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Research article

Defining clogging potential for permeable concrete

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ABSTRACT

Permeable concrete is used to reduce urban flooding as it allows water to flow through normally impermeable infrastructure. It is prone to clogging by particulate matter and predicting the long-term performance of permeable concrete is challenging as there is currently no reliable means of characterising clogging potential. This paper reports on the performance of a range of laboratory-prepared and commercial permeable concretes, close packed glass spheres and aggregate particles of varying size, exposed to different clogging methods to understand this phenomena. New methods were developed to study clogging and define clogging potential. The tests involved applying flowing water containing sand and/or clay in cycles, and measuring the change in permeability. Substantial permeability reductions were observed in all samples, particularly when exposed to sand and clay simultaneously. Three methods were used to define clogging potential based on measuring the initial permeability decay, half-life cycle and number of cycles to full clogging. We show for the first time strong linear correlations between these parameters for a wide range of samples, indicating their use for service-life prediction.

1. Introduction

Permeable concrete, also known as pervious concrete, is used to alleviate local flooding in urban areas as it allows water to flow through normally impermeable infrastructure. However, permeable concrete exhibits loss of performance over time due to clogging caused by a build-up of sediment particles on the surface or within the pore structure (Deo et al., 2010; Yong et al., 2013; Mata and Leming, 2012; Coughlin et al., 2012; Tong, 2011). Predicting the effect of clogging on the long-term performance of permeable concrete is challenging and there is currently no reliable means of characterising clogging potential to enable performance comparison between different pavement systems. This is important as it would enable designers and asset owners to make better informed decisions, develop effective maintenance strategies and provide accurate service-life predictions.

A number of studies have investigated the effect of sediment type on clogging under laboratory conditions. Coarse sand particles did not significantly reduce permeability as these large particles did not enter surface pores (Coughlin et al., 2012; Deo et al., 2010). However, Schaefer et al. (2011) and Tong (2011) found that sand caused significant reductions in permeability, while fine-grained silty clay produced almost no effect as it washed through the sample with no concentration in the pore structure. Combinations of silty clay and sand caused the highest permeability reductions, with complete clogging after a small number of cycles. This was attributed to the wide particle size distribution that increases the probability of retention, and the cohesive nature of clay causing more surface interactions and particle adhesion. Nguyen et al. (2017) found that silty clay and sand caused the most rapid clogging. The work of Coughlin et al. (2012) concluded that clay caused approximately ten times more clogging per unit mass than sand. Haselbach (2010) found very little clay infiltration in sectioned cores and samples exposed to bentonite clay clogged the most with particles accumulating on the top exposed surface creating a low permeability layer. Details of relevant research is summarised in Table 1.

The findings from such studies are not consistent, and this can be attributed to differences in the clogging material, the pore structure of the samples tested, exposure conditions and other variables. A comprehensive review was recently presented (Kia et al., 2017). 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 sediments are likely to clog within the permeable concrete or underlying soil (Chopra et al., 2010; Mata and Leming, 2012; Lucke and Beecham, 2011). These findings highlight the complexity of the clogging process and suggest there is no single location within the permeable concrete where clogging occurs.

There are also differences in exposure and test conditions that could influence results. In some studies, the clogging sediment is spread on top of the sample and permeability is measured by allowing water to flow through. In other studies (see Table 1), sediment is mixed in water and the slurry is then applied to the sample. Some studies have applied

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Table 1
Summary of selected recent studies on clogging of permeable concrete, arranged according to publication date.

Reference	Method	Findings
Deo et al., 2010	Fine (0.1–0.84 mm) and coarse (0.84–1.8 mm) grained river sand were used as clogging material. For each clogging cycle, 25 g of the sand was spread evenly on the specimen surface and permeability of water flow through the specimen was measured. This was repeated until the flow rate was very slow or when further sand additions did not result in noticeable changes in permeability.	Permeability decreased with increasing sand addition due to blocking of pore channels, porosity reduction and tortuosity increase. Higher porosity samples showed higher residual permeability at the end of testing due to larger pore sizes and pore connectivity. Coarse sand did not result in significant permeability reductions compared to fine sand because large particles are prevented from entering the sample.
Haselbach, 2010	Cores were exposed to various clay sediments mixed in water: 0.167 g/L and 0.233 g/mL of kaolin, 0.03 g/mL of bentonite, and 0.01 g/mL, 0.025 g/mL and 0.1 g/mL of red clay. After each clogging cycle, samples were dried in oven for at least 24 h. After the clogging cycles were completed, the excess clay was swept off with a brush from the top of the sample after drying. The sample was then exposed to rinsing cycles.	Full clogging occurred after four to ten cycles. Very little clay infiltration was observed. Most of the clay accumulated on sample surface creating an impermeable layer. Samples appear to have vertical porosity distribution with smaller pores near the top. The cores that were clogged with less cohesive clays tended to restore part of their permeability after exposure to 5–8 rinsing cycles.
Schaefer et al., 2011; Tong, 2011	Three sediments (sand, clayey silt and clayey silty sand) were applied over 20 cycles at 5 g or 40 g of each sediment type spread evenly on sample per cycle. Clogged samples were cleaned using three different techniques and permeability was measured to determine recovery rate.	Clayey silty sand caused the highest permeability loss. Samples with higher porosity had higher residual permeability after clogging. A significant quantity of sand and clayey silty sediments remained on the sample surface. Clay adhered to sand particles to form a mud layer on the sample surface.
Coughlin et al., 2012	Sample was exposed to eight clogging cycles: one without sediments, three with increasing sand (20, 60 and 140 g), three with increasing clay (2, 6 and 14 g) and 140 g of sand per cycle, and one after pressure washing. The clogging material was uniformly distributed on top of the sample.	Both sand and clay caused clogging, but clay produced approximately ten times more clogging per unit mass compared to sand. Pressure washing was ineffective at restoring infiltration capacity because of subgrade clogging.
Mata and Leming, 2012	Clayey silt and clayey silty sand was applied on top of the sample at 0.53 g/L each. Following permeability measurement, sample was drained and air-dried for 24 h. Sample was cleaned, pressure washed and the permeability re- measured. This procedure was conducted three times for each sample.	Clayey silty sand produced the highest permeability loss and lowest recovery. Sediment deposits were observed retaining on top or in the specimen. Significant quantities of clayey silt were deposited at the bottom of the sample, retained by the filter fabric
Kayhanian et al., 2012	Collected sediments (particularly clay and inorganic form) from the permeable concrete cores were ranging in particle size from 1000 to 38 µm.	The combined image analysis and porosity profile of the cores showed that most clogging occurred near the surface of the pavement.
Nguyen et al., 2017	Samples were exposed to 253 g of sediments (75% silty clay, 25% of sand, mixed in water per cycle for 5 cycles). After each clogging cycle, the sample was rinsed with water and permeability re-measured.	Permeability was reduced to lower than 95% of the initial value. The blended material was believed to be the most damaging clogging agent, leading to full clogging after a small number of cycles.

sediments for a set number of cycles while others have proceeded until the sample is fully clogged. Some research has included a cleaning cycle to simulate periodic maintenance (Haselbach, 2010; Deo et al., 2010; Patel et al., 2012; Mata and Leming, 2012; Coughlin et al., 2012; Schaefer et al., 2011; Tong, 2011; Nguyen et al., 2017). Therefore, the variable findings are due to researchers using a range of different test methodologies. It would clearly be beneficial to have a standardised approach to evaluate the long-term performance of permeable concrete under conditions that mimic natural exposure environments where clogging occurs.

The aim of this research was to improve understanding of clogging and the effects this has on permeable concrete, and to develop methods to characterize clogging potential as a performance indicator and/or for use in predictive modelling. The permeability of a range of porous materials was tested and this included packed glass spheres, packed gravel aggregates, laboratory prepared permeable concrete and commercially available permeable concretes. Packed glass spheres and gravel aggregates were tested because data from simple model systems can help support, validate and enhance our understanding of actual permeable concretes. Experimental variables were particle size (1.25–14 mm), effective porosity (7–36%), hydraulic gradient (ratio of hydraulic head to sample thickness: 0.33 to 5) and clogging method. Two laboratory exposure methods, combined "sand and clay" and alternate "sand or clay", were used to simulate clogging during flooding.

2. Experimental program

2.1. Samples

Four types of samples were tested: a) packed glass spheres (GS), b) packed gravel aggregates (AGG), c) laboratory prepared permeable concrete (PC-Lab) and d) commercially available permeable concrete (PC-Com). Close packed glass spheres and aggregates of varying sizes were used to study the effect of pore structure on clogging. Glass spheres of 2, 4 and 8 mm diameter were used. Thames Valley siliceous gravel aggregate from the UK was sieved into three size ranges: 1.25–2.5 mm, 2.5–5 mm, and 5–10 mm. These are referred to as 1.25 mm, 2.5 mm and 5 mm AGG respectively. Samples were prepared by placing the glass spheres or aggregate particles into a 90∅ × 150 mm cylinder in three equal layers and consolidated by vibrating each layer for 25 s. The gravel had a specific gravity of 2.51 and 24-h absorption of 1.76%. A total of 28 packed samples were prepared.

Permeable concrete samples (PC-Lab) with target porosity ranging from 11 to 30% were prepared using CEM I 52.5N and Thames Valley (UK) siliceous gravel (1.25–14 mm) at a water/cement (w/c) ratio of 0.35. These were proportioned using a developed mix proportioning method based on absolute volume. The required paste volume was calculated by deducting the design porosity from the packed aggregate void content and adding a 5% compaction index. The cement and water contents were calculated from paste volume and w/c ratio. Coarse aggregate content was calculated from design porosity and paste volume. Fine aggregate was not used. Trial testing showed this method produced samples with measured void content close to the design porosity. Two mixes showed "paste drain down" (explained in Section 3.2) and therefore a viscosity-modifying admixture (VMA) (MasterMatrix SDC 100) was used in these mixes. Mix proportions are shown in Table 2.

The PC-Lab samples were cast in steel moulds (100^3 mm^3) and

Table 2
Mixture proportions of laboratory prepared permeable concrete samples.

	PC-Lab					
	11% P	19% P	25% P	26% P	26% P*	30% P
Cement (kg/m^3)	315	255	255	180	255	105
Aggregate (kg/m^3)	1481	1581	1581	1581	1581	1581
Water (kg/m^3)	110	89	89	63	89	37
VMA (%, kg/m^3)	–	–	0.2, 0.5	–	0.3, 0.8	–
w/c	0.35	0.35	0.35	0.35	0.35	0.35
Paste vol. (%)	21	17	17	12	17	7
Target porosity (%)	11	19	25	26	26	30