Quantitative study of tailings segregation

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ABSTRACT
Segregation is a common occurrence in tailings disposal. Quantitative study helps in assessing the degree of segregation or mixing so that some form of quality control is achieved. Moreover, it can be used to describe the effects of different mechanisms. The degree of mixing or segregation is commonly expressed by measuring the statistical variation of composition using standard deviation. A review of available indices was presented. An index was proposed for quantitative study of segregation. The index accounts for the variability of sampling lengths by using section length as weight factor. Finally application of the index method was examined with static and dynamic segregation experimental data.

RÉSUMÉ
Ségrégation est une pratique courante dans l'élimination des résidus. Étude quantitative permet d'évaluer le degré de ségrégation ou de mélanger, de façon qu'une certaine forme de contrôle de la qualité est atteint. En outre, il peut être utilisé pour décrire les effets de différents mécanismes. Le degré de mélange ou de ségrégation est généralement exprimé en mesurant la variation statistique de la composition en utilisant l'écart-type. Un examen des indices a été présenté. Un index a été proposé pour étude quantitative de la ségrégation. L'indice représente la variabilité d'échantillonnage longueurs en utilisant la section longueur comme facteur de pondération. Enfin application de la méthode de l'indice a été examiné avec statique et dynamique de ségrégation des données expérimentales.

2 INTRODUCTION

As there is limited understanding in the subject of segregation, there is a need to quantify the degree of segregation or mixing so that some form of quality control or common way of describing the effect of different mechanisms. The degree of mixing or segregation is expressed commonly by measuring the statistical variation of composition using the standard deviation.(Buslik 1950) (Lacey 1954) , (Fuerstenau and Fouladi 1967) (Liss, Conway et al. 2004).

Segregation and Mixing, as two opposing phenomena, have prevailed in many industrial processes which are involved in the separation or blending of different ingredients. In the industry it is necessary to have some means of quantifying the quality of mixing so that, for example, the required performance of a mixer can be specified and then measured (Asmar, Langston et al. 2002).

According to (Davies 1971) mixing of solids is defined as an operation by which two or more solid materials in particulate form are intermingled randomly in the mixer by the random movement of particles. Lacey (1954) assumed that in all mixers, mixing is achieved by one or more of the following:

(a) Convective mixing: Transfer of groups of particles from one location to another
(b) Shear mixing: Setting up of slipping planes within the mass of material
(c) Diffusive mixing: Diffusion of individual particles over newly developed surfaces.

These mechanisms control mixing to a varying degree depending on the mode of operation of the mixer. De-mixing usually accompanies mixing and two mechanisms are proposed to describe these effect. The first is the percolation mechanism relating to the slipping of smaller particles through the voids created by the larger particles. The other mechanisms results from differences in trajectories of materials falling at an angle during free flight.

In the case where different phases are involved in the mixtures, differences in mobility of the particles usually yields the sorting of particles. The sedimentation process and multiphase flows in which different composition of properties are involved; the occurrence of segregation is more likely dependent upon the concentration and flow characteristics.

Differences in size, density or shape are main factors which contribute to the segregation of the mixture. It is widely accepted that difference in size may be the most dominant factor (Fan, Chen et al. 1970; Rhodes 1998; Vallance and Savage 1999)

Gravitational settling consisting of particles of different mobility results in segregation of particles. It is practically significant to express the degree of segregation in somewhat quantitative way. An expression as such may provide common basis for comparison and assessment of the quality of data output.

A quantitative index, called segregation index, has been in use by research group at University of Alberta, ((Suthaker 1995),(Tang 1997),(Chalaturnyk and Scott 2001). The index is calculated based on total solid content for the depth profile after sedimentation test is completed. Another term related to Segregation Index (SI) is the fine capture, FC, given as 100-SI. The segregation boundary, which divides the segregating type of slurry and the otherwise, is the fine capture value of 95. A value of fine capture less than 95 is categorized as segregating mix. Such an index calculation is in agreement with the definition of segregation as given by (Kuepper 1991). She defined segregation as "the tendency of solid fraction (or part of it) to settle, creating a concentration gradient with in the mass". The segregation index constructed on the overall solid content may somehow indicate the size segregation indirectly, one finds, however, some difficulty in communicating with other experimental results(Kenney and Westland 1992) (Kaushal and Tomita 2002).

3 LITERATURE REVIEW OF QUANTITATIVE STUDY

(Davies 1971) presented an index for degree of mixing for samples of similar size as

[1] $$M = S / \sigma_R$$

Where S is the estimated standard deviation and σ_R is standard deviation for completely random mixtures. The standard deviation S (for unbiased estimation) given by Eqn(1) is

[2] $$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x)^2}{n-1}}$$

Amongst the most popular indices using standard deviation is Lacey's index (Lacey 1954), which defines a mixing index M, based on the number of particles in a sample, as

[3] $$M = \frac{S_o^2 - S^2}{S_o^2 - S_R^2}$$

where S_o^2 is the variance for completely segregated mixture, S_R^2 is the variance for completely random mixture and S^2 is the variance of the mixture between fully random and completely segregated mixtures. This index suffers from three drawbacks: it is limited to same size particles, very sensitive near the completely segregated state, and relatively insensitive in the final stage of mixing (Fan, Chen et al. 1970),(Davies 1971) (Williams 1976) and (Asmar, Langston et al. 2002).

(Asmar, Langston et al. 2002) introduced an index called Genaralised Mean Mixing Index (GMMI) in their Discrete Element Method (DEM) simulations. The GMMI in one of the axes direction, say z, is defined as:

[4] $$GMMIz_i = \left[\frac{\sum_{j=1}^{n}(z_j - z_{ref})}{n}\right] \Big/ \left[\frac{\sum_{k=1}^{N}(z_k - z_{ref})}{N}\right]$$

Where n is the number of particles of type I, N is the total number of particles, z is the z-coordinate of the position of the particle centre and z_{ref} is the reference z-coordinate.

The GMMI will be the average of the three direction computed. The use the index appears simple. However, its application is limited to DEM simulation where the position of individual particles is known.

In the study of segregation of granular filter materials, (Kenney and Westland 1992) applied the term *Segregation Index* and *Relative Segregation Index* to determine the extent of segregation. They carried out the rotary-drum test, in which the drum is half filled with soil sample and tumbled. After the test, they divide the drum into three parts, inner 25% volume, the middle 50% and the outer 25%. Grain size analysis is carried out for samples taken from each component and plotted as percent finer vs. grain size. They determined the logarithmic mean particle size (using Popovics' equation), and they defined Segregation Index as follows

[5] $$SI = \log(d_c/d_f)$$

Where d_c and d_f are logarithmic mean particle sizes of the coarse and fine zones, respectively. They defined Relative Segregation Index (RSI), as the ration of SI (test) to the segregation Index calculated for the state of perfect segregation, SI_p.

[6] $$RSI = SI(test)/SI_p$$

They found out that the middle 50% volume is characterised by similar grain size distribution as that of the initial sample. The definition of fines and coarses, according to their work, is relative to test material,(sand may be fine for gravel and sand mix) as the division contains all particles which lie in the inner 25% and the outer 25% volume respectively. They reported that it is only under perfect segregation that complete sorting according to size may be achieved.

The application of the Eq. 6 to design of filter in embankment dam is discussed in(Milligan 2003). It is also shown that for grain size distribution varying in two decades; segregation is independent of grain size and grain size distribution. The idea of separating in different zones after the test and undertaking the grain size distribution seems attractive to be applied for other similar cases too.

Other similar studies in bulk material handling (granular mixing) were using index calculation based on statistical means. According to Lacey (1954), it is generally agreed that the most useful way of expressing degree of mixture is by measuring the statistical variation of composition among samples drawn from it. A summary of different mixing indexes as used by different authors are presented by (Hastie and Wypych 1999). (Fan, Chen et al. 1970), referring the works of Lawrence and Beddow(1969), stated that particle density and shape were found to have little effect upon the extent of segregation.

A term degree of mixedness, as it is used by (Fuerstenau and Fouladi 1967) for the study of packed particles of two different sizes, is defined as

[7] $$M = 1 - \frac{\sigma}{\sigma_o}$$

Where M is the degree of mixedness, σ, is the observed standard deviation of sample taken from the mixture; σ_o is the expected standard deviation of samples taken before any mixing had occurred and is given by

[8] $$\sigma_o = \sqrt{p(1-p)}$$

Where p is the mass fraction of larger particles in the mixture.

(Yamane 1999) defined segregation index, which is a different version of Eq.7. His index is equivalent to 1-M.

A standard deviation approach was followed by (Liss, Conway et al. 2004). They introduced Relative Standard Deviation (RSD) to characterize the relative degree of segregation. The form of the expression is shown in equation

[9] $$RSD = \sqrt{\frac{\sum_{i=1}^{n}(\mu - x_i)^2}{n-1}}$$

where n is the number of samples taken, μ is the mean value of all the samples, and xi is the value of the i^{th} sample. RSD ranges between the limits 0, perfect mix, and 1, completely segregated.

The review of the literature shows that there is no universally accepted index. Most of the proposed mixing indices are developed for binary solid-mixtures and are based on statistical analysis, mostly the standard deviation, variance or coefficient of variation.

4 PROPOSED INDEX

The uniformly mixed slurry is poured into standpipe then after the sedimentation process is complete, the release water is decanted and the sediment is divided into different layers and samples for moisture content and grain size analysis. From the grain size analysis, it is possible to estimate the composition of each size in the different layers.

The profile of concentration of each particle size is plotted, which indicate the extent of segregation with respect to size groups. It is believed that a quantitative description of the extent of segregation may give some form of comparison for different test conditions. The following index, Segregation Index (SI), is proposed for the works that follow.

[10] $$SI = \sqrt{\frac{\left(\sum h_i S_i^2 - \frac{\left(\sum h_i S_i\right)^2}{\sum h_i}\right)}{\sum h_i}}$$

where S_i is the solid content of sample section with height of h_i. This equation takes the variability of sampling depths into account by weighing them in their separate section (h_i) by assuming that the sample represents a section height/length from which it is taken.

Such an index calculation can also be used for a test which involve different size group. It can also applied be to dynamic segregation cases.

The advantages of the proposed equation can be described as:

- It is simple and very convenient to calculate
- it can be applied to multi-size particle presence
- it can account the sampling depth/length variation.

It is to notice that indices which are statistical in nature are basically different forms of mean deviation, standard deviation or variance.

5 APPLICATION EXAMPLES

The application of Eq. 10 was tested for two common segregation mechanisms: static and dynamic segregation. In the context of this study, static segregation refers to a standpipe test and dynamic segregation refers to flume segregation test. The sampling thickness (hi) describes the thickness

4.1 STANDPIPE TESTS

Different standpipe tests with varying solid contents, fine-water ratios and sand-fine ratios were used to calculate segregation index. Profiles with respect to sand content were produced. Typical examples are shown in Figures 1 and 2. Figure 1 shows the sand content profile at different sampling time for a design solid content of 35.7% sand-fine ratio of 4 and fine-water ratio of 10%. Details definitions of sand –fine ratio and fine-water ratio is referred to elsewhere (Mihiretu, Chalaturnyk et al. 2006)

The calculated segregation indices at each time are summarized in Table 1.

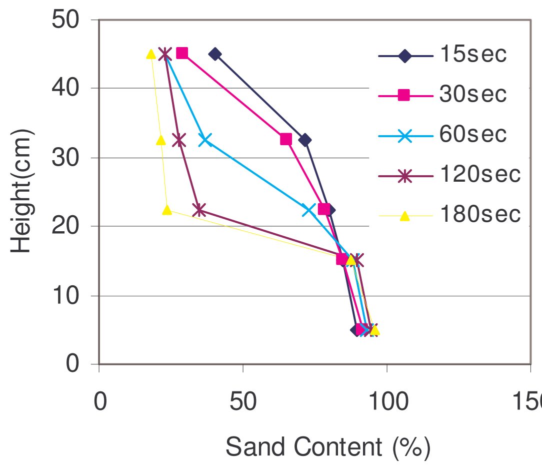

Figure 1 Sand content profile at different time for design solid content of 35.71% , SFR=4 and FWR =10

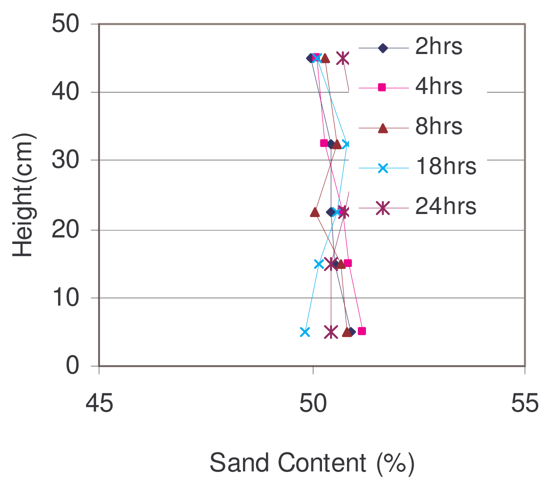

Figure 2 Sand content profile at different times for deign solid content of 571%, SFR=1 and FWR = 10

Figure 2 shows another sand content profile for a different solid content, sand-fine ratio and fine water ratios. The segregation indices were calculated for different times and are presented in Table 1. In all the standpipe tests sand content profile was used to calculation segregation index.

Table 1 Summary of standpipe test segregation index calculation.

S=35.71%, SFR=4, FWR =10 (Figure 1)		S=57.1%, SFR=4, FWR=10 (Figure 2)	
Time(sec)	SI	Time(hrs)	SI
15	17.5	2	0.30
30	22.0	4	0.38
60	28.0	8	0.27
120	31.4	18	0.36
180	34.7	24	0.78

Figures 1 and 2 illustrate typical cases of a segregating and non-segregating standpipe tests. It is apparent that segregating type slurries show higher segregation index values versus non-segregating slurries which show lower values of segregation index. Based on analysis of segregation index on standpipe tests with different slurry composition, a segregation index value of 5 was found appropriate to serve as a dividing index for segregating and non-segregating mixes.

4.2 FLUME TESTS

The segregation index calculation for flume test shows the variation of sample content along the flume length. The sampling length (hi) in this case represents the section length of the flume from which the sample was taken.

Table 2 Flume test Segregation index calculations.

Solid Content(%w)	Flume Slope (degree)	SFR	SI
57.6	0	1	0.5
57.6	5	1	0.5
57.6	10	1	1.0
57.9	0	2	1.2
57.9	5	2	1.8
57.9	10	2	3.6
55.5	0	4	3.7
55.5	5	4	3.2
55.5	10	4	5.5

The index indicates that as the slope and sand-fine ratio increases, the segregation index also increases showing a segregating trend. Similarly an index value of 5 could be used as a segregation boundary in the flume test.

In both the standpipe and flume test the proposed index quantifies the degree of segregation clearly. The definition of segregation boundary is very arbitrary and is based on the observation of a profile. It can be varied for different testing condition and to the choice of the user. The other advantage of the index is that, it gives the flexibility that an index can be subdivided to differentiate segregating, partially segregating and non-segregating types.

6 CONCLUSION

A review of quantitative study of segregation or mixing is presented. A Segregation Index (SI) based on standard deviation is proposed. The index has the flexibility of describing degree of segregation. Different standpipe and flume test data are examined with proposed index. Higher index values are generally related to a segregating type profiles and vice versa. A segregation index of 5 is applied as a segregation boundary for the test data examined.

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