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Estimation of elastic modulus of cement asphalt binder with high content of asphalt

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HIGHLIGHTS

- Models for the elastic modulus of two-phase composite were reviewed.
- The volume fractions of various phases of CA binder were experimentally determined and theoretically calculated.
- The models for estimating elastic modulus of CA binder with high content of asphalt were suggested.

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ABSTRACT

In this paper, the effects of asphalt-to-cement ratio (A/C) and water-to-cement ratio (W/C) on the elastic modulus E_c of cement asphalt (CA) binder were studied through measuring the stress-strain curves and phase volume fractions of various CA binder specimens. The results illustrate that the CA binder with high asphalt content (A/C $\geqslant$ 0.6) is a two-phase composite with complicated microstructure formed by both cement hydrates and asphalt agglomerates. The elastic modulus of CA binder decreases with the increase of A/C and W/C, especially A/C. A composite model that describes the CA binder in terms of the properties of asphalt and volume fractions of cement phases is suggested, and E_c of CA binder can be predicted by this model according to A/C, W/C and properties of asphalt.

1. Introduction

Up to September 2016, 20,000 km of high-speed railway (HSR) lines have been completed and come into service in China [1]. In addition, Chinese government has planned about 10,000 km of HSR lines which will be built in the next five years. China Rail Track System (CRTS) I-type or II-type slab ballastless track structures were widely used in China's HSR lines. They are vertically layered structure systems consisting of seamless welded rail and its fastening, track slab, cushion layer, and concrete base plate. Yet, track slabs, cushion layers and base plates are longitudinally disconnected in CRTS I-type structure and connected in CRTS II-type structure. Among them, a cushion layer is cast-in-place with fresh cement asphalt (CA) mortar. In order to reduce vibration and noise and to improve the comfort ride, the mechanical properties of hardened CA mortar must satisfy the requirements of dynamics of slab track structure. For example, CA mortar for CRTS I-type structure is specified to have lower elastic modulus (100–300 MPa) [2]; whereas CA mortar for CRTS II-type structure is specified to have higher elastic modulus (7000–10,000 MPa) [2].

Fresh CA mortar is made by mixing cement, emulsified asphalt, water, fine sand, and several chemical admixtures. Hardened CA mortar is an organic–inorganic composite material, in which cement hydrates and asphalt commonly form a binary cement-asphalt (CA) binder. Hence, CA mortar is an obvious viscoelastic material due to the existence of high content of asphalt. In order to prepare CA mortars with specified elastic modulus, it is necessary to understand the relationship between mechanical properties and asphalt content of CA mortar.

There were few studies dealing with the mechanical properties of CA composites. Xie et al. [3] analyzed their creep mechanism. Qiu et al. [4] and Fu et al. [5] proposed a fatigue model and a stress relaxation model for CA mortar respectively. Liu et al. [6] found that the peak stress and elastic modulus of CA mortars declined with the increasing A/C and temperature. Yuan et al. [7] refined the dynamic mechanical thermal analysis (DMTA) method for CA

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composite. However, a quantitative relationship between the mechanical properties and composition of CA mortar has rarely been reported.

Many models have been proposed for estimating the elastic modulus of ordinary mortar/concrete and mortar/concrete modified by low content of polymer. These models have been reviewed in several articles [9–12], for example Voit (parallel phases) [13], Reuss (series phases) [14], Popovics [9], Lichtenecker [15], Hirsch-Dougill [16,17], Maxwell [18], Halpin-Tsai [11], Counto [19], and Hashin-Hansen [20] models. All of these models were developed based on composite theories of rigid inclusions in a rigid matrix and regression analysis of experimental data [12].

CA mortar is a composite consisting of a non-rigid matrix and rigid sand grains. For a composite of this type, a number of mechanical models were also proposed to correlate the elastic modulus with the volume fraction of filler [14], including Einstein [21], Kuhn models [22], Frankle-Acrivos [23], Quemada [24], Kerner [25], Guth [26], Thomas [26], and Mooney [27] etc. However, the matrix of CA mortar is a two-phase binder including cement hydrates and asphalt agglomerates. Actually, the mechanical properties of CA mortars are mainly dependent on CA binder. However, the effects of the composition on the mechanical properties of CA binder are not well understood.

In this paper, the stress-strain curves of various CA binder with high asphalt content (A/C $\geqslant$ 0.6) were measured, whose phase volume fractions were also analyzed. Through comparing experimental results with the value predicted by the existing models, a model for estimating the elastic modulus of CA binder was suggested.

2. Experimental programs

2.1. Materials

The cement used was P·II 52.5 Portland cement that complies with the Chinese Standard GB 175-1999. The compositions and properties of the cement are detailed in Tables 1 and 2, respectively. The emulsified asphalt, whose main properties are listed in Table 3, was a cationic asphalt emulsion consisting of water and AH-90 petroleum asphalt modified by styrene-butadienestyrene copolymer (SBS). In addition, tap water and a small amount of silicon defoaming agent were used for mixing CA paste.

2.2. Specimen preparation

The important factors of CA paste are A/C and W/C ratios. A/C ratios of CA paste used in this study were 0.6, 0.7, 0.8, 0.9 and 1.0. W/C ratios of 0.55, 0.6 and 0.67 were employed. The mix proportions of CA binder specimens in the forms of volume and mass are given in Table 4. It is worth to mention that the water in emulsified asphalt was counted in the calculation of W/C ratio.

CA pastes were prepared by the following procedures: emulsified asphalt and water were first poured into the stirring pot and slowly stirred at 30 rpm for 1 min. During stirring process, a little defoaming agent (about 50 mg/l) was added to eliminate the bubbles on the surface of the liquid phase. Then, the cement was slowly added into the stirring pot, and it took about 30 s. Afterwards, the mixer was stopped for 10 s, and the paste on the wall of stirring pot was scrapped into the slurry. The slurry was then slowly stirred at 30 rpm for 1 min, followed by quickly mixing at 120 rpm for 2 min and slowly mixing at 30 rpm for another 30 s to eliminate big bubbles in the slurry.

Table 2
Physical and mechanical properties of cement.

Specific surface/ $m^2 \cdot kg^{-1}$	Density/ $g \cdot cm^{-3}$	Bending strength (28d)/MPa	Compressing strength (28d)/MPa
338	3.12	9.2	59.3

After mixing, the fresh CA slurry was poured into the cylindrical PVC moulds with the inner diameter of 71 mm and height of 130 mm. The specimens were demoulded after 24 h, and cured at 20 ± 2 °C and 65% RH for 180 days.

In order to ensure the parallel surfaces and avoid eccentric compression, the upper and bottom portion of all CA binder specimens were cut off by about 9 mm respectively, and then two surfaces were polished by a double-end face automatic polishing machine. The final size of the cylindrical CA binder specimens was φ (71.00 ± 0.10) mm × (100.00 ± 0.10) mm.

2.3. Test methods

2.3.1. Measurement of stress–strain curve

Stress-strain curves of CA binder specimens cured for 180 days were measured by an electronic universal testing machine system. Firstly, a CA binder specimen was preloaded for 3 times at the loading and unloading rate of 1.0 mm/min, and the preload was 0.1 MPa. Then, its stress–strain curve was measured at the loading rate of 1.0 mm/min and the experimental data were collected. The ambient temperature was about 21 ± 2 °C.

2.3.2. Measurement of capillary porosity

The capillary porosity of all CA binder specimens was evaluated by the water loss of the saturated sample under low relative humidity. Firstly, three slice samples with about 3 mm thickness cut from a CA binder specimen were saturated in a vacuum saturation apparatus. Secondly, the weight in air m_1 and the weight in water m_2 of the saturated slices were measured, respectively. Thirdly, the saturated slices were placed in a desiccator where the bottom of the desiccator was filled with saturated $MgCl_2$ solution (RH was about 33% at 25 °C). After the constant weight (m_3) was reached, the capillary porosity V_p of the slice sample can be calculated by Eq. (1):

$$V_p = \frac{V_w}{V_s} = \frac{m_1 - m_3}{m_1 - m_2} \quad (1)$$

where V_p is the capillary porosity of a slice sample (%); V_s and V_w are the volume of the saturated slice sample and the water loss after the desiccation of the saturated sample, respectively. The average value of 3 sliced samples was calculated as the capillary porosity V_p of this mix.

2.3.3. Measurement of volume fraction of asphalt

The asphalt content of all CA binder specimens was determined by the dissolution method. A slice of sample with about 3 mm thickness was placed in a 200 ml glass conical flask filled with 150 ml trichloroethylene. In order to make the asphalt completely dissolve from the slice sample, the glass conical flask was sealed

Table 1
Chemical and mineral compositions of cement (w/%).

Component	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2Oeq	f-CaO	Ignition loss	C_3S	C_2S	C_3A	C_4AF
Content	21.20	65.66	5.43	3.87	0.87	0.91	0.56	0.95	2.5	60.91	15.68	7.84	11.76