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Application of compressible packing model for optimization of asphalt concrete mix design

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HIGHLIGHTS

- Compressible packing model was used for the first time to optimize asphalt mix design.
- Optimization was done for two different mixes based on nominal maximum aggregate size.
- Asphalt mixes were fabricated using the obtained gradation envelopes.
- The mixes had higher compactibility than the conventional mix.
- The mixes could meet stiffness requirement of high performance asphalt mix.

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ABSTRACT

Packing of an aggregate blend is a measure reflecting how solid part and air voids would share the volume occupied by the blend. It is usually measured in terms of "packing density". In this paper, Compressible Packing Model (CPM) is described as a potential technique to optimize aggregate blend by optimizing the packing density in asphalt mixes. Gradation envelops for high-performance asphalt mixes or Enrobé à Module Élevé (EME) were determined for two different mix types (12.5 mm NMAS and 19 mm NMAS) using CPM. Further, asphalt mixes were fabricated using two types of modified asphalt binders. Compactibility and volumetrics of the mixes were assessed. Dynamic modulus test was performed to evaluate the rheological behavior of the mixes at elevated temperatures as well as loading frequencies to develop master curves. Results of this study showed that the gradation limits obtained from CPM were very close to the grading control points of EME mixes and that the asphalt mixes had higher compactibility than the conventional mix. Dynamic modulus test results also depicted the designed mixes could meet stiffness requirement of EME mixes, and the mixes behaved more elastically.

1. Introduction

Asphalt Concrete (AC) is a composite material composed mainly of aggregate particles and asphalt binder. Large amount of aggregate particles, around 95% by weight, or 85% by volume, is used in AC. Different fractions or sizes of aggregate materials each with specific quantity are used in asphalt mix to assure required mix design (volumetrics and performance) parameters. In traditional concept, large aggregate sizes provide skeleton of the mix that transfer and distribute stresses induced by traffic loads from vehicles to sublayers of pavement structure. In addition, fines together with asphalt binder form mastic which fills the voids between coarse aggregates and make the mix more durable by providing adequate bonding between them.

There has been always a need to determine optimum aggregate gradation that should be used with respect to available aggregate sources/types and fractions to achieve the optimum mix performance in field. In this regard, Packing Density (PD) of an aggregate blend, which is a measure of how good the aggregate particles would fill up the volume of the blend, can play a key role [1].

According to the literature, much attention has been paid to this concept in the field of Portland cement concrete (PCC) materials specifically in case of Self-Consolidating Concrete (SCC) and High-Performance Concrete (HPC) [2].

There are different methods that have been used for PCC mix proportioning based on PD. One of the methods is Compressible Packing Model (CPM) which was introduced by de Larrard, 1999 [3] to predict the packing density of aggregates, cements and cementitious materials along with properties of fresh and

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hardened concrete. CPM is a mathematical based model and considers combined effects of shape, texture and grading of particles. In addition, CPM includes the compaction method to describe the actual packing density of the mix. Thus, compared to other mixture proportioning methods, CPM is relatively complex. The main objective of this paper is utilizing CPM as potential method to optimize aggregate blend in AC by optimizing the packing density.

2. Packing density (PD)

Packing Density (PD) is the ratio of solid volume of aggregates to bulk volume of them and can be measured under compacted or uncompacted conditions. It is determined by Eq. (1):

$$\text{Packing density(PD)} = \frac{\text{Solid volume of particles}}{\text{Bulk volume of aggregates}} \tag{1}$$

Further, voids ratio can be calculated using Eq. (2):

$$\text{Voids ratio} = 1 - \text{PD} \tag{2}$$

Therefore, as PD increases, the voids ratio or mix porosity is reduced. PD can be determined under either condition. If it is determined under compacted condition, the method of compaction needs to be mentioned since compaction energy applied in each method is different. PD value can be very close to one if particles in blended aggregates are mixed together such that smaller particles fill the voids created by larger aggregates indefinitely. However, it is somehow unrealistic to achieve a packing density very close to one since there is always a limitation in particle size distribution. In addition to that, the fine particles cannot be too fine and, therefore, there is always voids remained unfilled. Shape of aggregates also plays important role in PD of aggregate blend, specifically particle Shape Factor and Convexity ratio. A low shape factor and/or a low convexity ratio would adversely affect the packing density since they contribute to large aggregate interlocking and higher voids ratio in the blend [4]. According to the literature, the major factors affecting the packing property of blended aggregates are:

i. Gradation (e.g. continuously-graded, gap-graded);
ii. Shape of the particles (e.g. cubical, round and flat and elongated particles);
iii. Texture of aggregate surface (e.g. rough, smooth);
iv. Type and amount of compaction effort;
v. Aggregate strength;
vi. Layer thickness [5–9].

3. Compressible packing model (CPM)

CPM can predict the packing density of polydisperse blend using three known parameters:

1) packing density of monosize aggregate;
2) size distribution of aggregates and;
3) used compaction energy.

In theory, CPM calculates Virtual packing density of the blend. It is defined as the maximum packing density which can be achieved by placing the grains one by one while keeping their original shapes [3]. Actual packing can be determined using the virtual value with respect to the compaction method.

In general, blending different classes of monosize aggregate particles would result in higher packing density. However, two interactions between these classes or sizes of aggregates should be considered. These are "wall effect" and "loosening" or "disturbing effect" as illustrated in Fig. 1.

The wall effect is defined as the interaction of aggregate particles in presence of any type of wall such as mold and pipe. This can also be referred to as interaction exists between coarse aggregates and fines. Additionally, if the amount of fine particles increases in the blend, at some point the courser particles are pushed away by fines due to the loosening effect [3,6]. Both the wall and loosening effects depend on size ratios of the particles interacting with each other as well as volumetric proportions of the different size particles. This implies that the grading of the aggregate is a controlling factor of these two effects [10]. In order to obtain virtual and consequently actual packing density of a blend, CPM considers these two interactions as additives. In the literature, several studies have investigated use of CPM in mixture proportioning of Portland cement concrete (HPC and SCC) [11–14].

4. Experimental procedures

4.1. Materials

In this study, five classes of aggregate particles were obtained from Havelock Quarry located in Northern Ontario, Canada. Gradation curve of each class is plotted in Fig. 2.

Two types of asphalt binders were used (PG 82-28 and PG 58-28). High performance elastomer additives (modifiers) were used to modify PG 58-28 asphalt for enhancing the binder properties. The main advantage of using this type of modification is in adding the additives directly to the mix as method of dry process which is less demanding and more environmentally friendly compared to conventional binder modification in which the additives are mixed with virgin binder using a high shear mixer. It is worth mentioning that 10% of these additives by weight of total modified asphalt binder were used.

4.1.1. Determination of aggregates shape parameters using image analysis

As explained earlier, the morphology of the aggregates would significantly affect the packing of the aggregates, the compaction and the stability of the asphalt mix under heavy traffic.

Morphological parameters of aggregate particles greatly affect the compaction ability (compactibility) of the mix. Aggregate fractions with the same gradation sizes which obtained from different sources or processing methods would unlikely have the same compaction behavior due to different induced internal friction energy. That is to say different compaction efforts need to be applied for the same aggregate fraction with different morphological parameters to reach the same PD.

The morphological parameters of midsize and fine aggregates were obtained using OCCHIO belt aggregates image analyser [15], see Fig. 3, and the results are listed in Table 1. It is worth noting that Concavity and Elongation of particles are gradually reduced for bigger particle sizes while Shape Factor is increased. It can also be noticed that midsize particles have higher Roundness.

4.2. Dry packing density of aggregates

In order to determine PD of an aggregate blend in a laboratory, the basic procedure is mixing the aggregate particles, put them into a container of known volume, and weigh the aggregate particles in the container. PD, which represents how well the aggregate are packed together, can then be measured by knowing the aggregates weight, density and the volume of the container. From this, the voids content, the volume of voids in the bulk volume of aggregate to be filled up with asphalt, may also be determined.

In this study, in order to determine more realistic values of PD of aggregate blend for asphalt mix, it is measured using Superpave Gyratory Compactor (SGC), according to a method used by