Measurement 62 (2015) 81–87

Contents lists available at ScienceDirect

Measurement

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

Measurement of pore water pressure in asphalt pavement and its effects on permeability

Junqi Gao [*], Chengcheng Guo, Yutao Liu

Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, 29 Yudao Street, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 13 November 2014
Accepted 19 November 2014
Available online 26 November 2014

Keywords:
Pore water pressure
Fiber optic hydraulic pressure sensor
FBG
Asphalt pavement
Permeability coefficient

ABSTRACT

On the effect of pore water pressure in a saturated asphalt pavement, fluid velocity and water infiltration rate will increase, which have a disadvantage influence on asphalt mixture strength. In order to measure the pore water pressure in pavement, a fiber optic hydraulic pressure sensor (FOHPS) is designed. The theoretical correlation between the applied pressure and the center wavelength shift of the FOHPS is derived by laboratory experiment. The pore water pressures in asphalt pavement at some running speeds were measured in situ. Furthermore, a falling head permeameter method was used to measure the permeability coefficients of asphalt mixture exposed to hydraulic pressures which were from 40 kPa to 350 kPa, and the correlation between permeability and hydraulic pressure was obtained. The experimental results showed that the pore water pressure would increase with the increasing car's speed, but the lifetime of pore water pressure decreases with the increasing speed. The permeability coefficients of SMA-13 and AC-20 mixtures decrease with the increasing hydraulic pressure, but the water infiltration rate increases on an approximate linear curve as the hydraulic pressure increased from 40 kPa to 350 kPa.

1. Introduction

Asphalt concrete pavement is directly exposed to the natural environment, and traffic loads, environmental temperature and moisture are the major external factors which influence pavement performance. Some cracks will appear in the surface layer under the action of external loads. Water will infiltrate into pavement through connected pores and cracks. Under the repeated action of wheel loads, the pore water pressure in asphalt pavement is formed, which would make pavement surface layer spalling or loose, and finally cause pavement structural damage. Pore water pressure in pavement is considered to be one of the major causes of the asphalt pavement damages.

There have been significant efforts in researching pore water pressure in asphalt pavement. Kutay et al. [1–3] computed dynamic water pressure gradient, pore water pressure and shearing stress at the solid–water interfaces by means of the lattice Boltzmann method. Masad et al. [4,5] calculated the distribution of the pore water pressure gradient by means of the finite difference method. Kettil et al. [6] simulated wet asphalt pavement deformation and water flow. Zhou et al. [7] calculated the pore water pressure in saturated asphalt pavement and showed that when the permeability coefficient of asphalt mixture is 1×10^{-4} cm/s and the load time is 0.005 s, the pore water pressure is 0.57 MPa. Dong et al. [8] also computed the pore water pressure in the asphalt pavement surface, whose value is 0.44 MPa. Cui and Jin [9] studied the pore water pressure in asphalt pavement. Li and Deng [10] built a theory model in which the asphalt pavement was regarded as an axial symmetrical body of multilayered saturation elastic half space, and pore water pressure in

---

[*] Corresponding author. Tel./fax: +86 25 84891754.
E-mail address: junqi_gao@nuaa.edu.cn (J. Gao).

http://dx.doi.org/10.1016/j.measurement.2014.11.013
0263-2241/

asphalt pavement under mobile load was calculated. In addition, Gao et al. [11] measured the dynamic water pressure in asphalt pavement surface. The results showed that when car speed is 80 km/h, the water pressure is about 0.2 MPa.

Permeability of an asphalt pavement is one of the most important parameters that have a direct influence on its design life. Fixed head test and falling head test are often used to measure permeability coefficient of asphalt mixture [12]. Moreover, some models which are used to estimate asphalt mixture permeable coefficient have been suggested [13]. The Kozeny–Carman equation has been used over the years to approximate the permeability of granular materials. It was derived based on representing the air voids as capillary tubes and applying the hydraulic radius theory. Based on Kozeny–Carman equation, Masad presented a simple equation for approximating the permeability of asphalt mixes [14]. The permeability coefficient is required to be provided to calculate the pore water pressure by finite element model, and it is generally considered as constant. This assumption would be appropriate at low pressure head and not appropriate for higher hydrodynamic pressure head.

At present, field data of pore water pressure in asphalt pavement is still relatively few. In order to verify some established theory models, it is required to obtain a lot of field measurements of the pore water pressure. Fiber Bragg Grating (FBG) sensing technique can overcome the weak of conventional testing method, and the pore water pressure can be measured accurately by FBG sensing. In this paper, a FOHPS is designed, and using this fiber sensor to measure the pore water pressure in asphalt pavement is studied. After calibrating the fiber sensor, a field pressure testing was conducted. In addition, the permeabilities of different asphalt specimens exposed to pore water pressures are studied using water and a falling head approach.

2. Optical fiber sensor design

The FOHPS is designed as shown in Fig. 1. The appearance of the sensor is like a cylinder, which is composed of an aluminum enclosure, a circular diaphragm, a fiber grating and seals. When the water in asphalt pavement flows into the sensor and acts on the diaphragm, the diaphragm will produce deformation that transfers to the fiber grating pasted on back surface center of the diaphragm. Then axial strain will occur in the grating. By detecting the wavelength shift of the grating, we can obtain the pore water pressure that exists in saturated asphalt pavement under loads.

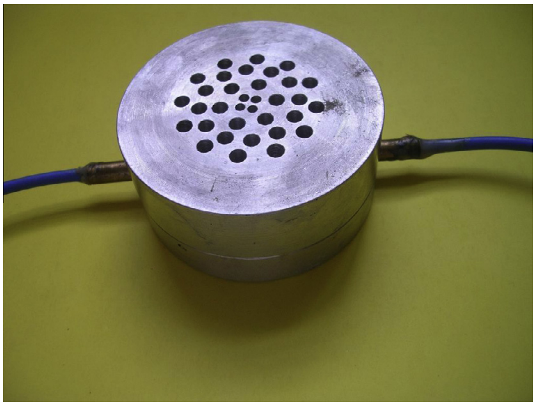

Fig. 1. Fiber optic hydraulic pressure sensor.

The radius of the designed sensor is 27 mm with a height of 26 mm, and the diaphragm radius is 15 mm. The fiber grating is attached to the back surface of the diaphragm in a two-step process. First, the diaphragm is cleaned with alcohol until the alcohol evaporates. Second, a tension is applied to the fiber grating and then the grating is bonded on the diaphragm with an epoxy resin, which can also protect the sensor from damage.

Under the action of uniform pressure p [11], the radial strain on the point with a distance r from the diaphragm center can be expressed as

$$\varepsilon_r = \frac{3p}{8h^2E}(1-\mu^2)\left(R^2-3r^2\right) \tag{1}$$

where E is the Young's modulus of the metal diaphragm, μ is Poisson's ratio, h is the thickness of the diaphragm, and R is the radius of the metal diaphragm.

From Eq. (1), it can be seen that the grating strain ε_r varies according to different distance r, and at the center of the round diaphragm its strain ε_r is maximum. In the designed sensor the length of the grating is about 10 mm, and the diaphragm radius R is 15 mm. By using these data, the FBG average strain can be calculated as

$$\varepsilon_r = \frac{2.89p}{8h^2E}(1-\mu^2)R^2 \tag{2}$$

By using Eq. (2), the linear relationship between strain ε_r detected by FBG and pressure p can be observed when other variables does not change.

3. Calibration tests

Three fiber optic hydraulic pressure sensors (S1, S2 and S3) were designed. The peak wavelengths of S1, S2 and S3 are 1558.365 nm, 1561.447 nm and 1555.552 nm respectively. Diaphragm materials used in these sensors are stainless steel, whose elastic modulus is 200 GPa, Poisson's ratio is 0.3, and thickness is 0.3 mm. For sensors S1, S2 and S3, the pressure loads were 0.05 MPa, 0.1 MPa, 0.14 MPa, 0.2 MPa, 0.24 MPa, 0.3 MPa, 0.35 MPa, respectively. During the load procedure, the pressure load was applied by using the pneumatic pump and maintained for 5 min to measure the strain of diaphragm. The outputs of these sensors were monitored by a si425–500 optical sensing interrogator (Micron Optics, Inc., USA). Furthermore, the si425–500 communicated with the control terminal, a notebook computer, via an Ethernet cable for the transmission of the enormous monitoring data.

Before the field measurement, a calibration test for sensors S1, S2 and S3 was implemented to evaluate their respective behavior of linearity. The measurement results here and subsequent have been corrected for temperature compensation using a free FBG. Fig. 2 demonstrated the