Construction and Building Materials 66 (2014) 549–566

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Evaluation of particle simulation methods using aggregate angularity and slump tests

Taeyoung Yun *, Yeonbok Kim

Department of Highway Pavement Division, Korea Institute of Construction Technology, 1190, Simindae-Ro, Goyang-Si, Gyeonggi-Do 411-712, Republic of Korea

HIGHLIGHTS

- The feasibility of three particle simulation methods was rigorously evaluated.
- The laboratory tests are accurate to capture the effect of aggregate size.
- The equivalent spherical particle best simulated the dynamic behavior of aggregates.

ARTICLE INFO

Article history:
Received 21 April 2014
Received in revised form 26 May 2014
Accepted 26 May 2014

Keywords:
Particle packing
Discrete element method
Slump test
Angularity test
Eliipsoidal particle
Aggregate simulation

ABSTRACT

In this paper, three particle simulation methods were rigorously evaluated using several quantitative metrics to verify their feasibility for aggregate packing and mixing simulations in which determining the volumetric properties under multiple phases and conditions is essential. The physical properties and representative volume of each size of aggregate were determined by laboratory tests and image processing techniques. The sieve size sphere method, equivalent sphere method, and equivalent ellipsoid method were used with several combinations of friction coefficients to determine the significance of the particle simulation method on the dynamic aggregate behavior in discrete element method (DEM) simulations. The measured weight, height, diameter of the aggregate spread, and falling time duration from laboratory aggregate slump tests and aggregate angularity tests were compared to those from DEM simulations. The comparisons between the laboratory tests and simulations indicate that the aggregate angularity test and aggregate slump test were sufficiently accurate to capture the effect of the aggregate size on the dynamic behavior. No particle simulation method satisfied all of the conditions as well as the aggregate slump test and angularity test results, such as height, spread, weight, and simulation time; however, most of the particle simulation methods had good potential to simulate individual laboratory tests. Therefore, a more realistic particle simulation method that is capable of considering the morphological characteristics of aggregates should be developed to successfully perform packing and mixing simulations.

1. Introduction

Improving the packing density of particles is an important issue in several areas of engineering because it often affects the transportation or storage cost of materials. The packing density of materials is significant in civil engineering for both reducing the volume or amount of aggregates and improving the strength or performance of mixtures with various aggregate and binder contents. Several analytical packing density models (PDMs) have been developed to estimate the variation of particle packing density of aggregate mixtures, including the Furnas model Furnas [1], Aim and Goff model Aim and Goff [2], Toufar model [3] linear packing density model [4], Andersen and Johansen model Andersen and Johansen [5], and compressible packing model [6]. Several of the models have been found to correlate well with laboratory test results. Because all of these analytical models were developed from logical modeling concepts that utilize spherical particles of aggregate, possible issues due to the morphological complexity of the aggregate in aggregate mixtures are not appropriately addressed even though additional concepts, such as the loosening effect and wall effect, have been introduced to enhance the predictability of the models for various aggregate mixtures. Because of the inherent limitations of analytical PDMs, many researchers have recently suggested including morphological parameters, such as form, texture, and the angularity of the aggregate, by utilizing digitalized

* Corresponding author.
E-mail addresses: tyun@kict.re.kr (T. Yun), ybkim@kict.re.kr (Y. Kim).

http://dx.doi.org/10.1016/j.conbuildmat.2014.05.102

image processing techniques [7,8], Brzezicki and Kasperkiewicz [9] to better understand the influence of morphological properties of aggregates and to estimate the volumetric characteristics of the aggregate mix in drying and wet mixing processes.

The discrete element method (DEM) is a numerical analysis technique that mechanically simulates the dynamic behaviors of particles, including packing density. An increasing number of researchers have utilized DEM models with digital image processing techniques to simulate aggregate packing processes in civil engineering because a discrete element analysis that is highly correlated with experimental data can be used to minimize the number of repetitive laboratory experimental tests and to investigate the effect of the aggregate characteristics on the mechanical properties of the hardened mixture [10,25]. As in other numerical simulation methods, several mechanical properties, such as the elastic modulus, Poisson's ratio, restitution or damping coefficient, and rolling and static friction coefficients, are required as input parameters in DEM models. However, both the mechanical and morphological properties of the aggregate should be considered to obtain results that are optimized in terms of the accuracy and computational cost because the mechanical properties in DEM models are conceptualized from meso-scale Newtonian mechanics and are not directly equivalent to the morphological properties.

Single spherical particles have been utilized in simulations by researchers in many areas [11–16] because of their simplicity and low computational cost in dynamic simulations. Meanwhile, simulations that use polyhedrons or multiple overlapping spheres have also been developed by many researchers [17–21] because they minimize possible errors due to morphological discrepancies between the simulated particles and actual aggregate; however, they require a higher computational cost than spherical particles. Studies that have applied elliptical particles [22–24] are important because the use of ellipsoidal particles with overlapping spheres is often effective in reducing the computational time and enhancing the accuracy of simulations. However, more attention must be paid to systematic particle simulation methods that consider the volumetric properties of the particles as well as to verifying simulations against multiple test conditions because although several researchers have made progress in this type of simulations [10,36,25], volumetric properties have not been rigorously considered.

The volumetric characteristics of aggregates are known to have significant effects on the mechanical behavior of aggregates and on the optimum binder contents in asphalt concrete mixtures and the water contents in cement concrete mixtures. In addition, DEM simulations with fixed mechanical properties and volumes of spherical particles must be verified under multiple test conditions to simulate multi-phase processes, such as sample fabrication from aggregate packing to semi-solid specimen compaction. Therefore, this study evaluates three aggregate simulation methods, including the conventional sieve size sphere method, equivalent sphere method, and equivalent ellipsoid method with overlapping spheres, to investigate the applicability of simple particle simulation methods in DEM models while considering the volumetric characteristics. Details about the particle simulation methods and verification measures as well as the laboratory test methods and physical properties of the aggregates are presented in the following sections.

2. Laboratory tests for characterization

2.1. Testing materials and methods

One hundred aggregates were randomly selected from a 19 mm crushed aggregate stockpile that contained aggregates that passed a 25 mm sieve and were retained by a 19 mm sieve. The aggregates were washed and dried to eliminate uncertainties. Then, 2D digital images of the aggregates were taken and processed using the open source image processing software Image J to determine the length (L) and breadth (B) of the aggregates. A Vernier caliper was used to measure the thickness (T) of the aggregates. Additionally, the dry weight of each aggregate and the submerged weight of each aggregate clump were measured to calculate the volume of the individual aggregate particle and the representative volume of the aggregate. These processes were repeated for the 13 and 10 mm aggregates from the same aggregate source. The X-ray microtomography is known to be one of advanced analysis methods [38,39] but it is not utilized in this research since it requires very expensive equipment and computational time intensive analysis processes. However, it will be worthwhile to capture the characteristics of aggregates by using the equipment if it is available. These three sets of physical data were utilized to determine the particle size in the DEM model and to correlate the volumetric properties due to the aggregate sizes with the mechanical properties in the numerical simulation. Five coarse aggregate angularity tests [31] and aggregate slump tests were performed for each aggregate size to capture the mechanical characteristics of the aggregates and to determine the parameters of DEM model.

2.2. Physical property test

The measured weights, thicknesses, breadths, and lengths of selected 19, 13, and 10 mm aggregates are presented in Fig. 1(a)(d), (b)(e), and (c)(f), respectively. Despite the scatter, the number of samples appears to represent the morphological characteristics of each aggregate size. Table 1 also shows the mean values, standard deviation (SD) and calculated weights for each size of aggregates. The calculated weight of the aggregate that is determined by multiplying the density by the retained sieve size for each aggregate is represented by the solid lines in Fig. 1.

The comparison of the measured weight to the calculated weight (Fig. 1(a)–(c), and Table 1) shows that the calculated weights are different from the measured weights. For the 10 mm aggregate, the mean weight and calculated weight are 3.14 g and 1.42 g, respectively, which means that more than 100 particles should be added to make the total weight of the simulation particles equal the total weight of the actual aggregates when the particle diameter is equivalent to the retained sieve size. Because 100 aggregate particles were used to measure the properties, this discrepancy is rather large. Because the number of particles of a certain size is directly related to the total volume of particles, which is important for determining the optimum binder contents or water contents when designing mixtures, it is important to minimize the discrepancy between the volumes of the DEM particles and aggregate particles for realistic simulations.

Aggregates are occasionally classified by the flatness ratio and elongation ratio Lee and Chou [26], as shown in Eqs. (1) and (2), respectively.

$$\text{Flatness ratio } (R_f) = T/B \tag{1}$$

$$\text{Enlongation ratio } (R_e) = B/L \tag{2}$$

The significance of this classification method on the degree of particle packing and the mixture design is not clearly quantified, but it appears that this classification indicates an approximate relationship between the influence of the shape of the aggregate and the performance of the mixture. Fig. 2(a)–(c) present the flatness and elongation ratios of the selected 19, 13, and 10 mm aggregates, respectively; the morphological features of these three aggregates are classified as thick plates, spheres, ellipsoids, and short rods. The circles in the figures represent the representative flatness ratio and elongation ratio of each class. Low elongation