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Micromechanics-based analysis for predicting asphalt concrete modulus*

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Abstract: The elastic modulus of asphalt concrete (AC) is an important material parameter for pavement design. The prediction and determination of elastic modulus, however, largely depends on laboratory tests which cannot reflect explicitly the influence of the microstructure of AC. To this end, a micromechanical model based on stepping scheme is adopted. Consideration is given to the influence of interfacial debonding and interlocking effect between the aggregates and asphalt mastic using the concept of effective bonding. Tests on asphalt mixture with various microstructures are conducted to verify the proposed approach. It is shown that the prediction is generally in agreement with experimental results. Parameters affecting the elastic modulus of AC are also discussed in light of the proposed method.

Key words: Asphalt concrete (AC), Micromechanics, Microstructure, Effective bonding, Optimum design, Elastic modulus
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1 Introduction

Asphalt mixtures are visco-elastic by nature, and their stress-strain relationships are both time and temperature dependent. The ratio between the stress and strain is referred to as the secant stiffness of the mix, which will approach the elastic modulus when the mixture is loaded at rapid loading rate and low temperatures. Furthermore, despite its visco-elastic characteristics, the asphalt concrete (AC) is usually simplified and reduced to an equivalent elastic body in practice (Suhaibani *et al*., 1997; Li *et al*., 1999; Shashidhar and Shenoy, 2002). Therefore, the elastic modulus of AC becomes one of the key material parameters and plays an important role in the design of asphalt pavement structures (Suhaibani *et al*., 1997). For instance, using a theoretical analysis, a thicker AC surface course with a high modulus has the same fatigue cracking resistance as a thinner AC with a low modulus (Li *et al*., 1999). A stiff AC improves the load spreading ability of the asphalt layer and hence reduces the stress and strain in underlying layers, including the subgrade, as well as reduces the potential of fatigue cracking in the asphalt layer itself (Suhaibani *et al*., 1997). An overly high stiffness can result in durability problems and the possibility of thermal cracking in surface layers. On the contrary, a soft AC can be adopted to avoid low temperature cracking of asphalt pavements.

The commonly used approaches in practice for determining the elastic modulus include the laboratory test on a standard specimen and adopting empirical formulas. A laboratory test is conducted according to the ASTM 4123-82 (1998) and the AASHTO TP91-94 (2000). Although the laboratory test is widely used in engineering practice, it is often time-consuming and unable to obtain the modulus until the asphalt mix design has been completed. On the other hand, some empirical formulas are available,

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such as the Witczak model and the Hirsch model (Andrei *et al*., 1999; Christensen *et al*., 2005; Dongre *et al*., 2005). However, the accuracy of the empirical formulas depends largely on the parameters associated with the manufacturing process of AC. Moreover, both the laboratory tests and empirical formulas are based on macroscopic analysis, and could not account for the micro-scale features of AC. Therefore, a suitable micromechanical-based model is required to determine the elastic modulus accurately at an earlier stage to improve the proficiency of mix design and the accuracy of prediction of pavement performance.

The different sizes of the aggregates and mineral fillers in asphalt mixture have long been recognized to influence the overall performance of the asphalt pavement. Micromechanical models can account for the roles of constituent materials in a composite. A number of investigations have been carried out based on micromechanical models to predict the elastic modulus of AC mixtures. The bounds, originally established by Voigt and Reuss (Paul, 1960), and later improved by Hashin (1962), can be used to estimate the elastic modulus of AC. Christensen and Lo (1979) developed a three-phase sphere model, with a spherical-shaped matrix-coated particle embedded in an infinite equivalent composite medium. However, both methods cannot take into account of the effect of aggregate gradation accurately, and hence are not applicable for a composite with particle sizes over a wide range, such as AC (Ranganath, 1997).

The influence of the particle size and its distribution on the behavior of AC has been investigated by numerous researchers in the last few decades. Lytton (1990) proposed a three-phase micromechanical model, and the elastic modulus of AC was predicted in a two-step approach, from binder-air system to aggregate-binder-air mixture. Li *et al*. (1999) developed a two-layer built-in micromechanical model by embedding an asphalt-coated circular aggregate into an equivalent AC medium. But the validity of this model was only examined by comparing with other theoretical models rather than experimental results. Shashidhar and Shenoy (2002) presented a simplified generalized self-consistent scheme using an order of magnitude analysis to describe the mechanical behavior of asphalt mastics. Li and Metcalf (2005) employed two-phase models to predict the modulus of AC in a two-step approach. They suggested that more tests on different binders and mixture designs are required to further verify any proposed approaches or existing models. Huang *et al*. (2007) provided the analytical modeling of three-layered hot mix asphalt (HMA) mixtures by considering the coarse aggregate coated with gilsonite first, then mixed with the fine aggregate and asphalt binder. Shu and Huang (2008) obtained closed-form equations based on the particulate-filled composite theory to predict the elastic modulus of the HMA mixtures, and the equations considered the air void effect. More recently, Shu and Huang (2009) predicted the modulus of asphalt mixtures using the differential method.

The microscopic analysis by Anderson and Goetz (1973) showed that the reinforcement in the asphalt mastics was influenced by a number of factors, especially the interlocking effect among aggregates, which was neglected in all above micromechanical investigations. Therefore, the existing models could only be applicable to the prediction of properties of typical suspended AC mixture, in which aggregates are mainly floated in or only interacted with the surrounding asphalt binder, without direct contact between adjacent aggregates. In this regard, the existing micromechanical models can hardly be used to predict the modulus of AC with interlocking effect. In addition, due to different gradations, the AC may have varying microstructures to satisfy various functions of the asphalt pavement. It is therefore essential to develop effective micromechanics models to account for different gradations and different microstructures in AC, to better predict the elastic modulus and to set quality control parameters that will lead to a satisfactory performing mixture.

In this paper, based on the multi-inclusion micromechanical model, a stepping scheme is presented for predicting the elastic modulus of AC with different microstructures. The effects of deboning between aggregate and asphalt binder and interlocking between aggregates are considered by virtue of an effective bonding (or equivalent imperfect bonding) model. Parameters affecting the elastic modulus of AC will be discussed in the perspective of the proposed method. Modulus tests of asphalt mixture with three different microstructures, including suspended dense structure, framework void structure, and framework dense structure, are conducted to verify the proposed approach.

2 Stepping-scheme-based micromechanical model

Asphalt mixture is a complex multi-phase material consisting of aggregates, binders, additives, and air voids. There are three types of asphalt mixture with different microstructures as shown in Fig. 1. Fig. 1a shows the suspended dense structure, characterized by no direct contact between aggregates. The particles are floating in the softer asphalt mastic. The framework void structure in Fig. 1b indicates particle-particle contact of coarse aggregates, which is considered to play a dominant role in AC performance. There are many air voids in the asphalt mixture after compaction because of the low content of fine aggregates. The framework dense structure is shown in Fig. 1c, which exhibits a dense state of the mixture because of the lack of medium-sized aggregates. Framework void structure and framework dense structure have apparent interlocking patterns, and it is difficult to establish an idealized theoretical model to simulate exactly their microstructures.

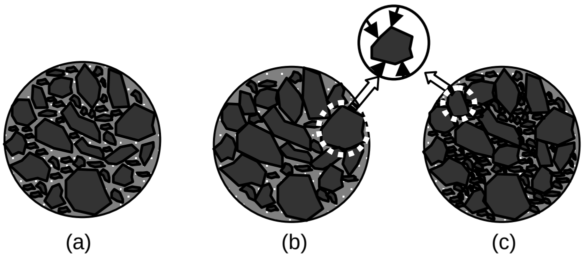

Fig. 1 Asphalt mixture with different microstructures
(a) Suspended dense structure; (b) Framework void structure; (c) Framework dense structure

In the following, a multi-inclusion micromechanical model will be proposed, and certain modifications will be made according to different microstructures shown in Fig. 1. The micromechanical model is developed with the following assumptions: (1) The asphalt mastic and the aggregates are linearly elastic; (2) The aggregates and air voids are treated as spherical inclusions with different sizes; (3) The effect of direct contacts between aggregates is neglected. The first assumption is valid when the temperature is low and the loading rate is high (Lytton, 1990; Buttlar and Roque 1996; Li *et al*., 1999; Huang *et al*., 2003; Li and Metcalf, 2005), which satisfy the condition of our laboratory experiments. The second assumption facilitates a simplified analysis and has been widely adopted in micromechanical analyses of AC (Anderson and Goetz, 1973; Lytton, 1990; Buttlar and Roque, 1996; Buttlar *et al*., 1999; Li *et al*., 1999; Li and Metcalf, 2005). The third one is applicable to the suspended dense-graded asphalt mixture in Fig. 1a. The effect of direct aggregate interlocking in the other two types of AC (Figs. 1b and 1c) will be counted by making some further modifications, as will be shown later.

The stepping scheme proposed by Yang (2007) can be seen as the different form of the differential scheme, but it is more convenient to be used in the numerical implementation. With this scheme, the effective properties of the asphalt concrete containing *N* different kinds of inclusions, which are classified according to their properties including modulus, shape, and size, can be established. It treats all kinds of inclusions individually and calculates the effective elastic modulus in each step. In the first step, the first kind inclusion of modulus $\boldsymbol{C}_1$ and volume $\boldsymbol{V}_1$ is put in the mastic of modulus $\boldsymbol{C}_0$ and volume $\boldsymbol{V}_0$. Using the Mori-Tanaka approach (Mroi and Tanaka, 1973), the effective modulus tensor of the resulting composite can be written as

$$\bar{\boldsymbol{C}}_1 = \boldsymbol{C}_0 + v_1[(\boldsymbol{C}_1 - \boldsymbol{C}_0)^{-1} + (1-v_1)\boldsymbol{P}_1]^{-1}, \qquad (1)$$

where $\boldsymbol{P}_1$ is the fourth-order tensor, given by $\boldsymbol{P}_1 = \boldsymbol{E}_1\boldsymbol{C}_0^{-1}$, with $\boldsymbol{E}_1$ as the Eshelby's tensor for spherical inclusion, and $v_1 = V_1/(V_0 + V_1)$ is the volume fraction of the first kind inclusion.

Supposing the procedure has been carried out $i-1$ times, and the current effective modulus is $\bar{\boldsymbol{C}}_{i-1}$. Now put in the *i*th kind inclusion in the mastic with effective modulus $\bar{\boldsymbol{C}}_{i-1}$. The effective modulus of the new composite can also be calculated with Eq. (1), i.e.,

$$\bar{\boldsymbol{C}}_i = \bar{\boldsymbol{C}}_{i-1} + v_i'[(\boldsymbol{C}_i - \bar{\boldsymbol{C}}_{i-1})^{-1} + (1-v_i')\boldsymbol{P}_i]^{-1}, \qquad (2)$$
$$i=2, 3, \ldots, N,$$

where $\boldsymbol{P}_i = \boldsymbol{E}_i\bar{\boldsymbol{C}}_{i-1}^{-1}$, and v_i' is the servo volume fraction and defined as

$$v_i' = \frac{V_i}{V_0 + V_1 + \cdots + V_i}, \quad i=2, 3, \ldots, N, \tag{3}$$

where V_i is the volume of the ith kind inclusion. Repeating this procedure until all kinds of inclusions are put into the mastic, one can easily derive the effective modulus of the multi-inclusion composite. It is also noted that air void is also treated as one particular kind of inclusion, say the (i−1)th type, with modulus $\boldsymbol{C}_{i-1}$=0. Eqs. (1)–(3) are valid when the inclusions and mastic are perfectly bonded.

3 Modulus prediction of asphalt concrete

To predict the AC modulus using Eq. (1) through Eq. (3) requires the input parameters: volume fractions, moduli of asphalt mastic, and aggregates of different sizes. In a mix design, the aggregate gradation and asphalt-aggregate ratio are pre-determined, which can be used to calculate the mass of asphalt mastic and aggregates of different sizes in AC samples. Then, supplemented by measurements of air void fraction as well as densities of different types of aggregates and asphalt (Table 1), the volume fraction of each type of aggregates and asphalt mastic can be readily obtained. Four types of asphalt mixture are prepared in this study to simulate different AC microstructures. Type 1 is the open graded ultra-thin AC (UTAC10-Open), with a suspended dense structure. It can be seen from Fig. 2 that this type of AC has a continuous and smooth variation aggregates proportion, which makes large aggregates mainly float in asphalt mastic. Type 2 is the gap graded ultra-thin AC (UTAC10-Gap), with a framework dense structure. This type lacks the aggregates with size in the range of 4.75–2.36 mm. Therefore, large aggregates will be surrounded by more fine aggregates, which form a dense structure. Type 3 is the stone AC (SAC13), with a microstructure between suspended dense and framework dense ones. There are relatively more fine aggregates and less medium-sized aggregates embedded in the AC, which exhibit the characteristic between Types 1 and 2. Type 4 is the open-graded friction courses (OGFC10), mainly of a framework void structure. This type contains almost 70% aggregates with size between 9.5 mm and 4.75 mm. In addition, because of very low content of fine aggregates, larger aggregates will contact directly, wherein large air voids may readily form. The optimum asphalt contents of the four types are 4.4%, 4.3%, 4.5%, and 4.5%, respectively. The aggregate gradation curves are presented in Fig. 2.

Table 1 Modulus and density of inclusion and matrix*

Sieve size (mm)	Density (kg/m^3)	Modulus (MPa)			
		Type 1	Type 2	Type 3	Type 4
Air void	–	0	0	0	0
13.20	2.850	–	–	4×10^4	–
9.50	2.852	4×10^4	4×10^4	4×10^4	4×10^4
4.75	2.858	4×10^4	4×10^4	4×10^4	4×10^4
2.36	2.680	4×10^4	4×10^4	4×10^4	4×10^4
1.18	2.651	4×10^4			
0.60	2.615	4×10^4			
0.30	2.567	4×10^4			
0.15	2.559	4×10^4	82.6	50.2	27.3
0.075	2.563	4×10^4			
<0.075	2.784	4×10^4			
Asphalt	1.022	3.8			

* For Type 1, the asphalt is considered as binder, while for Type 2–Type 4, the asphalt and fine aggregates (≤1.18 mm) are considered as binder

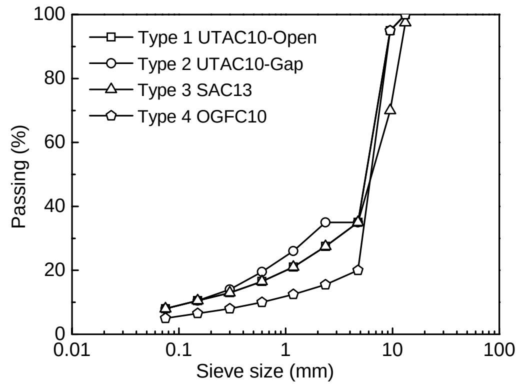

Fig. 2 Aggregate gradations for four types of AC

The modulus of limestone aggregates, which are used in the experiment, varies from 33 GPa to 48 GPa (Barksdale, 1991). The change of Poisson's ratio of the asphalt mix and the aggregate modulus is insensitive to the modulus of AC. The possible error is within 2% if using the modulus 40 GPa for aggregates (Li and Metcalf, 2005). Thus, in our calculation, the Poisson's ratio of asphalt is assumed to be 0.4, and the modulus of aggregates is taken as 40 GPa. For Type 1, even though there may have certain contacts between the coarse and fine aggregates, their effect is negligible as compared to that due to the interaction between the aggregates and the asphalt mastic. The aggregates and air voids act as individual components floating in the asphalt mastic. For other three types, Zhu and Nodes (2000) pointed out that the coarse aggregates were coated by asphalt binder mortar, which itself consisted of fine aggregates and asphalt binder. Therefore, it is the asphalt mastic rather than the asphalt alone playing the role of the binder bonding the large aggregates. In other words, there may be some contacts between the large aggregates and the fine aggregate-filler-binder in the sub-mixture. According to their study, the truncated size of coarse and fine aggregates is set as 1.18 mm. In this regard, for Type 1, aggregates with different sizes and air voids are all treated as inclusions and the asphalt is considered as binder (mastic). Experiment indicates that the modulus of asphalt binder is 3.8 MPa. For the other three types, coarse aggregates (>1.18 mm) of different sizes and air voids are treated as inclusions and the asphalt-fine-aggregate is considered as the mastic. Tests are also carried out to determine the moduli of the asphalt-fine aggregate mastic, and the results are 82.6 MPa, 50.2 MPa, and 27.3 MPa for Types 2, 3 and 4, respectively. Table 1 gives the parameters used in the modulus prediction of AC.

Table 2 Modulus test results of Types 1–4

Type	Modulus (MPa)†	Error between measured and predicted results (%)
1	1021±88	0.20
2	1088±24	0.60
3	1573±66	0.80
4	653±48	13*, 2.45#

† Modulus is presented as mean±standard deviation; * Unmodified; # Modified

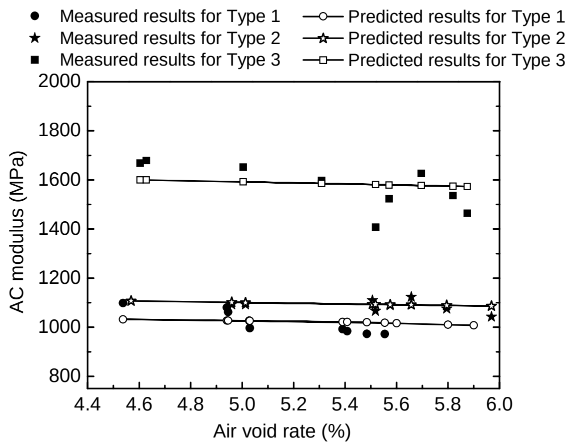

Fig. 3 Measured and predicted results of AC modulus for Types 1–3

4 Comparison between predicted and measured results

The resilient moduli of 18 test samples of each type (72 in all) are measured in laboratory, in a sequence from low to high air void fraction, on MTS810 (materials testing machine), which has a computer-controlled temperature chamber. A relatively low temperature, 15 °C, is set to insure that the AC sample is close to an elastic body. The test procedure follows the AASHTO TP31-94 (2000), which was developed based on the ASTM D4123-82 (1998). The sample is loaded cyclically by a half-sine pulse load for 0.1 s along with an unloading period of 0.9 s. The load amplitude is selected to be 25% of the mean indirect tensile strength at 15 °C. Table 2 shows the mean value and standard deviation of the experimental data. The errors between measured and predicted results are also presented. The degree of reliability of the measured modulus is up to 95%.

As shown in Fig. 3, the predictions are very close to the experimental results, indicating that the assumptions made in the multi-inclusion model are valid for Types 1–3. Interestingly, it is noted that the modulus of Type 3 is about 1.5 times higher than that of Type 1, though the volume fraction of coarse aggregates (>1.18 mm) in Type 1 is close to that in Type 3. As shown in Fig. 2, they also have almost the same gradation for fine aggregates (≤1.18 mm). The reason behind the difference between moduli of Types 1 and 3 is mostly due to the different microstructures they have. For Type 1, since most large aggregates float in the mixture, the interlock effect on the AC properties is negligible compared to the more dominant interaction between the large aggregates and the asphalt mastic. On the contrary, Type 3 presents relatively apparent particle-particle contact characteristic produced by its microstructure, which enhances the overall properties of AC. Obviously, a simple model which treats the coarse aggregates as one phase and all other constituents as another phase (two- or three-phase model) cannot differentiate the behaviors shown in Fig. 3.

As shown in Fig. 4, however, a relatively large difference between the two methods exists for Type 4, and modification must be made to account for the interlocking between aggregates.

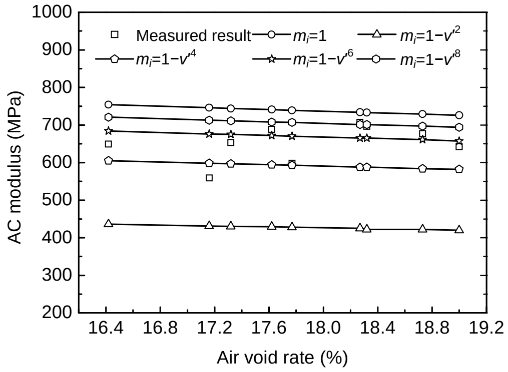

Fig. 4 Effect of debonding on the modulus of Type 4

For Type 4, the direct contact of coarse aggregates is believed to play a dominant role affecting the mechanical properties of a mixture. Actually, the volume ratio of asphalt mastic (binder) in Type 4 AC is small, so that coarse aggregates more easily contact each other. The direct interaction between aggregates leads to a remarkable reduction of bonding surface between the aggregates and the asphalt mastic. Furthermore, because of high air void fraction and low content of fine aggregates, the effective thickness of the asphalt binder membrane, enclosing the aggregate, is also very thin, so that the bonding between aggregates and asphalt mastic is not perfect. Consequently, the multi-inclusion model represented by Eqs. (1)–(3) with perfect bonding assumption tends to overestimate the modulus of AC, and further modifications are required. Instead of trying to establish a model directly considering the contact of aggregates, as explained above, our modification is based on the concept of effective bonding between inclusions and mastic, as will be shown below.

Papanicolaou and Bakos (1992) suggested that a modified rule-of-mixture be used to consider the effect of bonding condition of particles when establishing the strength of composite. This idea is extended here to evaluate the average strain tensor in the composite with a two-phase micromechanical model

$$\bar{\boldsymbol{\varepsilon}} = v_0\boldsymbol{\varepsilon}_0 + v_1 m\boldsymbol{\varepsilon}_1, \tag{4}$$

where v_0 and v_1 are the volume fractions of the matrix and inclusion, respectively. Since direct interaction between aggregates will lead to a certain reduction of bonding ability between the aggregates and the asphalt mastic, we try to employ an effective debonding parameter m, which can account for the interlocking effect. The parameter $m\in[0,1]$ is a volume fraction-dependent value and represents the degree of effective bonding between large aggregates and asphalt mastic. For perfectly bonded AC, m=1, while for the aggregate completely debonded from the asphalt mastic, the aggregate loses its all load-carrying capacity, giving m=0. Values between 1 and 0 imply a partial debonded interface between aggregates and asphalt mastic. Note that the interlocking phenomenon is related to the volume fraction of the aggregate (Huang *et al.*, 2003), we define the effective bonding parameter $m_i = 1-(v_i')^x$, where x is the parameter to be calibrated based on the test results. The parameter $\boldsymbol{\varepsilon}_0$ in Eq. (4) is the strain in the elastic mastic, and $\bar{\boldsymbol{\varepsilon}}$ is the macroscopical strain. Since $\boldsymbol{\varepsilon}_1=\boldsymbol{T}_1\boldsymbol{\varepsilon}_0$, where $\boldsymbol{T}_1$ is given by

$$\boldsymbol{T}_1 = [\boldsymbol{I} + \boldsymbol{P}_1(\boldsymbol{C}_1 - \boldsymbol{C}_0)]^{-1}. \tag{5}$$

Eq. (4) can be written in the form of

$$\boldsymbol{\varepsilon}_0 = \{v_0\boldsymbol{I} + mv_1\boldsymbol{T}_1\}^{-1}\bar{\boldsymbol{\varepsilon}}. \tag{6}$$

According to Mori-Tanaka's formula, the effective modulus of the composite can be obtained:

$$\bar{\boldsymbol{C}}_1 = \boldsymbol{C}_0 + mv_1(\boldsymbol{C}_1 - \boldsymbol{C}_0)\boldsymbol{T}_1(v_0\boldsymbol{I} + mv_1\boldsymbol{T}_1)^{-1}. \tag{7}$$

Substituting Eq. (5) into Eq. (7) yields

$$\bar{\boldsymbol{C}}_1 = \boldsymbol{C}_0 + mv_1[(\boldsymbol{C}_1 - \boldsymbol{C}_0)^{-1}(v_0 + mv_1) + \boldsymbol{P}_1 v_0]^{-1}. \tag{8}$$

Again using the stepping schemes for multi-inclusion micromechanical model introduced above, we can generalize Eq. (8) to the following form

$$\begin{aligned}\bar{\boldsymbol{C}}_i = \bar{\boldsymbol{C}}_{i-1} + m_i v_i'\{(\boldsymbol{C}_i - \bar{\boldsymbol{C}}_{i-1})^{-1}[(1-v_i') + m_i v_i'] \\ + (1-v_i')\boldsymbol{P}_i\}^{-1}.\end{aligned} \tag{9}$$

The modulus of Type 4 AC predicted by the modified model is shown in Fig. 5 with $m_i = 1-(v_i')^6$, which is determined by a trial-and-error method according to Fig. 4. It is seen that the modified formula behaves well as compared to the experimental results, indicating that the effective bonding model can properly account for the effect of direct interlocking between aggregates such as in Type 4 AC. From the results, it is found that Type 4 shows a much lower elastic modulus than that of Types 1–3. The reason lies in that Type 4 is an AC with very low fine aggregates content resulting in a high air void fraction. Therefore, many clogging large air voids rather than asphalt mastic will exist between large aggregates. This will lead to debonding between the aggregates and the asphalt mastic, which will reduce the overall properties of the AC. The influence of different patterns of m_i on the modulus is also illustrated in Fig. 4. For perfect interfacial bonding (m=1), the elastic modulus is two times higher than the weak interfacial bonding ($m_i=1-(v_i')^8$). The elastic modulus decreases with the interfacial debonding, which agrees well with the conclusion given by Tschegg *et al.* (2007).

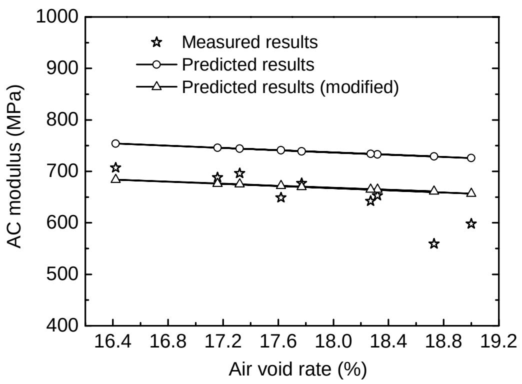

Fig. 5 Measured and predicted results for Type 4

5 Discussion

Understanding various reinforcing mechanisms will obviously be helpful in arriving at a better design of AC with appropriate aggregate gradation and filler contents, as well as in controlling the tolerance ranges which shall be used in practical production. Based on the theoretical model proposed in this study, some major findings are discussed as follows:

1. Fig. 6 shows the effect of elastic modulus of aggregate, E_{ag}, on the elastic modulus of AC, E_{AC}. With the increase of E_{ag}, E_{AC} increases at initial stages. Afterwards, especially after E_{ag} reaches 40 GPa, E_{AC} almost remains constant, which qualitatively agrees with our assumption. Thus, assuming the value of aggregate modulus is larger than 40 GPa, the influence of E_{ag} on E_{AC} can be neglected.

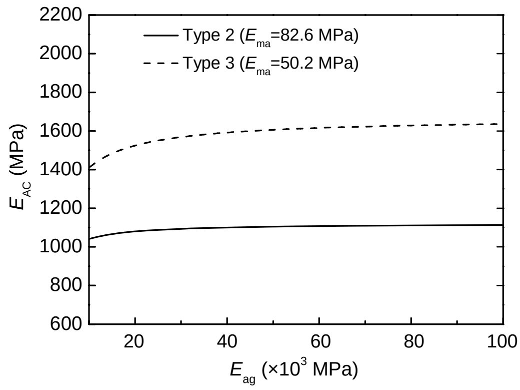

Fig. 6 Effect of elastic modulus of aggregate on elastic modulus of AC

2. The effect of elastic modulus of asphalt mastic E_{ma} on E_{AC} for two types is shown in Fig. 7. The variation of E_{AC} with E_{ma} is more obvious than that with E_{ag}. Since asphalt mastic is available with elastic modulus varying over a large range, it is more effective to change E_{ma} to improve E_{AC}.

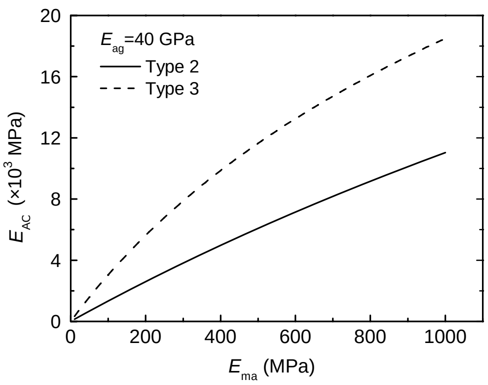

Fig. 7 Effect of elastic modulus of matrix on elastic modulus of AC

3. From Fig. 7, it is seen that the modulus of Type 3 AC (SAC13) is more sensitive to E_{ma}. A possible reason is that Type 3 has a microstructure between suspended dense and framework dense structure, in contrast to Type 2, which has a single framework dense structure. Type 2 has more apparent interlocking patterns than Type 3, thus weakening the effect of asphalt mastic on the properties of AC. On

the contrary, for Type 3, the larger aggregates have more chance to interact with the surrounding asphalt mastic, indicating that the effect of asphalt mastic on the AC properties is more remarkable. This may be useful to control the modulus of AC according to its microstructure.

4. The declining tendency is observed in Figs. 3 and 5 of AC modulus versus air void fraction. The samples for each type used to obtain the elastic modulus, however, all belong to the same group of parallel experiments. Therefore, the elastic modulus of samples only varies marginally in a certain range with the increase of the air void fraction. To further illustrate the effect of air void on AC modulus, we show the obvious relation between the AC modulus and the air void content in Fig. 8. To illustrate the effect of air void fraction on AC modulus more clearly, we further treat AC as a three-phase model, namely aggregate, asphalt mastic, and air void as three constituents. The three-phase model is very appropriate for modeling the macroscopic behavior of AC and also very convenient for calculation. The method introduced in this study is used for the prediction, and the results are presented in Fig. 8, where a relationship between AC modulus and air void fraction is clearly observed. The three-phase model somehow gives an overestimated value of the AC modulus, but the observed tendency is correct. Note that the declining tendency becomes less apparent with the decrease of asphalt mastic modulus. It indicates that when the asphalt mastic modulus is smaller, the predicted AC modulus will be less sensitive to the air void fraction, as shown in Figs. 3 and 5.

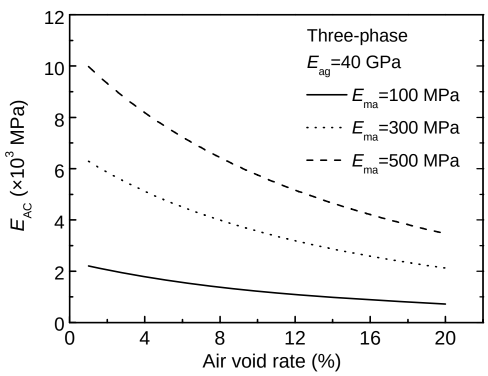

Fig. 8 Effect on elastic modulus of AC by air void

5. Take Type 3 (SAC13) for example. The conventional optimal aggregation gradation leads to three curves indicated by the upper limit, the lower limit and the medium limit of the gradation in Fig. 9. The moduli of different gradations are calculated by the present approach and the corresponding results are shown in Fig. 10. It is seen that the modulus changes in a descending order from the lower limit, to the medium limit, and finally to the upper limit of gradation. This is reasonable because the content ratio of coarse aggregates for the lower limit of gradation is larger than those of the other two. This suggests that we may use the lower limit of gradation in the AC design to obtain a road pavement with higher modulus.

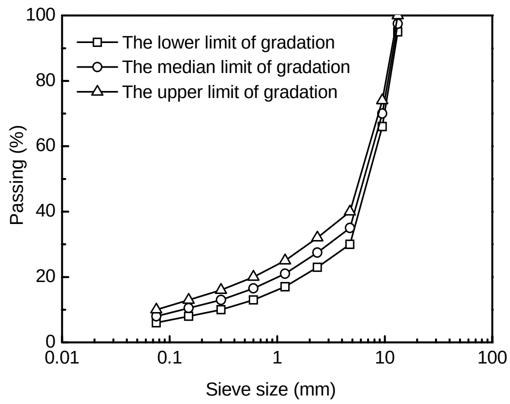

Fig. 9 Aggregate gradation for Type 3

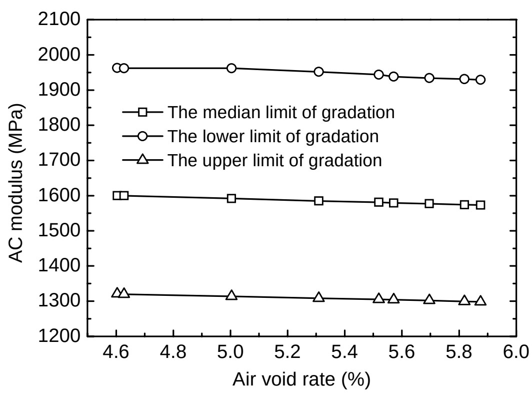

Fig. 10 Predicted modulus of Type 3

In the light of the above findings, a better design guide of AC can be followed. For example, to enhance the low temperature cracking resistance, a lower elastic modulus of AC should be used. In this case, the microstructure of the target AC should be determined at first. Then, the relatively soft asphalt mastic is adopted according to its microstructure, which can be achieved by selecting soft asphalt or reducing the content of fine-aggregates. Further, one can use the upper limit of gradation and/or control the content of air void in the design. Finally, the theoretical approach proposed in this study can be used to predict the AC modulus. In such a way, one can get several alternative schemes from which the most favorable one can be selected. Other than a proper stiffness, however, the performance of road pavement involves many other factors, such as water stability, low compaction, slide resistance, noise reduction, and so on, which should also be considered in the design to achieve a desired mixture.

6 Conclusions

In this paper, a stepping scheme based multi-inclusion micromechanical model is formulated and employed for predicting the elastic modulus of AC with different microstructures. Aggregates, additives, and voids of different geometric size and material properties are treated as different inclusions and their effects on the effective properties of AC are considered separately. A modified model is further suggested to account for the interlocking between aggregates using the concept of effective bonding between inclusion and mastic. Laboratory experiments are conducted to validate the developed models, and the procedure is also introduced to obtain the better design of AC. The following conclusions can be drawn from the present study:

1. For AC with a framework dense structure, it can be assumed that there is no direct particle-particle contact between coarse aggregates. Therefore, a simplified theoretical model can be established by assuming that direct interaction only exists between large aggregates and the fine aggregate-filler-binder sub-mixture.

2. Because of high air void fraction and low content of fine aggregates, only a small portion of aggregates is well bonded to the asphalt mastic in AC with a framework void structure. Therefore, a modified theoretical model accounting for imperfect bonding can be established. The modulus of AC decreases as the degree of interfacial debonding increases. Thus, measures have to be taken to reduce the interfacial damages in practical pavement engineering.

3. Some factors have significant effect on the modulus of AC, including the microstructures of AC, the elastic modulus of asphalt mastic, the air void fraction, and aggregate gradation.

4. The knowledge of various reinforcement mechanisms in AC by micromechanical analysis can be directly applied to optimize the design of AC.

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