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Experimental Investigation into Segregation of Bulk Solids During Gravity Filling of Storage Bins

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Experimental Investigation Into Segregation of Bulk Solids During Gravity Filling of Storage Bins

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Summary

This paper explains the phenomenon of segregation and previous methods used in its quantification. Also explained is the current research, which has attempted to develop a two dimensional sampling technique to quantify the degree of mixing present under gravity fill conditions. Binary mixtures have been prepared in varying proportions and charged into a test rig where sampling has taken place and the results analysed. From these results, a relationship between degree of mixing and product proportion has been developed.

Nomenclature

M	Mixing Index	
n	Number of sample points	
p	Numerical proportion of particle with highest quantity in mixture	
p_i	Percentage of product present in a sample square	
ρ_{bl}	Loose poured bulk density	kg/m^3
ρ_s	Solids density	kg/m^3
σ	Standard deviation among samples	
σ_0	Standard deviation before mixing	
σ_r	Standard deviation of the complete random mixture	
σ^2	Variance among samples	
σ_0^2	Variance before mixing	
σ_r^2	Variance of the complete random mixture	

Introduction

The segregation of bulk solids is an extremely important issue in both storage and transportation. The occurrence of segregation can have a detrimental effect on the quality of a product, especially in the case of food stuffs such as muesli and mixed cereals where strict ratios of the constituents are required.
There are various issues which are of importance when dealing with segregation:

- the various methods in which segregation can occur, such as sifting and dynamic effects,
- the sampling technique used to extract representative portions of the mixture,
- the method used to quantify the degree of segregation present in the given mixture, such as using mixing indices.

1. Previous Research

1.1 Segregation Mechanisms

Segregation mechanisms exist under wide ranging conditions, several of which are described below.

1.1.1 Heap Segregation

As product is poured into a heap, segregation occurs and is generalised as heap segregation. However Mosby et al.[11] explain that heap segregation is often described as one form of segregation where in fact it is a combination of several individual segregation mechanisms interacting with each other. These could include sifting, fluidisation and dynamic effects.

1.1.2 Sifting

The sifting mechanism is one of the most common causes of segregation. When particles of different sizes are poured into a bin or a heap, the finer particles concentrate under the filling point while the coarser particles roll down the pile to the edges. Finer particles also fall through the voids produced by the coarser particles [3,18], the end result shown typically in Figure 1.

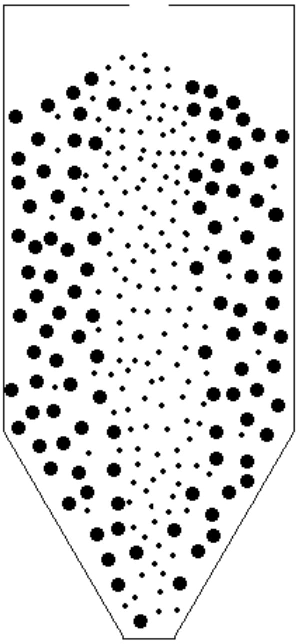


Figure 1 : Sifting mechanism

1.1.3 Trajectory

Trajectory effects are present when pouring product into a heap from a chute. Carson et al.[4] explain that due to differing frictional drag, different materials will move at different velocities. A product having a higher drag will have a lower velocity when it leaves the chute and generally fines have a higher frictional drag and hence will be deposited closer to the base of the chute than larger coarse particles.

1.1.4 Fluidisation

A vertical segregation pattern can form due to fluidisation where the coarse material is located at the bottom of the bin while the fine material produces a layer at the top of the bin [3]. Johanson[9] suggests that fluidisation can be reduced using a deflector plate to reduce the vertical component of the particle velocity, or by using a tangential entry when pneumatically conveying product.

1.1.5 Dynamic Effects

Johanson[9] explains that resilience can directly affect the way in which segregation occurs. When particles hit the top of a pile with a high velocity, a flat spot will form and particles which are not resilient enough to bounce out will be trapped. The particles which have enough resilience will concentrate at the outer limits of the pile due to them being able to escape from the central flat spot.

1.2 Sampling Methods

Sampling of a mixture to determine the degree of segregation present has been performed in numerous ways in the past, by using sampling probes, coloured dyes and computer imaging, the technique used being determined by the mixture content.

Carley-Macauly and Donald[2] used sampling probes as shown in Figure 2 to take samples of fine products, each sample containing a maximum of 60 particles. Rochowiecki[12] also used a sampling probe, as shown in Figure 3, taking a maximum of 200 particles in each sample.

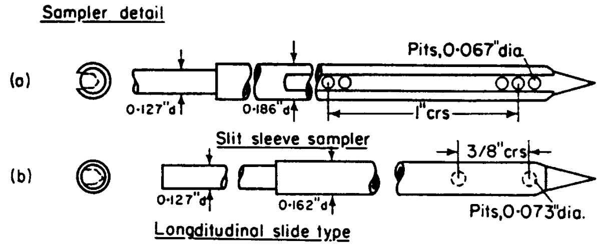


Figure 2 : Sampling probes[2]

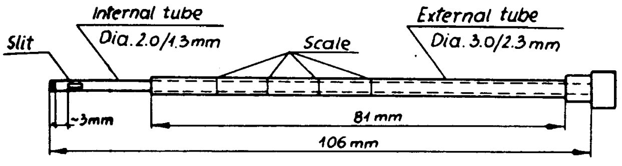


Figure 3 : Sampling probe[12]

Rumpf and Mueller[14] used an organic dye to coat a portion of fine calcite powder. Samples were taken then washed in water to remove the pigment. Using a photometer, the intensity of the pigment solution was then determined.

Broyles et al.[1] used an image analyser constructed around a personal computer to perform shape analysis on materials. By hand, analysing 100 particles was very time consuming, but the image analyser cut down this time to as little as 10 minutes.

Scott and Bridgwater[15] believed that approximately 40 samples had to be taken from a mixture to obtain decent results, however this made the analysis monotonous.

Rogers and Clements[13] listed two limits to the amount of sampling which could be conducted: (i) the sampling probes being placed too close together, the insertion of one interfering with the product being collected by another, and (ii) analysing large numbers of samples being too time consuming and expensive.

1.3 Mixing Indices

Mixing indices are used to evaluate the degree of mixing, or mixedness, in a mixture. There is a wide range of mixing indices available for use, which have been developed by a number of researchers and they involve statistical parameters such as variance or standard deviation[7].

A short list of mixing indices is displayed in Table 1 along with the operating ranges of the mixing indices. Generally the mixing indices range in value from 0 to 1, 0 being for full segregation and 1 for complete mixing, or vice versa depending on the representation of the variance or the standard deviation in the formula. There are others however that do not follow this trend and can range from 0 up to extremely large numbers.

A number of the mixing indices has been derived by modifying existing indices. For example, Williams[17] stated that Ashton and Valentin modified the mixing index derived by Lacey, shown as Equation (7), due to there being a discrimination present as the mixing process was coming to completion. The modified equation became that shown as Equation (8) and although there is still some discrimination, it is an improvement[17].

Table 1 : Mixing indices

EQUATION	MIXING INDICES	AUTHOR(S)	RANGE OF VALUES SEGREGATION to MIXED
(1)	$M = \frac{\sigma}{\sigma_o}$	FAN, CHEN, WATSON [5]	1 to 0
(2)	$M = \frac{\sigma_o}{\sigma}$	SMITH [16]	1 to >>1
(3)	$M = 1 - \frac{\sigma}{\sigma_o}$	FUERSTENAU, FOULADI [7]	0 to 1
(4)	$M = \frac{\sigma^2}{\sigma_o^2}$	FAN, CHEN, WATSON [5]	1 to 0
(5)	$M = 1 - \frac{\sigma^2}{\sigma_o^2}$	HOGG, CAHN, HEALY, FUERSTENAU [8]	0 to 1
(6)	$M = \frac{\sigma^2}{\sigma_o^2} - 1$	FAN, CHEN, WATSON [5]	0 to -1
(7)	$M = \frac{\sigma_o^2 - \sigma^2}{\sigma_o^2 - \sigma_r^2}$	LACEY [10]	0 to 1
(8)	$M = \frac{\log\sigma_o - \log\sigma}{\log\sigma_o - \log\sigma_r}$	WILLIAMS [17]	0 to 1

Note,

$$\sigma_o = \sqrt{p(1-p)} \tag{9}$$

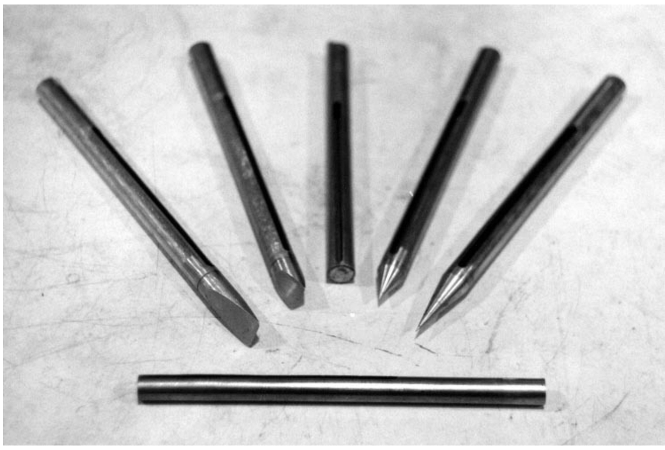
$$\sigma_o^2 = p(1-p) \tag{10}$$

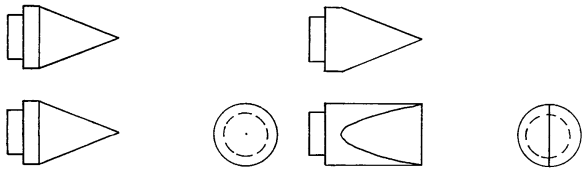
$$\sigma = \sqrt{\frac{\Sigma\left(p_i - p\right)^2}{n-1}} \tag{11}$$

$$\sigma^2 = \frac{\Sigma\left(p_i - p\right)^2}{n-1} \tag{12}$$

2. Sampling Probe Designs

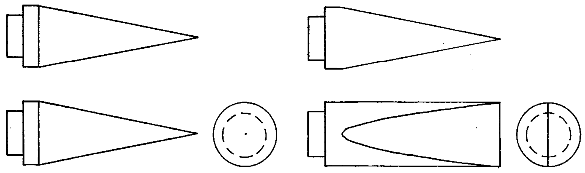
Five new sampling probes were designed, shown in Figure 4: a flat tip, two conical tip probes, Figures 5a and 5b, and two chisel tip probes, Figures 5c and 5d. The sixth tube shown in Figure 4 is inserted inside the other five to collect the samples. Using a sampling box representing a small portion of the full scale rig, sampling tests were performed on the five designs. The outer sampling probe tubes had an outside diameter of 19.05 mm and the inner sampling probe tube, an outside diameter of 15.95 mm.





(a) 25 mm Long Conical Tip

(c) 25 mm Long Chisel Tip



(b) 50 mm Long Conical Tip

(d) 50 mm Long Chisel Tip

Figure 4 : Initial sampling probe designs

Figure 5 : Additional sampling probe tip designs

While testing, observations immediately showed that for the flat ended probe, a substantial quantity of product was being displaced in front of the sampling probe while being inserted. This was also the case for the other four tips but to a reduced degree. In a full scale situation this could have a detrimental effect on the product in adjacent sampling areas giving rise to inaccurate results. This resulted in the use of mechanical sampling probes being abandoned.

3. Test Products

There was a number of criteria which needed to be met in order for a product to be suitable for use, they being;

- comparable loose poured bulk densities (to minimise density effects)
- approximately spherical particle shape
- two distinctly different coloured products (for visual observations)
- distinct size difference (ease of separation)
- non-degradable products (to eliminate/minimise replacement of sample)
- low static (using perspex for the bin could cause problems).

Rape seed and white plastic pellets, Table 2, met all the listed criteria and were selected for the full scale tests.

Table 2 : Product sizes and densities

Product	Size range, mm (sieved)	Solids density, ρ_s, kg/m^3	Loose poured bulk density, ρ_{bl}, kg/m^3
Rape seed	1.0 - 2.0	1166	661
White plastic pellets	3.8 - 5.6	910	536

4. Test Rig

The rig used for full scale testing consisted of two parts: firstly, a 20 litre Forberg mixer [6] and storage bin arrangement, Figure 6a, where binary mixtures were prepared for testing and secondly, the observation rig, Figure 6b, where the storage bin was positioned above the perspex bin and hopper. Feeding from the storage bin was controlled via a full-bore ball valve and discharge from the perspex bin was achieved by a slide valve, both pneumatically controlled.

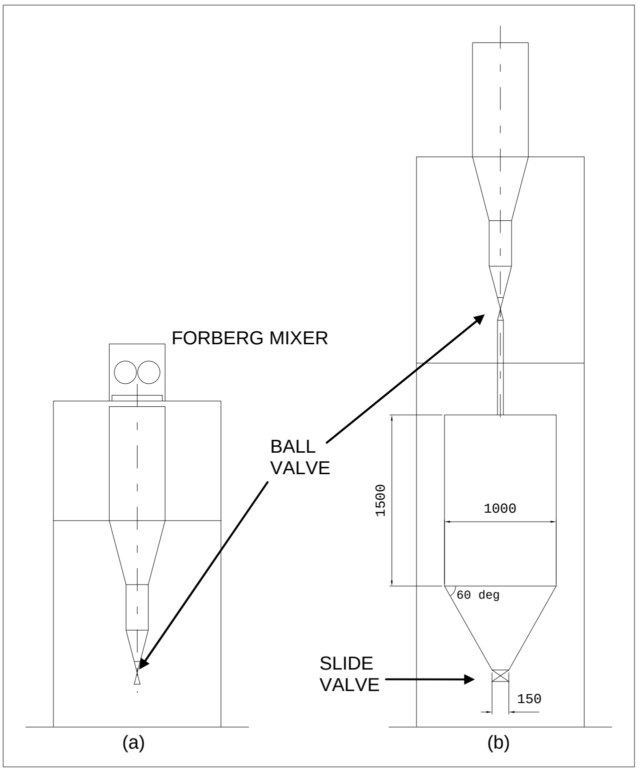


Figure 6a : Mixer and storage bin arrangement
Figure 6b : Storage bin, perspex bin and hopper arrangement

The perspex observation bin had internal dimensions 1500 x 1000 x 150 mm and the hopper had a hopper half angle of 30º to the vertical and an outlet size of 150 mm. A grid of 110 x 110 mm was drawn on the bin and hopper, giving 134 sampling squares.

5. Computer Image Sampling and Analysis

A computer based method was sought where non-intrusive sampling could be employed. With the aid of a video camera, a piece of computer hardware called Snappy was obtained which captures high resolution digital images and places them onto a computer. Once saved, the images were analysed to extract the required data to determine the degree of segregation.

The software package Optimas was used for this purpose, by analysing the images in black and white two threshold regions could be selected, the dark region for rape seed and the light section for white plastic pellets. Once these thresholds were selected, the percentage areas of each could be calculated by Optimas. These percentages were then recorded to be used in calculating the mixing indices.

6. Testing

6.1 Monitoring Mixture Quality

Before full scale testing could begin, it had to be determined whether there was any segregation occurring in the mixture before it entered the perspex observation bin. A 20 litre batch of product was prepared for three mixtures and dropped onto a conveyor belt from the storage bin. Three samples were taken from each mixture drop and analysed, the results shown in Table 3.

These results indicate that there was negligible segregation occurring in the mixtures at the exit of the storage bin, the maximum variation being 0.9%.

As a final check to rule out any significant segregation of the mixtures before they entered the sampling bin, three stream sampling tests were performed. By preparing three 240 litre batches of product as would be used in a full scale test, 10 cup samples were taken from the stream at regular intervals as it entered the top of the perspex bin, each sample being analysed and the results are shown in Table 4.

The maximum variation in these sampling tests was 1.8% and indicated that the segregation that was occurring to the mixture before entering the perspex bin was minimal.

Table 3 : Results of conveyor belt sampling tests

Initial product mixture	Rape seed % volume	White plastic pellets % volume
25/75 % volume	24.6	75.4
50/50 % volume	49.1	50.9
75/25 % volume	75.5	24.5

Table 4 : Results of stream sampling tests

Initial product mixture	Rape seed % volume	White plastic pellets % volume
25/75 % volume	23.2	76.8
50/50 % volume	49.5	50.5
75/25 % volume	74.1	25.9

6.2 Full Scale Testing

Full scale testing was performed on binary mixtures containing between 10% rape seed and 75% rape seed by volume, each test consisting of 240 litres of mixed product. All tests were recorded on video for later viewing. Once a mixture was prepared for testing, the ball valve at the bottom of the storage bin was opened and the product allowed to stream into the perspex bin.

Various segregation mechanisms were observed in the perspex bin as it was filling. The sifting mechanism was the most prominent, the smaller rape seed particles concentrating at the centre of the bin while the larger white plastic pellet particles concentrating at the sides of the bin. Another segregation mechanism present was that due to dynamic effects. From the apex of the heap, rape seed could clearly be seen bouncing outward and a small crater present where the stream made contact with the heap. This effect would have been continually changing due to decreasing drop height as the perspex bin filled with product.

After a test had been completed, each sample point was captured using Snappy and a video camera.
Figure 7 depicts the results of the 50% rape seed and 50% white plastic pellets by volume test, the segregation, as explained above, can clearly be seen. Two bands of light are visible across the perspex bin in Figure 7, these were as a result of the lighting source used and unavoidable.

7. Mixing Index Calculations and Graphs

The maximum number of sampling squares used in any one test was 107, due to the heap slope at the top of the pile some squares were empty or only partially full. To allow comparative results from one test to the next, the same number of sample squares were analysed for each test, reducing the number of sampling squares for analysis to 89. Figure 8 shows a representation of the sampling bin with the sampling squares numbered.

Once Optimas had been used to analyse each of the sample squares, graphs were produced, as in Figure 9, showing the segregation in each horizontal section of the perspex bin and hopper for the 50% rape seed and 50% white plastic pellets by volume test. The vertical axis representing the recorded volumetric percentage of rape seed in a given sample square and the horizontal axis representing the sample square in question.

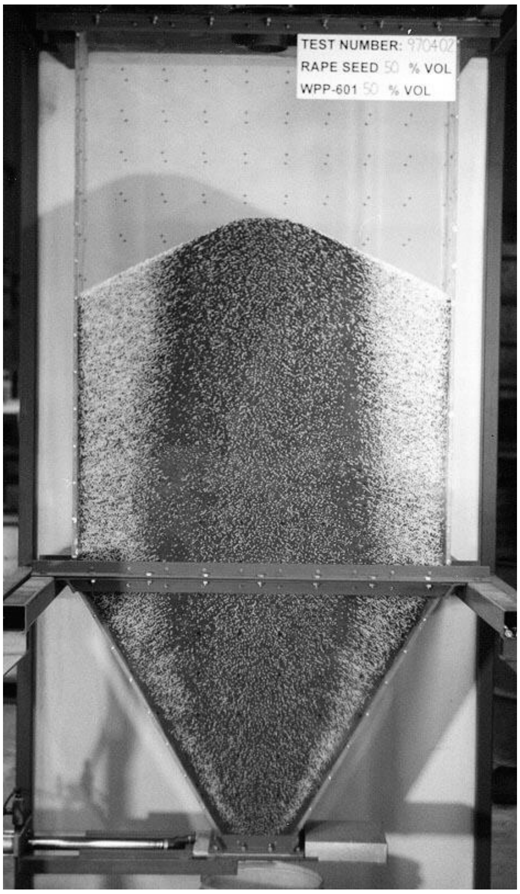


Figure 7 : Perspex bin showing result of a 50% rape seed and 50% white plastic pellets by volume segregation test

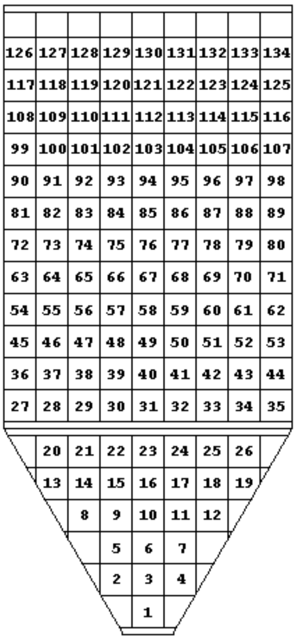


Figure 8 : Sample square locations

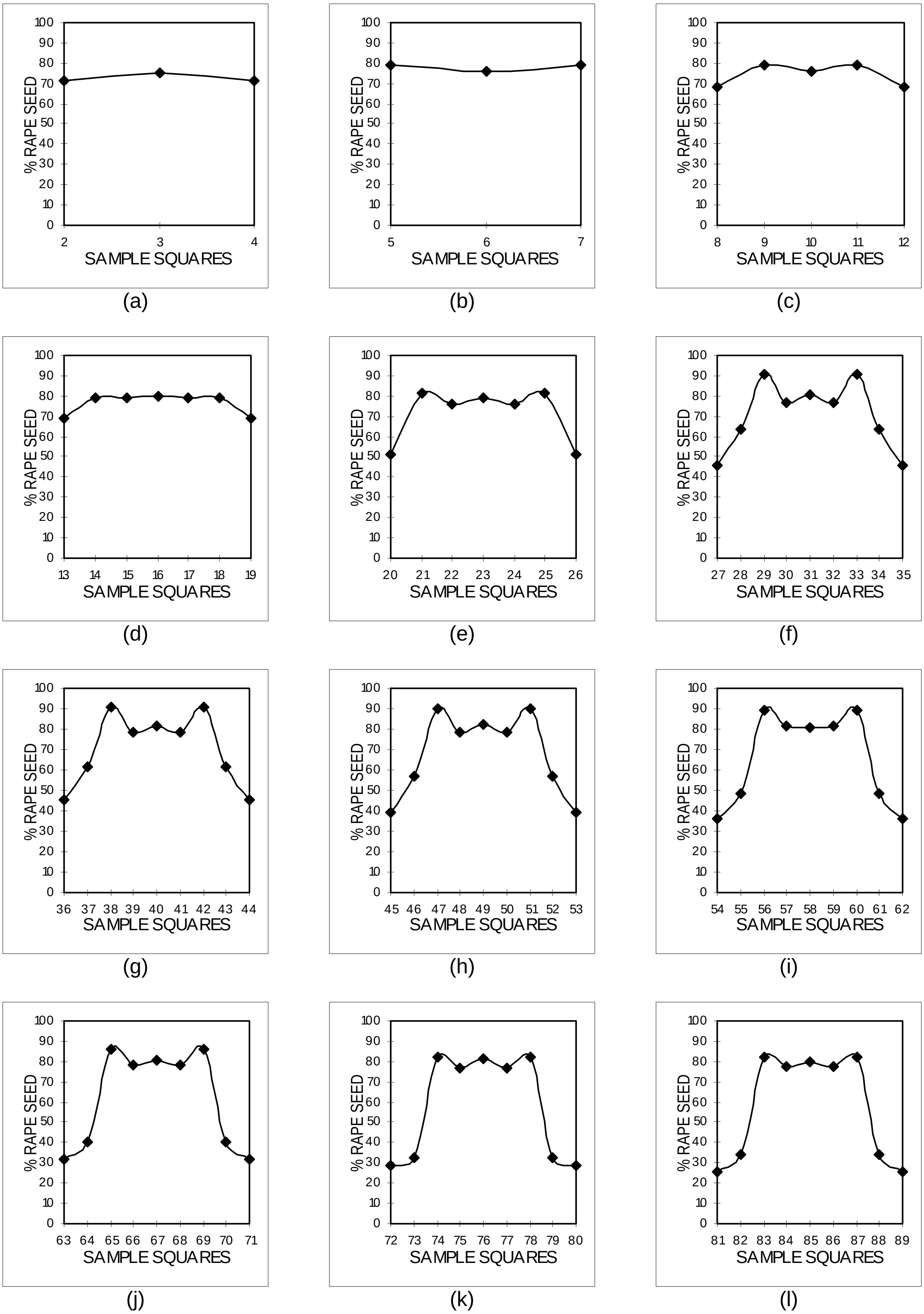
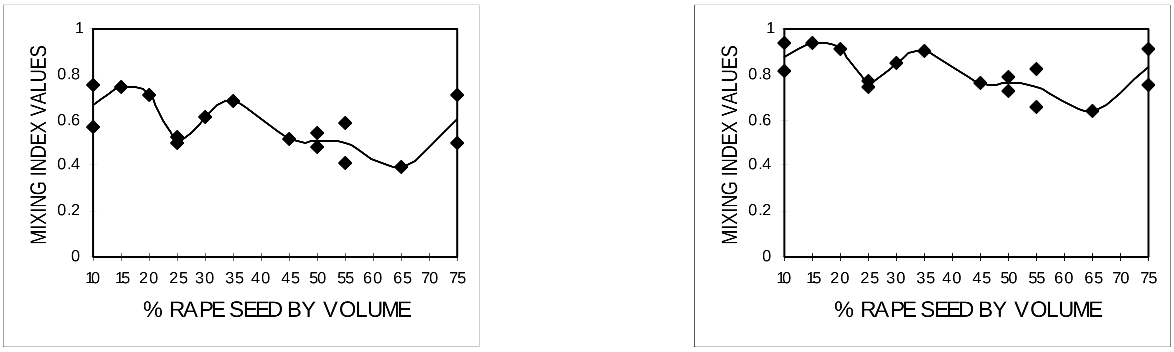


Figure 9 : Distribution of segregation in horizontal rows in the hopper and bin for the 50% rape seed and 50% white plastic pellets by volume test

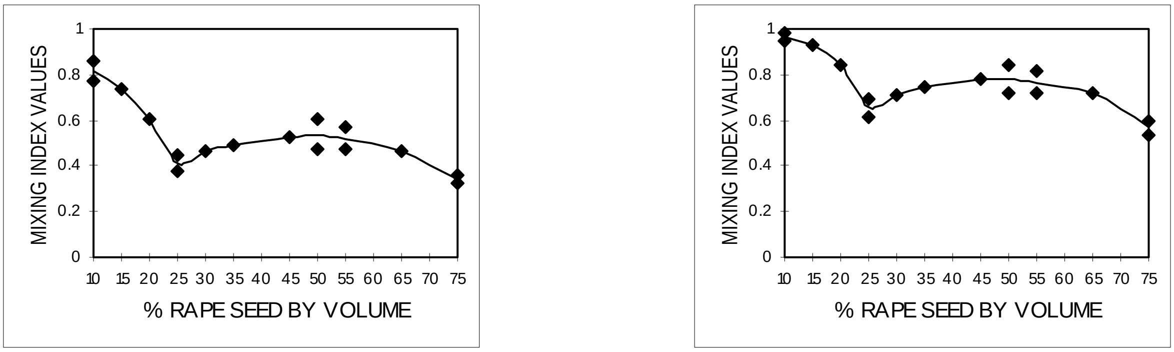
Two mixing indices were chosen to quantify the degree of segregation occurring in each test, Equation (3) and Equation (5). These two were chosen for their range of values, 0 being for segregation and 1 for fully mixed. Three sets of values were produced for each test, one for the 26 sample squares in the hopper, one for the 63 sample squares in the bin and one for the entire 89 sample squares. These were plotted with a curve of best fit added, producing Figure 10, Figure 11 and Figure 12.



(a) Using Equation (3)

(b) Using Equation (5)

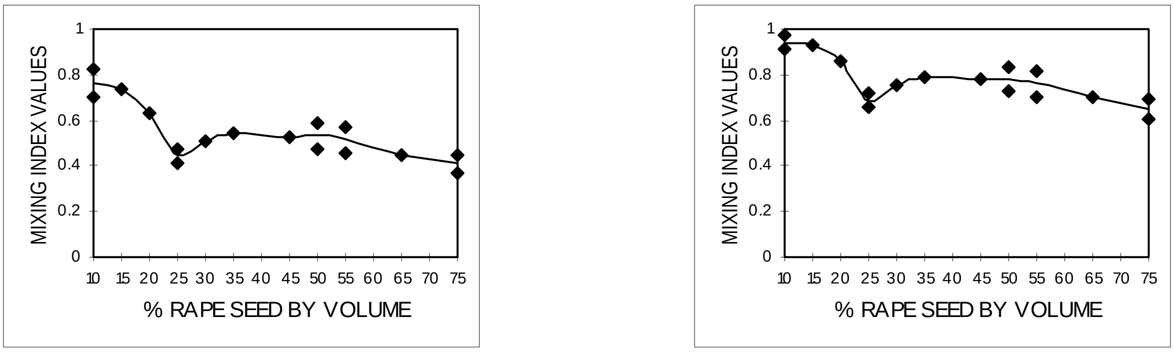
Figure 10 : Mixing index values Vs volumetric percentage of rape seed in the hopper section



(a) Using Equation (3)

(b) Using Equation (5)

Figure 11 : Mixing index values Vs volumetric percentage of rape seed in the bin section



(a) Using Equation (3)

(b) Using Equation (5)

Figure 12 : Mixing index values Vs volumetric percentage of rape seed in the combined hopper and bin sections

The graphs show that the segregation occurring in the hopper is very sporadic with no visible trend, but has a slight overall increase in mixture quality as the volumetric percentage of rape seed is reduced. This is most probably due to the increased influence of the dynamic effects due to the narrower angled walls of the hopper.

The curves representing the degree of segregation in both the bin and the whole bin and hopper showed very similar characteristics. As with the segregation in the hopper, there was an increasing mixture quality as the volumetric percentage of rape seed was reduced, however, at the 25% mark, a pronounced dip in both curves was observed.

This was unexpected, possible reasons for this occurrence are: a characteristic of this product combination; and/or a result of this particular bin and hopper geometry.

8. Conclusions

Existing sampling methods were found to be unsuitable for the proposed work in this research resulting in several new sampling probes being designed and tested. However, intrusive sampling was discarded and a non-intrusive computer based sampling method was developed in its place where a two dimensional sample of product was analysed.

Tests involving the conveyor belt and in-line stream sampling proved that very minimal segregation occurred in the mixture between leaving the Forberg mixer and entering the perspex observation bin, showing that the segregation that did occur was as a direct result of the filling operation.

As the testing program was being performed, segregation could clearly be seen. Segregation mechanisms such as sifting and dynamic effects were quite visible. The impact of dynamic effects decreased as each test progressed, as the drop height was continually decreasing.

The mixing indices used clearly represent the segregation present in each test. By combining the results from all tests performed, graphs for the hopper section, bin section and the combined hopper and bin section were produced, showing the variations from different mixtures.

9. Further Work

There is a substantial amount of work which still needs to be addressed, such as;
- the use of other products to determine whether the dip which occurred in Figure 11 and Figure 12 is a characteristic of this particular combination of products or whether it occurs in all cases,
- the use of a constant drop height to see what effect this has on the degree of segregation,
- modify the geometry of the perspex observation bin and hopper to observe the effect on segregation,
- different filling methods can be investigated, such as non-symmetrical filling, use of a chute and the use of spreader plates,
- computer simulation using discrete particle methods could be investigated to predict possible segregation,
- tertiary mixtures should also be looked into at a later date to investigate the segregation patterns present and trends that form.

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