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Percolation segregation of binary mixtures under periodic movement

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ABSTRACT

Three strain rates of 1.0, 0.5, and 0.25 Hz were selected for studying percolation segregation in binary mixtures of urea (spherical) and potash (angular). Mixed binary samples prepared from three mean coarse sizes with their corresponding three and two fines sizes for potash and urea, respectively. Herein, three coarse mean sizes 3675, 3075, and 2580 µm and three mean fine sizes 2180, 1850, and 1550 µm were selected for tests. Percolation segregation in mixed binary sample was quantified using the primary segregation shear cell (PSSC-II). Based on experimental results, the segregated fines mass, normalized segregation rate (NSR) and segregation rate of fines for binary mixtures increased with increasing strain rate from 0.25 Hz to 1.0 Hz. The NSR decreased with decreasing strain rate from 1.0 Hz > 0.5 Hz > 0.25 Hz for size ratios 1.7, 2.0, and 2.4 ($p < 0.05$). At these three strain rates, for size ratio 2.0, the NSR of coarse size 3675 µm with fines size 1850 µm was smaller than the NSR of coarse size 3075 µm with fine size 1550 µm in the binary mixtures ($p < 0.05$). At three strain rates of 1.0, 0.5, and 0.25 Hz, the NSR for potash was higher (53%, 56%, and 46%) than the NSR for urea for the same size ratio ($p < 0.05$).

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1. Introduction

Segregation is an unwanted phenomenon in particulates that affects the quality of mixtures during unit operations, such as mixing, conveying, filling, discharging, and compaction. Segregation can be defined as a bulk solid composed of particulates with differing constituent properties that evolve to a spatially non-uniform state [1]. The importance of mitigating segregation can be gauged by the diverse group of industries that are impacted; for instance, agricultural, ceramic, construction, food, nutraceutical, metal powder and metallurgy, and pharmaceutical. Researchers have reported that the physical properties of particles, energy input [2], particle movement direction [3,4], and devices used [5–7] during particulate material processing contribute towards particle segregation. Based on the above-mentioned parameters and new findings [8–10], a re-categorization of the segregation mechanisms (trajectory, air current, rolling, sieving, impact, embedding, angle of repose, push-way, displacement, percolation, fluidization, agglomeration, and concentration driven displacement) has been proposed. Of the above-mentioned thirteen segregation mechanisms, percolation segregation is the most common phenomena during unit-operations such as filling, conveying, storage, mixing, and flowability. Percolation segregation requires dynamic conditions such as those induced by shear and vibration in bulk solids [6], however even small movements can induce segregation by this mechanism. Given its pervasive nature and impact in numerous applications, percolation segregation in particulate materials was the focus of this study. Segregation can be mitigated, if not eliminated, by understanding the factors affecting the mechanisms [11]. Three approaches either to eliminate or to reduce segregation that have been reported are change of material, change of process, and change of equipment design [12].

Bridgwater and colleagues were the pioneers in identifying the dominant parameters responsible for segregation [13–20]. These researchers found that the size of particulates is the most dominant parameter contributing towards segregation. Results were later confirmed by several researchers (for instance, [21–26]). Subsequent researchers have reported that size and density are the two main parameters for segregation [27–30] of components, especially for blended fertilizers. Furthermore, percolation segregation was shown to be affected by shape in addition to size and density [31–33] as well as the operating conditions [34–35].

Under vibration conditions, the effect of physical properties such as particle size and distribution, density, and shape has been reported [36–37]. Binary mixtures of glass beads and steel of the same size were studied to observe the effect of vertical vibration on segregation [38]. When a mixture of different size particles was vibrated, the largest size particles rose to the top or sank to the bottom depending upon vibration frequency and amplitude [39]. Rise and sink of an intruder in a granular material bed depend on the particles' properties and intensity of vibrations [40]. Researchers have also studied the rise and sink behavior of an intruder in a vertically vibrated cohesive granular

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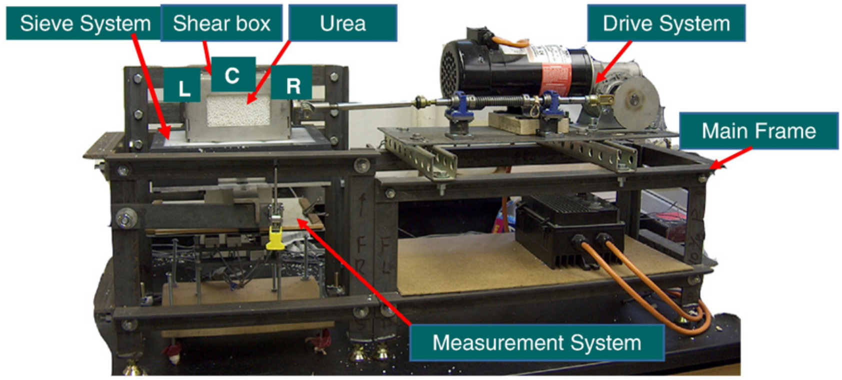

Fig. 1. Primary segregation shear cell of generation two (PSSC-II).

material [41]. Effect of shape and density on segregation in binary mixtures was quantified [42]. Limited understanding of time-dependent percolation segregation has been achieved by researchers [24,43–46]. Experiments were conducted for a limited number of binary size mixtures of glass beads (ideal material) under two strain rates, when a layer of fines was introduced at the surface of a bed of coarse particles [44]. Although wealth of information is available on segregation in the literature, these results have limited application in the real-world materials (actual materials used in industry for product manufacturing) either because the material was ideal material or studies were time-independent. One of the efficient approaches to gaining a deeper understanding of percolation segregation mechanism is by studying the cumulative effect of two or more parameters, i.e., allows one to build a roadmap by understanding the influence of individual parameters and their interactions that contribute toward overall segregation. While size has been identified as a dominant parameter, the magnitude (i.e., amount) and rate of percolation segregation of fines (during shear motion conditions) are not known a priori for specific operational conditions. Therefore, appropriate tests sufficiently representing the operational conditions must be performed to determine the amount and rate of segregation of fines.

Based on the above literature review and their limited application to real-world materials, the aim of this research was to study time-dependent percolation segregation in binary mixtures of particulate materials. Accordingly, the specific objectives of this study were to determine the effect of: 1) strain rate on size ratio 2) coarse size and fines size, and 3) materials used to formulate binary size mixtures.

2. Materials and methods

The second generation primary segregation shear cell (PSSC-II) has five main components [22]: shear box, measurement system, sieve system, drive system, and main frame (Fig. 1). The details, capabilities, and limitations of the PSSC-II can be found elsewhere [22,45]. A sieve of opening size 2360 µm was used throughout the experiments based on preliminary tests with different binary mixtures to ensure that coarse size particles did not block the sieve openings, while allowing the fines to fall unhindered through the sieve openings.

Binary, ternary, and quaternary size distributions were made and studied in addition to continuous distributions at different strain rates. The motivation for binary and multi-size study was to formulate mixtures representative of continuous size distribution when studying percolation response under different motion conditions. Binary size mixture is considered to be the foundation of multi-size and continuous mixture study. Therefore, results are presented for binary mixture in this article. Results of multi-size and continuous mixtures will be presented in subsequent articles. In the present article, nine different binary size ratios of potash and six different size ratios of urea in different mixing ratios were studied. The segregation results were analyzed using segregation determining metrics such as the effect of size ratio and mixing ratio on segregation, collected segregated fines mass, segregation rate (SR), and normalized segregation rate (NSR). NSR was defined as the amount of fines percolated from the initial fines in a binary mixture for the total time of operation of PSSC-II (kg/kg-h). Strain rate vs. strain is the most common approach to compare data among the scientific community; however, since our process is periodic with near ramp-type strain profile and segregation in bagged fertilizers being our motivation, time is the most appropriate representation in this specific situation. Therefore, analysis and interpretation of segregated fines mass, SR, and NSR are done with respect to time.

2.1. Test material selection and parameter determination

Two different materials, urea and potash, were selected as test materials for studying percolation segregation in binary mixtures. These two materials are the two major raw ingredients used for manufacturing blended fertilizers and selected based on their extreme shape and density among four raw ingredients, i.e., urea, potash, phosphate, and filler. Materials used in this research are referred to as real-world materials because these are used for manufacturing products. End users or blend manufacturers have very minimal to no control over particle size, size distribution, and shape as received from raw ingredient distributors/manufacturers. Elongated particle is a commonly used descriptor for potash along with angular-shaped and irregular because of a large variety of geographical origins of this material.

The particle densities of spherical urea and angular potash were 1459 kg/m^3 (standard deviation, SD = 2 kg/m^3) and 2291 kg/m^3, (SD = 3 kg/m^3), respectively. Typical particle size distributions of samples of urea and potash collected from a blend plant across Commonwealth of Pennsylvania are given in Fig. 2. Herein, potash and urea were representatives of irregular or angular-shaped and spherical-shaped particles, respectively [47]. The mean measured

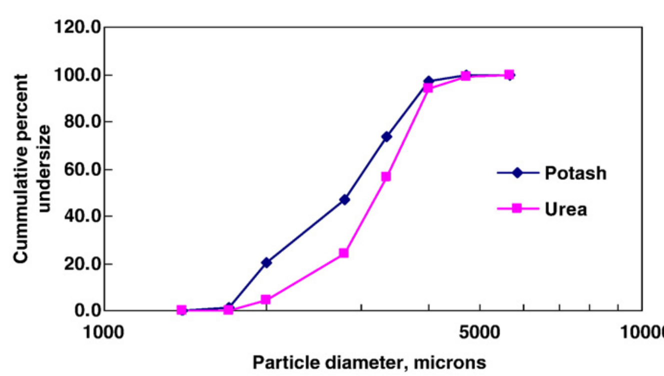

Fig. 2. Typical particle size distributions for blended fertilizer major raw ingredients.