Studies on the Effect of Moisture Content and Coarse and Fine Particle Concentration on Segregation in Bins†

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Abstract

Previous work by the author [1, 2, 3, 4] on particle size segregation in bins has been extended to consider the effect of the concentration of coarse particles. At low coarse concentrations a simplification can be achieved by plotting the non-dimensional concentration of coarse material \( C/C_F \) to summarise the profile. The present study reveals that at high values of \( C_F \), the coarse feed concentration, the segregation pattern is highly dependent on \( C_F \).

The addition of small amounts (less than 1%) of water to feed mixtures has a profound influence on segregation behaviour in many cases smoothing what would otherwise be severe segregation patterns with dry materials. Previous study contained speculation that segregation was reduced because the water caused an increase in cohesion of the fines content of the feed which in turn slowed the progress of coarse material relative to fine. Further discussion of this phenomenon is provided here.

1. Introduction

The deleterious effect of particle segregation in containers is well-known [5, 6, 7, 8]. In filling bins there is a tendency for coarser particles to separate outward from filling points with a resultant segregation, fine particles in the centre, coarser to the walls. Subsequent withdrawal of the material through a funnel flow hopper below will tend to allow the central material to emerge first with the outer material appearing later. A variation in flow rate and in particle size of discharge can thus readily result.

The same segregation phenomenon on filling can occur in charging a reactor or absorbing vessel and if performance is dependent on particle size or on fluid residence time in the vessel it is obvious that particle size segregation or fluid channelling as a result of it will affect performance.

Potentially most serious of all is the possibility, because of particle segregation, of uneven loading on container walls which possibly could lead to failure of the structure.

In the present study segregation was achieved by using only particles of the same density, by minimising lateral velocity of particles at the feed point and by having no impact velocity at the feed point. A diagram of the apparatus used in those studies and this is presented in **Figure 1**. Other workers have since used a similar apparatus [9, 10].

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**Fig. 1** Schematic Diagram of Segregation Box.
It was found that the concentration profiles for varying slope lengths could be correlated using a fractional (dimensionless) slope length, and, at low feed concentrations of coarse particles, the profiles could be correlated with concentration ratios. The latter finding is consistent with there being no interference between coarse particles.

Figure 2 presents typical results. When the fine fraction in the feed was reduced in particle size a reversal of profile resulted, Figure 3, indicating that, relatively speaking, the coarse particles were retarded in their flow down the slope. At high feed concentrations the wall region tended to have a flat, high concentration profile of coarse material, Figure 4. It was therefore concluded that segregation patterns in bins are dependent in a complex way both on feed concentration of coarse powder and, through some mechanism or other, on the fineness of the fine powder.

Measurements of the cohesion of the various fine fractions (including one to which a small amount of water was added) showed that even a very mildly cohesive powder has a very marked effect on segregation profile, with cohesion of about 0.25 kPa being associated with a reversal of the commonly discussed profile of coarse accumulation away from the feed point. A further increase to 0.5 kPa almost completely eliminated segregation; Figure 5.

The present work is an extension of that study with particular emphasis on:
(i) the concentration of coarse material in the feed mixture,
(ii) the size of the fine material and its cohesion as measured in the Jenike type direct shear tester,
(iii) the effect of added water on the segregation patterns, in particular in relation to cohesion of the fine fraction.

2. Experiments and results

Figure 6 shows the particle size distribution of the various sands employed in the present work with one sand being regarded as relatively coarse (16/30) while three other sands were available to mix with the coarse sand as binary feed mixtures.

The apparatus displayed in Figure 1 was used...
as in earlier studies [1, 2, 4]. For the current study the feed was delivered to the central point of the heap in the Perspex bin and samples were taken at 25 mm intervals across the contents of the poured heap at two levels. Allowing for symmetry of the heap when poured centrally there are thus four series of samples which could then be analysed and averaged to produce a good estimate of concentration profiles under various circumstances (eg, for different fine particle size distributions). Figures 7, 8 and 9 show the dimensionless segregation patterns of \( C/C_F \) each for a range of percentage coarse material (\( C_F \)) with Figure 7 having the coarsest fine material with a \( d_{50} \) of 330 \( \mu \)m, Figure 8 has \( d_{50} \) of 235, while Figure 9 has 145 \( \mu \)m.

One way of expressing these results is to calculate, for a given segregation pattern, the coefficient of variation or degree of segregation [11].

\[
\frac{\sum_{i=1}^{N} (C_i - C_F)^2}{N-1}
\]

where \( N \) is the number of samples across a profile and \( C_i \) is the coarse particle concentration of sample \( i \). Figure 10 displays the result of calculating this quantity for all the profiles of Figures 7, 8 and 9 and it is seen that segregation by this measure is worst at intermediate concentrations of coarse powder.

The result of adding one quarter percent of water to the various fine sands may be found in Figures 11, 12 and 13 where the fine particle size decreases in that order and where a comparison is visible between dry fine sand and “damp” fine sand on each graph. The decrease in segregation is obvious though in the case of White Fines 0.5% proved more effective (Figure 12).

Table 1 summarises various fine particle properties, the \( d_{50} \) sizes, the cohesion as measured by intercept of the linear regression of the yield loci of the material (for an arbitrarily chosen consolidating stress...
of 6.7 kPa) for various percentages of water and the calculated terminal velocity of the $d_{50}$ size in air assuming a spherical quartz particle.

Fig. 10 Coefficient of Variation of Segregation Pattern as Function of Coarse Concentration.

3. Discussion

Drahun and Bridgwater [12] noted a flattening of concentration profile as the percentage coarse material increased from "low" up to 73%. Examining the concentration profiles in the present work it is clear that the device of non-dimensionalising the concentration as $C/C_F$ is at best an approximation for low concentrations and in the case of the finest powder (Figure 9) a reversal appears similar to the patterns of Figure 3.

Previous work [1] speculated that it was cohesion exhibited by fine particles which retarded the coarse ones in their passage down the slope of the heap as it is poured. This could then lead to a flattened or even a reversed profile. The present work shows little evidence of profile reversal, the outstanding case is Figure 9.

It is, however, worth considering the phenomena which could alter a segregation pattern and cohesion is but one of them: one with a close interaction with particle size and moisture content as can be seen from the cohesion results of Table 1.

Another possibility, not related to moisture content, is that fine particles have lower terminal velocities

Table 1 Properties of Fine Sands

| Designation | KH6 Fine | White Fine | KH Fine |
|-------------|----------|------------|---------|
| $d_{50}$ ($\mu$m) | 145 | 235 | 330 |
| Moisture Content | 0 | 0.25 | 0.5 | 1.0 |
| Cohesion (kPa) | 0.12 | 0.40 | 0.27 | 0.48 | 0.35 |
| Terminal Velocity of $d_{50}$ Sphere m/s (in air) | 0.7 | 1.9 | 2.7 |
(either free or hindered) and hence may not settle on the heap as readily. This could lead to their enhanced transport to the wall leading to a profile flattening [11].

Moreover, the concept of the “quasi particle” can be invoked [13, 14, 15, 16] where large particles, under cohesive influences, gather around them smaller ones. Thus large particles can transport smaller ones towards the wall of a bin. The effect will be more pronounced with water present and the end result may be a flattening or perhaps a reversal of the profile.

Whatever the mechanism it may be seen from Figures 11, 12 and 13 that a small amount of water reduces the segregation from that occurring with dry powders. The addition of moisture to a powder may not be acceptable in some circumstances (for example with highly water soluble product) but could prove beneficial with ores or coal and conceivably could allay a dust problem.

Turning to Figure 10 which plots degree of segregation as a function of coarse feed percentage, it is seen that maxima occur at intermediate concentrations. This may be viewed as a quantitative picture of the result of the influences which cause or lessen segregation. Some influences tend to enhance the transport of coarse from the feed point, some will tend to retard the progress. The same remark may be made about fine particles.

Large particles tending to the wall

Brown [17] suggests that vibration during flow will tend to move large particles to the wall more than small ones. Williams [18] also discusses this mechanism while Matthee [19] postulates different frictional resistances for large and small particles.

Brown suggests that protuberances in the surface will stop small particles sooner than large ones. Further he states that small particles near the feed point which are moving slowly will soon stop and hence concentrate near the feed while small particles moving quickly will soon hit large ones and stop.

Dense and/or large particles will sink beneath the line of fall or will roll down the slope [17]. Drahun and Bridgwater [12], however, point out that their experiments do not confirm this.

If the feed were directly onto the slope, such as was usual in the inclined plane work, the collisions Brown considered would be too weak to cause the displacements implicit in his reasoning. His analysis could be applicable to pouring with a free-fall height, although he ignored the possibility of small particles being carried down the slope by bounding. A high free-fall height has been found to cause reversal of the distribution of ‘sinkers’”.

Williams [20] suggests that small particles will tend to percolate down into a bed and it may be that the large ones will reach the periphery by default.

Drahun and Bridgwater [12], Matthee [19] and Syskov and Tszi Lyan [21] all allude to a rolling mechanism as a major mechanism for large particles to reach the far part of a bin. In particular Drahun and Bridgwater point out that there are always some large particles near the wall even though the major concentration of them may not be there.

Small particles tending to the wall

There are several feasible mechanisms whereby the trends discussed above may be reversed. Reference has been made already in this Discussion section to the possible influence of cohesion [1, 2], to quasi particles carrying fines with them [13, 14, 15, 16] and to slowly settling fines which may transport to the wall. Concerning the last factor Table 1 gives the terminal velocity of the $d_{50}$ particles. The particle size distributions contain many smaller (and of course more slowly settling) particles. Small particles inherently will fall through air more slowly and the effect of many together is aggravated by air percolated effects. See for example Reference [22].

Drahun and Bridgwater [12] refer to the possibility of small particles bouncing down a slope (in contrast to Brown’s argument [17] that small ones will be stopped).

Finally, Lawrence and Beddow [8] reported a reversal of the usual segregation pattern (with the coarse to the wall) with a volume of fines greater than 60%. They considered that the small number of large particles simply could not get through the matrix of fines.

4. Conclusion

The phenomenon of segregation is becoming more complex the deeper the study. It appears that non-dimensional groups are not able to correlate the phenomena. The segregation patterns resulting when mixtures of particles are poured on to a heap are strongly dependent in a complex fashion on the concentration of coarse material in the feed.

It is worth noting that the author [4] found no speed effect in feeding material on to a heap and
This was held to be a simplification enabling some generalisations to be made about the segregation phenomenon. However, the particles studied at that time were coarse and it may be that with fine particles there are interstitial air effects producing a feed rate effect. Lawrence and Beddow [8] and Syskov and Tszi Lyan [20] found the extent of segregation decreased if the pouring time decreased.

It is the intention of the author to further the study of particle segregation paying particular attention to:
(i) the scale of the apparatus,
(ii) the feed rate on to a heap,
(iii) the concentration of coarse particles, and,
(iv) by no means least, the segregation patterns resulting with particles much finer than those studied to date.

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Author's short biography

David Bagster graduated in engineering from the University of Queensland and gained a PhD in chemical engineering from the University of Cambridge. After ten years in the sugar industry he joined the Department of Chemical Engineering at the University of Sydney. David Bagster's research interests are in particle mechanics, mineral processing and risk analysis.