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A method for quantifying the packing function of particles in packed aggregate blend

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HIGHLIGHTS

- The PCPV provides a new way to understand the composition of aggregate blend.
- The PCPV shows compaction energy and morphology independent.
- The $RC_{s_i}^{P-B}$ can be used to quantifying the packing functions of particles in blend.
- A positive $RC_{s_i}^{P-B}$ means major skeleton building function.
- A negative $RC_{s_i}^{P-B}$ means major air voids filling function.

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ABSTRACT

This paper proposes a method to quantify the packing function of particles in packed aggregate blend. Three indicators are defined to capture the composition of aggregate blend and the packing function of particles in packed aggregate blend, which are the percentage of contribution to the packing volume (PCPV), the percentage of contribution to the bulk volume (PCBV), and the relative change between the contribution of particles to the packing volume and that to the bulk volume ($RC_{s_i}^{P-B}$). Packing strategies to quantify PCPV and $RC_{s_i}^{P-B}$ are developed based on the loose filling test, the dry-rodded test and the Superpave gyratory compactor (SGC) test. Two typical aggregates, one with good angularity (denoted as crushed stone) and the other with poor angularity (denoted as gravel), are selected for investigating the proposed method with 3 stone matrix asphalt (SMA) gradations and 3 asphalt concrete (AC) gradations. The test results show that the PCPV provides a new way to understand the composition of aggregate blend. The $RC_{s_i}^{P-B}$ can be employed to quantitatively investigate the packing functions of the particles in packed aggregate blend. The zero of $RC_{s_i}^{P-B}$ represents the balance point between air voids filling function and skeleton building function. A positive $RC_{s_i}^{P-B}$ means more skeleton building function. And the bigger $RC_{s_i}^{P-B}$ the stronger the skeleton building function. A negative $RC_{s_i}^{P-B}$ means major air voids filling function. And the smaller $RC_{s_i}^{P-B}$ the more significant the air voids filling function. The balance size for the SMA gradation with the nominal maximum particle size (NMPS) of 16 mm is 2.36 mm, which is also considered as the balance size for the reference upper limit and a designed gradations of AC with the NMPS of 26.5. The balance size for the reference gradation lower limit gradation of AC is bigger than 2.36 mm but smaller than 4.75 mm. The compact energy of the filling test and the particle morphology have no impacts on the PCPV and $RC_{s_i}^{P-B}$ but significant effects on the air void content. The SGC test is recommended to quantify the indicators.

1. Introduction

Aggregate blend is the main portion forming the skeleton of asphalt concrete and cement concrete. Suitable aggregate blend characteristics are important to ensure good field mixture performance. The grain size distribution is usually employed to describe the composition of aggregate blend, which is considered highly related to the mixture performance [1,2]. The optimizing direction

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is to obtain the maximum density in traditional gradation design. Fuller [3] proposed the gradation design method on the basis of the power function curve, which is known as the *n* method. Originally, 0.5 was adopted for *n*. Now 0.45 is usually used after many times modification [4].

However, not all mixture characteristics can be ensured merely in accordance with the principle of the maximum density. The packing characteristics of aggregate blend are also usually referenced to optimize the gradation [5,6]. Weymouth [7] analyzed the particle interference effects and proposed a method to improve the workability of concrete mixture. Some methods, such as the Bailey method and the coarse aggregate void filling (CAVF) method, included the volume parameters getting from packing tests to assess the packing characteristics of aggregate blend and improve the gradation design [8–11]. Aggregates are usually categorized into coarse aggregates and fine aggregates for separately assessing in gradation design. It is usually considered that the coarse aggregates is to form the skeleton and the fine is to fill the air voids [12]. However, there are many different criteria for discriminating the coarse and fine. Typically, the size of 4.75 mm or 2.36 mm is employed [13,14]. But the maximum particle size isn't taken into account in that criterion. Brown et al. [15] proposed to use 4.75 mm to discriminate the coarse and fine particles for the stone matrix asphalt (SMA) with the nominal maximum particle size (NMPS) of 12.5 mm and 19 mm, and use the 2.36 mm for the SMA with the NMPS of 9.5 mm. In Bailey method, the size of 0.22 times of the NMPS was defined as the primary control sieve size (PCS) for discriminating the coarse and fine [8,9], while Lin [16] suggested using 0.25 times of the NMPS. However, the packing characteristics of aggregate blend are complicated. The concepts of coarse and fine aggregates can't totally meet the needs of gradation optimization in practice.

Kim et al. [17,18] proposed a new framework to analyze the composition features of aggregate blends, in which some particles was identified as dominant aggregate particles by the defined dominant aggregate size range (DASR). It was suggested that the DASR particles should be composed of coarse enough particles and the porosity of the DASR part should be no greater than 50%. The particles smaller than the DASR were considered to fill the voids between the DASR particles along with the binder and fillers. The particles larger than the DASR were thought to simply float in the mixture. The DASR identification was performed graphically and could be somewhat subjective. Guarina et al. [19] found some specific particles could disrupt the DASR structure. Then the ratio between the potentially disruptive interstitial component (IC) particles and the volume of DASR voids were referred to as the disruption factors to assess the potentials. Yideti et al. [20] divided the skeleton of unbound granular materials into two basic components, the load carrying skeleton (primary structure), built by the DASR particles, and the finer fraction (secondary structure). Then, a model describing the disruption potential (DP model) was proposed based on the division of the 2 components. The framework provided a new way to investigate the packing characteristics of aggregate blend. However, the function of each size particles could be different in the packed aggregate blend. And the packing function of aggregate particles is not always skeleton building or voids filling. The particles with given size might have both the 2 functions with different proportions. A quantitative framework in which the function of each size particles can be quantified might be more efficient for understanding the packing characteristics of aggregate blend.

This paper focused on the concern about quantifying the packing function of particles in packed aggregate blend. A series of indicators were defined to capture the composition of aggregate blend and the packing function of particles in packed aggregate blend. Then, packing strategies to quantify the indicators were developed based on the loose filling test, the dry-rodded test and the Superpave gyratory compactor (SGC) test. Six typical gradations as well as two kinds of typical aggregates, one with good angularity and the other with poor angularity, were selected to investigate the proposed method. The test results showed that the method proposed in this paper provided a quantitative way to understand the composition of aggregate blend and the packing function of particles in packed aggregate blend.

2. Definitions

Employ A to represent an aggregate blend with given gradation and mass. The sieve sizes involved in the gradation are numbered in an ascending order as s_i ($i = 0, 1, \ldots,$ M), in which s_0 means the sieve bottom, s_M means the maximum aggregate particle size in the gradation. Then denote A_{s_i} as the particles of A passed sieve s_{i+1} but retained on sieve s_i. Employ A_{s_i-sM} to represent all the particles of A bigger than s_i. Denote the packing volume of A under given packing method as V_P, which is composed of the bulk volume of all particles of A and the air voids volume between all the particles. Record the packing volume of A_{S_i} and $A_{S_i-S_M}$ under the same packing method as $V^P_{S_i}$ and $V^P_{S_i-S_M}$. Fig. 1 depicts the relationships between $V^P_{s_i}$, $V^P_{S_i-S_M}$, and V_P.

The percentage of contribution to the packing volume (PCPV) is defined as Eq. (1) to describe the contribution of $A_{S_i-S_M}$ to the packing volume of A. The contribution of A_{s_i} to the packing volume of A is defined as Eq. (2).

$$PCPV_{s_i-s_M} = \frac{V^P_{s_i-s_M}}{V_P} \tag{1}$$

$$PCPV_{s_i} = PCPV_{s_i-s_M} - PCPV_{s_{i+1}-s_M} \tag{2}$$

Denote the total bulk volume of A as V_B. Record the bulk volume of $A_{S_i-S_M}$ as $V^B_{s_i-s_M}$. Then the percentage of contribution to the bulk volume (PCBV) is defined as Eq. (3) to describe the contribution of $A_{s_i-s_M}$ to the total bulk volume of A. The contribution of A_{s_i} to the bulk volume of A is defined as Eq. (4).

$$\mathrm{PCBV}_{\mathrm{s_i-s_M}} = \frac{\mathrm{V^B_{s_i-s_M}}}{\mathrm{V_B}} \tag{3}$$

$$\mathrm{PCBV}_{\mathrm{s_i}} = \frac{\mathrm{V^B_{s_i}}}{\mathrm{V_B}} \tag{4}$$

Generally, the packing function is divided into skeleton building and air voids filling. The packing volume is composed of the bulk volume of the aggregate particles and the air voids volume between the particles. When adding an amount of given size particles to a blend, the packing structure of the blend will be changed. If there is only a decrease of air voids content but no packing volume increase, the function of the added particles can be totally considered as air voids filling. If the added particles increase the packing volume, and the increased proportion is bigger than their corresponding bulk volume proportion in the blend, they can be considered have skeleton building function. Mostly particles in each size, except the maximum size, have the 2 functions at the same time to various extents. The packing function of particles in packed aggregate blend can be quantitatively discriminated in accordance with the concepts of PCPV and PCBV. It can be considered that the major function of the particles of A_{s_i} is build the skeleton in the packed A when the value of $PCPV_{s_i}$ is bigger than that of $PCBV_{s_i}$. If the value of $PCPV_{s_i}$ is smaller than that of $PCBV_{s_i}$, the air voids filling function will be more than the skeleton building function for the particles of .. The relative change between the contri-