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Lab assessment and discrete element modeling of asphalt mixture during compaction with elongated and flat coarse aggregates

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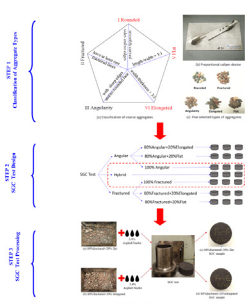
HIGHLIGHTS

- Analyze the influences of coarse aggregates' shapes on asphalt mixture compaction.
- Mixtures with 100% angular/fractured aggregates were easier to compact than hybrid.
- The larger ratio of elongated/flat aggregates, the worse compactability of mixtures.

GRAPHICAL ABSTRACT



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ABSTRACT

Superpave gyratory compactor (SGC) is usually used for analysis of volumetric properties of asphalt mixture, evaluation of mixture densification properties, estimation of sensitivity to aggregates' shapes, field quality control and other testing purposes. The specimens produced by SGC very closely simulate the density, aggregate orientation and structural characteristics of asphalt mixture on actual pavement. Aggregates make up the major volume or mass of asphalt mixture, and their shapes significantly impact both the structural and mechanical performance of mixtures. The objectives of this study were to analyze the influences of selected coarse aggregates on asphalt mixture compaction through lab testing and modeling. First, coarse aggregates were classified into five types, and testing samples were produced with designed percentages of different types. Second, images of selected coarse aggregates were obtained by 3D scanning and saved in STL (Stereolithography) files. Finally, the air void curves and results of discrete element modeling (DEM) were used to evaluate the influences of selected coarse aggregate shapes on asphalt mixture compaction. It was found that the asphalt mixtures with 100% angular or 100% fractured coarse aggregates were easier to compact compared with asphalt mixtures of hybrid coarse aggregates in a SGC test. Results also clearly indicated that the larger percentage of elongated and flat aggregates, with a 3:1 ratio, results in worse compactability of asphalt mixtures under laboratory conditions, and the influences of flat aggregates were greater than that of elongated. Therefore, special attention should be paid to asphalt mixtures with a large percentage of elongated or flat aggregates.

1. Introduction

Asphalt mixture compaction is one of the key factors affecting the performance of asphalt mixture. The quality of asphalt pavement in construction and service stages hinges largely on

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compaction degree [1,2]. Under-compacted asphalt mixtures usually lead to relatively low density, reduced stiffness, accelerated aging, less fatigue life, rutting, raveling, moisture susceptibility and decreased durability [3,4]. The over-compaction of asphalt mixtures causes the appearance of bleeding and rutting distresses, which is a result of inadequate voids for expansion and contraction during the variation of temperature [5]. Many attempts have been made to analyze the factors that influence compaction of asphalt mixture. The classification methods of particles were proposed in some standard techniques, such as the American Society for Testing Material (ASTM D4791/5821/2488) and the American Association of State Highway and Transportation Officials (AASHTO TP 61). Many previous studies investigated the shapes of coarse aggregates and their influence on the performances of asphalt mixtures. Researchers discussed mathematical characterization of aggregate shapes, reconstruction of asphalt mixtures' structure and the influence of aggregate shapes on performances of mixtures [6,7]. Some glass aggregates were utilized to replace the natural aggregates, and the mixtures were analyzed for the relationship between geometrical features on rheological performances and the stage of asphalt mixture compaction [8,9]. For describing movement of coarse aggregates in the laboratory formation process of asphalt mixture, Guo et al. proposed the equivalent-sphere mathematical model to express dimensions of coarse aggregates [10]. In addition, many researchers aimed to study the parameters, characteristics of compaction and performance prediction by laboratory methods [11–20]. In recent years, Discrete Element Method (DEM) was introduced into civil engineering. Some researchers utilized DEM to study the properties of asphalt mixtures: the feasibility of the DEM method has demonstrated to be a suitable tool to analyze the performances of asphalt mixture compaction [2,21]; You et al. focused on the dynamic modulus simulation by the combination of DEM and X-ray Computed Tomography (X-ray CT) [22]; Liu et al. developed a new approach through the combination of DEM and Matlab methods to simulate the realistic particle shapes in stone-based mixtures [23].

Significant work has been done in analyzing the relationship between aggregates and compaction characteristics of asphalt mixture. Most of this work has revolved around the gradation of aggregates, compaction temperature, loading condition, gyration number and gyration angle, while little work has been done with the influence of selected coarse aggregate shapes on compaction properties such as the air void or the degree of the compaction. The development of clump technique in DEM provided a feasible way to simulate and analyze the influence of aggregate shapes on mixtures. The objectives of this research were to utilize lab test and numerical modeling for analyzing the effects of selected coarse aggregate shapes on the asphalt mixture compaction. For these reasons, specifically selected coarse aggregate shapes with designed proportions were applied to a SGC test and corresponding DEM numerical modeling was employed to verify testing results.

2. Source materials and aggregate selection

2.1. Source material properties

The source materials used in this study were made up of two main components: aggregates from Eagle River, Wisconsin, United States (with the gradation of aggregates shown in Table 1) and PG 58–28 asphalt binder from Detroit, Michigan, United States (with detailed properties shown in Table 2).

2.2. Aggregate classification and selection

First, coarse aggregates used in this research were sieved according to the AASHTO T27/ASTM C136. Further, the coarse aggregates were categorized into five different types according to the characteristics of angularity, fractured faces and the dimensional ratios in ASTM D4791/5821/2488, AASHTO TP 61 specification. Fig. 1(a) shows the type graph of coarse aggregates and the typical characteristics of each type are as follows:

- Type I Rounded particles (R): the aggregate particles have smooth sides and no edges;
- Type II Fractured particles (Fr): the aggregate particles contain at least a minimum number of fractured faces (usually one or two, one is used in this study);
- Type III Angular particles (A): the aggregate particles have sharp edges and relatively plane sides with unpolished surfaces;
- Type IV Elongated particles (E): the dimensional ratio (length/width) is greater than 3:1;
- Type V Flat particles (F): the dimensional ratio (width/thickness) is greater than 3:1.

Table 1
Gradation of Aggregate.

Sieve Size No. (mm)	Passing Percent (%)
½″ (12.5 mm)	93.9
3/8″ (9.5 mm)	86.3
#4 (4.75 mm)	68.2
#8 (2.36 mm)	49.2
#16 (1.18 mm)	38.4
#30 (0.6 mm)	27.8
#50 (0.3 mm)	15.0
#100 (0.15 mm)	6.7
#200 (0.075 mm)	4.5
pan	0

Table 2
Properties of PG 58–28 Asphalt Binder.

Test properties	Test Result	Specification	Method
Specific gravity	1.03	–	AASHTO T 228
Rotational viscosity at 135 °C (Pa S)	0.320	<3.0	AASHTO T 316
Dynamic shear of original binder, $G^*/\sin\delta$ at 58 °C (kPa)	1.218	>1.1	AASHTO T 315
Dynamic shear of RTFO residue, $G^*/\sin\delta$ at 58 °C (kPa)	2.916	>2.2	AASHTO T 315

3. Experimental testing plan and aggregate selection analysis

3.1. Experimental testing plan

The proportion design of asphalt mix in this study was based on the Superpave mixture preparation process from the Michigan Department of Transportation (MDOT) [24]. The detailed design parameters of the E3 asphalt mixture with expected design traffic volume from 1 to 3 million equivalent single axle loads (ESAL) over a 20-year design life are shown in Table 3. In order to analyze the influence of the elongated and flat shapes of coarse aggregates on asphalt mixture compaction, the key step was to determine the percentage of different types of coarse aggregates before the SGC test. As shown in Fig. 2, three control groups were designed in the dashed circle: asphalt mixture with the hybrid coarse aggregates (unselected aggregates with five types), 100% proportion of fractured and 100% proportion of angular coarse aggregates. In the other test groups, angular and fractured coarse aggregates were the two main shapes used; 20% of elongated and flat coarse aggregates were used to replace equal amounts of these main