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RESEARCH AND APPLICATION OF PERVIOUS CONCRETE AS A SUSTAINABLE PAVEMENT MATERIAL: A STATE-OF-THE-ART AND STATE-OF-THE-PRACTICE REVIEW

Rui Zhong[1], Zhen Leng[2], Chi-sun Poon[3]

[1]Ph.D, Postdoctoral Fellow, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University

Hung Hom, Kowloon, Hong Kong

Email: rui.zhong@polyu.edu.hk

[2]Corresponding Author, Associate Professor, Civil and Environmental Engineering, The Hong Kong Polytechnic University

Hung Hom, Kowloon, Hong Kong

Email: zhen.leng@polyu.edu.hk

Tel.: +852 27666007

[3]Chair Professor, Civil and Environmental Engineering, The Hong Kong Polytechnic University

Hung Hom, Kowloon, Hong Kong

Email: cecspoon@polyu.edu.hk

ABSTRACT

Pervious concrete (PC) has gained renewed interest in the past decade due to its positive environmental impacts. Extensive research employing a variety of strategies has been conducted to improve the overall performance of PC. Numerous literatures have been published. With the advances in high performance pervious concrete (HPPC), widespread application of this material has been made possible. This paper reviews the state-of-the-art and state-of-the-practice research and application of PC. Emphasis has been laid on the pore system characterization (PSC) and its influence on the mechanical, hydraulic and acoustical properties of PC. Among the various applications of PC, this review focuses on its application as a sustainable pavement construction material.

Keywords: pervious concrete; pore system characteristics; sustainable pavement; noise reduction; compressive strength

1 INTRODUCTION

Pervious concrete (PC), also known as porous or permeable concrete, is a class of concrete characterized by a relative high volume of connected pores, typically in the range of 15% to 30% with pore sizes ranging from 2 to 8 mm [1], and a water permeability of about 2 – 6 mm/s [2-3]. This is achieved by intentionally incorporating continuous voids through gap grading the coarse aggregate and eliminating or minimizing the usage of fine aggregate. Typical designs of PC are presented in **Table 1**. The American Concrete Institute (ACI) defines PC as "concrete containing little, if any, fine aggregate that results in sufficient voids to allow air and water to pass easily from the surface to underlying layers" [4].

Table 1 Typical compositions of PC

Water to binder ratio (*w*/B)	Aggregate to binder ratio (A/B)	Fine sand (%)	Authors
0.26~0.33	3.2~3.7	0~15	Kevern et al. [5]
0.32~0.33	1.7~6.0	-	Deo at al. [6]
0.22~0.55	2.5~3.5	-	Zhong and Wille [7]
0.25~0.35	3.2~3.9	-	Yang [8]
0.37~0.42	2.9~4.2	-	Ghaffori and Dutta [9]
0.27~0.35	3.4~4.5	0~6.5	Huang et al. [10]
0.27~0.51	4.0~4.7	0~20	Meininger [11]

Although PC has been used for over 30 years, the material is attracting renewed interests recently. It is attributable to the Federal Water Pollution Control Act [12] and the Environmental Protection Agency (EPA) storm water regulations [13] that require control of both the quantity and quality of storm water runoff. The ability to allow water penetrating through its open pore structure makes PC a very effective tool to control storm water runoff. Additionally, the rapid expansion of impermeable surfaces and associated issues such as heat island effect, tire-pavement interaction noise, ground water depletion and traffic safety is another factor contributing to the increasing popularity of this material, as PC demonstrates potential to resolve these issues [14-15]. Therefore, it is promoted as a construction material for parking lots and road surfaces. **Fig. 1** schematically illustrates the advantages and disadvantages of PC in comparison to conventional impervious concrete (CIC).

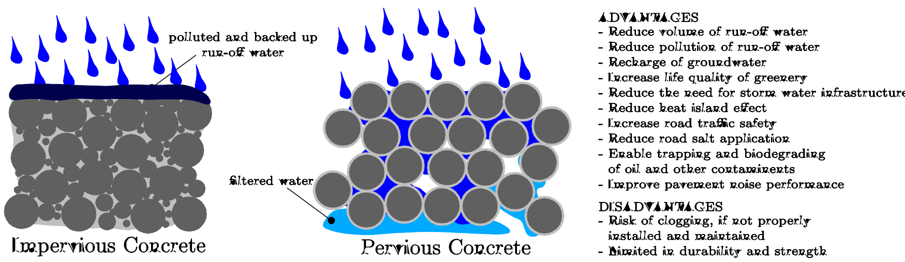

Fig. 1 Comparison of PC to CIC

Fig. 2 shows the number of publications related to PC over the last decade. A survey of the literature indicates that this development spreads over the major continents, and is particularly intense in Europe, US and Japan. It indicates that we have entered an intense phase of research on the development of high performance pervious concrete (HPPC) and the pace of research will likely continue to accelerate. There has been a number of review articles on PC [16-18]. The purpose of this article is not to repeat these reviews, but rather to promote the concept of sustainable pervious concrete pavement (SPCP). Therefore, the literatures referenced are not meant to be exhaustive of what has been published. Specifically, this paper is aimed at highlighting the advantages and limitations of PC, to stimulate additional research to overcome current obstacles, and to generally accelerate convergence of PC technology developments that support the realization of SPCP. In light of that both structural and functional properties of PC pavement are dependent on the pore system characteristics (PSC) of PC [19-21], the review has been focused on the quantification of PSC and their influence on the mechanical, hydraulic and acoustic performance of PC. As for the structural application of PC, emphasis was laid on pavement.

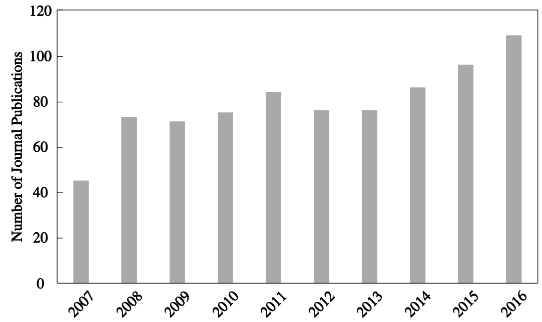

Fig. 2 Archived journal publications on PC over the last decade (2007-2016) (Source: Google Scholar online)

2 PERVIOUS CONCRETE

2.1 PORE SYSTEM CHARACTERIZATION

2.1.1 POROSITY

Porosity is one of the most important PSC. However, there is still confusion as to the definition of porosity and which type of porosity should be used to characterize PC. Not all voids in PC are effective for liquids to flow through. Some pores are isolated from others and therefore are not available for water penetration. In addition, there are smaller pores, such as capillary pores and dead-ended pores, that retain fluids due to surface tension and capillarity effect and therefore are not effective for transport of fluid. Nevertheless, these pores affect the strength of PC. Zhong and Wille suggested that the pore system in PC should be differentiated as effective porosity and total porosity [22]. Effective porosity is defined as the ratio of the volume of accessible pores (connected pores) to the total volume of the material. It is critical for the hydraulic property of PC. Total porosity is defined as the ratio of total pore volume to the total volume of material. It dictates the strength of PC. The total porosity takes into account the volume of non-accessible pores and accessible pores. The volume of non-accessible pores may be further divided into non-connected pores left in the space between aggregates and the pores in the matrix.

Mercury intrusion method specified in ASTM D4404 is commonly used to determine pore sizes and their distribution for CIC. However, this method is not applicable to PC due to its large pore volume and connected pore system. Therefore, a variety of methods is proposed to quantify the porosity of PC. Crouch et al. [23] modified the AASHTO T166 Standard Method and proposed a test method for the porosity of PC. This method differs from the other porosity test methods since it uses an InstroTek Corelok® System to improve the extraction of air and the penetration of water into the porous matrix of PC. It is expected that less air is entrapped in the sample and water penetrates into PC faster compared to a simple submersion approach due to the vacuum condition in the polymer bag. However, this method requires the use of a proprietary equipment. To overcome this limitation, Montes and his coworkers developed a method based on the Archimedes principle using standard laboratory equipment [24]. The porosity of PC can be calculated using **Eq. (1)**

$$P=[1-((W_D-W_S)/\rho_w)/V_T]\times 100 \qquad (1)$$

where P is the porosity of the specimen; W_D and W_S are the dry mass and submerged mass of the specimen, respectively; ρ_w is the density of water; V_T is the total volume of the specimen.

Statistical determination of porosity using image analysis (IA) and statistical counts has also been proposed to quantify the porosity of PC. 16-bit greyscale X-ray planar images of a series of PC thin sections were employed by Zhong and Wille [19] to calculate the total porosity of PC. The original X-Ray images were cropped to remove the background and eliminate the wall effect (**Fig. 3**). Then the cropped images were reduced to binary images by thresholding. Otsu's method integrated in a Matlab Image Processing Toolbox was used to conduct the conversion and the porosity was calculated based on the converted binary images.

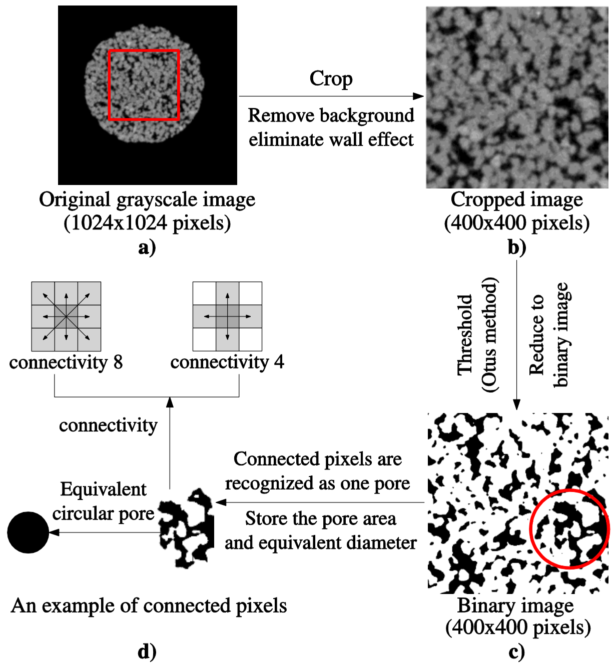

Fig. 3 Illustration of the IA process

A similar IA approach was also employed by Akand et al. [25], Neithalath et al. [26] and Marolf and his coworkers [27] to quantify porosity. Different facilities such as X-ray computed tomography and flatbed scanner have been used to obtain the original images. A variety of strategies were applied to improve the quality of the obtained images. Significant edge effect or irregularities were discarded [26]. The original images were cleaned by a filter and a mask was then applied to improve the contrast between the different phases [27]. The processed images were then analyzed using different software such as ImageJ® and ImagePro®. The porosity of pervious concrete is eventually extracted after thresholding. It is expected that the accuracy of the IA approach is higher than the experimental methods. Additionally, more detailed PSC can be revealed employing the IA approach. However, the general experimental method for porosity determination is easy to use. If the major parameter of interest for an application is porosity only, the experimental method is suggested. In contrast, if the hydraulic performance and mechanical response, both of which are dependent on the PSC, are concerned, IA approach may be a better option due to its ability to provide additional information such as pore size distribution.

2.1.2 PORE SIZE, ITS DISTRIBUTION AND CONNECTIVITY

While porosity is undoubtedly one of the most important PSC of PC, such a property alone cannot determine the performance of PC. For different PC with the same porosity, different pore size distribution and tortuosity, and thus microstructure can be present leading to varying mechanical, hydraulic and acoustic performance. Deo et al. found that the compressive response is influenced by the pore sizes, their distributions and spacing [1]. Zhong and Wille also confirmed the influence of pore size and its distribution on the compressive response of PC [19]. Rehder et al. demonstrated that although fracture toughness is primarily dependent on the porosity of PC, an increase in pore size leads to a reduction in fracture toughness at a given porosity [28]. Neithalath and his coworkers [21] reported that for a similar porosity, variations in acoustic absorption coefficient (an indicator of a material’s ability to absorb acoustic energy) and permeability were observed. Zhong and Wille demonstrated that porosity is a necessary but insufficient parameter to determine the hydraulic conductivity of PC. The accuracy for the predicted hydraulic conductivity was improved once the pore tortuosity was taken into consideration for the modeling [20]. Based on these observations of performance dependency on pore size, its distribution and tortuosity, it is believed that appropriate characterization of these PSC can result in a better understanding and an enhanced prediction accuracy of the behaviors of PC and facilitate optimum mixture design for desired performance.

2.1.2.1 IMAGE ANALYSIS

Due to the random nature and spatial complexity of the microstructure of PC, it has been either over simplified or ignored in a variety of empirical models for the performance prediction of PC. Mathematical knowledge and techniques have been developed and actively used to analyse and characterize the microstructure of porous materials [29]. Stereology combined with IA, can be a powerful tool for inferring PSC from two-dimensional analysis. Recently, IA has been successfully adopted by many researchers to capture the details of the pore structure of PC. Digital images of two dimensional thin sections are usually obtained in the form of grey-scale image either by X-ray, scanning electron microscopy (SEM) or high performance scanner. These grey-scale images are then be transformed to binary images by thresholding. A threshold can then be chosen, either manually or by a threshold algorithm, so that all pixels with grey levels above this threshold are white (solid) and all below are black (pores). Once the binary images with good quality are obtained, further processing is performed to eliminate artefacts and noise. Mathematical morphology is a very powerful tool for this purpose. Eventually, different PSC can be extracted.

2.1.2.2 PORE SIZE

Stereological, morphological and probabilistic approaches have been proposed to extract pore size of PC based on IA. Marolf and his coworkers defined a characteristic pore size (d_c) as an approximation for the representative pore size [27]. It is calculated from the median of all the pores with a size greater than 1mm obtained from IA. Pores smaller than 1mm were excluded since incorporation of a large number of such small features always led to an unrealistic pore size. An empirical equation as shown in **Eq. (2)** was proposed to correlate the characteristic pore size to a single sized aggregate (D_{agg}).

$$d_c = 1.44 + 0.36D_{agg} \tag{2}$$

Neithalath et al. proposed the concept of effective pore size (d_{50}) based on the stereological method [26]. The equivalent diameters were calculated assuming the pores were circular once the area of each individual pore was obtained from two dimensional images. Pore size histograms and cumulative frequency distribution curves of the pore size were then produced. The effective pore size is defined as the pore size at 50% of the cumulative frequency distribution. Pore diameter derived from morphological method using two-point correlation (TPC) function or granulometric density function were also employed to characterize the pore system in PC [26]. The characteristic pore diameter (d_{TPC}) based on TPC function is estimated according to the correlation length (l_{TPC}) as follows:

$$d_{TPC} = \frac{l_{TPC}}{1 - \phi_A} \tag{3}$$

where ϕ_A is the pore area fraction of the image, the correlation length (l_{TPC}) is defined as the abscissa of the intersection point of the slope of TPC function at l=0 and the horizontal asymptote at which $l\rightarrow\infty$. Another morphological function has also been assessed. This method involves the application of a series of morphological opening with structuring elements (SE) of increasing size. Progressive transformations on the same object leads to a group of objects, from which information about the size of the original object could be inferred. For each opening, the normalized pixel size distribution function can be calculated according to **Eq. (4)**.

$$\mathrm{N(k)} = 1 - \frac{P_s(k)}{P_s(0)} \tag{4}$$

where $P_s(k)$ is the sum of all the pixels in the image opened by the kth structuring element, and $P_s(0)$ is the sum of all the pixels in the original image. The granulometric density function G(k) can then be derived as:

$$\mathrm{G}(k) = \mathrm{N}(k+1) - \mathrm{N}(k) \tag{5}$$

The local maximum of the granulometric density function is related to the critical pore radius of the material. Therefore, the critical pore size (d_{cri}) obtained in this way is a potential candidate to characterize the pore system in PC. Zhong and Wille proposed the mean pore size $(\overline{d_p})$ from the cumulative pore size distribution derived from linear-path function (LPF) [19]. The LPF is the cumulative distribution function (CDF) of the probability of finding a line segment of length z entirely in one phase of a two phase material when randomly placed into the sample. PC can be treated as an impenetrable equal particle system based on two assumptions: 1) aggregates used to produce PC are single sized or gap graded; 2) the matrix covering the aggregates is relatively thin compared to the aggregate size. Therefore, the LPF for the impenetrable equal size particle two-phase random system was selected and the explicit formulation to calculate the mean pore size was then derived as follows:

$$\overline{d_p} = \begin{cases} \dfrac{2\phi_t d_a}{3(1-\phi_t)} \; for\ two\ dimentions\ (D=2) \\ \dfrac{\pi\phi_t d_a}{4(1-\phi_t)} \;\; for\ two\ dimentions\ (D=3) \end{cases} \tag{6}$$

where ϕ_t and d_a are the total porosity and the diameter of the aggregate, respectively.

2.1.2.3 PORE SIZE DISTRIBUTION

While it is typical to represent the pore system in a porous material using a single characteristic pore size, the pore size distribution (PSD) in a porous material is also of great importance. This is especially true for a heterogeneous porous medium such as PC. Therefore, a single value of pore size alone might not be sufficient to characterize the material behaviour. Indeed, a variety of studies have demonstrated that the mechanical, hydraulic and acoustic performance of PC are dependent on the PSD of the pore system [19, 21, 30]. Mercury intrusion porosimetry (MIP) is generally used to determine PSD of CIC. However, this method is not applicable to PC due to its large pore volume and connected pore system. A few innovative investigations have been conducted to overcome this obstacle [1, 19]. Based on the observation that the PSD extracted from two dimensional images is right-skewed, Neithalath et al. suggested to use Weibull and log-normal families of distributions to model such right skewed process [1]. A two-parameter Weibull distribution (WBD) was selected as shown in **Eq. (7)**:

$$\mathrm{F}(\mathrm{d};\alpha,\beta) = \begin{cases} 1 - exp\left[-(d/\alpha)^{\beta}\right] & d \geq 0 \\ 0 & d < 0 \end{cases} \tag{7}$$

where α, β and d are the scale parameter, shape parameter and pore size, respectively. It was selected for the following reasons: (1) it is able to cover a wide range of statistical distributions by changing the Weibull shape parameter; (2) it can be used for samples with small size; (3) it could provide additional flexibility when an exponential distribution might be adequate. The parameters in the Weibull distribution were determined using probability plotting method due to its best performance for intermediate sample sizes (n<20).

Zhong and Wille proposed a PSD based on probability theory [19]. LPF was tailored for PC as follows:

$$L(z) = \begin{cases} \phi_t exp\left(-\frac{3(1-\phi_t)z}{2\phi_t d_a}\right) \; for\ three\ dimensions\ (D=3) \\ \phi_t exp\left(-\frac{4(1-\phi_t)z}{\pi\phi_t d_a}\right) \; for\ three\ dimensions\ (D=2) \\ \phi_t exp\left(-\frac{(1-\phi_t)z}{\phi_t d_a}\right) \; for\ three\ dimensions\ (D=1) \end{cases} \quad (8)$$

where ϕ_t and d_a are the total porosity and the diameter of the aggregate, respectively.

Based on the definition of LPF and the physical meaning of the CDF, the following cumulative pore size distribution frequency (CPSDF) equations as shown in **Eq. (9)** have been obtained:

$$F = \begin{cases} 1-exp\left(-\frac{3(1-\phi_t)z}{2\phi_t d_a}\right) \; for\ three\ dimensions\ (D=3) \\ 1-exp\left(-\frac{4(1-\phi_t)z}{\pi\phi_t d_a}\right) \; for\ three\ dimensions\ (D=2) \\ 1-exp\left(-\frac{(1-\phi_t)z}{\phi_t d_a}\right) \; for\ three\ dimensions\ (D=1) \end{cases} \quad (9)$$

It has been reported that the LPF method outperforms the WBD method based on the lower variation of extracted cumulative pore size distribution frequency curve.

2.2 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity, sometimes referred as water permeability, is a quantitative measure that characterizes the flow of water through a porous media. It is an important design parameter for the desired functionality of PC. Since the hydraulic conductivity of PC is several orders of magnitude larger than water transport property of CIC, conventional methods of measuring water transport properties of CIC are not applicable. Constant head and falling head are the two of the most commonly used methods to experimentally determine the hydraulic conductivity of PC. For the falling head method, water pressure head is recorded at predetermined intervals after the experiment starts, until water stops flowing out of the system and the pressure head is reduced to a desired level. The data obtained from each experiment is analysed using the following equation:

$$K = \frac{aL}{At} In \frac{H_1}{H_t} \quad (10)$$

where K is the hydraulic conductivity, a is the cross-sectional area of the pipe holding the sample, A and L are the cross-sectional area and the length of the PC sample, respectively; t is the time water head reaches the predetermined final level. For constant head method, the water head difference between the in-flow and out-flow is kept constant and the out-flow overtime is continuously tracked. The hydraulic conductivity is given by **Eq. (11)** as follows:

$$K = \frac{QL}{Ah} \quad (11)$$

where K is the hydraulic conductivity, Q is the flow rate of water, L and A are the length and cross-sectional area of the sample, respectively; h is the water head difference of the in-flow and out-flow. It worth pointing out that these two equations are derived based on Darcy's law which is only valid for laminar flow. Its applicability to PC remains a controversial issue. Previous study demonstrated that Darcy's law may not be valid for pervious concrete due to its very high porosity [10]. There are also experimental study [24] that substantiates the laminar flow assumption.

To achieve a successful design of PC with a desired hydraulic conductivity, it is critical to understand the influence of PSC and be able to develop appropriate models to predict the permeability. Water transport property has been extensively studied and a variety of empirical equations correlating hydraulic conductivity to porosity were proposed (**Table 2**).

Table 2 Equations to predict hydraulic conductivity of PC

No.	Model	Equation	Used by	Type
1	Linear	$K^{*}=m\phi+n$	Luck et al. 2006 [31]	empirical
2	Power	$K^{*}=m\phi^{n}$	Ghafoori et al. 1995 [9]	
3	Exponential	$K^{*}=me^{n\phi}$	Deo et al. 2010 [32]	
4	Kozeny-Carman	$K^{*} = 18\frac{\phi^3}{(1-\phi)^2}$	Montes et al. [33]	semi-empirical
5	Katz-Thampson	$k^{**} = \left(\frac{1}{226}\right)\frac{\sigma}{\sigma_0}d^2$	Neithalath et al. 2010 [30]	

*K hydraulic conductivity, ϕ porosity, m and n empirical constants

**σ electrical conductivity of porous material, σ_0 electrical conductivity of conducting medium

However, the empirical models (linear, power and exponential model) only account for the influence of porosity. Research has demonstrated that pore tortuosity plays an important role in determining the hydraulic conductivity [20, 34]. Few studies have been carried out quantifying the influence of pore tortuosity on hydraulic conductivity of PC. By combining the Kozeny-Carman model and the modified parallel effective conductivity model, a hydraulic connectivity factor was introduced by Neithalath et al. [34] to account for the influence of pore tortuosity. But this method is difficult to be used for practical applications due to the requirement of complicated measurement. Zhong and Wille correlated tortuosity to relative mean pore size based on the fact that the mean pore size is derived from PSD which is an indicator of the microstructure of the pore system [20] (**Fig. 4**). This method uses readily available design parameters to quantify the tortuosity thus is easy to use for practical design purpose.

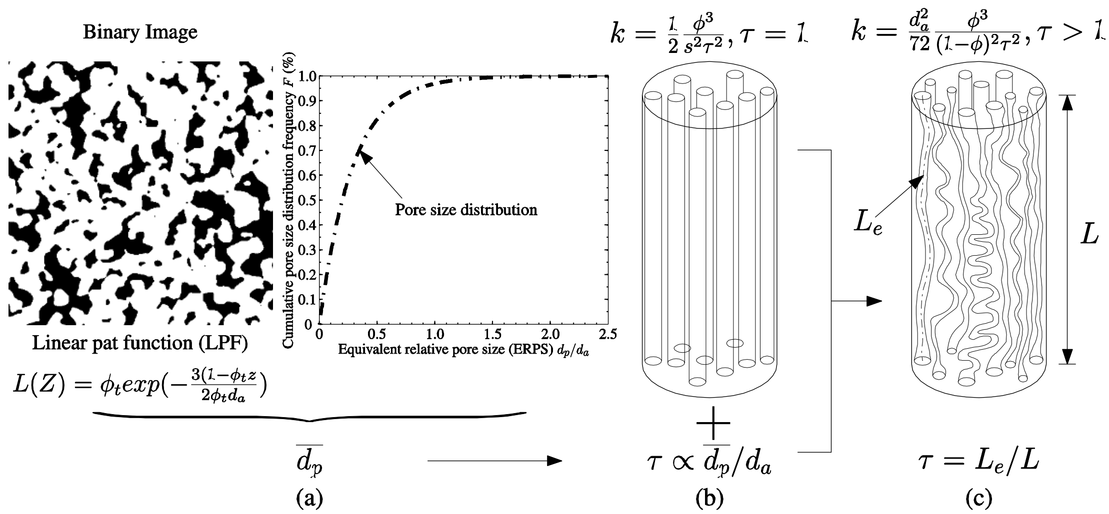

Fig. 4 Influence of tortuosity on the hydraulic conductivity of PC

2.3 SOUND ABSORPTION

Noise pollution is increasingly being recognized as a serious environmental issue. Although noise is usually generated from various sources, traffic noise has been shown to be a major source of the total environmental noise [35]. Noise generated by traffic is annoying to nearby residents, which in turn undermines the quality of their life [36]. It can cause health problems such as sleeping disturbances and learning disabilities [37]. Therefore, there is an increasing demand for quieter pavement. Among all sources of traffic noise, tire-pavement interaction noise (TPIN) is the dominant one, especially when vehicles move at medium to high speed [38]. Different noise reduction approaches have been adopted to combat TPIN. However, commonly used techniques, such as erection of noise barriers and use of insulating materials, are proven to be expensive [27, 38]. Therefore, researchers throughout the world started using alternative pavement surfaces in an attempt to mitigate noise at source. Application of a PC layer on top of CIC has been suggested as one potential solution for this problem [34]. The effectiveness of PC as a TPIN abatement tool is attributable to lower noise generation and improved sound absorption. The porous surface is believed to reduce the structure borne air pumping effect (currently thought to be one of the primary noise generation mechanisms) to minimize noise generation while the pore system of the material absorbs the sound energy through internal friction. A large number of experimental studies have been conducted to develop acoustically efficient PC. Gerharz found that 4-8 mm aggregates were appropriate to produce PC for sound absorption purpose [39]. Marof et al. investigated the influence of aggregate size and gradation and concluded that PC produced using properly blended aggregates can lead to improved acoustic absorption [27]. Park and his co-workers assessed the influence of void ratio and recycled aggregates and reported the optimum void ratio and recycled aggregate content of 25% and 50%, respectively [40]. Khankhaje et al. used different sizes of oil palm kernel shell (KS) and cockle shell (CS) to partially replace natural coarse aggregate and suggested that it is practical to use KS and CS to produce cleaner and quieter PC pavement [41]. Kim and Lee evaluated the influence of cement workability and aggregate type [42]. It was found that the workability of cement did not drastically affect the acoustic absorption of PC within the investigated range and the size of aggregate had slight effects on the acoustic absorption for the aggregate size of 4-19mm. Neithalath et al. studied the influence of pore connectivity [34]. A pore connectivity factor was defined and extracted using electrical impedance approach. It was found that pore connectivity factor and the maximum acoustic absorption coefficient were linearly related.

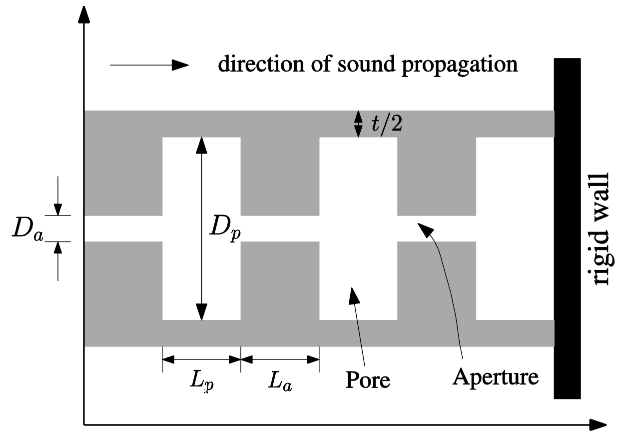

Fig. 5 Idealized alternating cylinder model for sound propagation in PC

In addition to experimental studies, limited theoretical investigation has also been conducted. A model originally proposed by Lu and Chen for sound absorption analysis of cellular metals with semi-open cells was adopted to predict the acoustic absorption of PC [21]. PC has been idealized as a series of alternating cylinders as shown in Fig. 5. A simplified structure factor proposed by Allard et al. as presented in **Eq. (12)** was used to account for the tortuosity of the pore system in PC [43].

$$\tau = \frac{4}{9}\frac{(D_a^2 L_a + D_p^2 L_p)}{(L_a + L_p)D_p^2} \tag{12}$$

where D_a and D_p are the diameters of the aperture and pore, respectively; L_a and L_p are the lengths of the aperture and pore, respectively;

2.4 MECHANICAL PERFORMANCE AND DURABILITY

Typical compressive strength of conventional PC with porosities between 15% and 30% ranges from 7 to 25 MPa [22]. Different strategies have been employed to improve the strength of PC. Compressive strength over 20 MPa was reported by reducing the aggregate to binder ratio [44-45]. Compressive strength of PC exceeding 40 MPa was achieved through the incorporation of supplementary cementitious materials (SCMs) such as silica fume (SF) and fly ash (FA), polymer modification of the matrix or combination of SF and fine sand [46-47]. It is worth noting that PC with compressive strength more than 50 MPa was reported in literature. However, a 2 MPa mold pressure was applied during testing and the compressive strength was reduced to 27 MPa when the mold pressure decreased to 1 MPa [48]. Recently, HPPC characterized by a compressive strength in excess of 40 MPa was designed by Zhong and Wille [7, 22].

Prediction of the mechanical behaviour is essential for appropriate design and effective utilization of this material. Since porosity is one of the most important and easily obtainable PSC, studies have been focused to predict the compressive strength of PC using this parameter. Several exponential models have been proposed as shown in **Table 3** (model 1 and 3). Nevertheless, due to the random nature of the pores in PC, its mechanical performance cannot be reliably predicted using porosity alone. The mechanical response of PC is also strongly dependent on other PSC [19]. Deo et al. used IA technique to extract PSC such as area fraction of pores, number averaged pore size, specific area and mean free spacing of pores [1]. A multiple non-linear model was proposed to calculate the compressive strength of PC (**Table 3**, model 2). However, IA is time consuming and challenging to be used in practical application and the input parameters are not readily available or measurable. Motivated by the limitations, a model (**Table 3**, model 4) using easily accessible parameters was proposed by Zhong and Wille [19]. A LPF for impenetrable equal size particle two phase random system was selected and tailored for PC to extract the pore size distribution (PSD) of PC. The mean pore size is then derived based on probability theory. The obtained mean pore size along with total porosity and matrix strength were used to construct a model that predicted the compressive strength of PC very well. Attempts were also made to correlate the stress-strain response of PC and their PSC. Zhong and Wille employed Popovic's model and Carreira and Chu's model for the ascending part and descending part of the stress-strain relationship, respectively [22]. Three correction factors are correlated to relative mean pore size and pore size distribution density. The same models were adopted by Deo et al [1]. Multiple linear models were constructed to calculate different correction factors using a variety of PSC, such as porosity, number averaged pore size, three dimensional pore distribution density and mean free spacing of pores. Rehder and his coworkers investigated the fracture behaviour of PC [28]. It was found that porosity is the dominant factor that dictates the facture toughness of PC. For a similar porosity, a reduction of facture toughness was observed for samples with larger pore size.

Table 3 Summary of compressive strength prediction models for PC

No.	Equation	Author	Year
1	$\sigma = \sigma_0 exp[-(m - n\xi)\phi]^{*}$	Chindaprasirt [49]	2009
2	$\sigma = \alpha_0 + \alpha_1 \left[\frac{In(d_{MFS})}{In(\overline{d_n})}\right] + \alpha_2 \left(\frac{\phi_A}{S_p}\right)^{-1} + \alpha_2 In(\Gamma_{3D})^{**}$	Deo et al. [1]	2010
3	$\sigma = \sigma_0 \sqrt{(1-\phi)^m e^{-n\phi}}$	Lian [47]	2011
4	$f_c' = f_{c0}'(1 - m\phi_t)\left(\frac{d_a}{\overline{d_p}}\right)^n$	Zhong et al. [19]	2016

*m and n are empirical constants, σ_0 is the matrix strength, ξ is the fineness modulus of aggregate
$^{**}d_{MFS}$ is the mean free spacing of pores which is defined as the average value of uninterrupted surface-to-surface distances between all the neighboring pores, ϕ_A area fraction of pores from 2D images, S_p is specific area of pores, Γ_{3D} is three dimensional pore distribution density, $\overline{d_n}$ is the number averaged pore size and can be calculated from $\overline{d_n} = \frac{\sum N_i d_i}{\sum N_i}$, in which N_i is the number of pores with an average diameter of d_i
$^{***}f_c'$ and f_{c0}' are the compressive strength of PC and the matrix, respectively; $\overline{d_p}$ is the mean pore size; *m* and *n* are empirical constants

The high void content of PC makes it more vulnerable to different distresses than CIC. Therefore, durability is a concern for the application of PC. Laboratory tests and field investigation have been conducted for the freeze-thaw (F-T) and abrasion durability of PC. Zhong and Wille investigated the matrix type, pore system characteristics and fiber reinforcement on the F-T durability of PC [50]. It was demonstrated that use of higher strength matrix, smaller aggregate can lead to better F-T durability whereas no improvement can be achieved through fiber incorporation unless ultra-high strength matrix is employed. Comparative study on the laboratory and field performance of PC were conducted by Shu et al. showing that addition of air entraining agent (AEA) could still help to improve the F-T resistance [51]. Wu and his coworkers and Dong et al. assessed the abrasion durability of PC [52-53]. Their results indicated that adding latex desirably improved the abrasion resistance of PC.

3 PC PAVEMENT

Despite the various positive environmental impacts, the application of PC remains limited to parking lot, sidewalk and pathways. This is attributable to the drawbacks inherited from its random porous structure, such as limited strength, susceptibility to clogging and concerns for durability. Nowadays, with the increasing concern for sustainable development along with recent advances in HPPC, there has seen a rise on the application of PC for pavement construction.

3.1 STATE-OF-THE-ART PAVEMENT APPLICATION

For highway applications, PC usually overlays a CIC as a wearing course as illustrated in **Fig. 6**, providing both functionality of TPIN reduction and water drainage [54-55]. It is typically constructed through a "wet-on-wet" process. Noise abatement of this multilayer composite system is achieved due to PC's acoustical absorption capacity, while strength and durability are improved by the reinforcement of the underlying CIC pavement layer [54]. Both criteria of sufficient strength and durability under site-specific loading and environmental exposure must be satisfied to achieve a successful design of PC for the application of surface-wearing course. The following sections reviews the current pervious concrete pavement (PCP) practice around the world.

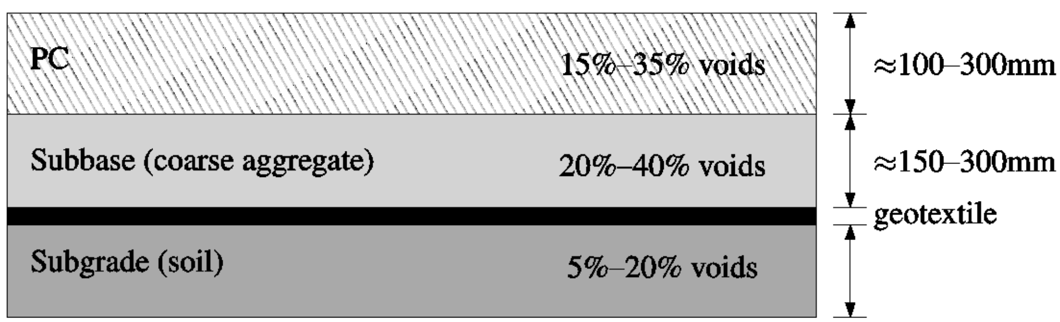

Fig. 6 Schematic cross section of PC wearing course on CIC

3.1.1 USA

PC is typically used in the United States as a tool for storm water runoff management [56]. Currently, typical full-depth application of PC in the United States is parking lots, pathways, and, in some cases, low-volume roads for storm water control applications [2]. Goede et al. conducted distress surveys on two collector streets in use for 20 years. They were constructed using PC and were subjected to equivalent traffic stresses. Pavement condition index (PCI) ratings demonstrated that properly designed PC can be used for most residential streets and many collector streets for a typical design service life (20-30 years) while maintaining satisfactory structural performance [57]. While PCP is used primarily for low-volume facilities, PCP as a single structural layer is also possible due to recent advance of HPPC [22]. A project on the mixture design of freeze-thaw durable PC has recently been finished at Iowa State University (ISU) [3]. The results of this study have demonstrated that a strong, F-T durable PC mix design is possible. The strength can be enhanced through the incorporation of a small quantity of fine sand and/or latex admixture to improve the bond between aggregate particles in the mixture. A comprehensive investigation on the mixture design of PC for the application of wearing course has been completed at ISU partnered with the Minnesota Department of Transportation (MnDOT) [58]. PC was constructed in 2008 on Cell 39 of the Low-Volume Road facility at MnDOT. CIC originally constructed during July 1993 was underneath the PC overlay. The nominal thickness of PC top surface is 4 in. (100 mm). Three condition surveys were conducted in June of 2009, 2010 and 2011, respectively. Detailed analysis of the survey data indicates that the overall performance and durability are good except localized distresses of pavement. Operations during rain events confirmed the good permeability of the PC overlay. The rainwater is quickly removed from the pavement surface and migrates laterally to the side of the pavement. These results demonstrated that PC is efficient in improving the safety of driving through splash and spray migration and hydroplaning reduction. TPIN was characterized using on-board sound intensity (OBSI) method according to AASHTO TP76. Results indicated that PC would be a promising method to mitigate TPIN in urban areas. A PC shoulder was installed along a rest stop on Interstate 4 in central Florida [59]. The PC shoulder was monitored over one year for wear and storm water management performance. No visual wear was noted on the PC. The average rate of infiltration over one year was higher than 1.5 inches per hour. It was concluded that this PC application was successful taking into consideration of wear, water quantity and quality.

3.1.2 JAPAN

Surface course of roadway is a typical application of PC in Japan [60]. Based on the current policy, all pavements in Japan will be replaced with pervious systems due to its improved safety and driving comfort [55]. Thin bonded PC overlays is considered as the most preferable option to switch from current concrete pavement to a pervious system. Simulation experiments in laboratories have shown that PC is rutting resistant and outperforms porous asphalt in terms of wear resistance to tire chains. Two experimental PC sections with a thickness of 200 mm (8 in.) were assessed in Japan [61]. In comparison with dense asphalt pavements, they demonstrated noise reduction of 6 to 8 dBA and 4 to 8 dBA for dry surfaces and wet surfaces, respectively. This investigation was performed under a condition that cars travelled at a speed ranging from 40 to 75 km/h. For heavy tracks, noise reduction was 4 to 8 dBA for dry surfaces and 2 to 3 dBA for wet surfaces.

3.1.3 EUROPE

Field performance evaluation of several pavements constructed in Europe using PC has demonstrated great potential in TPIN abatement and wet weather spray reduction [39, 62]. PC has also been applied to high-volume roadways as a surface-wearing course in Europe [3, 63]. Based on the experience from the limited applications, it has shown to be promising in reducing roadway noise, improving splash and spray, and friction. Undesirable durability in freezing weather was observed when PC was first constructed in Belgium [64]. However, once polymer additives were incorporated and a higher cement content was used, significant improvement in the service life was achieved. In a separate Belgian investigation, 5 dBA decrease in roadway noise was reported when PC with 19% porosity was used [65]. A recent European Scan (sponsored by the Federal Highway Administration/FHWA) demonstrated that the European prefers exposed aggregate concrete (EAC) to PC. The issues of PC such as clogging, ravelling, and winter maintenance were the explanation for the declining use of pervious pavements in Europe. However, participants in the European Scan pointed out that the concept of PC as a viable paving alternative was not given enough time for fully exploration [64].

3.1.4 CHINA

Nowadays, China is facing increasingly serious issue of urban flooding. Significant expansion of impervious area resulted from rapid urbanization of China since 1980s is one of the major contributing factors for this issue. Construction of conventional storm water management facilities, such as drainage system, is the common practice to tackle this issue. However, conventional drainage system is not capable of absorbing, maintaining or purifying water to relieve the water scarcity or prevent ground water pollution and depletion. Additionally, the drainage system in China is underdeveloped and the designs are obsolete [66]. Therefore, China has launched a nationwide initiative called "Sponge City" in 2012. It is an integration of a series of specific rainwater management technologies which aims to reduce storm water runoff at source [67]. PCP has been proposed as an alternative to CIC and has been constructed or planed in the pilot cities selected in 2015 and 2016. In addition to urban pavement applications for the development of Sponge City, PC has also been used as surface layer for highway pavement and tunnel pavement. Chen at al. studied the performance of PC applied as a surface layer for highway pavement [68]. They suggested that the top layer PC should be casted after initial setting of the underlying CIC. Smoothing should be avoided for improved interface bonding. Li and his coworkers assessed the influence of the timing of applying the PC overlay on the performance of a double-layer tunnel pavement [69]. The optimal time of paving for the PC top layer is between the initial setting time and the final setting time of the underlying layer. Zheng et al. investigated the joint space of PC used as a base for cement concrete pavement [70]. Recommendations were made for joint space when the thickness of concrete pavement is within the typical range.

3.2 FUTURE WORK FOR PC PAVEMENT APPLICATION

Use of PC as a pavement construction material is emerging but its application remains scare in comparison with the CIC. Further research is necessary to facilitate a wider application of PC as a sustainable pavement construction material.

- *Mixture design approach and standard test methods.* A large number of parameters affect the performance of PC. However, trial and error remains the common practice for the design of PC in the laboratory. Up to now, no standard approach is in place for the mixture design of PC. Therefore, meaningful comparison cannot be made between results from different laboratories. Additionally, either customized methods by individual researcher or standard test methods developed for CIC have been used for PC. Customized test methods vary from laboratory to laboratory. Test methods standardized for CIC may not be applicable to PC due to its unique porous structure. Thus, lack of standard test methods developed specifically for PC further complicates the comparison between different investigations and impedes the convergence of PC technology developments that support the realization of PCP.
- *Structural design code and procedure.* Due to the increasing concerns for sustainability, modern pavement design has shifted from a single objective task to a multi-objective systematic project. With the development of HPPC, this material can be designed to satisfy both the structural and functional requirements for pavement application. However, specifications such as minimum strength, threshold hydraulic conductivity, desired noise abatement or optimum thickness remain missing. There is a need to develop an universal structural design code and procedure for PC similar to those of other pavement materials such as CIC and asphalt concrete.
- *Field Construction, quality control, maintenance*. Discrepancy between laboratory results and field performance has been observed. It is inherent for PC due to its random and

heterogeneous nature. However, this may also be attributable to the inappropriate field construction practice. Therefore, such variation can be minimized if field construction procedure is standardized and quality control measures are put in place. Premature failure of PC pavement due to the loss of functionality such as clogging are frequently reported. Thus, regular maintenance policy and robust methods need to be developed to maintain or restore the functionality of PCP.

- *Applicability on high volume road.* Despite of recent advances in HPPC and pioneering study on the performance of PCP, those conclusions are usually drawn based on short term performance. Therefore, further research is still needed for the applicability of PC as a construction material for high volume road, especially its long term performance.
- *Microstructural characterization and structural performance modeling.* It is well known that the performance of PC is strongly dependent on its PSC. However, only limited investigation has been conducted and very few models are available. Finite element analysis is not suitable to predict the behavior of PC because of its discrete nature. Hence, future efforts should be made using advanced techniques such as discrete element method for structural performance modelling.
- *Life cycle cost analysis.* The very limited work on cost analysis might be another reason that contractors are hesitate to use this material. PC is mechanically weaker and the initial cost is higher in comparison to conventional CIC based on limited studies [71]. Nonetheless, these conclusions are drawn based only on the initial construction cost. Life cycle cost analysis (LCCA) indicated that PC can reduce the LCCA by 30% [72]. Furthermore, the added benefits coming from the storm water management and low environmental impact need to be accounted for as long as cost-benefits is concerned. Therefore, further research is needed to address the cost concern in order to achieve a wide spread application of PC.

4 CONCLUSIONS

Recently, PC has attracted renewed interests among the media, engineers, contractors and academia due to its positive environmental impacts. This paper reviewed the state-of-the-art and the state-of-the-practice research and application of PC as an alternative sustainable pavement construction material. Emphasis was laid on the microstructural characterization and the influence of PSC on the mechanical, hydraulic and acoustical performance. Previous studies have demonstrated that PC performed well in low-volume road applications implying its promising prospects as an alternative pavement construction material. However, there exist several knowledge gaps that impede the wider application of PC. Hence, further research is needed to bridge these knowledge gaps so that a better understanding and improved overall performance can be achieved and eventually standard test methods, design code and construction procedures can be implemented in the future.

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Compliance with Ethical Standards

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