DESIGN OF BINS AND HOPPERS FOR THE STORAGE OF PARTICULATE MATERIALS. PROBLEMS ASSOCIATED WITH THE DISCHARGE OPERATION

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ABSTRACT

In ceramic tile, frit and ceramic colour production processes, large quantities of particulate solids of different nature are handled, which need to be adequately stored and discharged. On discharging these materials, flow stoppages as a result of doming in the bin, size segregation, etc. can occur. Some of these problems can be minimised and even suppressed by appropriate bin design. In this study, the Jenike theory has been applied to bin design for three types of particulate materials: spray-dried powder, used in porcelain tile manufacture, zinc oxide and quartz, used in ceramic frit production. For these materials the maximum angle that the wall needs to form with the vertical in the bin discharge zone, and the minimum outlet diameter required for appropriate, unbroken material flow during discharge were calculated. The influence was also analysed of the bin surface on the type of flow. Finally, experiments were conducted to verify the usefulness of the methodology tested for bin design.

1. INTRODUCTION

In ceramic manufacture, most of the raw materials used are found as particulate materials. The daily consumption of particulate materials in the Spanish ceramic tile manufacturing sector is assessed at around 40,000 tons, which is why it is important to know the rheological behaviour of these materials during charging and discharging in their storage containers (basically bins and hoppers).

The rheological behaviour of particulate solids is so complicated that it cannot be dealt with like that of liquids or suspensions, or like that of solids. This all too often leads to problems in handling: segregation, stoppages in bin or hopper discharges owing to doming, dead spaces in the bins, flooding, etc., which can detrimentally affect the production process. These problems can be minimised with appropriate bulk solids discharge from bins and hoppers. There are two types of particulate materials discharges: funnel or mass discharges. The existence of one type of flow or the other depends on the nature of the particulate solids and the storage container. Designing a bin with a specific type of flow therefore requires jointly considering the characteristics of the material and of the bin itself.

1.1 TYPES OF FLOW

1.1.1 Funnel flow

Funnel flow involves the formation of a flow channel aligned with the bin outlet, surrounded by a region in which the material initially stands still (Figure 1). During bin discharge, if the material is not very cohesive, the highest part next to the walls progressively crumbles, feeding the centre channel. If the material is very cohesive, the bin may stop emptying owing to the formation of an empty centre channel surrounded by non-moving material.

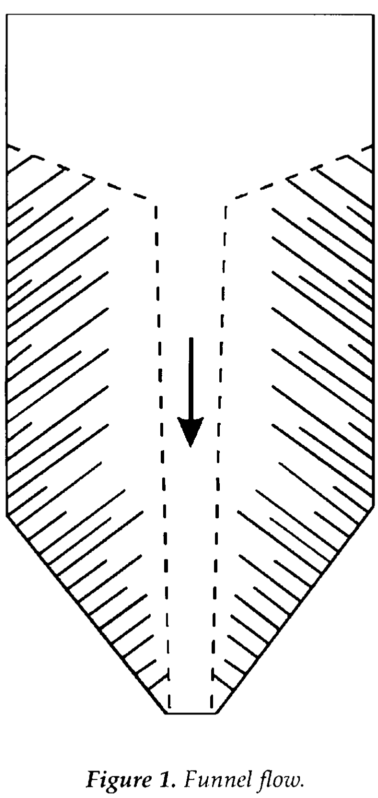

Figure 1. Funnel flow.

In discharge from a bin with funnel flow, the material does not all move together, which makes the material flow at the outlet and the bulk density of the resulting particulate bed change progressively in the course of the operation. Even when the bin has almost completely emptied, material is still left inside, which has not yet moved. This solid, accumulated in the bin's dead spaces, not only lowers bin effective capacity but can even become unserviceable if its properties change with time (by drying, oxidising, etc.). Furthermore, this type of flow makes the negative effects caused by any inhomogeneity of the stored powder, owing to possible size segregation during filling, more pronounced.

One of the few advantages of this type of flow is the decreased wear of bin walls, as friction is virtually negligible during powder discharge. Moreover, the walls of this type of bin need to withstand lower pressures, thus requiring less material to build them.

1.1.2 Mass flow

In this type of flow, all the material characteristically moves together during discharge; in particular, the material next to the wall slides over the wall and empties together with the rest. Once discharge starts no particle or agglomerate remains in its original position. They all move, preventing dead spaces from forming. The material that enters the bin first is the first to leave (first-in, first-out), which tends to keep a steady powder residence or storage time in the bin in a continuous process.

Mass flow discharge from the bin is not broken by channelling, as all the material moves at the same time. Moreover, the stresses that arise during discharge are predictable. The bin can therefore be designed to prevent arches from forming and causing discharge stoppages.

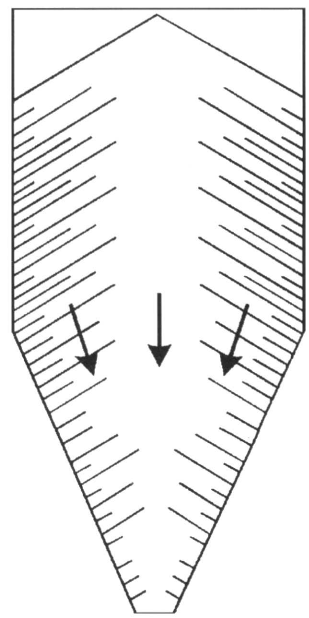

Figure 2. *Mass flow.*

The discharge flow rate and density of the resulting powder bed during emptying are less variable than in the case of funnel flow. Another no less important advantage of this type of flow is the reduction or elimination of the problems that can arise during charging associated with segregation. The effect of all the material moving together produces a certain re-mixing that tends to raise the homogeneity of the exiting powder. Thus, bins with mass flow are sometimes recommended as solids blender systems.

Mass Flow	Funnel Flow
-Eliminates the possibility of flow obstructions -Minimises the effects associated with size segregation -Renews material (no dead spaces) -Flow is uniform and readily controlled -The density of the discharged powder bed is practically constant -The whole storage capacity is used (no dead spaces)	-Less headspace is required for the same capacity -The walls need to withstand lower pressures -The walls are subject to less abrasion

Table 1. *Comparison between mass flow and funnel flow. Advantages.*

1.2. BIN DESIGN

This involves determining the maximum angle that the bin walls form with the vertical in the discharge zone, θ, and the smallest outlet size, D, at which bin discharge occurs by uninterrupted mass flow (Figure 3).

1.2.1 Preliminary considerations

1.2.1.1 Outlet obstructions

Bin outlet size must be sufficiently large to keep from becoming obstructed during discharge. This phenomenon can stem from doming if the powder is cohesive, or from blocking up as a result of structures forming if the particles are sufficiently large.

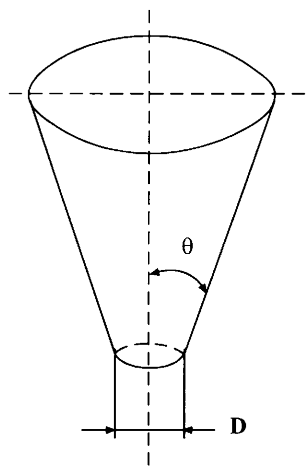

Figure 3. *Design variables.*

To keep flow stoppages from arising as a result of the latter mechanism, it suffices to have an opening one order of magnitude larger than that of the particles or agglomerates making up the powder. The calculation of the discharge diameter to keep stoppages from occurring by the former mechanism is more laborious and is based on the theory developed by Jenike [1, 2, 3] in the mid sixties. Some aspects of this theory are dealt with below.

1.2.1.2 System requirements to prevent flow stoppages

Let us analyse what happens to an element of solid in contact with the bin wall during solids discharge (Figure 4). When the element is located at the top of the bin, it is not compacted (p=0), as it is subject to no pressure. However, as it descends, it undergoes compaction because the pressure reigning in the bin (p) grows. Figure 4 shows that

[1] JENIKE, A. W. *Gravity flow of solids.* Bulletin of the University of Utah. No 123, 1961.
[2] JENIKE, A. W. *Storage and flow of solids.* Bulletin of the University of Utah. 53(26), 1964.
[3] JJENIKE, A. W.; JOHANSON, J. R. *Review of the principles of flow of bulk solids.* CIM Trans.,73, 141-146, 1970.

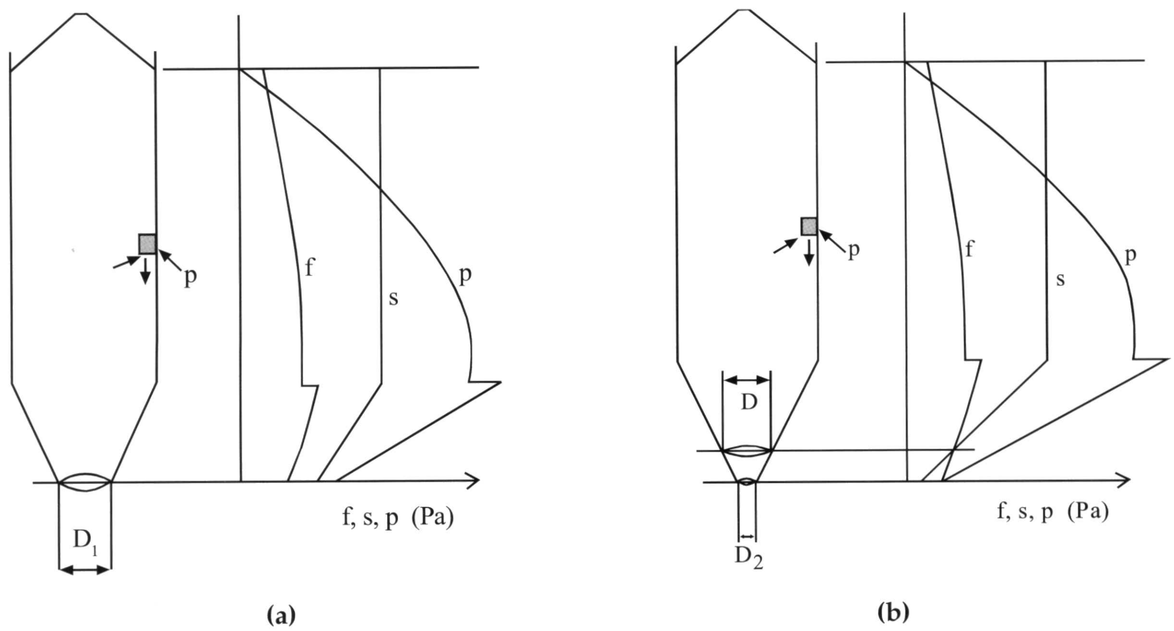

Figure 4. Pressure (p) distribution, powder shear strenght (f) and shear stress (s) inside a bin.

pressure initially increases considerably with depth, until approaching the end of the bin vertical, where it remains constant. At the intersection between the vertical wall and the sloping wall, the pressure generally increases sharply. Beyond this point, pressure drops as the material approaches the discharge opening.

A solid's shear strength (f) varies similarly to the variation of pressure, as this property of the powder bed is a function of compactness, which in turn depends on the pressure to which the material is subject, which changes as the material shifts. Therefore, during discharge, the material's shear strength alters according to its position in the bin. On the other hand, the element involved is permanently subject to maximum shear stress (s), whose magnitude also depends on the position of the element in the bin as depicted in Figure 4.

In the example shown in Figure 4a, the maximum shear stress that the element is subject to (s) is always greater than its shear strength (f), so that no flow-impeding domes can form during discharge from the bin.

However, if the bin outlet is reduced from D_1 to D_2 (Figure 4b), keeping the other variables constant (wall angle, type of powder, etc.), so that at some point in the system the condition is met that the material's shear strength (f) exceeds the maximum shear stress to which it is subject (s), doming will occur at this point. Thus, the value of the outlet diameter, D, which corresponds to the intersection of lines f and s in Figure 4b, is the minimum diameter at which no doming takes place.

1.2.2 Material flow function (MFF)

The flow function of a particulate material (MFF) is the variation of shear strength (f) of the powder bed compacted at a given pressure (p), as a function of this variable (p).

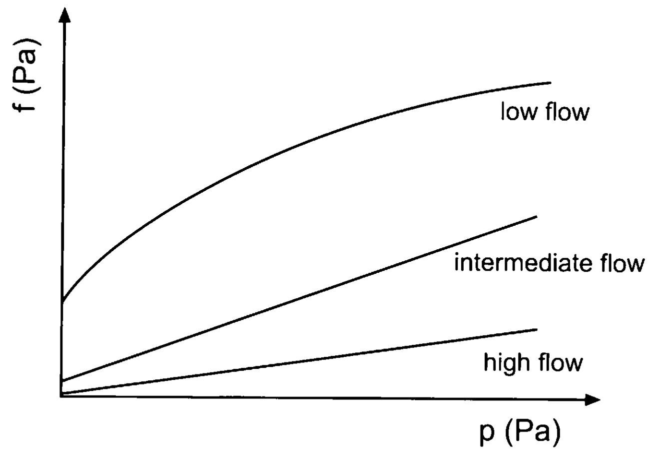

Figure 5. Flow functions of different materials.

Figure 5 plots the flow functions of a series of materials. This property determines the rheological behaviour of a particulate material at different compaction pressures and is therefore considered a measure of its flowability. Thus, the larger the intercept at the vertical axis and the higher the slope of the plot, the lower is powder flowability. The flow function of a particulate material is found by performing the shear experiments set out in point 3.3.1.

1.2.3 The flow factor of the system bin-material (ff)

The flow factor (ff) of a bin-particulate material system is the plot of the maximum shear stress (s) that acts on an element of solid stored in a bin versus the pressure to which it is subjected. Jenike observed that in each system, the quotient of both values was constant.

The calculation of the flow factor (ff) involves solving the differential equations representing the stresses that appear in the bin during discharge. These solutions were published by Jenike for bins with different geometry, in the form of graphs commonly known as flow factor charts (Figure 6).

The flow factor (ff), unlike the material flow function (MFF), is a property of the bin-material system, so that it depends on certain characteristics of the two. To calculate the flow factor of a system it is necessary to know: the powder effective angle of internal friction (δ), the angle of friction between the material and the bin surface (ϕ), the angle of the wall in the bin discharge zone (θ) and bin geometry. The value of the material's effective angle of internal friction (δ) and the angle of friction between the material and the bin surface (ϕ) are determined by the shear experiments set out in points 3.3.3 and 3.3.4.

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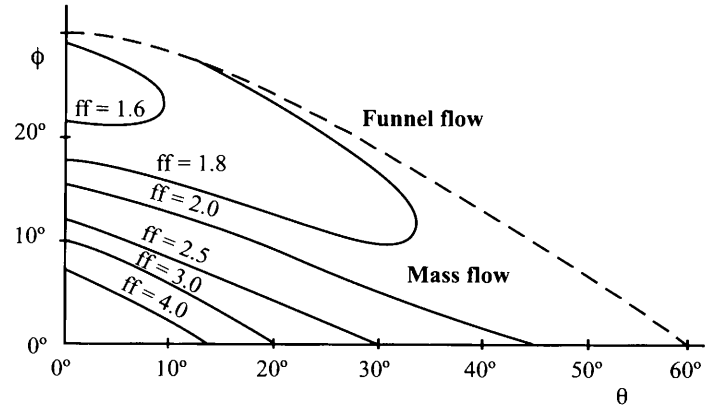

Figure 6. Jenike graph for a cylindrical bin and an angle of internal friction (δ) of 30°.

1.2.4 Calculation of the design variables

1.2.4.1 Calculation of the maximum angle of the bin wall in the discharge zone (θ)

The value of θ is calculated from the flow factor charts (Figure 6). The triangular area of these graphs represents the conditions for which the material exhibits mass flow during discharge, in accordance with the Jenike theory.

The dashed line that separates both regions determines the system's boundary conditions. Thus, this line represents the pairs of values maximum wall angle (θ), angle of friction of the powder-wall system (ϕ) at which mass flow is found. As a safety margin, it is advisable to use an angle 3° smaller than the estimated angle.

1.2.4.2 Calculation of the minimum outlet diameter (D)

In accordance with Figure 4, on plotting the material flow function (MFF) and the inverse of the system's flow factor (1/ff) together, Figure 7, the flow condition s=f is obeyed at the intersection of both plots. That is, at this point, the maximum shear stress to which the powder is subject (s) is equal to the strength of the bed (f). This stress is called the critical stress (CAS) and its value is used to calculate the minimum bin outlet size. For a conical bin with a circular opening, minimum outlet size (D) is calculated from the equation:

$$D = (2 + \frac{\theta}{60}) \cdot \frac{CAS}{\rho \cdot g} \qquad (1)$$

where:

D: outlet diameter (m)
θ: angle between the vertical and the bin wall in the discharge zone (°)
CAS : critical stress (Pa)
ρ: powder bed density (kg/m³)

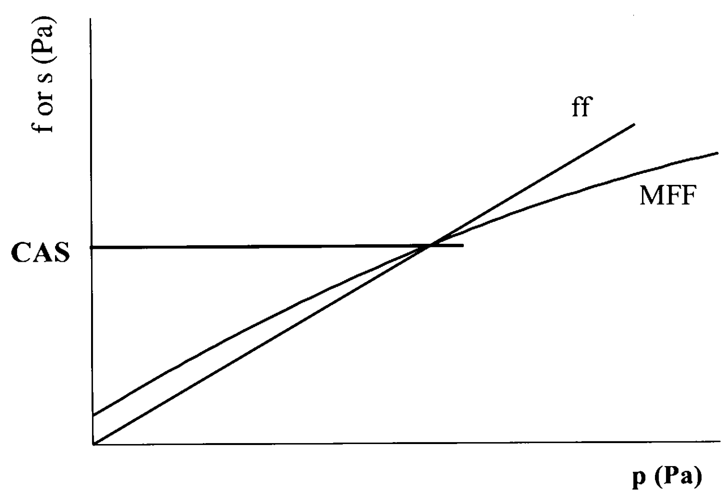

Figure 7. *Flow criterion.*

2. OBJECTIVE

The objective of this study is to apply the methodology set out above, based on the Jenike theory, to the design of bins for the particulate solids used in the ceramic industry, with a view to:

- Reducing the problems caused by the size segregation of spray-dried powder.
- Facilitating the discharge of the highly cohesive materials used in frit production.
- Analysing the influence of the bin surface on material behaviour during discharge.

3. MATERIALS, EQUIPMENT AND EXPERIMENTAL PROCEDURE

3.1 MATERIALS USED

To visually observe size segregation, mixtures of two granulated glazes with different sizes and colours were used. One was coarser, with a black colour and size exceeding 500 μm. The other was finer, with a white colour and sizes below 500 μm. The mean sizes of the two granulates were 800 μm and 350 μm respectively.

To study the behaviour of highly flowable materials, three types of spray-dried powder were used, which are employed as a base for making porcelain tile, whiteware bodies and redware bodies. Their granule size distributions are shown in Figure 8.

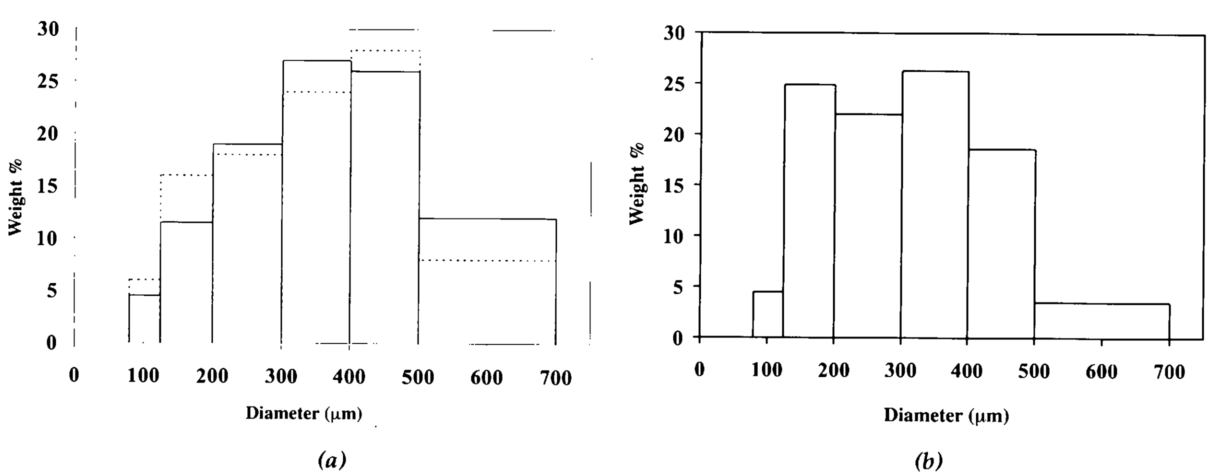

Figure 8. Granule size distribution of the spray-dried powder used for making redware bodies (—) and whiteware bodies (---) (a) and a porcelain tile (b).

To study the discharge of medium and highly cohesive materials, quartz and zinc oxide of the type commonly employed as raw materials in the frit production process were used. Quartz mean size, determined by laser diffraction was 40 μm (SE-6 quartz) and zinc oxide mean size was 2 μm.

3.2 EQUIPMENT USED

3.2.1 Shear cells

The material flow function (MFF) is obtained by shear cells. The best known ones are the Jenike cell, annular cell and rotational cell [4, 5, 6] Figure 9 presents a schematic illustration of the Jenike shear cell. The cell consists of a ring that is set on a base and filled with the material to be tested. To ensure test reproducibility, it is necessary to carefully and repeatedly fill the assembly.

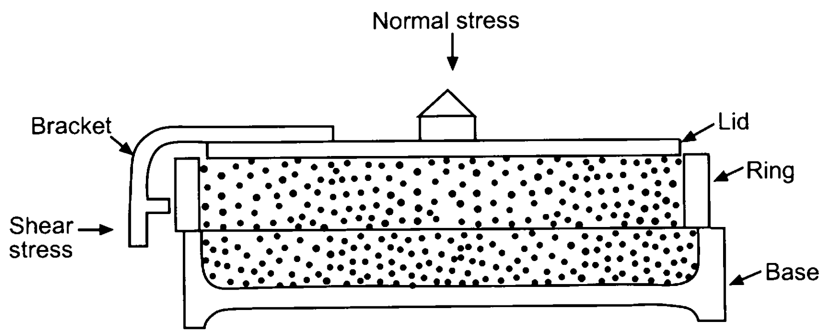

Figure 9. Jenike cell.

Although the Jenike cell is more intuitive and simpler to handle than the others, it requires longer experimentation times, so that in this study a rotational cell was used. In the rotational cell, sample preparation and stress application are similar to those of the Jenike cell.

The rotational cell (Figure 10) consists of a cylindrical cavity (base) on which the ring is set. The assembly is filled with the powder to be tested. The base-ring system is covered with a lid and locked to a turntable driven by a motor that makes the base rotate at constant speed. The lid is connected to a cylinder that exerts a normal stress on the powder and transmits the shear stress to the load cell.

3.2.2 Pilot-scale bins

To visualise material flow during bin filling and discharge, a metal bin with a semi-circular cross section was used, with a height of 1.50 m. The flat side was closed by a transparent methacrylate surface. In this bin, the conical discharge zone can be changed to determine the effect of the angle on this type of flow.

To confirm the validity of the design methodology used, a cylindrical steel bin was built (AISI 304), similar to industrial bins but with a smaller size (1.5 m high), with an exchangeable, truncated, cone-shaped discharge zone, having an outlet with a diameter of 0.025 m.

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[4] INSTITUTION OF CHEMICAL ENGINEERS; *Standard shear testing technique for particulate solids using the Jenike shear cell.* European Federation of Chemical Engineers, publ. IchemE, Rugby, U.K. 1989.

[5]. CARR, J; WALKER, D.M. *An annular shear cell for granular materials.* Powder Techol., 1, 369-373, 1967/1968.

[6]. PESCHL, I. A. S. Z. *Equipment for the measurement of mechanical propertiesof bulk materials.* Powder handl. proces., 1(1), 73-81, 1989.

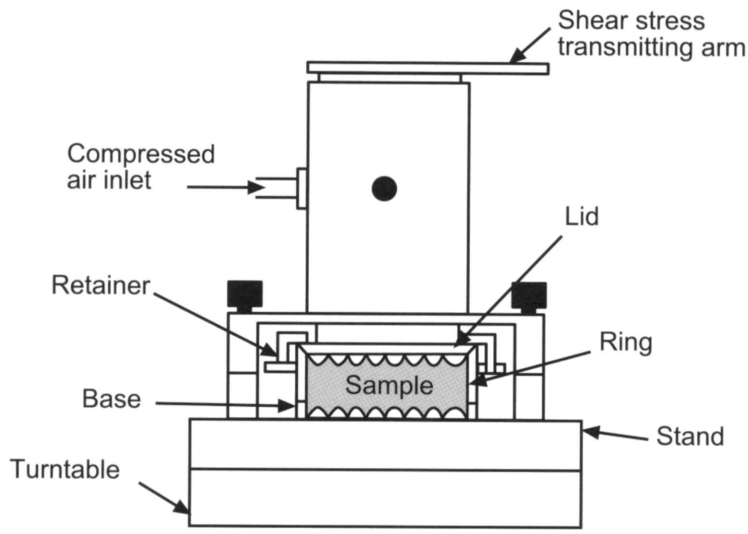

Figure 10. Rotational cell..

3.3 EXPERIMENTAL PROCEDURE

To calculate design variables, D and θ, it is necessary to experimentally determine the following parameters: material flow function (MFF), the material's angle of internal friction (δ) and the angle of friction between the material and the bin wall (ϕ) [7, 8]

3.3.1 Determination of the material flow function (MFF)

This is determined from the flow curves measured using the shear cell. These are found by the following experimental procedure:

- A metal ring is set on the cell base together with an accessory that allows raising the height of the cylindrical cavity of the base-ring system. The assembly is filled with the powder to be tested.
- A pressure is applied to the powder bed during a set time (pre-consolidation pressure). The accessory is then withdrawn, the powder is scraped off flush with the height of the ring, the lid is placed on the assembly, the base is fastened to the turntable and the ring is locked in place.
- The programmed consolidation pressure (σ_{mi}) is applied to the lid while simultaneously rotating the base at a constant speed. The rotating movement produces a progressive rise in the shear stress, which acts on the powder bed in the plane between the base and the ring until reaching a value (τ_{mi}) at which material flow initiates.

[7] WILLIAMS, J.C.; *The storage and flow of powders.* In: RHODES, M. J., (ed.). Principles of powders technology. Chichester: John Wiley, 1990.
[8]. SVAROVSKY, L. *Powder testing guide*. London: Elsevier. 1987.

- Subsequently, without withdrawing the powder from the cell, lower pressures (σ_i) than the consolidation pressure (σ_{mi}) are applied to the lid, repeating the experiment described. Pairs of values (σ_i, τ_i) are thus found, which form the flow curve of the powder bed compacted at normal stress σ_{mi} (Figure 11).
- The procedure is then repeated, applying different consolidation pressures (usually 5), to obtain a set of flow curves of the powder bed on compacting at different pressures.

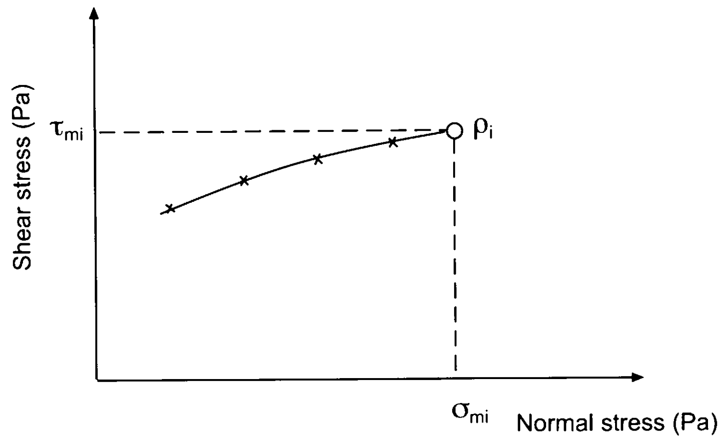

Figure 11. *Flow curve of a particulate material.*

3.3.2 Calculation of the material flow function (MFF)

It can be shown, based on applying tensor calculation to soil mechanics, that for an element of solid sliding down the inside of a bin by mass flow, with compactness ρ_i, the value of the pressure that consolidates the powder bed (p_i) and its strength (f_i) can be calculated from the flow curve found for a powder bed with the same compactness (ρ_i).[9, 10, 11, 12]

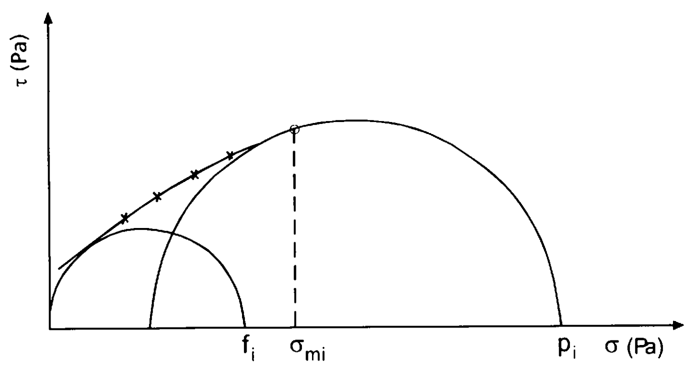

Figure 12. *Determination of a point (p_i, f_i) of the flow function.*

[9] FEODOSIEV, V. I. *Resistencia de materiales.* 2ª ed. Moscú : Ed. Mir, 1980.
[10] ONODA, G. Y.; JANNEY, M. A; *Application of soil mechanics concepts to ceramics particulate processing.* In . Chin, G.Y. Advances in Powders Technology.Ohio: ASM, 1981.
[11] ATKINSON, J.H.; BRANSBY, P.L.; *The Mechanics of soils. An introduction to critical state soil mechanics.* London: Ed. McGraw-Hill University Series in Civil Engineering, 1978
[12] BROWN, R.L.; RICHARDS, J.C.; *Principes of powder mechanics.* Pergamon Press, 1970

Thus, semi-circles are drawn tangential to the flow curve corresponding to a compactness of the bed ρ_i, obtained on applying a consolidation stress (σ_{mi}), which go through the origin of the co-ordinates and through the end point of the curve (Figure 12). The intersections of these circles with the horizontal axis determine the bed's strength (f_i) and consolidation pressure (p_i).

Applying the same procedure for each flow curve yields pairs of values (p,f) that constitute the material's flow curve. This curve represents the bed's strength (f), at different compactness values (ρ) as a function of the consolidation pressure at which they were obtained (p).

3.3.3 Determination of a material's angle of internal friction (δ)

This is calculated from the flow curves obtained with the shear cell as set out in point 3.3.1. The material's angle of internal friction is the angle formed by the straight line that goes through the end points of the flow curves with the horizontal axis (Figure 13).

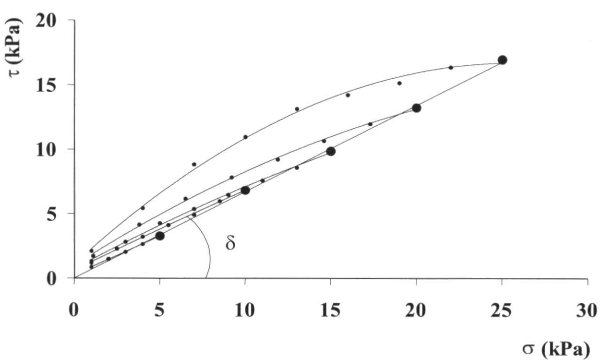

Figure 13. *Spray-dried powder angle of internal friction (δ)*

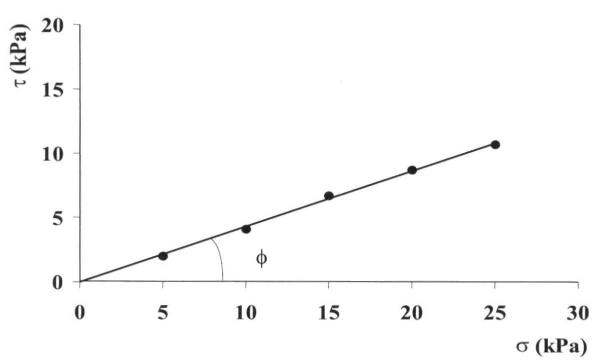

Figure 14. *Powder-bin angle of friction (ϕ) for spray-dried powder and a metal surface.*

3.3.4 Determination of the angle of friction between the bin wall and the material (ϕ)

Shear tests were run to assess the friction between the bin surface and the material, in which the cell base was replaced by a surface of the same nature as the bin wall. The only difference with regard to the experimental method set out in point 3.3.1 was that the applied normal stresses were always rising.

The plot of the evolution of the shear stress that causes material flow over the bin surface versus applied pressure yields a straight line (Figure 14). The angle that this straight line forms with the horizontal axis is ϕ.

4. RESULTS AND DISCUSSION

4.1 STUDY OF SIZE SEGREGATION DURING THE HANDLING OF A POWDER AGGLOMERATE. INFLUENCE OF TYPE OF FLOW DURING BIN DISCHARGE ON THE HOMOGENEITY OF THE EXITING MATERIAL.

On filling bins with powder agglomerate, hence with high flowability, segregation usually occurs when the size distribution is quite heterogeneous. If the bin is filled from a fixed pour point, which is the most common situation, the material accumulates at the falling point, forming a heap. The small agglomerates are held up in the gaps that form between the agglomerates, producing a column under the pour point. However, the large agglomerates continue to roll and tumble to the sides of the bin, concentrating at the walls.

During bin discharge the greater or lesser homogeneity of the powder may depend on the type of flow. Thus, if the bin empties with funnel flow, the first agglomerates to be discharged will be the finest and the last the coarsest, which means that the exiting powder granule size distribution varies with time. On the other hand, if bin discharge occurs by mass flow, the re-mixing effect at the outlet will reduce or even suppress the segregation occurring during filling [13, 14, 15, 16].

4.1.1 Visual determination of the segregation arising during bin filling

To study the segregation that takes place on filling a bin with highly flowable granular materials, a 50-50 mixture (by weight) was used of the granulated glazes with different colours and sizes in the semi-cylindrical bin described above. Figure 15 presents some of the most representative images, filmed by a video camera. It can be observed that on keeping a fixed filling point, a little heap forms as the bin is filled, in which the finer (white) granules gather in the centre, while the coarser (black) ones roll over these to reach the bin walls, concentrating in this area as expected.

4.1.2 Influence of type of flow during bin discharge on exiting powder characteristics

A series of filling and emptying experiments was performed using the above-mentioned transparent bin and mixture of granulated glazes, with two discharge cones

[13] CARSON, J. W.; Royal, T.A.; Goodwill, D. J. *Undestanding and eliminating particle segregation problems.* Bulk solids handl., 6(1), 139-144, 1986.
[14] GOODWILL, D. J. *Solving particle segregation problems in bins.* Process eng., 70(6), 49-50, 1989.
[15] WILLIAMS, J.C. *The design of solids handling plants to minimize the effects of particle segregation.* Powdex 92. Madrid, 7-8 Mayo 1992
[16] CLAGUE, K.; Wrigth, H. *Minimising segregations in bunkers.* ASME Paper No 72-MH-16. Second Symposium on storage and flow of solids, Chicago. Sept. 1972.

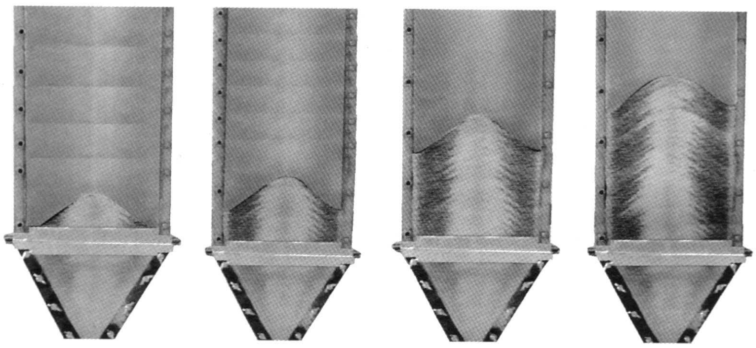

Figure 15. Picture sequence of bin filling.

having angles of 16 and 25° to produce two types of flow. During discharge, samples were collected of the exiting material, determining their size distribution by dry sieving.

Figure 16 plots the evolution of the percentage of coarse agglomerates in the exiting powder mixture versus time for the two types of flow.

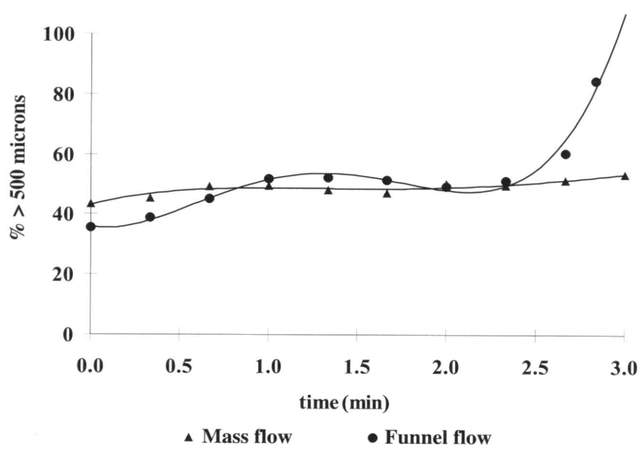

Figure 16. Influence of type of flow on exiting powder homogeneity.

The type of flow during discharge was observed to considerably affect the consistency of exiting powder characteristics. It was confirmed that if segregation takes place during filling and the bin empties by funnel flow, exiting powder characteristics change with time. However, when discharge takes place by mass flow, even though the same degree of segregation occurs as in the previous case, the material exhibits practically no change during discharge, as a result of the re-mixing effect mentioned above.

4.2 DESIGN OF BINS FOR STORING MATERIALS USED IN THE CERAMIC INDUSTRY

4.2.1 Influence of the nature of the powder on bin design parameters

This section applies the methodology described above to the design of bins in which material discharge needs to occur by mass flow for various reasons. Thus, spray-dried powder exhibits the two conditions that produce segregation during bin filling: wide granule size distribution (125-750 μm) and high material flowability. In the specific case of the spray-dried powder used for tile manufacture, if discharge takes place by funnel flow, the segregation that occurs during bin filling will cause variations in the exiting powder flow and moisture content. The finest particles with the lowest flowability and moisture content will be discharged first and the coarsest granules with low flowability and high moisture content will exit last. In porcelain tile manufacture, besides these drawbacks, the inhomogeneity of the discharge will give rise to shades in the end product.

For powders with medium and low cohesiveness, the problems are quite different, as owing to the low flowability of these materials, segregation cannot occur. The main problem that usually appears on handling these materials is flow stoppage during discharge as a result of doming or funnel formation (Figure 1). As an example of these materials, zinc oxide and quartz were used, with similar particle sizes to those used in frit and glaze production.

In every case, the foregoing problems are abated or eliminated if bin discharge takes place by mass flow [17, 18, 19]. The method used for determining the minimum outlet diameter (D) and maximum bin wall angle with the vertical (θ) in the discharge zone is schematically presented in Figure 17.

Figure 18 plots the flow functions of the three studied powders and Table 2 lists the values of each particulate material's angle of internal friction (δ) angle of friction between the bin wall and the material (ϕ) and bed density (ρ).

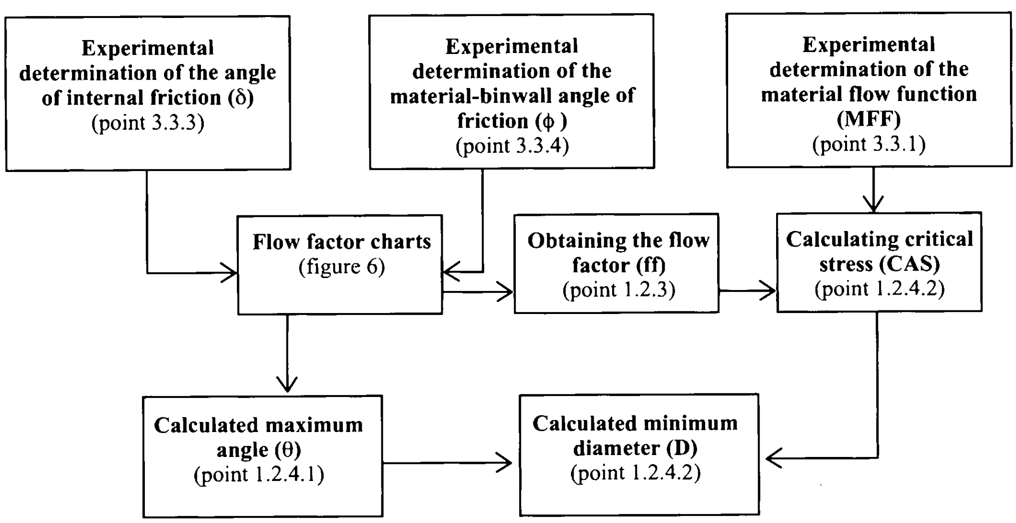

Figure 17. *Flow diagram of the design method followed.*

An analysis of the findings shows there is a direct relationship between mean size of the powder (made up of agglomerates and particles) and material flowability, reflected in the corresponding flow functions. The value at the intercept on the vertical axis, termed cohesiveness, and that of the slope of these plots, parameters inversely related to powder flowability, rise considerably as powder mean particle or agglomerate size decreases.

[17] MARINELLI, J.; CARSON, J. W. *Solve solids flow problems in bins, hoppers and feeders.* Chem. Eng. Prog., 88(5), 22-28, 1992.
[18] PURUTYAN, H.; PITTENGER, B.; CARSON, J. W.; *Solve solids handling problems by retrofitting.* Chem. Eng. Prog., 94(4), 27-39, 1998.
[19] Schulze, D.; Schwedes, J.; *Storage and flow of bulk solids in silos and information for planning new instalations.* VGB Kraftwerkstechnik 70(9), 665-669, 1990.

Material	Angle of internal friction, δ (°)	Powder-wall angle of friction, ϕ (°)	Density, δ (k/m^3)
Spray-dried powder	34	25	1050
Quartz	40	23	950
Zinc oxide	43	24	600

Table 2. *Design parameters used for the different materials.*

The cohesiveness of the spray-dried powder, the coarsest studied particulate material, was about 10 times less than that of the finest powder, the zinc oxide, and around four times lower than that of quartz, which was of intermediate size.

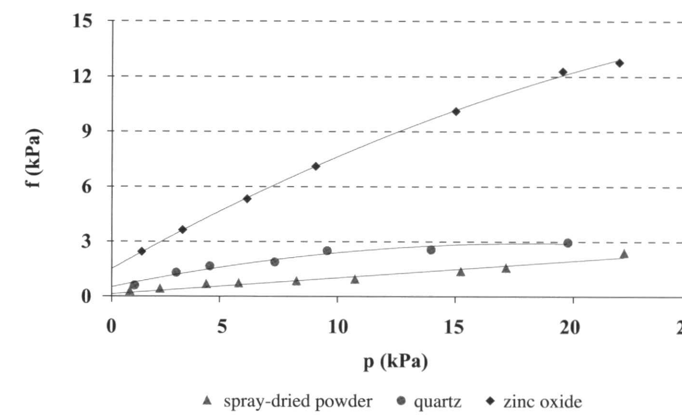

Figure 18. *Flow functions of the studied materials.*

The internal angle of friction (δ), Table 2, which is also related to powder flowability, reflects the same trend, albeit less markedly. Thus, although the variation in mean powder size is considerable, the powder angle of friction only changes by nine sexagesimal degrees.

With regard to the powder-bin wall angle of friction (ϕ), this value hardly changes, which suggests that for the studied powders this parameter practically only depends on the nature of the bin surface.

Using the data detailed in Table 2 and the method schematically set out in Figure 17, the maximum angle of the wall to the vertical (θ) and the minimum outlet diameter (D) were calculated for discharge of these materials in a cylindrical bin with metal walls by mass flow. Table 3 presents the values calculated for both parameters.

Material	Maximum wall angle, θ (°)	Minimum outlet diameter, D (m)
Spray-dried powder	23	≅ 0.02
Quartz	21	0.45
Zinc oxide	20	4.20

Table 3. *Bin design parameters calculated for the studied materials.*

It can be observed in Table 3 that the maximum angle, θ, at which bin discharge takes place by mass flow rises slightly as powder flowability or size increases, as was to be expected. The minimum outlet diameter, D, to keep flow stoppages from occurring as a result of doming rises considerably on lowering powder flowability or size. This parameter is much more sensitive to powder characteristics than the maximum angle of the discharge zone (θ). Thus, the value of the maximum diameter calculated for zinc oxide is about 200 times larger than that for the spray-dried powder, while the difference in maximum angles (θ), is hardly three sexagesimal degrees.

The extremely high value found for zinc oxide (4.2 m) indicates that it is virtually impossible to have a cylindrical bin with metal walls that empties by mass flow without doming. The discharge of bins containing highly cohesive materials like the studied material, will need to be assisted by installing systems to facilitate discharge, by practically instantly breaking up the domes as they form (vibrators, etc.).

4.2.2 Effect of the nature of the bin inner wall on design parameters

To determine the effect of the nature of the bin inner surface on the maximum cone wall angle (θ) and on the minimum outlet diameter (D), a series of experiments was conducted with the Teflon-spray-dried powder system, to determine the angle of friction between both materials. Following the same procedure as in the foregoing section (Figure 17), the design parameters were determined of a bin with a Teflon-lined inner wall. Table 4 presents the outcomes.

Design parameters	Inner wall surface material	
	Teflon	Metal
Powder-wall angle of friction, ϕ (°)	15	25
Maximum wall angle, θ (°)	35	23
Minimum outlet diameter, D (m)	≅ 0.02	≅ 0.02

Table 4. *Design parameters used for the studied materials.*

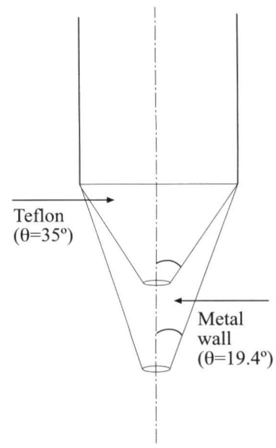

Figure 19. *Effect of the nature of the surface on the required maximum wall angle.*

It was verified that for the studied spray-dried powder, the maximum wall angle in the bin discharge zone (θ) rose considerably on reducing the friction between the powder and wall surface (ϕ), which raised bin capacity without modifying bin height (Figure 19).

4.3 Validation of the bin design methodology

In view of the minimum diameter outlet values found for the various materials (Table 3), a series of experiments was performed on a pilot scale with spray-dried powder to verify the validity of the design method used.

Two exchangeable cones were built, with discharge angles of 18° and 26° respectively, below and above the design angle, which fitted the semi-circular bin described above. To visualise the type of material flow during discharge, the bin was alternately filled with red and white-coloured spray-dried powder, forming layers of different colours. Bin discharge with the two cone angles was filmed with a video camera. Figures 20 and 21 present some of the most illustrative pictures.

It was found that on using a slightly larger cone angle than the calculated one, powder discharge was by funnel flow (Figure 20), whereas on using a smaller cone angle than the theoretical one, discharge was clearly by mass flow (Figure 21). Both findings confirm the validity of the design method used.

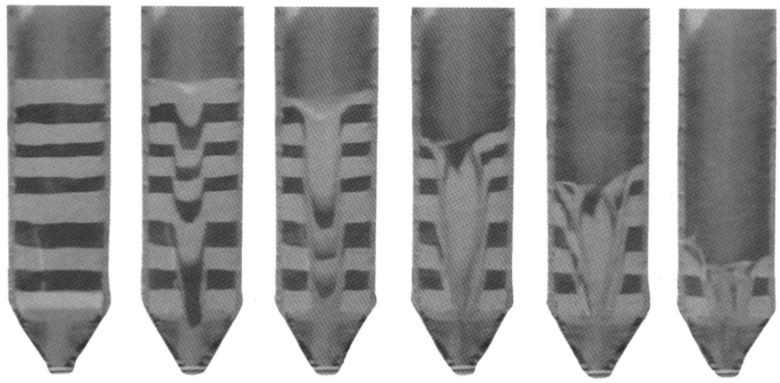

Figure 20. *Picture sequence of bin discharge funnel flow.*

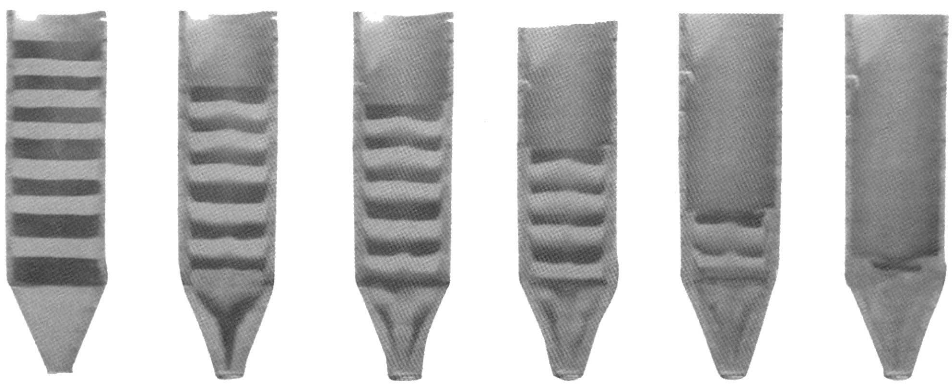

Figure 21. *Picture sequence of bin discharge with mass flow.*

5. CONCLUSIONS

The following conclusions can be drawn from the study:

- If a fixed pour point is held during bin filling, which is a fairly common situation, solids segregation occurs owing to the different trajectories followed by the particles in accordance with their size. This problem increases as the flowability and difference in particle size of the particulate material rises.
- The variation in bin exiting powder characteristics, owing to the segregation that takes place during bin filling, is abated or suppressed if powder discharge takes place by mass flow, which depends on the discharge zone angle. For the spray-dried powder used in the study, this angle was found to be 23º for a cylindrical metal bin.
- Continuous discharge of a cohesive material can be achieved by designing a bin that empties by mass flow and has a suitable outlet diameter. Both parameters can be determined when the rheological behaviour of the material is known, applying the bin design methodology.
- The surface properties of the bin wall affect the outlet diameter and the angle of mass flow. Raising the angle of friction between the material to be stored in the bin and the bin wall increases the minimum outlet diameter required to keep domes from forming and reduces the maximum angle of mass flow.