Percolation Segregation and Flowability Measurement of Urea under Different Relative Humidity Conditions[†]

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Abstract

Dry blended fertilizers are known to segregate. Furthermore, researchers have documented that the size of blended fertilizers is the most dominant physical property contributing towards segregation. Additionally, it is known that flowability is also affected by the size and moisture content of blended fertilizers. Therefore, segregation and flowability of binary size mixtures were studied at three different equilibrium relative humidity conditions 40%, 50%, and 60% with the goal to evaluate the feasibility to mitigate segregation using moisture content. To that end, binary size mixtures were prepared using coarse and fine size urea of size ratio 2.0 and 1.7 mixed in weight proportions 33:67 and 50:50, respectively (commonly found in 10-10-10 blends). Urea is the most hygroscopic and expensive component of the blended fertilizers. Percolation segregation was quantified using the Primary Segregation Shear Cell (PSSC-II). Based on experimental results using the PSSC-II, the segregated fines mass, normalized segregation rate (NSR), and segregation rate (SR) of fines for binary urea mixtures were higher at equilibrium relative humidity of 40% vs. 50% and 60%. The NSR is defined as the amount of fines percolated from the total initial fines in the binary mixture based on the total time of PSSC-II operation (kg/kg-h). For size ratios 2.0 and 1.7, only 2.8% and 7.0% decrease in NSRs were recorded for the increase in relative humidity by 10 points (from 40% to 50%), respectively, whereas 36.0% and 45.0% decrease in NSRs were recorded for increase in relative humidity by 20 points (from 40% to 60%), respectively ($P < 0.5$). Additionally, the flowability of binary size mixtures was quantified using a true Cubical Triaxial Tester (CTT). For size ratios 2.0 and 1.7, angle of internal friction increased from 31.3° to 35.9° to 39.0° and 27.4° to 32.0° to 36.0° when relative humidity increased from 40% to 50% to 60%, respectively. The angle of internal friction values were significantly different ($P < 0.05$) but cohesion values, at different relative humidity conditions were not significantly different ($P > 0.05$). Based on experimental results, relative humidity, if implemented carefully, could be used as a tool to mitigate segregation in blended fertilizers.

Keywords: cubical triaxial tester, primary segregation shear cell, segregation rate, normalized segregation rate, angle of internal friction, and cohesion

Introduction

Particulate materials are handled in several industries such as agriculture, ceramic, construction, food, nutraceutical, pharmaceutical, power, and powder metallurgy. The physical and mechanical properties'

difference during handling, mixing, conveying, and storage causes an unwanted phenomenon known as segregation. Segregation is defined as "demixing" or reverse mixing (Popplewell et al., 1989; and Rollins et al., 1995). Segregation causes uneven quality of fertilizers and tablets, fluctuating packet weights, low mechanical strength of compacts and abrasives, poor refractory materials, and low rates of contact and reaction (Shinohara, 1997). For example, different size granules in blended fertilizers separate from one another during conveying, transportation, and storage causing uneven distribution of fertilizer in the field

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that leads to localized over- and under-supply. For blended materials, the uniformity of blend is highly dependent on physical attributes, such as, density, particle size and size distribution, shape, hardness, surface texture, and moisture content.

Several researchers have reported that size of granular materials is the most important parameter responsible for segregation (Tang and Puri, 2004; Bridle et al., 2004; and Bradley and Farnish, 2005). However, size segregation in conjunction with other physical parameters has greater detrimental effect than segregation by size alone. In addition, flowability of the blend is dependent on physical and mechanical properties of the constituents. Flowability of hygroscopic granular materials is one of the key mechanical properties for the quality of mixing and potential for segregation. High flowability of material has positive and negative effects: for mixing, high flowability is essential, whereas for segregation high flowability is detrimental. In the literature, relative humidity has been documented to reduce flowability and hence is expected to lower segregation. However, systematic and quantitative study correlating segregation with flowability of hygroscopic blended fertilizers could not be found in the literature. Therefore, percolation segregation and flowability were studied under different equilibrium relative humidities, with the objective to evaluate the use of relative humidity for mitigating segregation while maintaining flowability at acceptable level of blended fertilizers.

To know the flow properties at different equilibrium relative humidity conditions, quantifying their flowability is very important. Herein, a low pressure (<100 kPa) cubical triaxial tester (CTT) developed by Kamath and Puri (1997) was used to measure flowability using the Mohr-Coulomb model. The flexible-boundary of CTT allows unrestrained deformations in the samples and minimizes die-wall friction effect. The low pressure CTT is capable of measuring the three-dimensional response of cohesionless and cohesive particulate materials (Li and Puri, 1996).

The Mohr-Coulomb model, which states that the effective shear strength, τ , increases with effective normal stress, σ , on the failure plane, is the most

commonly used yield criterion in bulk solids flow theory. It can be represented by equation 1.

$$\tau = c + \sigma \tan \phi \quad (1)$$

where, c , is the cohesion of the material, and ϕ is the angle of internal friction.

For both of the parameters, c and ϕ lower values indicate higher flowability and higher flowability leads to higher segregation (Duffy and Puri, 1997). Therefore, the specific objectives of the study were: 1) to quantify the percolation segregation under three equilibrium relative humidity conditions, and 2) to evaluate flowability of binary size mixtures for the same three equilibrium relative humidity conditions.

2. Materials and Methods

2.1 Test material selection, preparation, and parameter determination

Urea is a readily available but the most expensive constituent of dry blended fertilizers, which was selected for studying segregation and flowability at three equilibrium relative humidity conditions, i.e., 40%, 50%, and 60%, for two size ratios with differing mixing ratios (**Table 1**). The shape of urea particles was round with sphericity of 0.97 (SD = 0.02). For this study, different size ranges of urea were obtained using US standard sieves of 2^{1/4} series. The three equilibrium relative humidities (ERHs) were selected based on long-term weather data of University Park, PA, i.e., the stored fertilizer component urea is likely to be subjected to these types of conditions. All the samples were equilibrated at test ERHs by placing the material in microprocessor controlled humidity chamber (Model 9000L, VWR international, Sheldon Manufacturing Inc, Cornelius, Oregon) for 48 hours spread in a single layer on sieves. Samples were placed on sieves to allow air to circulate through sieve perforations all around the urea granules. All tests were performed after mixing coarse and fine urea granules (**Table 1**) to form binary size mixtures using lowest speed setting of a six-speed bench-top 225-W mixer (Model-106772N, Type-M27,

Table 1 Binary size mixtures of urea used for both segregation and flowability studies

Coarse Size	3350-4000 ($d_{\text{mean}} = 3675 \mu\text{m}$) and 2800-3350 ($d_{\text{mean}} = 3075 \mu\text{m}$)	
Fine Size *	1700-2000 ($d_{\text{mean}} = 1850 \mu\text{m}$)	
Size Ratio Coarse: Fine	3675:1850 = 2.0**, Mixing ratio = 33:67	3075:1850 = 1.7**, Mixing ratio = 50:50
Equilibrium Relative Humidity	40%, 50%, and 60%	

* Based on segregation observed in dry blends that are normally stored in bagged fertilizers

** Rounded up

General Electric, Marketed by Wal-Mart Stores Inc., Bentonville, AR). The purpose of testing binary size mixtures was to lay the foundation for studying segregation potential of fines in multi-size mixtures leading to multi-size plus multi-component mixtures. The results from multi-size and multi-component mixtures will be presented in subsequent articles. Two size ratios 2.0 and 1.7, i.e., ratio of coarse:fines, were mixed by weight in the proportions 33:67 and 50:50, respectively. The two different size ratios and corresponding mixing proportions were selected based on size distributions of 10-10-10 and 10-20-20 fertilizer blend formulations collected from three blend plants in Pennsylvania. For flowability quantification, the binary size mixtures were tested at two confining pressures of 3.5 kPa and 7.0 kPa based on pressure in fertilizer bins under static storage conditions. All tests for segregation and flowability were conducted in an environment-controlled laboratory with average temperature of $22^{\circ}\text{C} \pm 3^{\circ}\text{C}$ and relative humidity less than 40%. On the average, each test lasted for 40 minutes when urea was exposed to these environmental conditions, which is expected to have minimal influence on urea granules' moisture content.

2.2 Segregation

For segregation study, three parameters including material bed depth of 85 mm (comparable to depth of 22.7 kg bagged blended fertilizers), particle bed strain of 6% (corresponding to available head space in bags), and strain rate 0.5 Hz (similar to conveyors used to transport bagged fertilizers) were selected for operating PSSC-II as shown in **Table 2** (Tang and Puri, 2005; Vursavus and Ozguven, 2004). The dry blended formulation 10-10-10 (i.e., 10% total nitrogen-10% available phosphate-10% soluble potash) was selected for test parameter determination because of the high demand (inexpensive) and its higher susceptibility to segregation under handling and operating conditions. The higher amount of fillers in the low analysis (10-10-10 and others) bags is the primary reason for large head space that leads to non-uniformity. For each treatment, segregated fines mass was collected using the eight load cells (range ± 0.001 g) installed at eight different locations and recorded using LabView (Version 6.0, National Instruments, Austin, TX). Based on published results (Duffy and Puri, 2002, and Tang and Puri, 2005), and preliminary testing with fertilizer blends, five replications were deemed sufficient for experimental data to be within the 95% confidence interval.

In this study, eight sampling points distributed in

Table 2 Experimental design for segregation testing of binary size mixtures of urea

Parameter	Number
Size ratios 2:0 (Mixing Ratio-33:67) and 1.7 (Mixing Ratio-50:50)	2
Equilibrium relative humidities (40%, 50% and 60%)	3
Strain rate (0.5 Hz)	1
Strain (6%)	1
Bed depth (85 mm)	1
Replications (5 per treatment)	5
Number of tests	30

two rows (4 load cells in a row) were configured (**Fig. 1**). The rationale for the locations of the load cell was to collect maximum percolated fines. For ease of reference, these load cells are identified as BR (back right), FR (front right), BCR (back center right), FCR (front center right), BCL (back center left), FCL (front center left), BL (back left), and FL (front left) as shown in **Fig. 1(b)**. Sieve number 8 (opening size = 2,000 μm) was used throughout the tests so that the percolating fines could exit while coarse particles did not block sieve openings.

2.3 Flowability

The flexible-boundary CTT developed by Kamath and Puri (1997) was used for testing the flowability of binary size mixtures (**Tables 1** and **3**). The cubical

Fig. 1 Collection pan for fines showing eight load cell locations, (a) top view of shear box and eight load cell positions for data collection, (b) top view of collection pan (all dimensions in mm).

Table 3 Experimental design for flowability testing of binary size mixtures of urea

Parameter	Number
Size ratios 2:1 (mixing ratio – 33:67) and 1.7:1 (mixing ratio – 50:50)	2
Confining pressures (3.5 kPa and 7.0 kPa)	2
Equilibrium relative humidities (40%, 50% and 60%)	3
Replications (3 per treatment)	3
Number of tests	36

triaxial tester uses two individual pressure controllers (Proportion-Air Inc. QB1TFEE015), which can apply pressures from 0 to 100 kPa with $\pm 0.2\%$ of accuracy over the entire range. Individual pressure controllers regulate horizontal and vertical pressures independently using software developed with LabView (Version 6.0, National Instruments, Austin, TX) by Kandala and Puri (2000). The flowability parameters were measured using the conventional triaxial compression (CTC) test. The CTC test begins with hydrostatic compression at pressure σ_c , or confining pressure. While this confining pressure is kept constant in horizontal directions, the pressure in the vertical direction (i.e., gravity directions) was increased until the sample failed. The failure stress was denoted as σ_f . These pressures (σ_c and σ_f) are the principal stresses that were plotted on the normal stress versus shear stress diagram to produce corresponding Mohr circles. Based on published results (Li and Puri, 1996; and Kandala and Puri, 2000), three replications were performed for each combination for testing flow behavior of samples using the CTT. A complete block design was selected for data analysis. One set of experiments was performed on binary size mixtures of urea equilibrated at relative humidity values of 40%, 50% and 60%. All the three data sets were analyzed separately and compared for determining flow properties corresponding to three different ERHs.

From the common tangent line of two Mohr circles, the angle of internal friction (ϕ) and the cohesion (c) of samples were determined. Before filling the cavity (50 mm $\times$ 50 mm $\times$ 50 mm), a low inflating pressure of 5 kPa was applied to ensure that membranes were in contact all around to prevent fertilizer from exiting or squeezing out. Then, well mixed binary size sample was placed into the cavity in three steps. In the first step, cavity was one-third filled and top surface was leveled off with a soft nylon brush; this was repeated for the next third and the final one third. The amount of test material in the cavity was 59 g $\pm$ 1 g. After placing the sample into the cavity, a

confining pressure was applied using a compressed air source. Subsequently, the pressure in the vertical direction was increased at 100 Pa/s until failure. The very low rate of pressure increase of 100 Pa/s was selected so that 1) particles have sufficient time for rearrangement, and 2) rate-dependent effects are minimized.

3. Results and Discussions

3.1 Physical properties determination

The characterization of physical properties of binary size mixtures such as bulk density, particle density, shape, and size of the test materials is essential before testing because of inherent variability of bulk solids (Table 4). The flow and segregation responses of bulk solids vary with variation in their physical properties.

In Table 4, for size ratios 2.0 and 1.7, both the particle density (PD) and bulk density (BD) increased with increase in RH from 40% to 60%. With increase in RH by 20% points (i.e., 40% to 60%), PD increased by 0.3% and 0.4%, respectively, whereas for increase in RH by 10% points (40% to 50%), PD increased by 0.1% and 0.1%, respectively. The small increase in PD with increase in equilibrium relative humidity was obtained because of surface air pores were filled by moisture ($P > 0.05$). The same trend was observed for bulk density for both the size ratios 2.0 and 1.7 ($P > 0.05$). No measurable change in porosity was noted when RH increased from 40% to 60%, which is beyond the detection capability of the multipycnometer used in this study.

3.2 Percolation segregation

The measured mass of segregated fines (g) for two binary size mixtures (2.0 and 1.7) conditioned at

Table 4 Physical property of binary size mixtures of urea (sphericity = 0.97) at three different equilibrium relative humidity conditions

Size Ratio	Mixing Ratio	Equilibrium Relative Humidity (%)	Particle density* (kg/m ³)	Bulk density* (kg/m ³)	Porosity**
2.0	33:67	40	1456 (2)	726 (2)	50
		50	1458 (3)	743 (3)	49
		60	1461 (5)	744 (4)	49
1.7	50:50	40	1455 (2)	727 (1)	50
		50	1458 (3)	732 (1)	50
		60	1461 (3)	733 (0)	50

* Measured values - Quantachrome multipycnometer (Model MVP-2) with ultra pure He- five replicates

** Calculated values

Table 5 Segregated fines, mean segregation rate and mean NSR for binary size mixtures of urea

Size ratio (Mixing Ratio)	ERH (%)	Average time for discharge(minutes)	Segregated fines (g)	Average segregation rate (kg/h)	NSR (kg/kg-h)
2 (33:37)	40	10.4 (0.1)	87.74 (1.15)	0.51 (0.01)	1.12 (0.02)
	50	10.4 (0.1)	85.69 (1.60)	0.49 (0.01)	1.09 (0.02)
	60	10.2 (0.2)	56.21 (1.52)	0.33 (0.01)	0.73 (0.02)
1.7 (50:50)	40	11.5 (0.0)	41.03 (1.19)	0.21 (0.01)	0.61 (0.02)
	50	11.4 (0.1)	38.40 (1.77)	0.20 (0.01)	0.58 (0.03)
	60	11.4 (0.2)	22.99 (1.29)	0.12 (0.01)	0.34 (0.02)

* Standard deviation values in parenthesis

Fig. 2 Typical segregated fines mass of binary size urea mixture for size ratio 2.0 equilibrated at 50% relative humidity environment with bed depth of 85 mm. The curves are for different load cell locations shown in **Fig. 1**.

Fig. 3 Typical segregated fines mass of binary size urea mixture for size ratio 1.7 equilibrated at 50% relative humidity environment with bed depth of 85 mm. The curves are for different load cell locations shown in **Fig. 1**.

three different ERHs (40%, 50% and 60%) are summarized in **Table 5**. **Fig. 2** and **3** show typical profiles of cumulative fines mass collected by the eight load cells in real-time for size ratios 2.0 and 1.7, respectively. Similar profiles were obtained at other ERHs. Both of these figures show that most of the segregated fines were collected at the two ends, which is in agreement with the results reported for glass beads by Duffy and Puri (2002) and glass beads and mash feed by Tang and Puri (2005). Since the time evaluation of segregated fines was recorded using the PSSC-II, two rate metrics: segregation rate (kg/h) and normalized segregation rate (kg/kg-h) are introduced. Herein, segregation rate is defined as the mass of fines segregated from the binary size mixture of urea per unit total time of PSSC-II operation; whereas, NSR is defined as the ratio of collected fines mass to total mass of fines mixed with coarse divided by total time of PSSC-II operation.

In **Table 5**, for size ratio 2.0, when RH increased by 20% points (40% to 60%) and 10% points (40% to 50%), segregated fines decreased by 36.0% and 2.3%, respectively. For size ratio 1.7, when RH increased by 20% points (40% to 60%) and 10% points (40% to 50%) segregated fines decreased by 44.0% and 6.4%, respectively. As expected, segregation declined with increase of moisture content. These results suggest that relative humidity could be used as a tool to mitigate segregation.

Figs. 2 and 3 show typical profiles of segregated fines mass of binary mixture for size ratio 2.0 and 1.7, respectively, collected by the eight load cells config-

ured four each in two rows (**Fig. 1**). The measured mass values are for binary mixtures of urea that were equilibrated at 50% relative humidity. Both of these figures show that fines masses collected by the eight load cells increased with time. Fines mass collected for size ratio 2.0 was higher compared with size ratio 1.7. Results confirmed that higher size ratio has higher segregation potential. Fines masses collected by eight load cells were different for both of these size ratios. For size ratio 2.0 (**Fig. 2**), fines mass collected by eight load cells were more uniform compared with mass collected for size ratio 1.7.

Fig. 4 shows iso-mass contours for segregated fines for size ratios 2.0 (**Fig. 4a**) and 1.7 (**Fig. 4b**) at the end of 10 minutes, which is the expected time duration of motion conditions for bagged fertilizer to experience between filling and transportation. Even though iso-mass contours are shown at the end of 10 minutes, these can be analyzed at any time from 0 to 10 minutes in the interval of 1 s. At the end of 10 minutes, the fines were collected more at both ends of the shear box such as BL, FL, BR and FR compared to the center zone such as BCL and FCL ($P > 0.05$). Load cells in the center received less fines compared to other load cells because of diffusive percolation mechanism. This result is in agreement with previous results obtained for size ratio less than 4.0 (Duffy and Puri, 2002).

3.3 Normalized segregation rate (NSR)

For size ratio 2.0, NSR decreased from 1.12 kg/kg-h to 1.09 kg/kg-h to 0.73 kg/kg-h when urea

Fig. 4 Iso-mass contours of segregated fines for binary size urea mixtures equilibrated at 50% relative humidity at the end of 10 minutes for size ratios: (a) 2.0 and (b) 1.7; x and y axes dimensions denote the opening size available at the bottom of the shear box for fines to percolate.

binary size mixtures equilibrated relative humidity increased from 40% to 50% to 60%. Similarly, for size ratio 1.7, NSR decreased from 0.62 kg/kg-h to 0.58 kg/kg-h to 0.34 kg/kg-h urea binary size mixtures equilibrated relative humidity increased from 40% to 50% to 60%. Figure 5 shows a typical profile of NSR at 40% RH of binary mixture for size ratio 2.0. The NSR declined rapidly in the first few minutes (<3 minutes) of PSSC-II operation followed by an asymptotic approach to linear decline. The rapid initial decline can be attributed to the availability of fines due to their low coordination number, which increases with time, i.e., fines become more constrained. Similar profiles were obtained for other ERHs (50% and 60%) and for size ratio 1.7. The NSR profiles could be used to predict the amount of segregation in the mixture under given operating condition in real-time.

3.4 Distribution of segregation rate

Distribution of segregation rate (DSR) metric was used to evaluate the spatial distribution of segregation rate (SR) corresponding to the eight load cell locations. **Figs. 6 and 7** show typical SR of percolated fines along the eight load cells at 50% RH for the size ratios 2.0 and 1.7, respectively. Results were in agreement with the NSR result, i.e., NSR decreased with increasing relative humidity. **Fig. 6** for size ratio 2.0, shows that SR was higher at both ends of the shear box compared with the center region and decreased with time, i.e., 60 s (**Fig. 6a**) to 120 s (**Fig. 6b**) to 180 s (**Figs. 6c**) ($P>0.05$). At 60 s, SR was higher in the center and right of the shear box because of initial percolated fines present initially in the bottom of the mixture. **Fig. 7** for size ratio 1.7 shows fines mass were collected more at both ends of the shear

box such as BL, FL, BR and FR compared to the center zone such as BCL and FCL ($P>0.05$) and SR decreased with time, i.e., 60 s (**Fig. 7a**), 120 s (**Fig. 7b**), and 180s (**Fig. 7c**). For both size ratios 2.0 and 1.7, load cells in the center received less fines compared to other load cells because of diffusive percolation mechanism. This result is in agreement with previous results obtained for size ratio less than 4.0 (Duffy and Puri, 2002).

3.5 Flowability

From the CTC tests, the failure stress values of binary mixtures were determined. **Fig. 8** illustrates the failure stress values of well-mixed binary size urea mixtures. For size ratio 2.0 at confining pressure $\sigma_c = 3.5$ kPa, the failure stress increased from 12.2 kPa to 15.5 kPa to 16.2 kPa when ERH increased from 40% to 50% to 60%. At relatively higher confining pressure $\sigma_c = 7$ kPa, the failure stress increased from 23.5 kPa to 29.3 kPa to 32.0 kPa for increase in ERH from 40% to 50% to 60%, respectively. For size ratio 1.7 at confining stress ($\sigma_c = 3.5$ kPa), the failure stress increased from 11.2 kPa to 14.5 kPa when ERH increased from 40% to 50% and plateaued thereafter, whereas the failure stress increased from 22.7 kPa to 28.0 kPa for increase in ERH from 40% to 60% at higher confining pressure $\sigma_c = 7$ kPa. A plausible explanation for the minimal to no effect of ERHs for size ratio of 1.7 at lower confining pressure ($\sigma_c = 3.5$ kPa) was a result of more tightly packed samples, i.e., 3.5 kPa of confining pressure was not sufficient to induce rearrangement of particles.

The results presented in this article demonstrated decreased segregation and flowability with the increase in relative humidity, as expected. Higher size

Fig. 5 Segregation rate at 40% ERH for size ratio 2.0.

Fig. 6 Iso-segregation rate of fines mass of binary urea mixtures for size ratio 2.0 and 50% ERH at, (a) 60 s, (b) 120 s, and (c) 180 s; x and y axes dimensions denote the opening size available at the bottom of the shear box for fines to percolate.

Fig. 7 Iso-segregation rate of fines mass of binary urea mixtures for size ratio 1.7 and 50% ERH at, (a) 60 s, (b) 120 s, and (c) 180 s; x and y axes dimensions denote the opening size available at the bottom of the shear box for fines to percolate.

Fig. 8 Failure stress difference for binary mixtures of size ratios of 2.0 and 1.7 and confining pressures of 3.5 and 7.0 kPa.

Table 8 Flowability parameters for binary size mixtures at three equilibrium relative humidities*

Size Ratio (Mixing Ratio)	Equilibrium Relative Humidity (%)	Angle of Internal Friction (ϕ)	Cohesion (c, kPa)
2 (33:67)	40	31.3° (1.2)	0.3 (0.2)
	50	35.9° (1.7)	0.5 (0.3)
	60	39.0° (2.3)	0.3 (0.4)
1.7 (50:50)	40	27.4° (1.9)	0.5 (0.4)
	50	32.0° (3.4)	0.9 (0.9)
	60	36.0° (0.0)	0.3 (0.0)

* Standard deviation values in parenthesis

ratio and equilibrium relative humidity tend to induce higher failure stress, which implies tighter packing strength of the samples.

The flowability determining parameters, i.e., the angle of internal friction and cohesion are summarized in **Table 8**. For size ratio 2.0, the angle of internal friction increased from 31.3° to 35.9° to 39.0° for increase in ERH from 40% to 50% to 60%, respectively. For size ratio of 1.7, the angle of internal friction increased from 26.8° to 36.0° when relative humidity increased from 40% to 60%. In all cases, size ratio of 2.0 showed higher angle of internal friction than size ratio of 1.7 suggesting that size ratio of 2.0 mixture has lower flowability.

For both size ratios of 2.0 and 1.7, cohesion values remained constant and were not significantly different ($P > 0.05$). Negligible cohesion values were consistent with visual observations.

Results showed that flowability of particles decreased with the increase in angle of internal friction while cohesion values were negligible. The lower flowability for size ratio of 2.0 compared to size ratio of 1.7 is because of the mixing and size ratios' differ-

ences; the large size ratio binary mixture had more fines compared to coarse (mixing ratio 33:67) and mixture's response was governed by the quantity of fines. For large size ratio, more pore spaces were available in the coarse particle bed vs. small size ratio. Furthermore, flowability parameter results also confirmed the segregation results. PSSC-II results also demonstrated that segregation in binary size mixtures of urea decreased with increasing ERHs from 40% to 60%. Results of flowability and segregation for binary size urea mixtures were in agreement with the results published by Duffy and Puri (1997) for food powders.

4. Conclusions

Percolation segregation was measured using the PSSC-II for binary size mixtures of urea prepared by blending fines (1700-2000 μm) with coarse (3350-4000 μm and 2800-3350 μm) equilibrated at three relative humidity values (40%, 50%, and 60%). All tests were conducted at bed depth of 85 mm, strain of 6%, and strain rate of 0.5 Hz. Results showed that the PSSC-

It is capable of quantifying segregation of binary size mixtures. For quantification of segregation, four metrics: 1) segregated fines mass, 2) segregation rate, 3) normalized segregation rate, and 4) distribution segregation rate of fines were used. The following conclusions were drawn from this study.

1. Size ratio 2.0

- Segregated fines mass values decreased from 87.7 g to 85.7 g to 56.2 g when ERHs increased from 40% to 50% to 60%, respectively. Only 2.0% of decrease in collected fines mass was recorded for increase in ERH by 10 points (from 40% to 50%), whereas 36.0% decrease in fines mass was recorded for increase in ERH by 20 points (from 40% to 60%).
- Segregation rate decreased from 0.141 kg/h to 0.137 kg/h to 0.091 kg/h when ERHs increased from 40% to 50% to 60%, respectively. Only 2.8% decrease in SR was recorded for increase in ERH by 10 points (from 40% to 50%), whereas 36.0% decrease in SR was recorded for increase in ERH by 20 points (from 40% to 60%).
- NSR decreased from 0.332 kg/kg-h to 0.323 kg/kg-h to 0.215 kg/kg-h when relative humidity increased from 40% to 50% to 60%, respectively. Only 2.8% of decrease in NSR was recorded for increase in ERH by 10 points (from 40% to 50%), whereas 36.0% decrease in NSR was recorded for increase in ERH by 20 points (from 40% to 60%).

2. Size ratio 1.7

- Segregated fines mass values decreased from 41.0 g to 38.4 g to 23.0 g when ERH increased from 40% to 50% to 60%, respectively. Only 6.0% of decrease in collected fines mass was recorded for increase in ERH by 10 points (from 40% to 50%), whereas 43.0% decrease in mass was recorded for increase in ERH by 20 points (from 40% to 60%).
- SR decreased from 0.060 kg/h to 0.056 kg/h to 0.033 kg/h when ERH increased from 40% to 50% to 60%, respectively. Only 7.0% decrease in SR was recorded for increase in ERH by 10 points (from 40% to 50%), whereas 45.0% decrease in segregation rate was recorded for increase in relative humidity by 20 points (from 40% to 60%).
- NSR decreased from 0.172 kg/kg-h to 0.161 kg/kg-h to 0.096 kg/kg-h when relative humidity increased from 40% to 50% to 60%, respectively. Only 7.0% decrease in NSR recorded for

increase in ERH by 10 points (from 40% to 50%), whereas 45.0% decrease in NSR was recorded for increase in ERH by 20 points (from 40% to 60%).

With the two different mixture of fines (1700-2000 μm) and coarse (3350-4000 μm and 2800-3350 μm) at three different ERHs (40%, 50% and 60%), conventional triaxial tests were performed to evaluate flowability using the CTT. From those results, the following conclusions were drawn:

- For size ratio 2.0, angle of internal friction increased from 31.3° to 35.9° to 39.0° when ERH increased from 40% to 50% to 60%, respectively.
- For size ratio 1.7, angle of internal friction increased from 27.4° to 32.0° to 36.0° when ERH increased from 40% to 50% to 60%, respectively.
- The measured negligible cohesion values were not significantly different ($P > 0.05$) for both size ratios 2.0 and 1.7 at all three ERHs.

In conclusion, addition of moisture could be used as a tool to mitigate segregation in granular materials by marginally reducing their flowability. Flowability should not be lowered below a critical value, otherwise flow issues may arise.

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Author's short biography

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