Construction and Building Materials 123 (2016) 627–637

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Comprehensive investigation of permeability characteristics of pervious concrete: A hydrodynamic approach

Anush K. Chandrappa, Krishna Prapoorna Biligiri *

Department of Civil Engineering, Indian Institute of Technology Kharagpur, West Bengal 721 302 India

HIGHLIGHTS

- Determined permeability of eighteen pervious concrete mixtures with varying heads.
- Discussed contribution of various mix parameters in respect of permeability.
- Quantified and described nonlinearity in Darcy's law for PC mixes through Izbash/power law.
- Utilized a modified Kozeny-Carman equation to discuss effect of macroporous features.
- Recommended a promising hydrodynamic approach to rationally design pervious concrete pavements.

ARTICLE INFO

Article history:
Received 17 April 2016
Received in revised form 3 June 2016
Accepted 14 July 2016

Keywords:
Pervious concrete
Permeability
Darcy's law
Izbash law
Taguchi design of experiments
Kozeny-Carman equation

ABSTRACT

Pervious concrete (PC) mixtures were designed and prepared to measure and study permeability characteristics at varying head levels using a falling head permeameter. A total of 1092 readings was used to study the permeability properties of eighteen PC mixtures whose porosity was in the range of 15–37%, and permeability in the realm of 0.076–3.5 cm/s. The permeability reduced as the head of water increased, and gradually attained an asymptotic relation with the head. Cement-to-aggregate ratio had largest contribution in controlling permeability of PC mixtures. Nonlinearity in Darcy's law was observed in respect of permeability of PC mixes, which was modelled using Izbash/power law, and was prominent for gradations consisting of larger sized aggregates due to inconsequential tortuous pore structure. Modified Kozeny-Carman equation was fitted for PC gradations to compare the results with Izbash law, which showed good agreement. This study is deemed to assist in understanding the hydrodynamics of water flow in pervious concrete, which in turn will aid in rational pervious concrete pavement system designs.

1. Introduction

The increased urbanization that has changed the hydrological characteristics of stormwater runoff has also necessitated the recommendation of strategies to counter the adverse effects caused by the increased volume of runoff on the built environment, including road pavements [1,2]. Pervious concrete (PC) is one of such strategies that was initially used as a building material, which later gained attention as a pavement material owing to its stormwater management abilities [3]. PC is a sustainable material, which is characterized by the presence of interconnected pore structure that allows water to pass through it. The interconnected pores in the matrix are achieved by reducing/eliminating the fine aggregates proportion such that the available coarse aggregates are coated with only cement paste [4,5]. The design of pervious concrete pavements (PCP) depends on the structural and pore properties. The major estimable pore properties of PCP include: porosity, permeability, pore connectivity, pore size and its distribution, and tortuosity [6,7].

The porosity of PC varies in the range of 15–40% with a minimum value of 15% as recommended by the National Ready Mix Concrete Association (NRMCA) [8,9]. Recently, PC has been further categorized as a conventional PC with porosity lower than 30%, and macroporous PC with porosity greater than 30% [10]. The pore connectivity, pore size and its distribution, and tortuosity have been investigated in a few studies using various techniques [11–13]. Based on the studies, it was found that pore connectivity was more dependent on aggregate type rather than size, and the connected porosity was found to be about 50–70% of the total porosity in different PC mixtures [13]. The pore size and distribution have

* Corresponding author.
E-mail addresses: anushkc@civil.iitkgp.ernet.in (A.K. Chandrappa), kpb@civil.iitkgp.ernet.in (K.P. Biligiri).

http://dx.doi.org/10.1016/j.conbuildmat.2016.07.035
0950-0618/

been studied using image analyses techniques where the median pore size was found to be 3–4 mm and mostly followed a normal distribution [11]. Tortuosity (*a dimensionless quantity*), which represents the sinuousness (*property indicating twisting and windings of pores*) of internal pore structure was found to be in the range of 2–5 as investigated using X-ray tomography (XRT) [12].

The permeability characteristics of PC mixes as one of the important properties have been investigated in several studies using either falling head permeameter and/or constant head permeameter. Permeability being a function of the aforementioned pore properties varies in the range of 0.1–5 cm/s, and is known to follow either a normal or Weibull distribution depending on the range of permeability values [7,8,12,14]. Furthermore, permeability of the in-service PCP is usually determined using ASTM C1701 [15] or the method prescribed by the National Center for Asphalt Technology (NCAT) [16,17]. Although several studies have been carried out to determine permeability of PC specimens, very few studies have discussed about the effect of head/hydraulic gradient on the permeability properties of these mixes. Qin et al. [18] discussed the differences in permeability measured with falling head and constant head permeameter, and found that those values measured with falling head method were normally lower than those obtained from constant head method. Recently, West et al. investigated the effect of head/hydraulic gradient on the Darcy's velocity of PC specimens using constant head permeability test method [19]. The study showed that there existed a nonlinearity in the Darcy's law that can be modelled using Forcheimmer's/quadratic equation. However, the study considered one type of PC mixture without giving due attention to the variations in pore structure over different types of PC mixtures.

In order to study whether nonlinearity exists in most of the PC mixtures, and if it exists to what degree will it be present is yet to be understood. Further, how this nonlinearity arises and gets influenced by the different gradations in PC mixtures needs to be answered. Therefore, this study investigated the research gap by considering a wide variety of PC mixtures with different pore structure features, which will throw more light on the understanding of the hydrodynamics of fluid flow in pervious concrete mixtures. Thus, the main objective of this research study was to investigate the permeability characteristics of PC mixtures using falling head permeameter, and utilize existing theories/laws in explaining the features of permeability. The research methodology included (Fig. 1):

- Design and production of eighteen PC mixtures with 6 gradations and 3 levels of water-to-cement ratio (w/c ratio) and cement-to-aggregate ratio (c/a ratio)
- Determination of permeability of PC mixtures with seven different head levels
- Assessment of the contribution of different mixture variables and relationships between permeability and porosity
- Understanding the nonlinearity in different PC mixtures using Darcy's law and Kozeny-Carman equation
- Recommendation of a novel methodology to investigate the hydrodynamics of water flow in porous mixtures which is deemed to assist in rational pervious concrete pavement system designs

2. Theoretical background

The flow of the fluid in the porous media is governed by the well accepted Darcy's law. According to the Darcy's law, the flow rate through a porous media is proportional to the pressure difference/head difference between the two points, and the proportionality constant is called hydraulic conductivity as shown in Eq. (1) [20].

$$Q = K * \left(\frac{\Delta h}{L}\right) * A = KiA \qquad (1)$$

where
Q = flow rate, m^3/s
K = hydraulic conductivity/permeability, m/s
Δh = head difference, m
L = length of the permeable media, m
A = cross-sectional area, m^2
i = hydraulic gradient

The Darcy's law neglected the inertial and velocity effects; however, these effects become more pronounced when the connected pores in the porous structure turn out to be larger in size. The change in the fineness of the porous structure gives rise

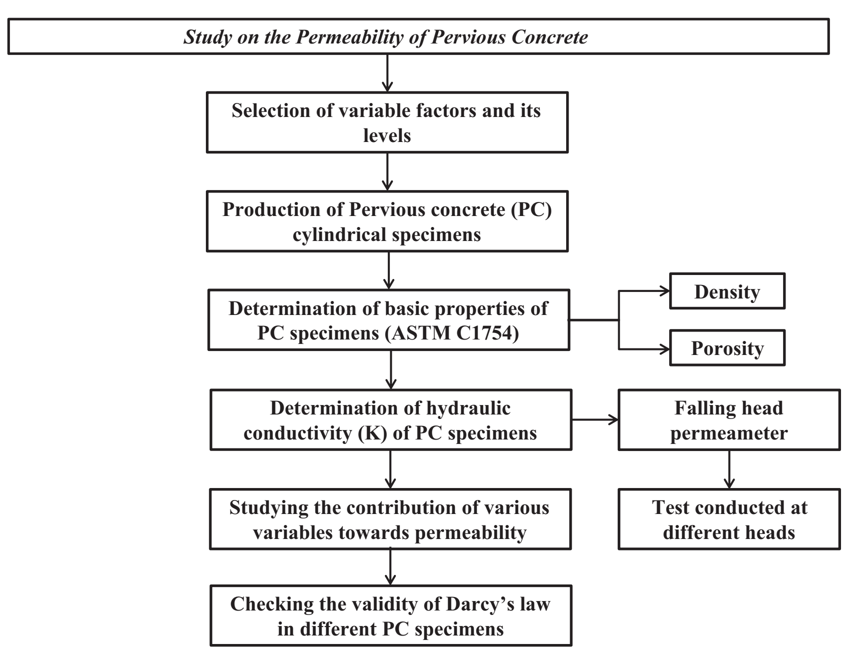

Fig. 1. Study methodology outline.