Fusion Engineering and Design 121 (2017) 356–360

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Research Paper

Study on the mechanical behaviors and elastic modulus of mixed fusion pebble beds

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ARTICLE INFO

Keywords:
Elastic modulus
Granular matter
Mechanical cycling
Discrete element method

ABSTRACT

Considering that the study on the mixed fusion pebble beds has been rarely conducted, in this paper the discrete element method (DEM) was used to report the mechanical behaviors and elastic moduli of mixed pebble beds which contain two kinds of solid materials. Several combinations of two kinds of solid materials were studied including the mixed Li_2O-Li_4SiO_4, Li_2O-Li_2TiO_3 and Li_4SiO_4-Li_2TiO_3 pebble beds. The effect of cyclic pressure p and the subtle difference in particle sizes within the granular system were considered. In this study, we observed that the stiffness of the mixed granular system falls in between the system consisting of softer solids and that consisting of stiffer solids as expected. We also observed that cyclic pressure (mechanical excitation) would stiffen the mixed granular system, but this effect will become smaller as the cycle number increases. This indicates that the stability of system will become stronger under this effect. Besides, the subtle difference in grain sizes was observed to soften the system although it caused a little higher packing density.

1. Introduction

Due to some of their specific characteristics, granular materials are widely used in various industrial applications. For instance, pebble beds have already been determined as one of the promising form of the tritium breeders (Li-based ceramic, such as Li_4SiO_4, Li_2TiO_3, Li_2O, etc.) and neutron multipliers (such as Be and BeO) for the fusion reactors [1]. For the assemblies consisting of particles, their behaviors under mechanical loads and especially the elastic moduli need to be fully studied before they can be applied. Owing to the discrete nature of granular materials, however, it's hard to quantify their properties in details and precisely using the continuum models [2]. And even for experiments, some data cannot be obtained or observed either [3,4]. With the help of probability and statistics, discrete element method (DEM) has been proved the effective and accurate tool to study the granular materials [5]. Using this method, pebble deformation, mechanical behavior and internal force distribution of the assembly can be obtained and visualized directly [4].

While some work on the mechanical behaviors of fusion pebble beds have been carried out, it's mainly limited to the unitary pebble beds which contain only one kind of solid materials [2–7]. The mixed pebble beds consisting of multiple materials have not been investigated, especially for the fusion applications. The study on the mixed pebble beds is very necessary since the mixed pebble bed is a completely different concept and it probably brings us many unexpected results. Besides, the elastic modulus of pebble beds affects their thermal properties viz., effective thermal conductivity of the pebble bed, which is most important in the development of TBM [8–10]. This indicates the importance of the relevant study.

In the previous work [7], the single size fusion pebble beds have been investigated in detail using the DEM method. Accordingly, in this paper DEM is still used to report the mechanical behaviors and elastic moduli of mixed ceramic pebble beds. To be more practical, the subtle difference in particle sizes within the system will also be taken into account as done in [7]. In addition, considering that fusion pebble beds might be exposed to the external loads periodically in their future applications [11], this study will pay attention to the effect of cyclic loads. This work is necessary since flow behaviors of the pebbles viz., angle of repose, angle of contact etc. induced by external excitations, will significantly affect the mechanical behaviors and elastic modulus of the pebble bed.

2. Discrete element method

The basic idea of DEM is that each discrete particle is treated as an individual and independent element. In DEM, the translation and rotation motions of every element are controlled by Newton's second law, and the contact relationships between particles are developed by the corresponding contact model.

By solving the positions of all microscopic particles corresponding

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http://dx.doi.org/10.1016/j.fusengdes.2017.08.006
Received 5 April 2017; Received in revised form 11 July 2017; Accepted 7 August 2017
Available online 18 August 2017

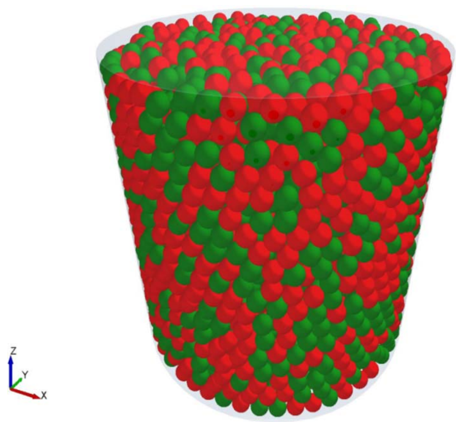

Fig. 1. Illustration of a sample randomly generated by DEM. Different colors represent different solid materials.

to external conditions, the macroscopic behaviors of a whole system can be obtained. Here to be realistic and reliable, the accurate and efficient Hertz-Mindlin contact model [12] was used to characterize the elastic contact behavior between particles.

In this study, two cylindrical box samples (illustrated in Fig. 1) filled with dry, noncohesive and uncrushable particles are used for simulations. One sample contains the particles of absolutely uniform size. Another one took the subtle change in particle sizes into account, considering that in practical applications grain sizes cannot be created to be absolutely equal [7]. The details about these two samples are listed in Table 1. From the table, the initial packing fractions for these two samples are respectively 60.56% and 60.62%, which are the typical values for single size pebble beds. Besides, for both of these two samples and the two kinds of solids within box are mixed homogeneously and their volume fractions are nearly equal ($\approx$0.5). To investigate the effect of cyclic loads, the sample 1 is repeatedly loaded and unloaded in one dimension (gravity or z direction) to monitor the evolution of its behaviors. Table 2 presents the material properties (at room temperature) used in simulations. These properties are all directly taken from the literatures [4–7,13–15].

One should note that the packing factor used in this work is much lower than the packing factor achievable in the breeder zone ($\sim$64%).However, the study on the pebble beds with higher packing factor is straightforward.

3. Results and discussion

In this section, the mechanical behavior and elastic modulus of the mixed pebble bed were reported with the help of DEM. The property of the pebbles viz., Young's modulus, which depends on the degree of compression or indirectly on the packing fraction or void fraction, was determined by Hooke's law.

Before presenting our numerical results and making discussions in this section, it's necessary for us to first show here the accuracy of our computations. In case of the Li_4SiO_4 pebble bed, An et al. [5] have reported that the packing density of 60.3% needs about 5 MPa to obtain the bed strain of 1%, and in the current study, the packing density of 60.56% needs about 4.5 MPa at the bed strain of 1% (see Fig. 2). The difference in these two values may come from the different sample geometry which has been hown to have an effect on the mechanical behaviors of pebble beds. Still, our results are in good enough accordance with the previous numerical study, suggesting that our calculations are reasonable.

It's necessary to note that the maximum bed strain value adopted in this work is about 1.3% to promise the contacts between grains are elastic. Besides, in the current study, we only focus on the randomly packed pebble beds since they are the practical ones for applications. The study on the regular arrangement of pebbles viz., hexagonal close packing, body centered cubic, face centered cubic, etc., is not discussed here and may be our future work.

Table 1
Details about the samples used for simulations.

Sample	Number of particles	Particle size distribution	Particle diameter d_p/mm	Initial packing fraction ρ_0
Sample 1	4962	uniform	0.5	60.56%
Sample 2	4982	normal	0.49 ~ 0.51	60.62%

Table 2
Properties of solid materials.

Prpperty	Li_4SiO_4	Li_2TiO_3	Li_2O	Steel (F82H)
Density, g/cm^3	2.352	3.189	1.529	7.9
Young's modulus E_p, GPa	91.4	200.6	70	217
Poisson's ratio ν_p	0.24	0.27	0.19	0.3
Static friction coefficient for particle-particle	0.1			
Static friction coefficient for wall-particle	0.1			

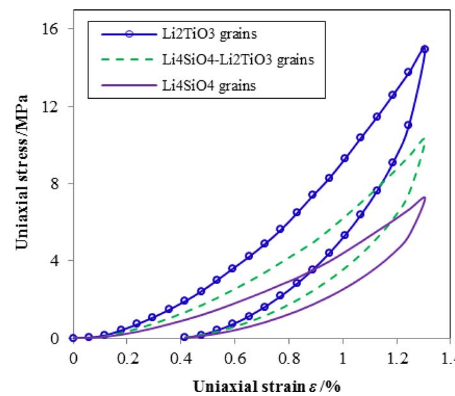

Fig. 2. Comparison between stress-strain behaviors of different particulate materials (based on sample 1) for the first loading-unloading cycle.

3.1. Uniform particle size distribution

Based on the sample 1 (absolutely uniform distribution in particle sizes, i.e. each grain has an equal size), the stress-strain curves of several pebble beds for the first loading-unloading cycle are plotted in Fig. 2 to show the relation between the unitary pebble beds and the mixed one. As expected, the stress-strain behavior of the mixed Li_4SiO_4-Li_2TiO_3 pebble bed falls in between the Li_4SiO_4 pebble bed and Li_2TiO_3 pebble bed. In Fig. 2, we can also see that the stress-strain behavior of the mixed Li_4SiO_4-Li_2TiO_3 pebble bed seems to be right in the middle of Li_4SiO_4 and Li_2TiO_3 pebble beds. This is somewhat unexpected although it's known to us that in the mixed bed the Li_4SiO_4 and Li_2TiO_3 grains are distributed homogeneously and have a nearly equal volume fraction. To further verify this observation, we plot the mean curve of Li_4SiO_4 and Li_2TiO_3 pebble beds in Fig. 3 to compare with the mixed Li4SiO4-Li2TiO3 pebble bed. From that, we can clearly see that they have a good agreement with each other on the whole, at least for the current problem.

Still base on the sample 1, the stress-strain behaviors of several mixed ceramic pebble beds are presented in Fig. 4, and their corresponding curves of bed effective moduli versus pressure are plotted in Fig. 5. Note that cycle number n = 0 means that the granular system has not yet undergone a complete loading-unloading cycle.