction, aggregate content, gradation and particle shape, water/cement ratio and compaction effort (ACI, 2010). These dependencies will be examined further in Section 3. Concretes with porosity < 15% tend to give very slow water percolation due to insufficient interconnected voids (Meinenger, 1988). Porosities > 35% result in highly permeable, but very weak concretes (Fig. 3)

2.4. Permeability

Permeability is a property that describes the relative ease with which a porous medium transmits liquid under a hydraulic gradient. It is dependent on the pore structure, but the exact relationship is complex. An extensive survey of literature reveals that the permeability of permeable concrete varies widely, from 0.003 to 3.3 cm/s (Montes and Haselbach, 2006; Wang et al., 2006; Deo et al., 2010; Sumanasooriya and Neithalath, 2011; Sumanasooriya et al., 2010; Sumanasooriya et al., 2012; NRMCA, 2009; Haselbach, 2010; Haselbach, 2010 (2); Kevern et al., 2010; Ibrahim et al., 2014; Coughlin et al., 2012; Crouch et al., 2006; Mata and Leming, 2012; Lian and Zhuge, 2010; Sonebi and Bassuoni, 2013; Meininger, 1998). The compiled permeability data is plotted against porosity in Fig. 4. Although a general trend of increasing permeability with increasing porosity is observed, there is large scatter and weak correlation, in contrast to the strength-porosity data shown in Fig. 3. This is partly because permeability is not only dependent on total pore volume, but also other characteristics such as size distribution, shape, degree of connectivity and tortuosity of the pores. Another reason for the scatter is that differences in testing procedure (e.g. falling head vs. constant head method) may influence results. An interesting observation from Fig. 4 is that some permeable concretes display near zero permeability despite having very high porosity (> 15%). These concretes were probably affected by "paste drain down" that causes localised pore blockage (see Fig. 5 and Section 3.1)

2.5. Durability

The service life of permeable concrete ranges from 6 to 20 years and end-of-life is usually caused by either clogging (discussed in Section 4), freeze-thaw degradation or excessive surface ravelling (Chopra et al., 2007). Similar to normal concrete, freeze-thaw degradation of permeable concrete increases at higher degree of saturation (Yang et al., 2006). Voids in permeable concrete can offer some resistance to freeze-thaw degradation provided they empty before freezing, and therefore placing permeable concrete over drainable sub-base is recommended (Tennis et al., 2004; Gunderson, 2008). Kevern et al. (2009) observed that air provides insulation that warms the pavement and underlying soils, delaying ice formation. However, clogging would prevent draining and exacerbate degradation. Furthermore, soil particles trapped within permeable concrete may become saturated and expand by 2-3% under freezing conditions. Measures that enhance resistance to freeze-thaw degradation include entraining air in cement paste (Tennis et al. 2004; Kevern, 2008), addition of fine aggregate (Wang et al., 2006; Kevern et al., 2008) and polypropylene fibres (Kevern, 2008; Yang, 2011). However, poorly compacted samples show rapid freeze-thaw deterioration (Suleiman et al., 2006). Premature failures of field permeable concretes have been documented (Hager, 2009; Weiss et al., 2015). For example, several incidences of premature failure of wearing surfaces (ravelling) led to a moratorium on permeable concrete in Denver by the Urban Drainage and Flooding Control District (UDFCD) (MacKenzie, 2008, 2013). Subsequent investigations found several factors had caused the failures including poor uniformity of void content, poor air entrainment, deicing salt scaling, and improper placement and curing.

3. Factors controlling the performance of permeable concrete

3.1. Cement content and water/cement (w/c) ratio

High compressive strength is achieved by increasing cement content, but excessive cement results in filled voids and reduced porosity. Conversely, insufficient cement results in poor aggregate coating and low compressive strength. The optimum cement content is dependent on aggregate size distribution (ACI, 2010). The optimum w/c ratio is typically between 0.26-0.45. Ghafoori and Dutta (1995) determined that the optimum w/c ratio was 0.37-0.42 for an aggregate/cement (a/c) ratio of 4-6. Smith (2004) reported that w/c ratio of 0.27-0.31 was necessary for proper performance of permeable concrete. ACI Committee 522 (2010) recommends w/c ratio of 0.26-0.40 to produce good aggregate coating and paste stability. Lower w/c ratios cause balling and sticking of the concrete during mixing, while higher w/c ratios produce a thin paste that can run-off the aggregate during placement, blocking pores (Meininger, 1988). Similarly, high cement paste content can cause localised clogging when the paste drains down the permeable concrete, resulting in a dense paste-rich lower layer. This effect, shown in Fig. 5, will produce concretes with poor infiltration capacity despite high porosity. The conventional inverse relationship between w/c ratio and compressive strength does not apply to permeable concrete. At constant aggregate and cement content, increasing w/c ratio increases strength because excess cement paste fills open voids. In contrast, reducing w/c ratio increases void content and infiltration rates (Schaefer et al., 2006).

3.2. Aggregates

Aggregates in permeable concrete are single-sized or narrowly graded between 9.5-19 mm (ACI, 2010). Narrow grading and larger particle size produces larger pores and improves permeability. Blending aggregates of different sizes improves mechanical properties, but this is not recommended for permeable concrete because it reduces porosity and infiltration rates (Schaefer et al., 2006). Rounded aggregates such as gravel produces lower void content and increases compressive strength. Angular aggregates tend to be oriented in one plane during compaction, adversely affecting contact area and bonding. Flaky and elongated aggregate particles are avoided. (Lian and Zhuge, 2010; Kevern et al., 2010; Tennis et al., 2004). Fine aggregate is usually excluded from permeable concrete, but addition of a small fraction (up to 7% wt. coarse aggregate) increases compressive and flexural strengths, density and freeze-thaw durability, while maintaining sufficient infiltration capacity (Schaefer et al., 2006; Wang et al., 2006; Kevern et al., 2008; Henderson and Tighe, 2012). Aggregate to cement (a/c) ratio is typically in the range of 4.0 to 4.5 (ACI, 2010). Increasing the a/c ratio increases permeability, but decreases compressive strength because less cement paste binds aggregate particles (Ghafoori and Dutta, 1995). Aggregate moisture content is important because dry aggregates reduce workability for placing and compaction, while wet aggregates contribute to paste drain down, potentially clogging the concrete (ACI, 2010). Therefore, aggregate moisture content should be accounted for in mix design, and batch water adjusted to compensate for aggregate absorption or excess water associated with wet aggregate.

3.3. Chemical admixtures

Chemical admixtures are used to improve the properties of fresh and hardened permeable concrete in a similar manner to normal concrete (ACI, 2010). Water reducing admixtures increase workability at low w/c ratio. Retarders are used to extend workability by decreasing the rate of cement hydration and reduce excessive heat of hydration during early ages. Retarders also act as lubricants to help discharge stiff mixes from the mixer, improving handling and the in-place performance of permeable concrete (ACI, 2010). Viscosity modifying admixtures can produce a more cohesive mix and inhibit paste drain down. Air entraining admixtures are used in permeable concretes susceptible to freeze/thaw degradation in cold climates (Schaefer et al., 2006; Kevern, 2008; Kevern et al., 2010). Unfortunately, no reliable methods exist to quantify the entrained air voids in permeable concrete (ACI, 2010). Therefore, ensuring adequate air entrainment (volume, spacing) for frost protection in field permeable concrete is difficult.

3.4. Placing, compaction and curing

Freshly mixed permeable concrete contains little excess water and so it should be placed close to its final position as soon as possible to prevent drying out, which can lead to low strength and surface ravelling. Compaction affects many properties of permeable concrete. Insufficient compaction causes low-strength and surface ravelling, while over-compaction reduces void content and the ability to drain surface water (Meininger, 1988; Schaefer et al. 2006; Sumanasooriya and Neithalath, 2011). Over-compaction may also cause paste drain down. Permeable concrete pavements are usually roller compacted. The roller consolidates near surface aggregates, resulting in a stronger bond but decreases surface permeability. Excessive rolling pressure can cause void collapse. Permeable concrete pavements are not finished in the same way as normal concrete because floating and trowelling operations close surface voids (Tennis et al., 2004; ACI, 2010; Obla, 2010).

Permeable concrete pavements are more susceptible to damage from improper curing than conventional concrete pavements because of the high surface area and open void structure. Curing of permeable concrete pavements typically uses plastic sheeting cover. This must start within ~ 20 minutes of placement and last for 7-10 days and longer in cold climates. Concrete not sufficiently cured may ravel if the cement paste dries out before achieving adequate strength (Tennis et al., 2004; Smith, 2004). The method of construction is regarded as most critical for permeable concrete, but many variations exist and their impact on long-term durability is not well understood. Furthermore, field quality control and assurance that proper compaction and curing is achieved on site is difficult.

4. Clogging mechanism

Permeable pavements will clog over time as solid particles are retained and accumulate. Percolating stormwater carries with it a range of solids and the problem is exacerbated by traffic that breaks these down into finer particles. The particles fill and block void spaces, allowing further accumulation of fines. On drying, the accumulated particles form a hard crust that seals the voids (Pratt et al., 1995). These processes reduce infiltration rates, eventually causing surface overflow and ponding when the infiltration rates become less than the rainfall intensity.

Materials that cause clogging include sediments (sand, silt, clay) that may have eroded from surrounding areas, debris from road surfaces or from other areas carried and deposited by vehicles, small particles originating from the pavement itself due to surface wear or other degradation, and organic matter from surrounding vegetation (Ferguson, 2005). Welker et al. (2013) analysed material removed from voids of permeable asphalt and permeable concrete taken from a car park. They found very little fine sediments and most material was from deterioration of the pavements. Permeable concrete showed greater surface ravelling. Details of the work are summarised in Table 2. Another study observed that the majority of the sediment removed consisted of particles >38 μm from surrounding vegetation (Kayhanian et al., 2012).

A number of studies investigated the effect of sediment type on clogging potential under controlled laboratory conditions. Some observed that coarse sand particles did not significantly reduce permeability as these large particles were prevented from entering surface pores (Coughlin et al., 2012; Deo et al., 2010). However, Schaefer et al. (2011) found that sand caused significant reduction in permeability, while fine-grained silty clay produced almost no effect. Combination of silty clay and sand caused the highest reductions in permeability, with complete clogging after a small number of cycles. This was due to the wider particle size distribution which increases the probability of retention, and the cohesive nature of clay led to more surface interaction and particle adhesion. The work of Coughlin et al. (2012) concluded that clay caused approximately ten times more clogging per unit mass than sand. The findings from such studies are not always consistent with each other, and this can be attributed to differences in the clogging material, pore structure of the tested samples, exposure conditions and other variables. The clogging potential is probably highest when the sediment particle size is close to the pore size of permeable concrete (ACI, 2010).

Kevern (2015) measured the infiltration rates of permeable concrete slabs (350 x 350 x 150 mm) clogged with silty soil slurry (34% < 0.074 mm), landscaping compost (15% < 0.074 mm) and a combination of soil slurry and compost. Despite all samples being prepared by a single operator using the same procedure, the initial infiltration rates of unclogged samples were highly variable and ranged from 140 cm/h to 1380 cm/h. After testing, the samples were washed with a standard hand-held hose and cleaned with an industrial vacuum cleaner to determine the extent of infiltration recovery. Samples clogged with compost had higher post-clogging infiltration and recovery rates than samples clogged with soil slurry. The greatest clogging effect was caused by a combination of soil slurry and compost. Samples with high initial infiltration also showed high recovery rates, but significant infiltration capacity was permanently lost as the recovery was only ~ 50% of initial capacity.

Some studies have observed that clogging usually occurs on the surface or in the upper layer of the permeable pavement (Kayhanian et al. 2012, Yong et al. 2013), while others found that particles are just as likely to clog within the permeable concrete or underlying soil (Chopra et al., 2010; Mata and Leming 2012). These variable findings suggest that there is no single location or depth within the permeable concrete where clogging usually occurs.

The actual deposition pattern will depend on the size of the clogging particles relative to the pore size in permeable concrete, as shown schematically in Fig. 6. Particles that are much larger than the pores will retain on the top surface (Fig. 6a), forming a blanket like deposition layer. Finer particles tend to trap within the permeable concrete away from the surface (Fig. 6b). Very fine particles such as silt and clay can be carried through but may still clog when deposited at pore constrictions or at the bottom of the pavement, at the interface with the aggregate sub-base or subgrade soil (Mata, 2008; Mata and Leming, 2012). Geotextile fabric (Fig. 2) may be used between layers to prevent transfer of fines and as a filter to improve water quality (Scholz, 2013), but accumulation of solids on the fabric increases clogging risk and reduces infiltration rates (Boving et al., 2008; Brown et al., 2009; Kayhanian et al., 2012).

Another factor influencing clogging is climatic exposure conditions. Yong et al. (2013) investigated the clogging process of permeable asphalt, block pavers and resin bound paving. Although these are not permeable concrete, the findings are relevant. Each permeable pavement type was tested by exposure to either constant storm-water inflow rate with no drying periods or variable inflow rates with drying periods. The flow contained sediments with 10% wt. particles < 5 μm and 10% wt. particles > 147 μm, obtained from actual storm-water. Each run was continued until the pavements were clogged, defined as when ponding was 30 mm above the surface or when outflow decreased to 10% of the initial rate. It was found that regardless of the pavement type, clogging was delayed in systems exposed to variable flow and drying periods, which had almost twice the lifespan of pavements receiving continual wetting. The earlier onset of clogging is believed to be caused by biological growth, which occurs faster in continuous wet conditions (Watson-Craik and Jones, 1995; Mackey and Koerner, 1999).

It is also worth noting that clogging accelerates freeze-thaw degradation. For example, Guthrie et al. (2010) evaluated the resistance of permeable concrete to freeze-thaw degradation at different levels of soil clogging and water saturation. Clogging was performed using poorly graded sand (fraction passing 0.297 mm sieve) collected from the vicinity of an actual permeable concrete slab to mimic field conditions. It was found that specimens that were clogged or fully saturated or both, deteriorated at a faster rate than those that remained unclogged and unsaturated. The average number of freeze-thaw cycles to failure was 93 for clogged specimens compared to 180 for unclogged specimens, and 80 for saturated specimens compared to 193 for unsaturated specimens. However, strength and stiffness measurements indicated no significant differences in structural properties between the clogged and unclogged locations. This was because only the upper 25-50 mm of the 180 mm permeable concrete was filled with soil in clogged locations and the remaining depth was water free.

5. Field investigations

Field measurements have observed huge variation in the properties of permeable concrete. For example, Kayhanian et al. (2012) measured the permeability of 20 permeable concrete pavements in car parks in California, with ages ranging from 1 to 8 years. Measurements were taken at the main entrance, an area with no traffic, and three measurements within a parking space at each car park. The permeabilities measured ranged from 0.0002 to 1.82 cm/s. Large variability was observed within each and between all parking spaces, and this was attributed to differences in traffic volume at each site, inconsistency in pavement construction and damage to the pavement in the testing area. The most important factors influencing permeability were the age of the concrete and the amount of accumulated fine sediments. Older samples showed lower permeability due to increased clogging.

The type of pavement use influences the permeability. For instance, traffic lanes have lower infiltration capacity compared to parking spaces because of the greater amount of sediments that typically falls on traffic lanes (Henderson and Tighe 2012). This is consistent with Kumar et al. (2014) who measured the in-situ infiltration performance of three permeable pavements (pavers, concrete and asphalt) placed in a car park over a four-year period. The highest infiltration rate was observed in permeable asphalt, followed by permeable concrete and permeable pavers. The infiltration rate in traffic areas was at least 50% lower than in parking areas. This was attributed to higher surface wear causing increased pore clogging in traffic areas.

Long-term field performance of permeable concrete pavements has been reported in a number of studies. A notable example is Radlinska et al. (2012) who worked on the Storm-water Research and Demonstration Park, Villanova University, constructed in 2002, and primarily used by pedestrians. However, it was demolished in 2012 due to degradation. Samples were examined for porosity, compressive strength and clogging. Significant variations were observed in strength (15.6-43.0 MPa) due to inconsistencies in placement and curing. Porosity examined using image analysis was found to range from 1 to 26%, with only a fifth of the samples having values >15%, which is the lower limit for permeable concrete. Porosity near the top surface was consistently lower than deeper sections, indicating loss in surface infiltration capacity. Moreover, the sediments in void spaces resembled hardened cement paste, indicating freeze/thaw induced spalling and clogging by loose particles. In addition, some samples had reduced surface void content due to excessive compaction. Field infiltration tests indicated that the top surface was sealed, preventing infiltration into the pavement. These results were consistent with porosity profiles from image analysis. Improper construction had led to irregular pore distribution, variable strength and sealed surfaces preventing infiltration.

Boogaard et al. (2014) reported the serviceability of 55 permeable pavements from Australia and the Netherlands with ages ranging from 1 to 12 years, evaluated using double ring infiltrometer testing. The permeable pavements were compared in terms of their ability to infiltrate either a 3-month average recurrence interval storm event for the Australian pavements, or to satisfy the minimum European infiltration rate of 97.2 mm/h for the Dutch pavements. Over 90% of the 55 pavements tested were able to infiltrate to these standards. However, the infiltration capacity of permeable pavements decreased with pavement age due to cumulative clogging by sedimentation, poor installation of older pavements and poor maintenance.

The Urban Drainage and Flooding Control District (UDFCD) have extensive experience with installing, testing and monitoring permeable concrete pavements in Colorado. By 2008, surface ravelling and erosion problems in a number of installations led the UDFCD to issue a temporary moratorium on permeable concrete until further investigation (MacKenzie, 2008). Subsequently, UDFCD collaborated with Colorado Ready Mix Concrete Association to develop new design guidelines for permeable concrete (CRMA, 2009) and lifted the moratorium. A permeable concrete demonstration pad was constructed at the National Renewable Energy Laboratory (NREL) using the new design specifications, but deteriorated heavily in 2011 after only two years of service. As a result of the failure at the NREL site and poor structural performances at other sites, UDFCD removed permeable concrete as a possible sustainable storm-water quality best management practice from their urban storm drainage criteria manual (MacKenzie, 2013).

6. Methods to unclog permeable concrete

Permeable concrete pavements require regular maintenance to preserve performance and effectiveness. The main focus of maintenance is removing particles causing clogging to recover infiltration capacity. Pressure/power washing with water and vacuum sweeping (or a combination of these) are the most recommended methods to rehabilitate clogged permeable concrete (EPA, 2004; Golroo and Tighe, 2012; Drake, 2013). Pressure washing uses a power head cone nozzle to weaken the bond between clogging particles and the pavement to enable their removal. In vacuum sweeping, clogging particles are sucked out to re-open blocked pores.

The recommended frequency of maintenance ranges from at least once per year (Drake and Bradford, 2013) to two to four times per year (Gunderson, 2008; Henderson and Tighe, 2012), depending on the site and weather conditions. More frequent maintenance is required in areas subjected to higher debris concentrations and deposition rates.

The effectiveness of pressure washing, vacuuming and combination of these techniques for restoring infiltration capacity of clogged permeable concrete has been investigated in a number of studies. Findings have varied between different studies and indeed, sometimes within a single study. These variations can be attributed to differences in the permeable concrete (mix design, construction technique, homogeneity, age etc.), pavement usage, clogging material and process, test procedure, and history prior to maintenance. Overall results suggest that these maintenance techniques can often restore permeability at least partially, although the economic and practical viability are questionable.

For example, Chopra et al. (2010) found that combining vacuuming and pressure washing gave the highest recovery in permeability, and pressure washing alone was more effective than vacuuming. However, this was based on laboratory experiments in which samples were washed with an open base, rather than mounted on a normal base course. Furthermore, high pressure washing dislodges particles and may push them into the pavement, causing further clogging. Coughlin et al. (2012) found that pressure washing was not effective at restoring infiltration of samples clogged with sand and clay because most of the head loss occurred in the subgrade rather than in the permeable concrete. Similarly, Haselbach (2010) reported clogging of permeable concrete by clay (bentonite, kaolinite and red clay) and subsequent improvements after drying, brushing and flushing with water, but found limited success in restoring infiltration rates because of the difficulty in cleaning samples in which clogging materials accumulated below the pavement surface.

Field tests by Henderson and Tighe (2011) found that pressure washing and vacuuming did not effectively rejuvenate permeable concrete pavements. Instead, they reported that sweeping with a stiff broom to agitate debris in surface voids, followed by rinsing the pavement with a garden hose was effective. However, mechanical sweeping is generally not a recommended approach because it pushes particles further into the pavement rather than removing them. Henderson and Tighe (2011) also observed that it is extremely difficult to restore permeability to initial values for pavements that had low initial infiltration rates (due to poor mix design and/or improper construction). Similarly, Schaefer et al. (2011) observed that maintenance methods were more effective on high porosity samples, but had negligible effect on specimens with <15% porosity. This is also consistent with Tong (2011) who found that samples with higher initial porosity achieved improved recovery. Therefore, the recovery rate is strongly influenced by sample porosity, pore size distribution and connectivity.

Vacuum sweeping is faster than pressure washing, but only extracts particles that are close to the surface of the pavement (Chopra et al., 2010; Schaefer et al., 2011; Vancura et al. 2012). Mata and Leming (2012) found that vacuum sweeping could partially restore the infiltration capacity of permeable concrete. Drake and Bradford (2013) found that vacuuming was effective at one site investigated but not at another. Manahiloh et al. (2012) measured porosity profiles of permeable concrete cores using X-ray tomography to assess the effect of age on the nature and extent of clogging. The average porosity of one-year old samples was 26.0%, compared to 18.1% for eight-year old samples. Vacuum sweeping increased the average porosity of one-year old samples from 26.0% to 29.0% and eight-year old samples from 18.1% to 19.1%. The lower porosity and recovery rates of old samples in comparison to young samples was related to the extent of clogging.

According to the ACI Committee 522 (2010), the most effective cleaning regimes use vacuum sweeping followed by pressure washing. Chopra et al. (2010) found that combining vacuuming and pressure washing produced the highest recovery in permeability. Schaefer et al. (2011) showed that vacuum sweeping and pressure washing gave approximately the same permeability recovery, while combining vacuum sweeping and pressure washing produced higher recovery. Hein et al. (2013) also found that pressure washing and vacuuming were effective initial cleaning methods, but that vacuuming followed by pressure washing and a second round of vacuuming was even more effective.

However, it should be noted that such maintenance practices do not fully recover initial infiltration rates. In fact, the recovery rates are fairly low. For example, Tong (2011) applied pressure washing or vacuuming on samples clogged with sand and clayey silty sand. The recovery rates were <15%. Combining vacuum sweeping and pressure washing increased recovery rates to 20-25%. Similarly, Schaefer et al. (2011) showed that for samples clogged with sand, pressure washing or vacuum sweeping recovered 10-20% of the initial permeability, while combining these methods produced 30% recovery. For samples clogged with silty clayey sand, applying pressure washing or vacuum sweeping recovered 10-20% of the initial permeability, while the combined method produced 20% recovery.

The effectiveness of maintenance also depends on the extent and location of where clogging occurs. When pavements are clogged with coarse sand particles that are mainly deposited on the surface, vacuum sweeping, pressure washing or a combination improves permeability. If the permeable concrete is clogged with silty clayey sand particles deposited within the bulk or towards the base of the sample, traditional cleaning methods are not effective (Mata, 2008). Mata and Leming (2012) exposed permeable concrete with 20% porosity to two cycles of sediment loading with washing after each cycle. Results showed that the majority of sand was trapped at the top surface, while clayey silt and clayey silty sand showed significant penetration and deposition at the bottom, retained by the filter fabric. Sand was largely removed by washing, and surface permeability recovered by 30% using either pressure washing or vacuum sweeping. Washing was less effective for clayey silt (recovery rates <20%) because of the difficulty in recovering material settled at the bottom. Finally, samples subjected to clayey silty sand showed the highest permeability loss and lowest recovery (<10%).

Vancura et al. (2012) compared the performance of a vacuum truck, vacuum street sweeper and regenerative air street sweeper in removing clogging material from in-service permeable concrete pavements. All three machines were only effective at removing clogging material within ~ 3 mm of the surface. It was found that some test locations required maintenance every month to sustain a functional level of permeability, and in spite of this, clogging material remained in the void structure. Drake and Bradford (2013) evaluated the effectiveness of several small and full-scale maintenance equipment including pressure washers, street sweepers and low/high suction vacuuming in restoring permeable interlocking concrete pavers and permeable concrete in eight car parks. The results suggest that these techniques were effective to some extent in clearing near surface clogging, but the improvements were not consistent throughout. This is possibly due to fines that have migrated too far into the pavement, becoming impossible to extract and permanently affecting permeability. These results show that even with maintenance, a degree of clogging of permeable pavement systems is unavoidable.

The review above shows that permeable concrete pavements will fail to infiltrate storm-water if maintenance is not carried out. Maintenance has to be regular or clogging will occur to such an extent that maintenance is no longer effective. Maintenance does not fully restore infiltration rates to initial values, even if carried out regularly and the performance the permeable concrete will decrease over time to unacceptable levels due to the cumulative effects of clogging.

8. Innovations and future research

This review has identified several unresolved issues concerning the performance of permeable concrete that need further investigation in order to optimize application. Despite significant recent advances in this area, a better understanding of how mix constituents and proportioning, and construction techniques (placement, compaction, curing) influence the properties of permeable concrete is still very much needed. Poor understanding of these fundamental issues contributes to the recurring problem of large variability in void structure and properties of field permeable concretes. Paste drain down is a major defect in permeable concrete that exacerbates degradation, but is difficult if not impossible to detect. This also suggests that quality control and quality assurance on site remains a major challenge for permeable concrete. Therefore, more accurate and reliable test procedures to assess and validate performance of permeable concrete are needed.

Many studies have investigated the properties of permeable concrete, but most of these typically span several months to a few years and do not evaluate the whole life performance. Thus, longer term testing and monitoring of field permeable concretes subjected to a range of service environments are needed. An improved understanding of clogging, the decrease in permeability over time and the degradation mechanisms occurring in the field over longer times is required. In addition, established methods to evaluate and quantify clogging of permeable concrete do not currently exist. Development of models to predict clogging and long-term performance are also lacking, and is an absolutely critical area that merits more attention. Such activities will facilitate more accurate life-cycle analysis and the development of improved designs.

The problem with current permeable concrete is that it is highly susceptible to clogging and periodic maintenance/cleaning is essential to retain function. Research has focused on different methods to restore the permeability of permeable concrete. However, the maintenance methods used are not particularly effective for clogging particles that accumulate below the surface. New improved maintenance methods that are more effective are needed. A better understanding of which methods are effective on different pavement types and service environments, and how frequent maintenance should be carried out, is required to optimise performance.

This review also highlights the need to develop new permeable concretes that are more resistant to clogging and that do not require frequent maintenance. Clogging resistant permeable concrete must retain sufficient porosity and permeability for storm-water to infiltrate throughout the service life. The pore network in permeable concrete is highly complex and heterogeneous. The pore channels are tortuous, with variable cross-section and random interconnectivity. Tortuosity is an intrinsic property of a porous material usually defined as the ratio of actual flow path length to the straight distance between the ends of the flow path (Bear, 1988). Tortuosity is also related to the inverse of connectivity. Therefore, different flow paths through permeable concrete have different tortuosity as shown schematically in Fig. 7. Particles moving in pores that are more tortuous and heterogeneous have greater probability of retaining and accumulating within narrow constrictions (pore necks). As such, the potential for clogging increases with increased tortuosity.

A clogging resistant permeable concrete will require uniform pore structure with low tortuosity. One approach being investigated involves engineering controlled connected porosity into the concrete in the direction of flow so that surface runoff is effectively transferred from one side of the permeable concrete pavement to the other with minimal risk of solids accumulating. The research challenge is to develop ways by which this type of permeable concrete can be poured on-site to form a low tortuosity pore structure, without reducing the mechanical properties of the concrete. Solving the problem of clogging will make permeable concrete more efficient, resilient and cost effective, thereby promoting wider use. Clog resistant permeable concrete will contribute significantly towards sustainable urbanisation and more general efforts at environmental protection.

9. Conclusions

Permeable concrete is characterised by highly interconnected porosity, typically in the range of 15–35% vol. that allows water to flow rapidly through the pore structure. A critical problem with permeable concrete is clogging due to surface blocking and infiltration of fine particles which causes loss of permeability and performance degradation. Clogging is related to the high pore tortuosity formed in current permeable concrete formulations. As a result, permeable concrete requires frequent maintenance, but current methods can only partially restore infiltration capacity and are not effective when clogging occurs some depth below the surface. This review has identified a number of unresolved issues concerning the design, construction, maintenance, testing and validation of long-term performance that require further investigation in order to optimize the application of permeable concrete as a sustainable urban drainage system. The review has also highlighted the need to develop new types of permeable concrete with low tortuosity as this will allow low maintenance permeable pavements to be produced that can effectively reduce storm-water run-off.

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Figure
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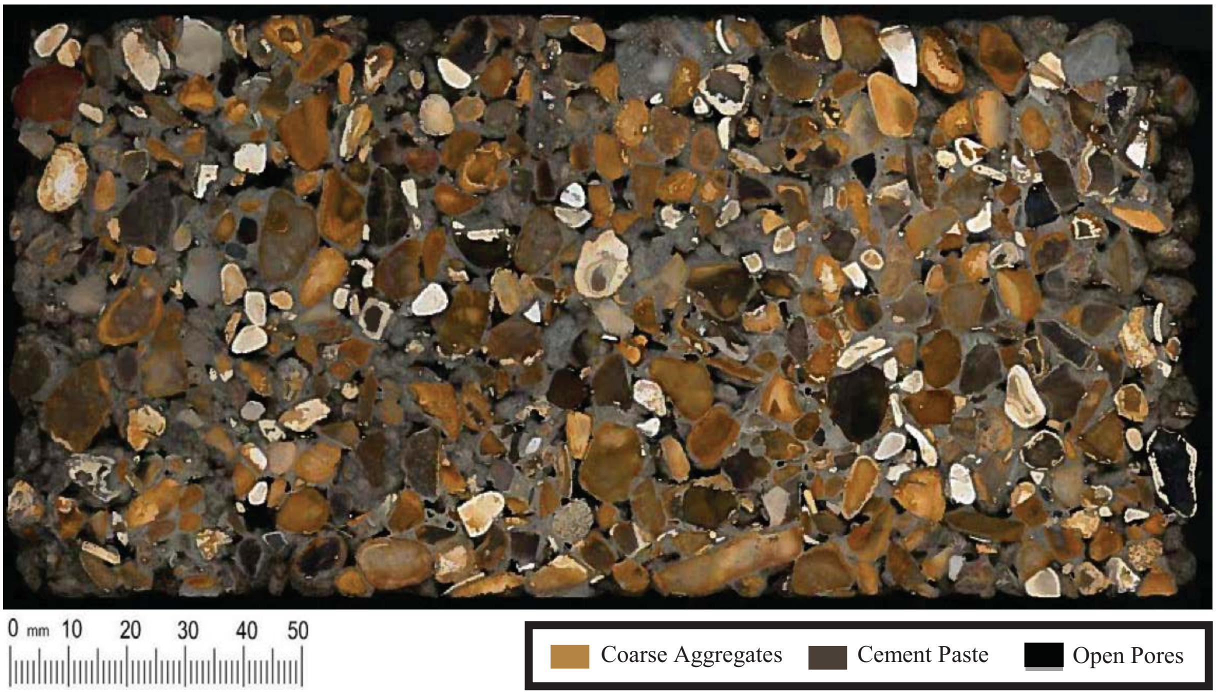


Fig. 1. Cross-section of a typical permeable concrete with porosity of 22%.

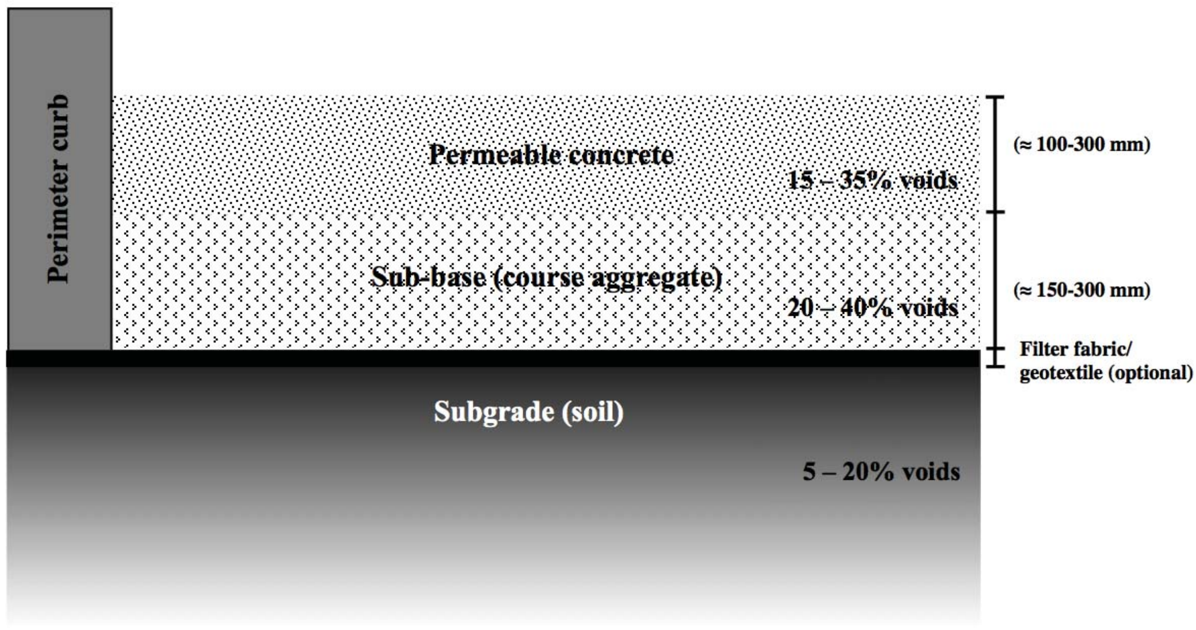


Fig. 2. Schematic cross-section of a typical sustainable urban drainage system incorporating a permeable concrete layer.

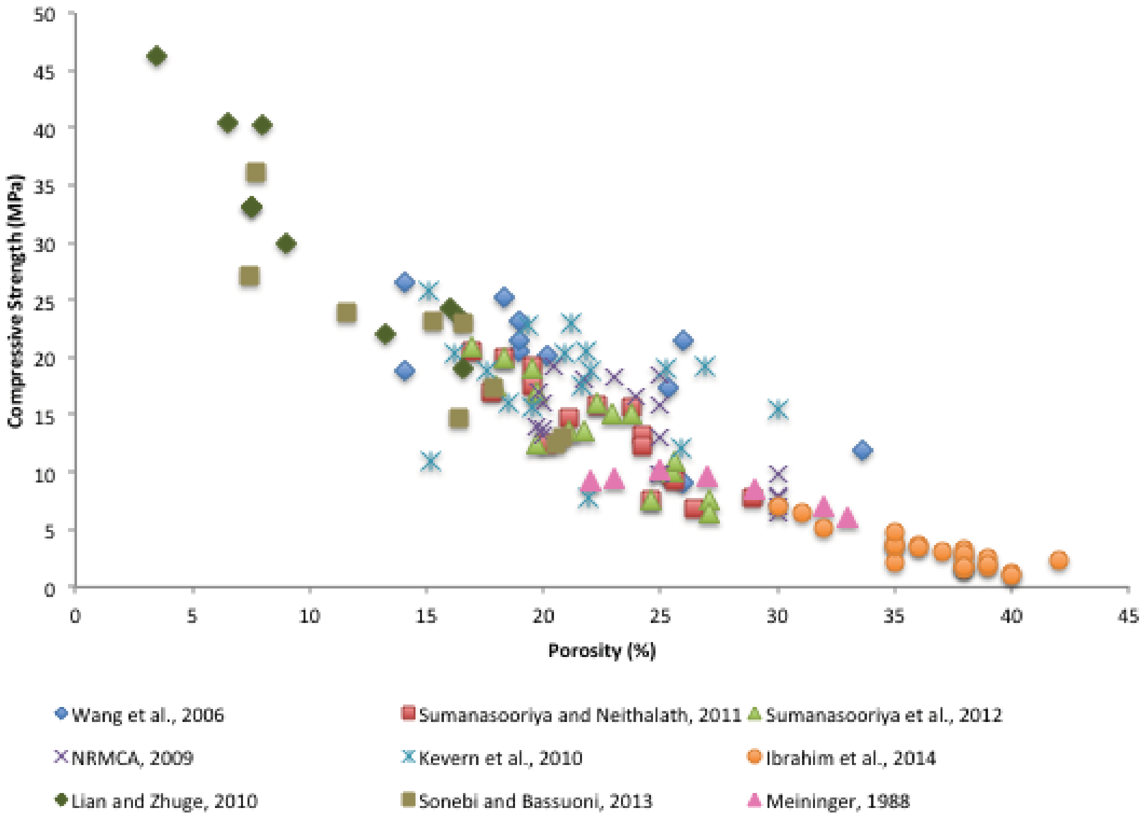


Fig. 3. Correlation between compressive strength and porosity for a wide range of permeable concretes reported in the literature.

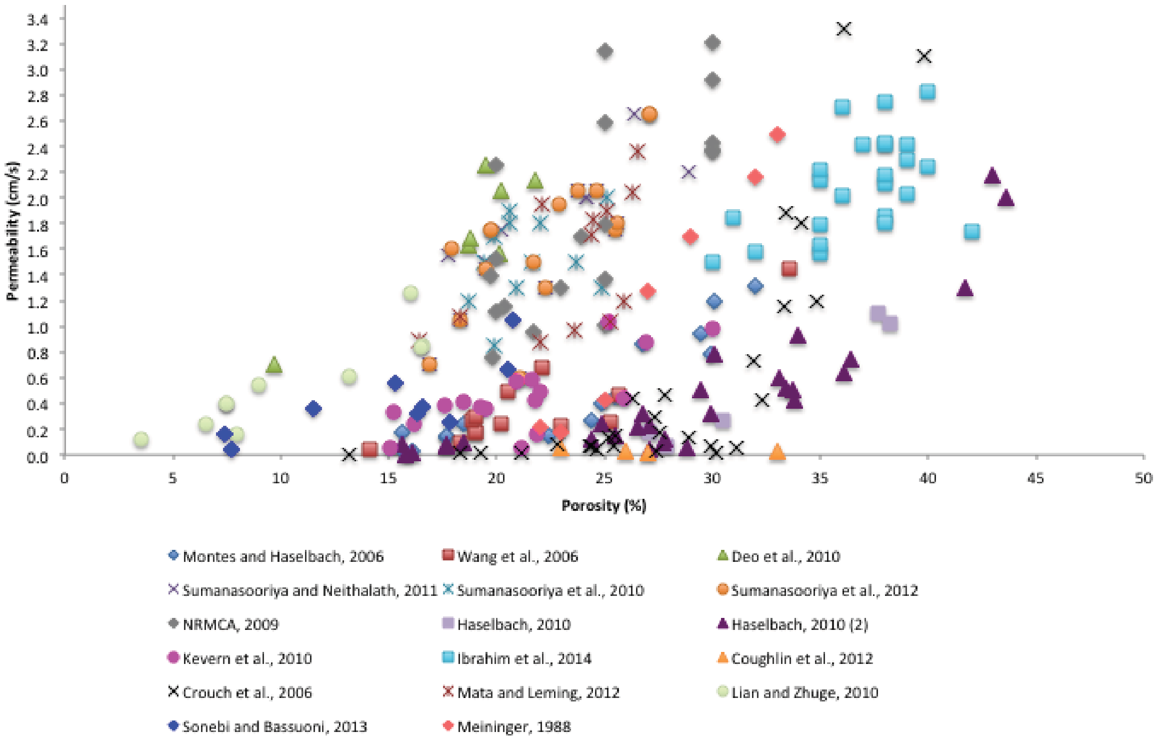
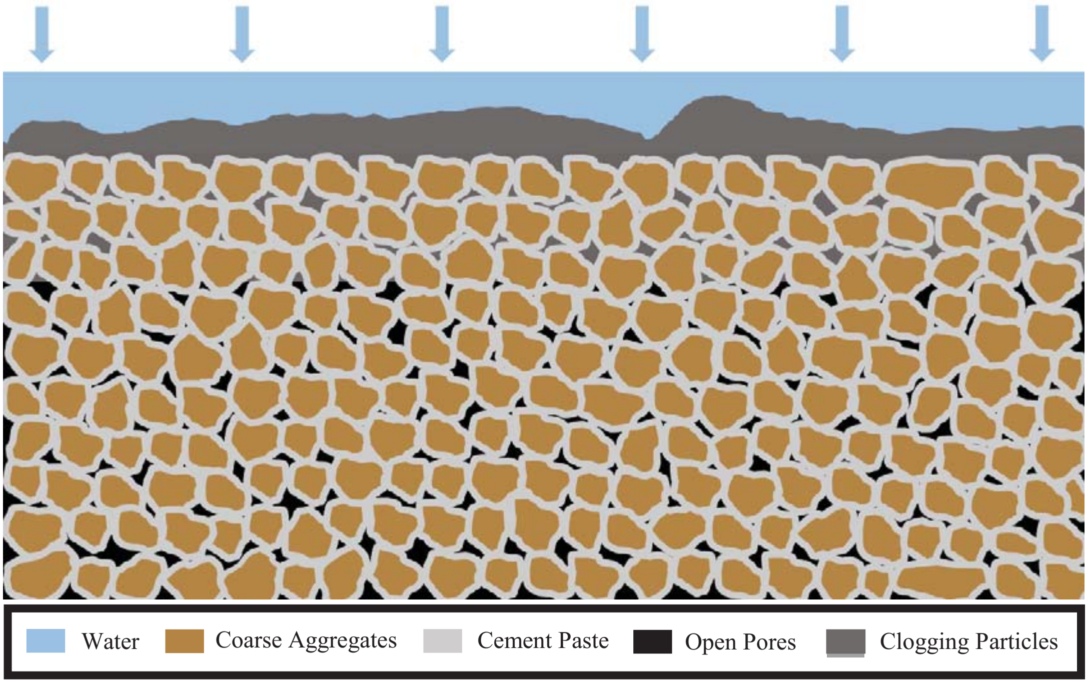


Fig. 4. Correlation between permeability and porosity for a wide range of permeable concretes reported in the literature.

a) b)

Fig. 5. Permeable concrete (a) as cast and (b) and rotated, showing the bottom is completely blocked by paste drain down, due to excessive cement paste content, w/c ratio and/or compaction. The sample is a 100 mm cube.

a)



b)

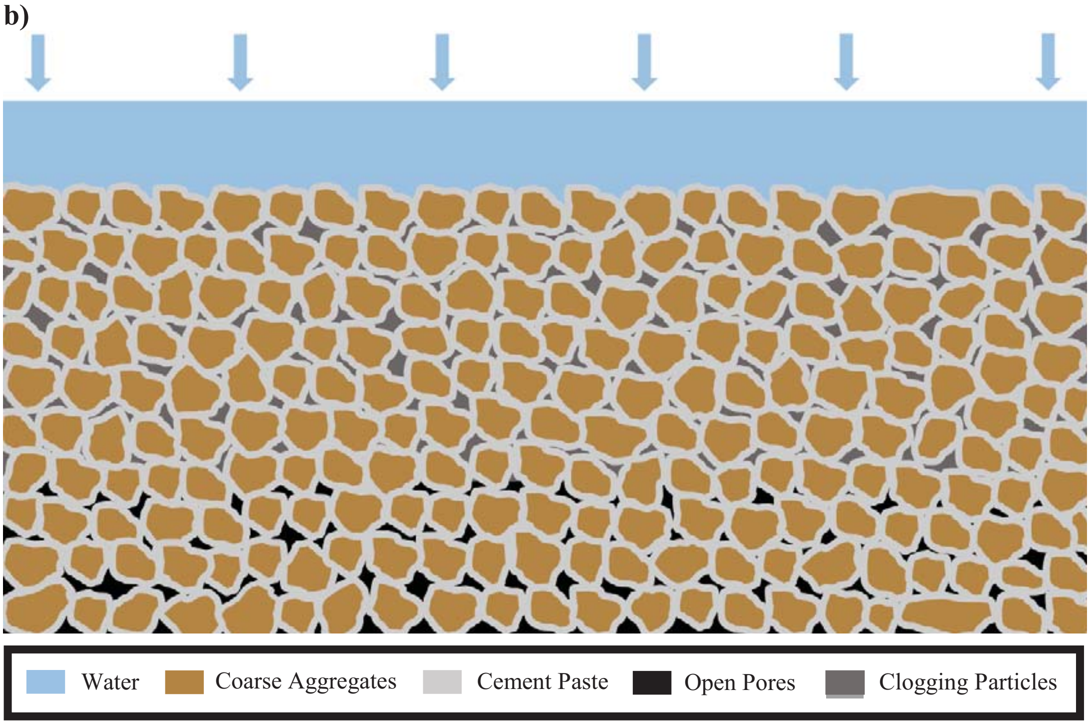


Fig. 6. Schematics showing how different sized particles are likely to clog permeable concrete: a) large particles relative to the pore size are predominantly caught at the top surface or migrate only a short distance into the concrete; and b) fine particles migrate deeper into the permeable concrete where they cause clogging.

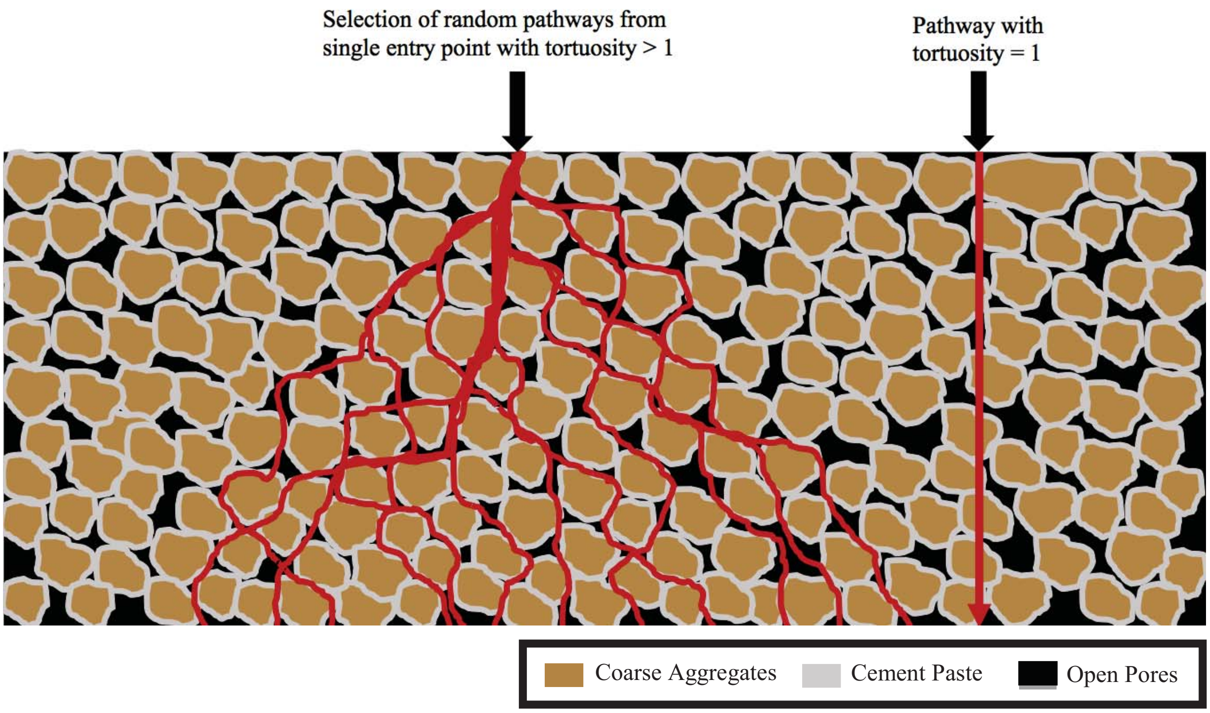


Fig. 7. Schematic showing the pathway with a tortuosity of 1 and various pathways through permeable concrete from a single entry point with tortuosity >1.

Table
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Table 1.

Mix proportion data reported in the literature for permeable concrete.

	Reported range
Cement*	150 – 700 kg/m^3
Coarse Aggregate	1100 – 2800 kg/m^3
Fine Aggregate**	0 – 100 kg/m^3
Water / Cement ratio	0.2 - 0.5
Aggregate / Cement ratio	2 - 12
Fine / Coarse Aggregate ratio	0 - 0.07

*Portland cements and blended cements containing supplementary cementitious materials, including fly ash (5-65% wt. cement replacement), ground granulated blast furnace slag (20-70% wt. cement replacement) and silica fume (5-12% wt. cement replacement) can be used in permeable concrete.

** Fine aggregate content is typically limited to 0-7% wt. coarse aggregate content.

Table 2.
Summary of selected studies on clogging of permeable concrete, arranged according to publication date.

Study	Details
Guthrie et al., 2010	Assessed the effects of clogging and water saturation on resistance of permeable concrete to freeze-thaw. Carried out field measurements of stiffness and compressive strength on slabs subjected to the following conditions: a) unclogged, soaked, and completely submerged in water; b) unclogged, soaked, drained, and sealed and; c) clogged, soaked, drained, and sealed. Clogging was performed using poorly graded sand (< 0.297 mm) collected from the site. Results showed that samples that were clogged or fully saturated or both, deteriorated at a faster rate than those that remained unclogged and unsaturated.
Tong, 2011	Subjected samples (15, 20 and 25% porosity) to 0.82 kg of sediments (sand and clayey silty sand) over 20 cycles to simulate 20 years of sedimentation load. Each consisted of clogging, rehabilitation and permeability measurement. Permeability of samples clogged with sand recovered by 4.0-9.4% when cleaned by pressure washing and by 2.4-9.6% when vacuum swept. Permeability of samples clogged with clayey silty sand recovered by 9.4-15.0% when cleaned by pressure washing and by 10.3-12.5% when vacuum swept. Samples with higher initial porosity achieved higher recovery following rehabilitation.
Schaefer et al., 2011	Exposed samples (15, 20 and 25% porosity) to 20 clogging cycles of either sand, silty clay or silty clayey sand (5 g per cycle) to simulate 20 years of service life. Samples with lower initial porosity showed less reductions in permeability because smaller voids prevented sediments from entering and clogging the sample. Silty clay and sand caused the highest reductions (93-96%) in the permeability of all samples, with complete clogging occurring after a small number of cycles due to the wider particle size distribution and the cohesive nature of clay.
Coughlin et al., 2012	Studied the effect of sand and clay clogging on pavement system made with permeable concrete overlying aggregate sub-base and sand subgrade. Infiltration rate and head loss were recorded for a series of eight runs: a) one run without clogging materials; b) three runs with increasing amounts of sand (20 to140 g); c) three runs with increasing amounts of clay (2 to 14 g); and d) one run after pressure washing. Concluded that clay caused ~ 10x more clogging per unit mass than sand. Pressure washing was ineffective at restoring infiltration capacity because of subgrade clogging.
Kayhanian et al., 2012	Measured permeability of 20 permeable concrete pavements from car parks, aged 1 to 8 years, and observed huge property variation within each and all sites. This was attributed to differences in age, clogging, traffic volume, construction and degradation. Image analysis and porosity profiles showed most clogging occurred in the top 25 mm, but some cores showed reduced porosity up to 100 mm below surface. Majority of sediment removed were particles >38 μm from surrounding vegetation and surface ravelling. Sediments <38 μm caused more clogging because of tendency to accumulate at the filter fabric. Other influencing factors included the number of days exposed to >30°C (influences tyre degradation) and the amount of vegetation near site.
Welker et al., 2013	Analysed clogging material from permeable concrete and asphalt pavements, both installed side by side in a car park subjected to similar runoff, pollutant and vehicular loading. Initial porosities of the pavements were 27% and 25% respectively. Pavements were maintained every six months by vacuum sweeping. Particle size analysis showed most of the collected material was large particles from deterioration of the pavements themselves (surface ravelling). Of the material collected, 66% came from permeable concrete and 34% from permeable asphalt, indicating that the former had greater surface ravelling.
Hein et al. 2013	Tested the effectiveness of power blowing, pressure washing, and vacuuming in recovering the infiltration capacity of 6 x 18 m permeable concrete parking slabs subjected to storm-water runoff containing silt, clay and organics. Samples had porosities of 18.5 to 27% and average infiltration rate of 2030 cm/hr. Infiltration tests were performed using falling head apparatus before and after cleaning. Results showed that vacuuming followed by pressure washing was most successful in improving infiltration rates. Pressuring washing was more effective than power blowing, but no improvements achieved by combining the two.