

Predicting the Permeability of Pervious Concrete

Advances in characterization of pore structure and transport properties

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The use of pervious concrete is on the rise due to its environmental advantages, such as reducing tire-pavement interaction noise, moderating storm-water runoff, and limiting the pollutants entering groundwater.¹⁻⁴ The fundamental material characteristic that makes pervious concrete a sustainable material with respect to its noise-absorbing and water-transport characteristics is its open pore structure (primarily the connected porosity and the larger pore sizes), which is facilitated by proportioning the concrete with gap-graded coarse aggregates and little to minimal amounts of fine aggregates. The characterization of the pore structure thus becomes important in the evaluation and prediction of pervious concrete performance.

POROSITY AND PERFORMANCE OF PERVIOUS CONCRETE

Currently, mixture proportioning of pervious concrete is primarily focused on obtaining a necessary pore volume. It's common to relate the performance of pervious concrete to its porosity because it's a relatively easy quantity to measure, aided by the millimeter-sized pores in the material. Figure 1 shows the porosity-permeability relationships of pervious concretes from a few reported studies. A general trend of increasing permeability with increasing porosity can be observed (although, clearly, porosity alone doesn't determine permeability). To design the material for specific performance requirements (such

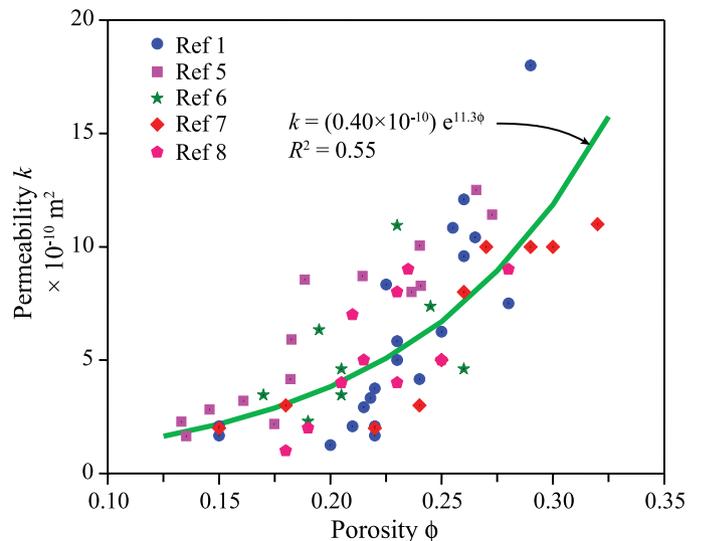


Fig. 1: Porosity-permeability relationships for several pervious concretes as provided in the indicated references. As the data show, porosities typically range from 15 to 30%

as permeability), an understanding of the features of the pore structure (porosity being one of them) that determine the performance is important. It's also important to understand how the material design parameters affect the pore structure. This article summarizes the current understanding and the advances made in pore structure-performance relationships in pervious concrete.

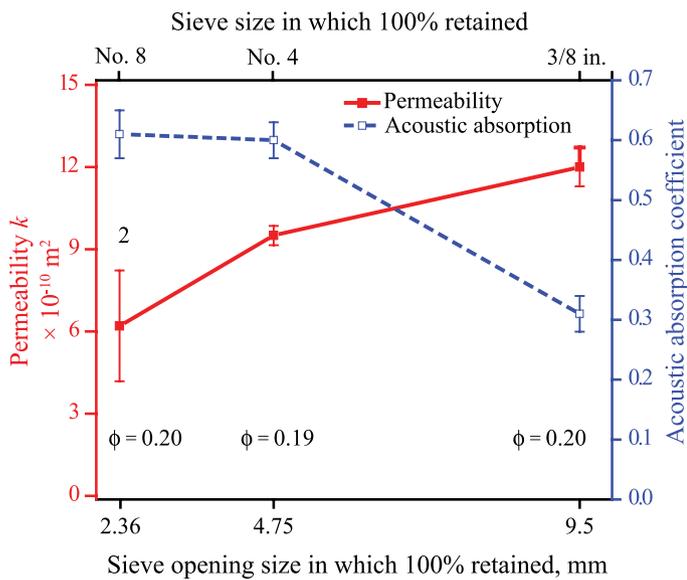


Fig. 2: Permeability and acoustic absorption coefficients of three pervious concrete mixtures having similar porosities^{5,6} as a function of the aggregate sizes in the mixture. Aggregate sizes are denoted by the sieve sizes in which particles are retained. The error bars correspond to one standard deviation on three replicate specimens

While porosity is undeniably one of the most important features of pervious concrete pore structure, it's a structure-insensitive property of the material—porosity doesn't depend on the configuration of the various elements in the structure. The question, then, is whether such a property alone can be relied upon to determine the performance of the material. Figure 2 shows the permeability and acoustic absorption coefficient (an index of the ability of the material to absorb acoustic energy) as functions of the aggregate size for three different pervious concrete mixtures having very similar values of porosity (about 20%). These mixtures were proportioned with carefully graded coarse aggregates:

- Passing No. 4 (4.75 mm) sieve and retained on No. 8 (2.36 mm) sieve;
- Passing 3/8 in. (9.5 mm) sieve and retained on No. 4 (4.75 mm) sieve; and
- Passing 1/2 in. (12.7 mm) sieve and retained on 3/8 in. (9.5 mm) sieve.

The permeability was measured using a falling head permeameter.^{1,9} The normal incidence acoustic absorption coefficients were determined on pervious concrete cylinders using an impedance tube in accordance with ASTM E1050, up to a frequency of 1600 Hz. Details on acoustic absorption coefficient measurements can be found elsewhere.^{9,10}

For the same porosity, an increase in aggregate size from No. 8 to 3/8 in. (2.36 to 9.5 mm) is found to increase

the permeability by as much as a factor of two and reduce the acoustic absorption coefficient to about half. This shows that pore structure features other than porosity are also influential in dictating material performance. Because permeability is found to increase with increasing aggregate sizes and the accompanying pore sizes (because there is typically a linear relationship between particle size and pore size¹¹), the size of the pores can be considered an important pore structure feature. In addition, the transport of water through or sound waves into the material requires that the pore system be connected. Therefore, connectivity is another significant pore structure characteristic. Both are discussed in the following sections.

PORE SIZES, CONNECTIVITY, AND IMPACT ON TRANSPORT PROPERTIES

One of the significant challenges in porous material characterization is obtaining relevant features of the three-dimensional (3D) pore structure from two-dimensional (2D) images. Geometrical-statistical methods (also called stereology¹²) are generally applied for this purpose. Image acquisition and analysis procedures have been elucidated in earlier publications.^{9,13}

Figure 3 shows representative planar images of pervious concrete sections from specimens made using the three aggregate sizes described previously. The complexities of the pore space in pervious concretes are evident from these images. Even though the porosities are similar, the pore sizes, their distributions, and likely their connectivities are very different. In these planar images, there are fewer and larger "pores" in the specimen made with larger aggregate. Also, for a given pervious concrete specimen, there are a multitude of apparent pore sizes in the 2D images of the material. This complicates the selection of a "characteristic" pore size that is representative of the pervious concrete mixture that could be used in the estimation of performance properties. A few methods to choose such a characteristic pore size are briefly discussed herein. Readers are directed to the corresponding references for more details.

Different methods of obtaining characteristic pore sizes

If a statistically significant number of random planar images from a particular pervious concrete mixture are used, then the area fraction of pores can be used as an unbiased estimator of (volumetric) porosity. Based on a 2D image, a direct representation of the equivalent pore sizes can be obtained through the use of an area histogram. The pore size corresponding to 50% of the cumulative frequency distribution¹³ d_{50} can be used as a characteristic pore diameter from area histograms. This is a particularly straightforward method of pore size estimation.

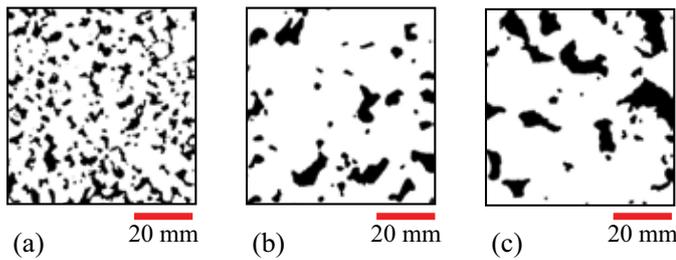


Fig. 3: Representative planar images from pervious concrete specimens of aggregate size: (a) 2.36 mm; (b) 4.75 mm; and (c) 9.5 mm. The pores appear black in these images (1 mm = 0.039 in.)

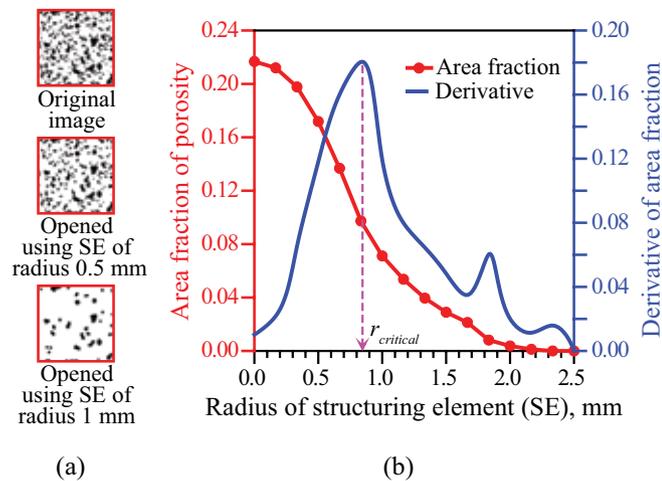


Fig. 4: A granulometric opening function is defined using structuring elements (SEs) of increasing sizes to “open” the pore phase: (a) original image and the resultant images after opening using SEs of 0.5 and 1 mm radii; and (b) critical pore radius $r_{critical}$ is defined using the first peak of the derivative curve of the granulometric opening distribution (1 mm = 0.039 in.)

Binary images similar to the ones shown in Fig. 3 can be subjected to certain transformations to obtain a quantitative description of the features of interest, such as the pore size. One such method is the use of a two-point correlation (TPC) function.¹³⁻¹⁵ TPC is obtained by randomly throwing line segments of length l with a specific orientation into a binary image and counting the fraction of times both end points of the segment fall in the phase of interest.¹⁶ The features of the TPC function along with the porosity can be related to a representative pore size d_{TPC} .

Another method that involves transformation of the images to determine the pore size distribution is a granulometric opening function. Structuring elements (SEs) of increasing sizes are used to “open” the pore phase. Figure 4(a) shows an original image and the images obtained by “opening” using SEs of two different

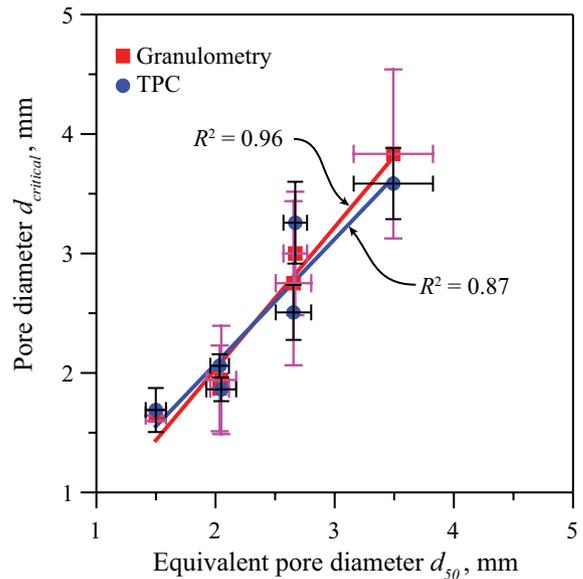


Fig. 5: Comparison of the characteristic pore size determined using different methods. The error bars correspond to one standard deviation on at least three images from a particular specimen (1 mm = 0.039 in.)

sizes. The size distribution is obtained by plotting the area fraction of the pore space remaining after opening by SEs of gradually increasing size, as shown in Fig. 4(b).

For normal cement pastes (pore size distributions often obtained by mercury intrusion), a critical pore size $d_{critical}$ is defined, associated with the inflection point in the pore size distribution curve. In a similar manner, the first peak of the derivative curve of the granulometric opening distribution (Fig. 4) can be considered as the critical pore radius for pervious concrete $r_{critical}$ that corresponds to the smallest pore that completes the first connected pathway in a material. Because this size relates to the percolation threshold, it could be used to determine the permeability of pervious concretes. Changes in the pore structure during service, such as clogging, can reduce the critical pore size, thus reducing water transport.

A comparison of the pore sizes obtained using the previously mentioned methods from a few pervious concrete specimens made using single-sized aggregates or chosen blends of these sizes^{9,10,13} are shown in Fig. 5. The pore diameters corresponding to 50% of the cumulative frequency distribution d_{50} are plotted on the x-axis, and the corresponding pore sizes obtained from granulometry and TPC functions are plotted on the y-axis.

A reasonably good 1:1 correlation can be seen between the pore sizes determined using all three methods for the limited number of specimens evaluated. TPC and granulometry provide characterizations of the pore sizes based on mathematical morphology (quantifications

based on changes in images when subjected to certain transformations), whereas d_{50} is a statistical quantity based on idealizing the observed 2D image structures into circles. While advanced characterization techniques such as TPC or granulometry are preferred to extract the pore sizes, the relationships in Fig. 5 show that in the absence of these techniques, d_{50} could also be used as a characteristic pore size of pervious concrete.

Connectivity of pore structure

Pervious concrete specimens filled with a conducting electrolyte (such as sodium chloride solution) can be approximated as a medium with a single electrically conducting phase (solid phase has a much lower conductivity as compared with the electrolyte-filled pore space). Therefore, the specimen conductivity σ can be expressed as

$$\sigma = \sigma_0 \phi \beta \quad (1)$$

where σ_0 is the conductivity of the electrolyte filling the pores of the specimens, ϕ is the porosity, and β is the pore connectivity factor. The lumped parameter $\phi\beta$ can be used as a single quantity that represents the combined effect of the amount of pore space and its connectivity. A simple measurement of the conductivity of the pervious concrete cylinder or core when filled with a conducting solution of known electrical conductivity (for example, 3% sodium chloride solution has a conductivity of 4.4 S/m) provides the value of the lumped pore structure parameter.⁹

Pore structure and its effect on water transport

It's instructive to examine the relative influence of porosity, pore size, and pore connectivity on the permeability of pervious concretes. Even though these factors are equally critical in acoustic absorption, this application is not detailed here for brevity.

The pore sizes chosen for this examination correspond to the values obtained from the granulometric distribution, as it's hypothesized that this provides a representative size of the percolated pores. Figure 6 shows the contour plot of measured permeability as a function of $\phi\beta$ and the critical pore size.

An increase in either the pore size or the pore structure factor $\phi\beta$ is found to result in increased permeability. For the same value of $\phi\beta$, an increase in pore size results in increased permeability as expected, especially at lower values of $\phi\beta$. Increasing the pore size (typically by using larger aggregates) at the same porosity is definitely a means of obtaining higher permeability, as was also observed in Fig. 2. At higher values of $\phi\beta$, pore size does not seem to influence the permeability significantly as seen from contour lines that are essentially parallel to each other. A higher value of $\phi\beta$ can be obtained by increasing either the porosity or the connectivity factor.

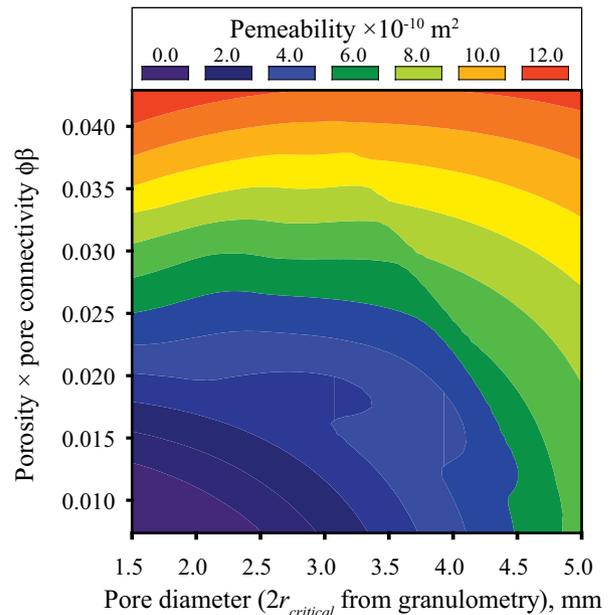


Fig. 6: Permeability as a function of critical pore size and the product of porosity and pore connectivity (1 mm = 0.039 in.)

Very high porosities (typically more than 25 to 30%) are generally undesirable from a viewpoint of mechanical properties. It has also been shown in an earlier study that higher porosities are not necessarily required to obtain higher connectivity factors.⁹ It's suggested that the connectivity factors be increased by careful aggregate gradations and/or blending to obtain desirable transport properties.

The pore structure parameter $\phi\beta$, which is equal to the normalized conductivity σ/σ_0 from Eq. (1), as well as the characteristic pore size d from any of the methods described previously, can be used in the Katz-Thompson equation¹⁷ shown in Eq. (2), which is a well-established method of the permeability k prediction of porous materials. The empirical constant (1/226) employed by Katz and Thompson¹⁷ was to provide a best fit to experimental data for a variety of rock specimens and, hence, this value could very well change for pervious concretes as

$$k = \left(\frac{1}{226} \right) \frac{\sigma}{\sigma_0} d^2 \quad (2)$$

X-RAY MICROTOMOGRAPHY AND 3D PORE STRUCTURE RECONSTRUCTION

Three-dimensional visualization of the pore space of pervious concrete can be accomplished through the use of X-ray microtomography. Several horizontal slices through the pervious concrete specimen (at 1984 by 1984 pixels with a spatial resolution of approximately

0.026 mm/pixel and a signal resolution of 8 bits) were obtained at the National Institute of Standards and Technology (NIST) using a commercially available X-ray microtomography unit and an image analysis procedure employed in all of the slices to produce requisite contrast between the pore and solid phases. These horizontal images were then stacked to obtain the volumes shown in Fig. 7. The pore space in each of the horizontal slices that make up this image (about 420 of them) can be tracked vertically to visualize and quantify the connected pore network, and in turn relate its characteristics to the permeability.

Because the availability of X-ray microtomography units is still somewhat limited, a recent study¹⁵ used a correlation filter-based 3D reconstruction algorithm to produce digitized virtual pervious concretes. Computer programs were used to compute the permeabilities and conductivities of the digitized 3D material structure. The permeability and conductivity values predicted from the digitized material structures matched reasonably well with the experimental values.

More recently, studies have been conducted using actual 2D images from several pervious concrete specimens to reconstruct the 3D pore structure and predict the permeability using computer programs developed at NIST.¹⁸ Figure 8 shows a starting 2D binary image of a pervious concrete specimen, the reconstructed 3D structure, and representative 2D slices from the reconstructed structure. Once again, comparisons between predicted and measured permeabilities were favorable.¹⁸ Material structure models for pervious concrete can be useful in achieving better material design and proportioning toward targeted performance characteristics as well as in predicting the material performance.

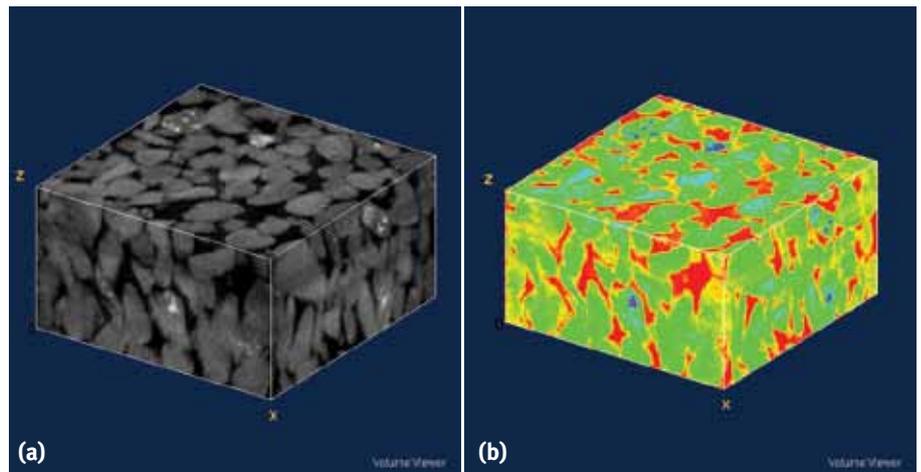


Fig. 7: X-ray microtomography images of a typical pervious concrete specimen: (a) a grayscale image; and (b) a color-thresholded image, with the pore space represented in red

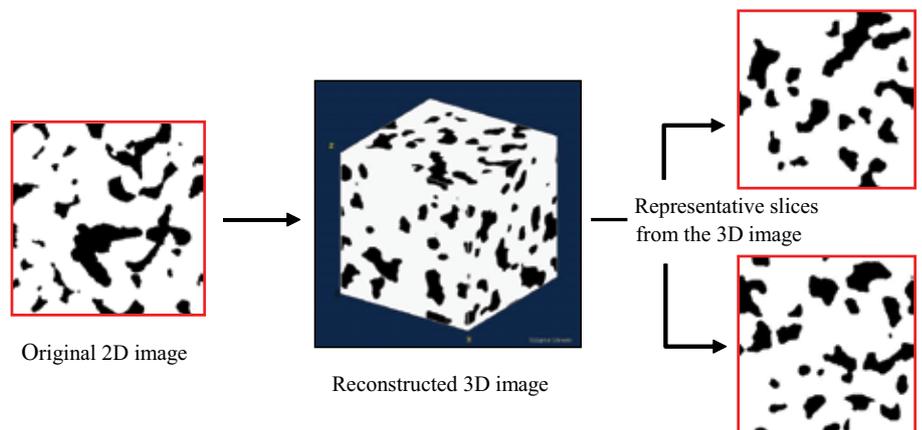


Fig. 8: 3D reconstruction of pervious concrete material structure from 2D images

SUMMARY

Increasing use of pervious concrete has led to an emphasis on mixture proportioning methods and test methods for performance. For a macroporous material such as pervious concrete, mixture proportioning methods must aim at achieving desired pore structure features that dictate the required performance. Characterization of the pore structure thus becomes important in material design and performance evaluation. This article has provided details on methods for characterizing pore structure features such as porosity, pore size, and pore connectivity.

The relative influence of the pore structure features on the transport behavior has been brought out. Recent studies using X-ray microtomography for visualization of the pore space, and computational models for 3D reconstruction and permeability prediction of pervious concrete from real 2D images promise to further advance quantitative structure-property relationships for this important class of materials.

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Note: Additional information on the ASTM standards discussed in this article can be found at www.astm.org.

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