Interaction between Feeding and Compaction During Lactose Compaction in a Laboratory Roll Press

O. Simon, Pr. P. Guigon
Université de Technologie de Compiègne
Département de Génie Chimique
Centre de Recherche de Royallieu

Abstract

Experimental work was carried out to determine the influence of operating parameters on the roll press compaction of lactose and the interactions between feeding and compaction. A laboratory roll press was specially instrumented. The press and instrumentation are described. The first part of the experimental work deals with the adjustment of the roll press parameters in order to produce compacts with good mechanical strength and aspect for several roll press throughput. The measured normal stresses applied to the powder, the roll gap variations and the roll press throughput are correlated with the ratio between the speed of the rollers and the screw feeder speed, also called work coefficient. The roll press throughput is principally governed by the screw feeder speed. The second part of the experimental work deals with characterisation of the influence of the feeding conditions on the compaction. The single screw feeder produces locally a periodic disturbance which is responsible for compact heterogeneity. The normal stress measured on the rollers was correlated with the period of the screw. A minor variation of the feeding pressure produces a great variation of the compaction stress.

1. Introduction

Roll press compaction is an agglomeration process for particulate solids. It was developed to produce coal briquets at the end of the 19th century. Today, large numbers of other powders are compacted using a roll press – generally in mass production industries, but also in the pharmaceutical or specialty chemical industries [1]. The primordial principle of compaction is that many particulate materials become a compact when they are subjected to high pressure. Such materials are compressible. The roll pressing process consists if squeezing compressible particulate materials between two rolls rotating in opposite directions (figure 1a). Due to the large pressure exerted in the roll gap, the particulate material is transformed into a compact. The compact can vary in shape. With smooth or pocketed rolls, either a strip of compacted material or briquets are produced, respectively. The strip of compacted material can also be crushed in order to produce granules.

The space between the rolls is commonly divided into three areas, each of which is shown in (figure 1b): the feeding, the compaction and the ejection areas. In the feeding area, the material slips along the surface of the rolls and the bulk density of the material increases by virtue of particle rearrangement. In the compaction area, the material is driven by the rolls and very high pressures are applied to the material. In this area, the density increases by virtue of particle fracture and plastic deformation. Finally, in the ejection area, the compact can re-expand as a result of elasticity.
When fine powders are compacted, feeding is often a problem [2,3]. First, because fine powders often have a poor de-aeration ability. The air squeezed between the particles has difficulty in leaving the mass of powder being compacted and counteracts the feeding of the press. Secondly, because fine powders exhibit poor flowability and this impedes the use of gravity feeding. Screw feeders are therefore employed. In which case the roll press parameters are not only the speed of the rollers and the roll gap, but also the screw feeder parameters. Moreover, the screw feeder interacts with the compaction process [4,5].

This paper presents the influence of the operating parameters of a laboratory roll press on the compaction of lactose as well as a characterisation of the interactions between the feeding and the compaction process.

2. Experimental set-up and materials

2.1 Laboratory roll press

Experiments were carried out on a laboratory roll press (Komarek® B100QC) shown in (figure 2) [6].

The roll press is equipped with smooth rolls of 130 mm in diameter and 50 mm in width that are vertically arranged. The initial roll gap is 0.8 mm. The powder is fed from a feed hopper (7) and is stirred by a paddle mixer (6) which prevents the occurrence of arches at the feed inlet. Feeding is achieved by a screw feeder (5). Between the screw and the rolls, there is a feed adapter with a Plexiglas® cheek plate (8). The upper roll is vertically moveable and is supported by a hydraulic system (4). The pressure in the hydraulic system is monitored.

![Fig. 2](image)

The laboratory roll press [1. Roll, 2. Bearing block, 3. Roll shaft, 4. Supporting hydraulic system, 5. Screw feeder, 6. Paddle mixer, 7. Feed hopper, 8. Cheek plate. (a) Piezoelectric transducers, (b) Displacement transducer]

2.2 Instrumentation

The laboratory roll press was specially instrumented in order to permit measurement of the compaction conditions. The upper roll is fitted with two flush-mounted piezoelectric transducers (a) [3,7] which measure the normal stress (0–200 MPa) exerted on the surface at 15 mm from both sides of the roll. The signals of the transducers are transmitted by means of a high-precision slip ring to the charge amplifier, which is connected to a computer via a direct memory access A/D converter card. The position of the piezoelectric transducers is detected once a roll rotation by a photoelectric cell. Displacement of the moveable upper roll is measured by a displacement transducer (b) and is recorded. The roller speed, the screw feeder speed and the hydraulic pressure are also measured and recorded. The acquisition frequency of the recorded values is 1000 Hz for the normal stress measured by the piezoelectric transducers and 2 Hz for the other data.

The laboratory roll press parameters are:
- the roller speed that can be set from 2 to 16 rpm (0.013–0.108 m.s⁻¹),
- the screw feeder speed that can be set from 7.5 to 300 rpm,
- the hydraulic pressure that can be set from 80 to 150 bar (1-10 tons on 5 cm roll width).

For the experimental study, the hydraulic pressure was set to the minimum (80 bar) in order to protect the piezoelectric transducers from overload.

2.3 Material

The material compacted during the study is pharmaceutical monohydrate lactose. It could not be compacted without internal lubrication because it stuck to the rolls. It was therefore mixed with 0.5 percent of magnesium stearate. The characteristics of the monohydrate lactose + 0.5% magnesium stearate are the following:
- mean diameter (d₅₀): 70 μm (without magnesium stearate)
- bulk density: 548 kg.m⁻³
- tapped density: 865 kg.m⁻³
- true density: 1530 kg.m⁻³
- internal friction angle: 39°⁺/⁻² (0.68 rad), wall friction angle (polished stainless steel): 9°⁺/⁻² (0.157 rad)

The particle size was measured by laser granulometry (granulometer Malvern® Mastersizer). The true density was measured by helium picnometry. The friction angle was measured using a Peschel shear cell.
3. Experimental study

3.1 Adjustment of the roll press parameters

3.1.1 General information

The roll press throughput is principally limited by two factors. On one hand, the feeding speed is limited by the powder de-aeration ability. On the other hand, the compaction speed is limited by the elasticity of the particles. Generally speaking, a poor-quality compaction takes place when a critical throughput is reached. In that case, either the air flow generated by compaction disturbed the feeding (bad de-aeration), or the compaction was too fast [1]. All experiments of the study were carried out below this critical throughput. In other words, when no strip of compacted powder was produced or when the strip was of poor quality, the problem was not caused by poor de-aeration or an excessively high roller speed (too short a compaction time).

3.1.2 Compaction rates, good compaction settings

A wide range of roller speeds and screw feeder speeds can be set on the laboratory roll press. We therefore investigated the condition of roller speed and screw speed that enables the formation of a compacted strip of lactose mixed with 0.5% magnesium-stearate. The screw feeder speed was fixed and the roller speed was set in order to visually detect the high and low limit of roller speed that enables the compaction. At low roller speed, over-compaction occurs, and at high roller speed, no strip was formed.

Three operating rates have been defined as follows:
- the sub-feeding corresponds to the operating rate of the roll press when the amount of powder provided by the screw feeder is too small. In that case, the particulate material is not compacted.
- the overfeeding corresponds to the operating rate of the roll press when the amount of powder provided by the screw feeder is too large. The compact is extruded between the rolls and the roll gap increase is important. In that case, the compacted material is of poor quality and the powder loss is very important.
- the “good compaction rate” is an operating rate between sub-feeding and overfeeding. It corresponds to the production of a strip of compacted material that exhibits sufficient cohesion and mechanical strength.

For a fixed screw speed, the limits of “good compaction rate” are the lower and the higher roller speed that enable the production of compacts. These limits were detected visually for the four following screw feeder speeds: 7.7 rpm, 15.7 rpm, 22.7 rpm, 25.7 rpm. They are represented in (figure 3).

As the limits of the “good compaction rate” are straight lines on the graph representing roller speed versus screw speed, the limit of sub-feeding or overfeeding corresponds to a constant ratio between the roller speed and screw speed. This ratio (roller speed: screw speed) is called the work coefficient [8]. We established that the work coefficient must be greater than 0.28 and less than 0.49 for a satisfactory compaction of monohydrate lactose on our roll press. The work coefficient is therefore an indication of the compaction rate. For example, overfeeding occurs for a work coefficient greater than 0.28, regardless of the roller speed.

3.1.3 Roll press throughput

The roll press throughput was measured at the following screw feeder speeds: 7.7 rpm, 15.7 rpm, 22.7 rpm, 25.7 rpm. The roller speed was set to obtain the limits of sub-feeding and overfeeding and then to a value corresponding to an average value between sub-feeding and overfeeding. The results are shown in (figure 4).

The results of these experiments are very interesting. At a constant screw speed, the roll press throughput is constant. For example: at a screw feeder speed of 22.7 rpm, the roll press throughput is 268 ±/−4 g.min⁻¹ for any roller speed set from 6 rpm to 10 rpm. So as long as compacts are produced, the roll press throughput does not depend on the roller speed. To sum things up, the influence of the roller speed on the roll press feeding is negligible. The roll press...
throughput is governed only by the screw feeder speed, regardless of the roller speed.

3.1.4 Roll gap variation

As the upper roll can move vertically, the roll gap increases from its initial value to an equilibrium value when the powder is compacted. This equilibrium value is a function of the mean stress applied by the rolls to the compacted material. It is also a function of the roller speed $V_r$, the roll press throughput $Q_c$, the density of the compacted material $\delta_s$, the roll width, and the slipping of the compacted material on the roll surface $\xi_s$:

$$ e = \frac{Q_c}{L.V_r.\delta_s. (1 - \xi_s)} \quad (1) $$

At a fixed screw feeder speed, the roll gap increases linearly with $1/V_r$ (figure 5). Because the variation of the density of the compacted material $\delta_s$ and of the slip between the compact and the rolls $\xi_s$ is negligible in relation to variation of the roller speed, this result confirms that the roll press throughput $Q_c$ is constant at a fixed screw speed $V_r$.

Furthermore, the roll gap increases linearly with the ratio screw feeder speed/roller speed ($1/C_w$) (figure 6).

$$ e = K_2 \frac{V_c}{V_r} = \frac{K_2}{C_w} \quad (2) $$

The screw feeder throughput is then proportional to the screw feeder speed:

$$ Q_s = K_1.V_r \quad (3) $$

The screw feeder throughput $Q_s$ can be calculated as follows [9,10]:

$$ Q_s = k \delta_s A_1 V_{in}, \quad A_1 = \frac{\pi}{4} (D_s^3 - D_{ss}^3), $$

$$ V_{in} = \pi.D_s.n_s.G(\psi, \phi), \quad G(\psi, \phi) = \frac{\tan \phi . \tan \psi}{\tan \phi + \tan \psi}. \quad (4) $$

$k$: filling ratio of the screw, $\delta_s$: relative bulk density at the outlet, $D_s$: screw barrel diameter, $D_{ss}$: screw shaft diameter, $n_s$: number of screw revolutions, $\phi$: screw helix angle, $\psi$: transportation angle.

$k$, $\delta_s$, and $\psi$ are process data and have to be measured. As the screw feeder throughput is proportional to the screw feeder speed, the variations of $k$, $\delta_s$, and $\psi$ are negligible for the range of screw feeder speeds investigated [10].

3.1.5 Normal stress

The normal stress is recorded once a roll rotation by the two piezoelectric transducers. Due to the
screw feeding, the normal stress fluctuates greatly per rotation. Therefore, a mean normal stress profile has to be calculated from a great many normal stress profiles. Fourteen normal stress profiles were used in our case. Some of the calculated average profiles corresponding to various roll press settings are shown in (figures 7 and 8). When a constant work coefficient is set, the normal stress profile does not change, regardless of the roll speed or the screw speed (figure 7). But when different work coefficients are set, then the profiles are also different (figure 8). For example, at a constant roller speed, the stress applied to the powder increases when the screw feeder speed is increased. This phenomenon can be explained by the increase of the feed pressure when the screw speed is increased and the roll speed remains constant. As demonstrated by Johanson [11], the stress exerted during compaction is in relation with the mean feed pressure. Therefore, identical compaction conditions exist for many different parameter settings.

By integrating the mean stress profile and assuming that this profile is exerted across the entire roll width, the separating force of the upper roll can be estimated (the tangential stress is not considered).

\[ F_{v} = \frac{L}{2} \int_{0}^{\pi} \sigma_{n}(\theta) \cos(\theta) \, d\theta. \]  

(5)

\( F_{v} \) was correlated with the roll gap variation in (figure 9). The roll gap and the separating force are proportional. This result is due to the elasticity of the upper bearing block. As the roll gap is easier to measure than the normal stress, it is a very good process control variable.

3.2 Characterisation of the influence of the feeding conditions

3.2.1 Fluctuations of the measured normal stress

Normal stress profiles are measured once a roll revolution. For reproducibility reasons, fourteen consecutive measurements (14 revolutions) were recorded by both piezoelectric transducers. The variations of the measured profile between consecutive revolutions (figure 10) would be much more important than expected if the stress distribution in the roll gap were not dependent on time. In fact, the stress applied locally to the powder by the rolls (maximum of the profile) \( \sigma_{n}^{\text{max}} \) fluctuates over time. Moreover, the stress measured simultaneously by the left and the right transducer is not similar even though the transducers are symmetrically mounted. In fact, when a major stress is measured by the left transducer, a minor one is measured by the right one and vice versa. The stress

![Fig. 7 Mean normal stress profile measured at a constant work coefficient \( C_w = 0.38 \).](image)

![Fig. 8 Mean normal stress profile measured at a constant screw feeder speed (7.7 rpm) for three work coefficients indicated on the figure.](image)

![Fig. 9 Estimated separating force versus roll gap variation](image)
distribution in the roll gap is thus not homogeneous across the roll width. As a conclusion, the stress applied to the powder in the roll gap depends on both time and position across the roll width.

3.2.2 Heterogeneity of the compacted strip

In order to determine the heterogeneity of the stress applied during compaction, the following method was employed. Five percent of coal measuring 200-400 μm particle size was added to the lubricated monohydrate lactose before compaction. During compaction, the coal particles are fragmented locally and crushed by the applied stress. The higher the stress, the larger the quantity of fine particles. Assuming that the distribution of the coal particles is homogeneous across the roll width at feeding, then after compaction, the number of particles is greater in the zones that have endured the highest stress. As can be seen in (figure 11), these zones appear darker. The darkest zones of the strip of compacted material are therefore representative of the maximum applied stress. The localisation of this maximum stress applied to the compacted material looks like a sinusoidal curve. This curve represents the localisation across the roll width of the maximum stress applied to the powder versus the time. Assuming no slip occurs between the rolls and the strip during ejection of the compacted material, then the time period of the sinusoidal curve is:

\[ T = \frac{60}{\pi D V_s} \]  

where \( l \) is the length [mm] of the period measured on the compacted strip.

This period has been found to be the same as the screw feeder period \( (\frac{60}{V_s}) \). The origin of the fluctuations is definitely the screw feeder. In fact, the feed pressure heterogeneity is linked with the geometrical properties of the screw extremity. As the screw turns, the feeding heterogeneity also moves, and that is the reason why we observe a sinusoidal curve.

3.2.3 Interpretation of the heterogeneity of the strip in terms of fluctuations of the measured normal stress

The stress applied to the powder is a periodic phenomenon (figure 11) but it is sampled once a roller revolution (408 mm) and only on two small sites across the roll width. The collecting period (period of roll rotation) is also much larger than the period of phenomenon (period of screw rotation). That is the reason why the periodicity of the stress is not easy to demonstrate.

Localisation \((x,y)\) of compacted strip zones that have endured a higher stress are simulated as follows. The value of \(y\) is calculated as a function of the length of the strip \((x)\) using the following relation:

\[ y = 0.02m \cdot \sin \left( \frac{2V_s}{D V_s} x \right) \]

Three portions of the 'simulated compacted strip' are shown in (figure 12). The stress is measured by the transducers (1) and (2) every roll revolution, that corresponds to every 408 mm (roll circumference). An example of this sampling is shown in (figure 11). An arbitrary initial localisation of the transducers is chosen for the first roll revolution and represented for the second and the third one. As we can see, the...
transducer (1) measures first a low stress, then a high stress, then a low stress again. Transducer (2) measures exactly the opposite. This phenomenon is exactly what can be observed in (figure 10). So the heterogeneity of the strip can be estimated by measuring the normal stress applied by the rolls using the piezoelectric transducers over many roller revolutions. For this purpose, the roller period should not be a multiple of the screw feeder period.

4. Conclusion

The feeding of a roll press is a complex process that interacts with the compaction process. When a screw feeder is used, the compaction process is not only controlled by the roller speed but also by the screw feeder speed. Therefore, there are many possibilities to set the roll press parameters. For example, the adjustment of the screw feeder speed can modify the stress applied to the powder. Moreover, we showed that the throughput of the press is governed only by the screw feeder speed, regardless of the roller speed (as long as compacted material is produced). When a constant screw feeder speed is set, a modification of the roller speed induces a variation of the roll gap and of the applied mean stress. The normal stress applied to the powder or the roll gap variation can be correlated with the ratio between the roller speed and the screw feeder speed, also called the work coefficient. In fact, the work coefficient is characteristic of the compaction rate. Another consequence for using a screw feeder is the heterogeneity of the feeding. We showed that the single screw feeder is responsible for fluctuations of the stress applied during compaction. These fluctuations can be measured using piezoelectric transducers and correlated with the heterogeneity of the stress applied to the strip of compacted material. As the difference between the highest and the lowest stress measured is important, we conclude that the feeding disturbances caused by the screw feeder have a large influence on the compaction conditions.

Nomenclature

\( A_s \) : area between the screw shaft and screw barrel [m²]
\( C_w \) : work coefficient
\( D \) : roll diameter [m]
\( D_s \) : screw barrel diameter [m]
\( D_{ss} \) : screw shaft diameter [m]
\( e \) : roll gap [m]
\( F_s \) : separating force exerted on the upper roll [N]
\( G(\Phi,\psi) \) : screw transportation coefficient
\( k \) : filling ratio of the screw
\( K_1 \) : proportionality constant between \( Q_s \) and \( V_v \)
\( K_2 \) : proportionality constant between \( e \) and \((C_w)^{-1}\)
\( l \) : length of the measured period of the compacted strip [m]
\( L \) : roll width [m]
\( n_s \) : number of screw revolution
\( p \) : time period of the fluctuation of the localisation of the maximum applied stress across the roll width [s]
\( p_s \) : screw feeder period [s]
\( Q_c \) : roll press throughput [kg·s⁻¹]
\( V_{ax} \) : transportation speed of the particulate solid in the screw [m·s⁻¹]
\( V_r \) : roller speed [rad·s⁻¹]
\( V_v \) : screw feeder speed [rad·s⁻¹]
\( x \) : length coordinate for the localisation of the maximum stress [m]
\( y \) : width coordinate for the localisation of the maximum stress [m]
\( \Phi \) : screw helix angle [rad]
\( \delta_s \) : density of the compacted material [kg·m⁻³]
\( \theta \) : rolling angle [rad]
\( \sigma_n \) : normal stress [Pa]
\( \sigma_{n\text{max}} \) : maximum of the normal stress profile [Pa]
\( \psi \) : angle of direction of solid movement [rad]
\( \zeta_s \) : slipping of the compacted material on the roller surface
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Author’s short biography

O. Simon

Olivier Simon graduated in chemistry from Ecole Superieure de Chimie Organique et Minérale, France 1996. He is currently in a third year Ph.D. program at the Université de Technologie de Compiègne in the powder technology group of Pr. Pierre Guigon, the subject of his thesis is: Study of the interactions between feeding and compaction in a laboratory roll press.

P. Guigon

Pierre Guigon is a Chemical Engineer from ENSIGC Toulouse (France 1971). Master of Engineering Science, UWO London Ontario, (Canada 1974), Docteur Ingénieur UTC Compiègne (France 1976), Docteur es Science UTC Compiègne (France 1987), Fellow of the Institution of Chemical Engineers and head of the Chemical Engineering Department at the University of Compiègne. His research is in the field of particle suspensions (fluidization, pneumatic transport) and particle technology (conmination and agglomeration).