Construction and Building Materials 150 (2017) 714–722

Contents lists available at ScienceDirect

Construction and Building Materials

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

Modeling compressive strength of cement asphalt composite based on pore size distribution

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HIGHLIGHTS

- A modified image analysis method was used for the spherical porosity of CA composite.
- The total porosity of CA composite was analyzed by NMR and image analysis method.
- A compressive strength model, based on Griffith theory and total porosity, was developed.

ARTICLE INFO

Article history:
Received 24 March 2017
Received in revised form 6 June 2017
Accepted 8 June 2017

Keywords:
Pore size distribution
Cement asphalt
Compressive strength

ABSTRACT

Cement asphalt composite is a porous material with various connected and closed pores, and pore structure is the major factor affecting its strength. In this paper, the pore structure of cement asphalt composites with different asphalt contents were analyzed by the combination of Nuclear Magnetic Resonance (NMR) and modified image analysis methods. The former one mainly detects the smaller and open pores, and the latter one mainly measures the larger and spherical closed pores. The total porosity is the sum of open and closed porosities. A model, based on Griffith theory and complete pore structure, was developed to predict the compressive strength of cement asphalt composites with high and low asphalt contents. It is demonstrated that the proposed models predict the compressive strength of cement and asphalt composite quite well.

1. Introduction

Cement asphalt (CA) mortar has been widely applied in the construction of ballastless slab track of high speed rail (HSR) in China. Two types of ballastless slab track, i.e. China Rail Track System (CRTS) I and II, adopt CA mortar with different elastic modulus. CRTS I ballastless slab track is a unit slab track system which adopts CA mortar with low elastic modulus (100-300 MPa), which is abbreviated as LECA. CRTS II ballastless slab track is a continuous slab track which employs CA mortar with high elastic modulus (7000–10,000 MPa), which is abbreviated as HECA. The largest HSR network has been formed in China. More than 6000 km of HSR lines implemented with CRTS I or II ballastless slab tracks. Numerous studies, especially in China, have been or are being carried out on various properties of CA mortar, including rheological properties, mechanical properties, durability, and construction technologies etc. [1–9].

Hardened CA mortar is a porous and organic-inorganic material, and its solid phase includes Portland cement hydrates, asphalt agglomeration, and sand. Due to hydration of cement, both gel pore and capillary pore exist in the hardened CA mortar [10]. In the presence of surfactants introduced by emulsified asphalt or air entraining admixture, spherical pores can be entrained in the matrix. The air content of fresh LECA is required to be 8–12%, and 0–10% for HECA [11,12]. The air bubbles in fresh CA mortars will turn into spherical air voids when the composite gets hardened. As a porous material, the pore structure has a paramount influence on its properties, such as strength, durability, elastic modulus, fracture energy, and permeability etc [13–16]. Since strength is the principal property required by engineer, and pore structure is the most important factors affecting the strength of porous material. A good understanding of the pore structure of CA mortar will be invaluable to help understand the mechanical performance of CA mortar.

The pore structure of hardened cement paste is well established [17]. The hydrated cement paste contains several types of voids including interlayer place of CSH gel (<10 nm), capillary voids (>10 nm, <5 μm) and entrapped or entrained air. Compared with

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http://dx.doi.org/10.1016/j.conbuildmat.2017.06.049

hardened cement paste, hardened cement asphalt paste may present different characteristics of pore structure due to the following reasons:

- Effect of emulsifier. The emulsifier in the emulsified asphalt can act as surfactants in fresh CA composites, and air void can be entrained. The size of the entrained air void is unknown.
- Effect of high content of asphalt. CA mortars used for the high-speed rail in China have a wide range of A/C mass ratio from 0.3 to 0.9 [18]. The agglomerates of asphalt particles may cause changes in the pore structure of CA mortar, particularly modifications in the capillary pores in CA mortar.
- The foaming of alumina powder. In order to avoid the early shrinkage of CA mortar, a small amount of alumina powder is introduced into fresh CA mortar used for HSR in China. Alumina powder reacts with the alkali to yield H_2 gas; consequently, air bubbles are entrained in the matrix and the volume of the mixture is increased. The entrained air bubble in CA mortar is not well documented.

Very few literatures dealt with the pore structure of CA mortar. Zheng et al. [10] studied the pore structure of CA mortar with nitrogen adsorption method. However, the study was carried out on very limited mixes, and nitrogen adsorption method cannot give a complete pore structure of materials. For the past decades, many testing techniques have been developed and proposed to determine the pore structure of porous material, i.e. Mercury intrusion porosimetry (MIP) [19], nitrogen sorption, water vapor sorption isotherm (WVSI) [20], nuclear magnetic resonance (NMR) [21], Small angle X-ray scattering (SAXS) [22] and microscopical for isolated air void system [23]. Some of the methods are very often used, and the other ones are rarely employed. However, it seems that two testing methods seldom give the same results on pore structure for a given material. What's more, not a single technique can give a complete pore structure of cement-based materials which have very complicated pore structure.

MIP is the most used method for porous materials [24–25]. However, due to the incorporation of high content of asphalt, the pore wall of CA mortar cannot withstand high pressure. Thus, MIP is not applicable to CA mortar. Polish of the surface can result in softening asphalt which may cover the pore, and thus the ASTM Standard method for air void system [23] is also not applicable to CA mortar. By comparing all the existing methods for pore structure, it is found that NMR relaxometry is a promising method to determine the open pore structure of CA mortar, and modified image analysis is suitable for measure the closed pores. And the complete pore structure of CA mortar is thus obtained by the combination of these two methods. The NMR relaxometry applied in CA mortar is detailed in the author's another paper [26]. This paper is focused on the relationship between pore size distribution and strength of CA mortar.

It has been long recognized that the reduction of porosity improves the compressive strength of porous materials [27–32]. Many empirical equations have been proposed to address the relationship between porosity and compressive strength of cement-based materials, as shown in Table 1, where σ is the compressive strength of porous materials, p is porosity, σ_0 is the strength at zero porosity and p_0 is the porosity when the material strength reaches zero, A, B, C and D are empirical constants. Although these equations have been experimentally verified and used [37–39], poor correlation is observed among all the equations by Kumar et al. [40]. This means that only considering the porosity, may give very crude estimation of the compressive strength of specific material, and cannot be used for general purpose [41]. In order to address the effect of pore size distribution (PSD) on strength, Atzeni et al. (Eq. (1a)) [42] and Chen et al. (Eq. (1b)) [39] introduced the average pore size into the relationship between strength and porosity of cement pastes:

$$\sigma = K\frac{\sigma_0(1-p)}{\sqrt{r_m}} \tag{1a}$$

$$\sigma = \sigma_0 \cdot \left[\left(\frac{p_c - p}{p_c}\right)^{1+m} \cdot (1 - p^{2/3})\right]^{1/2} \tag{1b}$$

where r_m is mean distribution radius, p_c is percolation porosity, m is the ratio of calculated average distance to the nearest pore, and $[(p_c - p)/p_c]^{-m}$ represents the average value of pore size according to Ficker et al. [43]. The value of σ_0 must be obtained empirically. Atzeni et al. [42] suggested the estimation of σ_0 from Hasselmann's empirical equation [33], however, Kumar et al. [40] validated that the estimation is likely to be grossly erroneous.

Based on the fracture theory of Griffith, Tang [44] developed a strength model based on pore size distribution (PSD), in which the pores were divided into different size groups, and the model was solved by a computer model. In this model, the critical failure criterion is given as follow:

$$\sigma_{cri} \geqslant \sqrt{\frac{K_m A_{mi}}{r_i}} \tag{2}$$

where A_{mi} represents the area fraction of solid matrix, r_i is the mean pore radius of the i th size group and K_m is an empirical constant which represents the mechanical properties of solid matrix including elastic modulus and surface energy. The model assumed that the cylindrical pores cross perpendicularly in three-dimensional space, and the solid matrix fracture progressively, and the fracture initiates from the largest pore size group to the smallest pore size group under the applied stress. The strength of material is obtained when the element, which contains the smallest pore size group, starts to fracture under the action of stress. The factor K_m is an essential parameter in this model, and obtained by data fitting.

In this paper, the complete pore structure of CA mortar was first measured by the combination of NMR and modified image analysis method. Based on the model proposed by Tang [44], the strength models for HECA and LECA mortars were proposed respectively.

Table 1
Empirical equations for the relationship between porosity and strength of cement-based materials.

Equations	Constants	Reference
$\sigma = \sigma_0(1 - Ap)$	A	Hasselmann et al. [33]
$\sigma = \sigma_0(1 - p)^B$	B	Balshin et al. [34]
$\sigma = \sigma_0 \exp(-Cp)$	C	Ryshkevitch et al. [35]
$\sigma = Dln(p_0/p)$	D	Schiller et al. [36]

2. Experimental program

2.1. Raw materials

P II 52.5R Portland cement complied with Chinese Standard GB175-2007 was used as binder for CA mortar. The density of the cement is 3.15 g/cm^3 and its chemical composition is given in Table 2. A cationic and an anionic emulsion asphalts were used for the preparation of LECA and HECA mortar specimens respectively. Their main physical properties are given in Table 3. The density of asphalt is 1.04 g/cm^3. The crushed silica sand with fineness modulus of 1.6, maximum particle size of 1.18 mm, and density of 2.64 g/cm^3 was employed. Organic silicon type defoaming agent was used to eliminate large air bubbles entrapped during the mixing process and control the air content of fresh CA mortar.