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THEORETICAL ESTIMATION OF DWELL AND CONSOLIDATION TIMES IN ROTARY TABLET MACHINES

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ABSTRACT

Knowledge of the time-dependent mechanical properties of pharmaceutical materials is critical to understanding of the compaction of tablets. In effort to determine the time-scale involved during compaction, equations for the dwell time and the consolidation time are proposed in this paper. Expressions for the consolidation time are obtained from generally accepted equations for punch displacement and separation between punch tips. These equations are deduced for rotary tablet machines with pressure rollers of the same and of different sizes. Specifically, the equations are applied to calculate the dwell and consolidation times for Manesty Betapress and Korsch Pharmapress Rotary tablet machines. The results are graphically presented.

INTRODUCTION

It is now generally accepted that consolidation of powders in a die by application of a force can take place by two mechanisms, namely deformation and fragmentation. Most of the solid powders undergo consolidation by a mixture of these two mechanisms.[1]

A perfectly-elastic, brittle particle shows no rate dependence. However, a viscoelastic particle is expected to undergo-time dependent deformation[2,3,4].To understand the time-dependent effect it is necessary to have a precise definition of the times involved in compaction event. The definitions more generally accepted are[5,6]:

- *Dwell time* : time at maximum force.
- *Consolidation time* : time to maximum force.
- *Contact time* : time for compression and decompression.

Different equations have been proposed [7,8] to evaluate the punch velocities and displacements. These equations have been used by different laboratories in the determination of punch displacements on multi-station tablet machines since actual measurement is difficult to obtain unless radio-telemetry is used to retrieve signals from the rotating turret[9].

The goal of this study is to establish the specific parameters of a rotary press that will, without instrumentation of the machine[10], define the experimental operating conditions of the press. This information will be useful in the development of tablet formulations, particularly when using different tablet machines during the scale-up to manufacturing.

For this purpose, this paper presents the relationship between the dwell and consolidation times and the parameters easy to measure on the tablet machine or the tablet itself. The relations are obtained using the equations describing punch displacement,[7,8] the technical references of the rotary machines and the dimensions of the U.S. standard punch.

BASIC EQUATIONS

The "tip speed" of a rotary tablet press is defined as the linear velocity of the punches in a direction tangential to their rotation. The angular velocity, in revolutions per minute, and the diameter of the mould table measured between the centers of two oppositely positioned punches are used to determine the tip speed, v, according to the following equation :

$$v = \pi \; \omega \, D_{mt} \qquad (1)$$

where: ω = angular velocity

D_{mt} = diameter of the mould table between the centers of two opposite punches.

A. DWELL TIME

The time at maximum force is equal to the time that the bottom of the upper pressure roll and the top of the lower pressure roll are in contact with the flat top of the head of the upper and lower punches, respectively. This dwell time, t_d, may be calculated from the tip speed :

$$t_d = l_{hp} / v \quad (2)$$

where l_{hp} = length of the flat head of the punch.

The dwell time, in milliseconds, for an ideal punch with a flat top of one-half inch in length can be calculated by the expression:

$$t_d = 7.62 * 10^5 / \pi \ \omega \ D_{mt} \quad (3)$$

where ω = angular velocity in revolutions per minute
D_{mt} = diameter of the mould table, in mm, between the centers of two oppositely positioned punches.

B. CONSOLIDATION TIME

B1. USING THE EQUATION OF PUNCH DISPLACEMENT

The time to reach maximum force may be calculated using the Rippie and Danielson[7] Equation (4):

$$D = [\ (r_1 + r_2)^2 - (r_3 \sin \omega t - x_2)^2\ ]^{0.5} \quad (4)$$

where:
r_1 = radius of pressure roller
r_2 = radius of punch head curvature
r_3 = radius of the circle in which the dies travel
x_2 = radius of the flat head of the punch
D = displacement of the punch

When the upper punch comes into contact with the powder in the die the displacement is D_{max}-H, where H is defined in Figure 1.

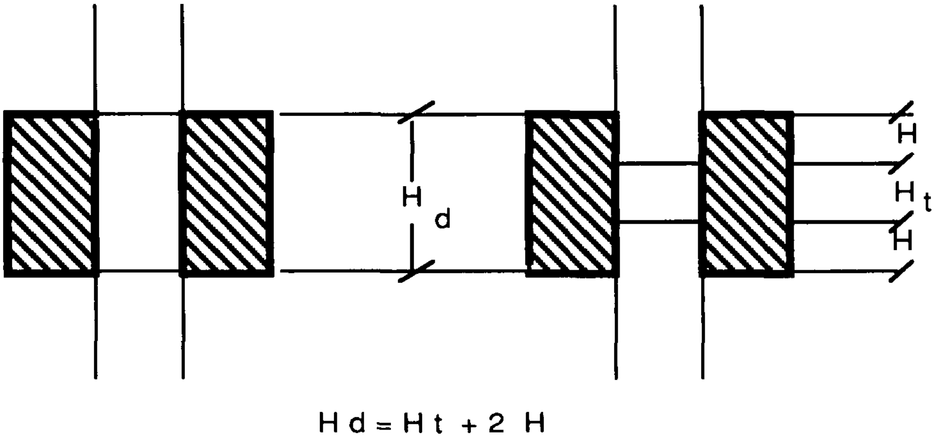


FIGURE 1.

H can be defined as the difference between the punch displacement when the punch comes into contact with the powder in the die and the maximum value of the punch displacement. From the previous figure, which corresponds to the case when the machine has rollers of the same size and assuming that the tablet is rigid, H is given by:

$$H = (H_d - H_t) / 2 \qquad (5)$$

where: H_d = height of the die

H_t = Height of the tablet

The maximum displacement of the punch, D_{max}, may be calculated by setting the first derivative of D with respect to time, t, to zero and solving. From equation (4) the first derivative equation is:

$$\frac{\delta D}{\delta t} = \frac{-\omega r_3 \cos \omega t \; (r_3 \sin \omega t - x_2)}{\sqrt{(r_1 + r_2)^2 - (r_3 \sin \omega t - x_2)^2}} \qquad (6)$$

This above equation will be equal to zero when:

1.- ωr_3 is zero, i. e. the tablet press is not running, which is an irrelevant case;

2.- $\cos \omega t$ is zero, i. e. when the angle, ωt, is $n \pi/2$ (n is any odd integer) which corresponds to a minimum of the punch displacement according to the definition of the angle (the value of the angle is zero when the center of the punch is in the same vertical line of the center of the pressure roller); and

3.- $r_3 \sin \omega t = x_2$, i. e. corresponds to the maximum displacement, D_{max}.

Substitution of case 3 into equation (4) gives the equation for maximum displacement, D_{max} :

$$D_{max} = r_1 + r_2 \quad (7)$$

Therefore, the punch displacement to compact the tablet, H ,will be:

$$H = (r_1 + r_2) - [(r_1 + r_2)^2 - (r_3 \sin \omega t_c - x_2)^2]^{0.5} \quad (8)$$

where: t_c = consolidation time in milliseconds

Upon substitution of the above expression for H in equation (5) and rearrangement, the following expression for consolidation time is obtained by:

$$t_c = \frac{\arcsin\left[\frac{1}{r_3}\left(\sqrt{(r_1 + r_2)^2 - \left[(r_1 + r_2) - \frac{H_d - H_t}{2}\right]^2} + x_2\right)\right]}{1.047 * 10^{-4}\,\omega} \quad (9)$$

It is worth noting that equation (9) expresses the consolidation time as a function of r_1, r_2, r_3 and x_2, which are characteristic geometrical parameters of the machine and the punch; ω, which is an operational parameter of the tablet machine; and H, which depends of the formulation and the tablet press setting.

The previous equations were derived for tablet presses with the upper and lower pressure roller of the same size; however, another possibility arises when the tablet press has two rollers of different size. In this case the upper punch displacement to compact the tablet is different than the lower punch displacement. Using the Rippie and Danielson equation (7) for both punches at t=0:

$$D_{u0} = [\,(r_u + r_2)^2 - x_2^2\,]^{0.5} \quad (10)$$

$$D_{l0} = [\,(r_l + r_2)^2 - x_2^2\,]^{0.5} \quad (11)$$

where : D_{u0} = displacement of the upper punch when the punch contacts the powder

D_{l0} = displacement of the lower punch when the punch contacts the powder

r_u = radius of upper pressure roller

r_l = radius of lower pressure roller

When the above equations are evaluated at t_c, the following expressions for maximum displacements are obtained:

$$D_{u1} = r_u + r_2 \qquad (12)$$

$$D_{l1} = r_l + r_2 \qquad (13)$$

Now two values of H must be defined. H_1 and H_2 are the difference between the displacement when the punch comes into contact with the powder in the die and the values of maximum punch displacement for the upper and lower punch, respectively. These values are given by the following equations:

$$H_1 = D_{u1} - D_{u0} \qquad (14)$$

$$H_2 = D_{l1} - D_{l0} \qquad (15)$$

One of these equations can written as a function of the other:

$$H_2 = H_1 A \qquad (16)$$

where

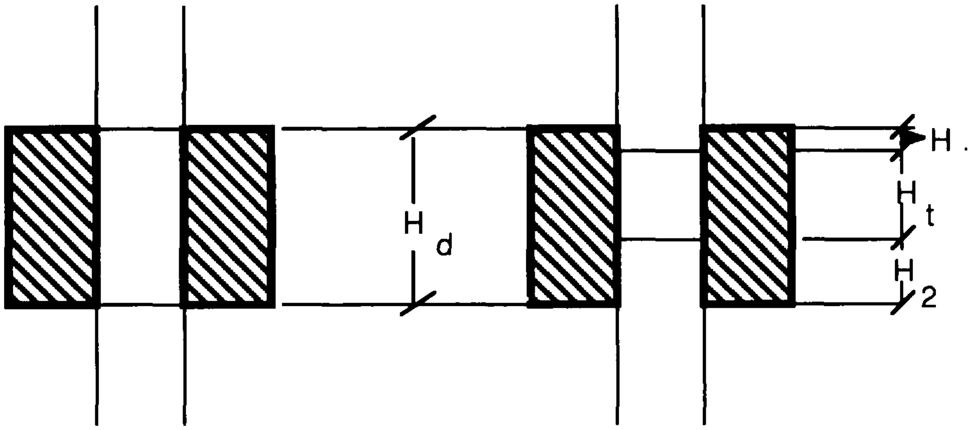
$$A = \frac{(r_l + r_2) - \sqrt{(r_l + r_2)^2 - x_2^2}}{(r_u + r_2) - \sqrt{(r_u + r_2)^2 - x_2^2}} \qquad (17)$$

Figure 2 shows the relations between H_1 ,H_2 ,H_d and H_t.

From this figure, H_1 may be expressed as:

$$H_1 = \frac{H_d - H_t}{1 + A} \qquad (18)$$

In order to calculate the consolidation time in machines with rollers of different sizes from equation (9), it is necessary to modify the equations by replacing H with H_1 and then using the rest of the parameters referring to the upper



Hd = Ht + H1 + H2

FIGURE 2.

pressure roll. The same can be done by replacing H with H_2 and then using the parameters referring to the lower pressure roll.

In the first case , the following equation is obtained:

$$t_c = \frac{\arcsin\left[\frac{1}{r_3}\left(\sqrt{(r_u + r_2)^2 - \left[(r_u + r_2) - \frac{Hd - Ht}{1 + A}\right]^2} + x_2\right]}{1.047 * 10^{-4}\,\omega} \qquad (19)$$

B2. USING THE EQUATION OF SEPARATION BETWEEN PUNCH TIPS

In the Charlton and Newton[8] equation the separation of the punch tips, P_s, is given by:

$$P_s = D_r - H - 2Lp + 2(R + r_c)(1 - \sin\phi) \qquad (20)$$

where: D_r = height of the upper roller above the cam track

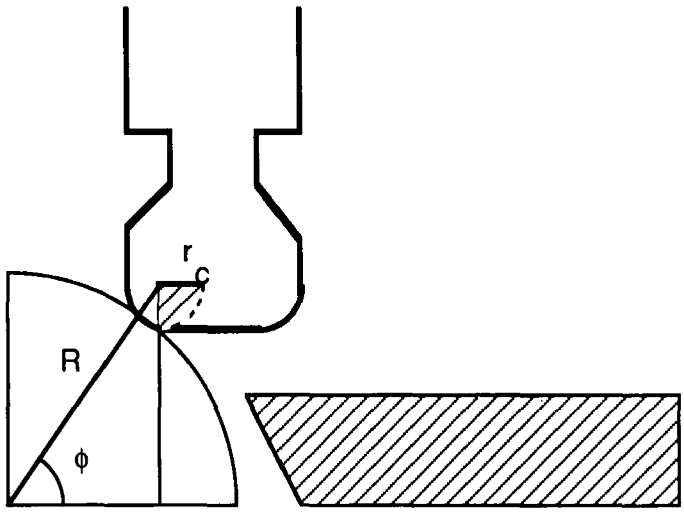


FIGURE 3

H = height of the lower roller above the cam track

L_p = length of the punch

R = radius of pressure roller

r_c = radius of curvature of the curved portion of the punch head

ϕ = angle between the horizontal cam track and the point of contact on the roller, measured from the center of the roller.

The relation between the horizontal displacement S_H, R and r_c, is shown in Figure 3.

From Figure 3, the following equation can be derived:

$$S_H = (R + r_c)\cos\phi \qquad (21)$$

the horizontal displacement may be expresed as a function of the tip speed defined in equation (1); the negative sign indicating that the horizontal displacement of the punches is defined in the opposite sense to the movement.

$$S_H = -\pi\ \omega D_{mt}\, t \qquad (22)$$

where D = diameter of the mould table

ω = angular velocity in rpm

From equations (20), (21) and (22), the following expression can be written:

$$\left(\frac{\pi\,\omega\,D_{mt}}{R + r_c}\right)^2 t^2 = \frac{Ps - Dr + 2Lp + H}{(R + r_c)} - \left(\frac{Ps - Dr + 2Lp + H}{2\,(R + r_c)}\right)^2 \quad (23)$$

Equation (23) gives the consolidation time when it is calculated from the difference between the time the punch tips are separated by a distance equal to the height of the die (H_d) and the time the punch tips are separated by the minimum distance, PSM. This latter value of punch tip separation, P_s, is obtained from equation (20) when ϕ =90:

$$PSM = D_r - 2\,L_p - H \quad (24)$$

The consolidation time in milliseconds is given by:

$$t_c = \frac{(R + r_c)\sqrt{\dfrac{Hd - Dr + 2Lp + H}{R + r_c} - \left(\dfrac{Hd - Dr + 2Lp + H}{2\,(R + r_c)}\right)^2}}{1.666\ 10^{-5}\,\pi\,\omega\,D_{mt}} \quad (25)$$

In the case where the tablet machine has pressure rollers of different size. The height of upper roller above the cam track is given by the expression below:

$$H_u = D_r - L_p + (R_u + r_c)(1 - \sin\ \phi_u) \quad (26)$$

where: R_u = radius of the upper pressure roller.

ϕ_u = angle between the horizontal cam track and the point of contact on the upper roller, measured from the center of the roller.

The height of lower roller above cam track is given by:

$$H_l = H + L_p - (R_l + r_c)(1 - \sin\ \phi_l) \quad (27)$$

where: R_l = radius of lower pressure roller.

ϕ_u = angle between the horizontal cam track and the point of contact on the lower roller, measured from the center of the roller.

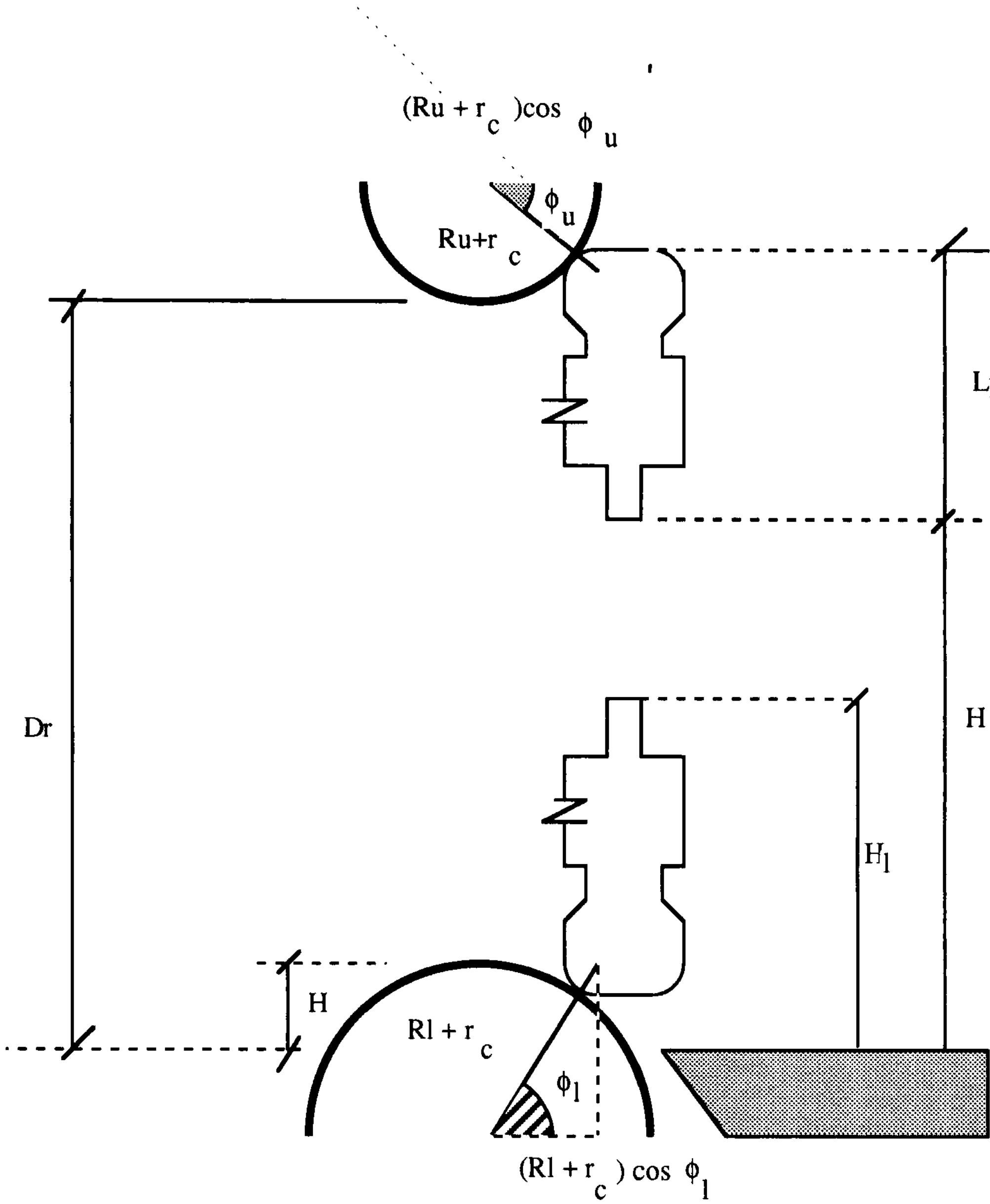


FIGURE 4.

From equations (26) and (27), the separation between punch tips P_S may be calculated:

$$P_S = D_r - H - 2L_p + (R_u + r_c)(1 - \sin\phi_u) + (R_l + r_c)(1 - \sin\phi_l) \qquad (28)$$

From Figure 4, the following equations can be derived:

$$\cos\phi_u = \cos\phi_l \frac{R_l + r_c}{R_u + r_c} \qquad (29)$$

$$\sin\phi_l = 1 - \cos^2\phi_l \qquad (30)$$

$$\cos\phi_l = \frac{5.23\ 10^{-5} \pi D_{mt}\, \omega\, t}{R_l + r_c} \qquad (31)$$

Using equations (28), (29), (30) and (31), the following expression for consolidation time is obtained:

$$t_c = \frac{(R_l + r_c)\sqrt{1 - \frac{(R_u + R_l + r_c) - (Hd - PSM)}{2(R_l + r_c)}}}{1.666\ 10^{-5} \pi D_{mt}\, \omega} \qquad (32)$$

where: $PSM = D_r - 2L_p - H$.

RESULTS AND DISCUSSION

During the development of a product in the authors' laboratory, it was observed that difficulties arose when compacting tablets on a 16 station Manesty Betapress tablet machine. This difficulty was somewhat surprising since the "scale-up" of the product from a single punch machine to a 6 station Korsch Pharmapress was conducted without any evidence of compaction problems. The reason for these compaction difficulties was thought to be related to the time-dependent mechanical behavior of the granulation, i.e. the granulation was suspected to be strain-rate sensitive. At the time the rotary presses were not instrumented in any manner to measure the dwell or consolidation time. In order to determine the time scale involved during compaction on the Manesty and Korsch tablet machines, a theoretical study was conducted to estimate the dwell and consolidation times based on easy to measure parameters. The theoretical equations, presented in the previous section, will be graphically presented and discussed in this section.

The dwell times for the Manesty and Korsch machines were calculated using equation (3). In these calculations, the following values were used: 25.4 mm for the flat head length of the punch (Lp) and 228.6 mm and 100 mm for the mould tablet diameter (D_{mt}) of Manesty Betapress and Korsch Pharmapress, respectively. The results of plotting the dwell times as a function of the angular velocity of the mould table or press speed are two hyperbolic curves, as shown in Figure 5. As can be seen in this figure, the dwell times for both presses decrease as expected with increasing angular velocity. The dwell time for the Korsch has a greater dependency on the angular velocity as indicative of its greater center of curvature. This is due to the difference in the the diameters of the mould table. It also is important to note that it is not possible to obtain the same dwell times on the Manesty Beta and Korsch Pharmapress. This may, at least in part, explain why the previously mentioned granulation did not compact as well on the Manesty press regardless of the press speed.

The consolidation times for the Manesty Beta and Korsch Pharmapress, based on the equation of punch displacement, can be estimated from the equations for pressure rollers of the same size (9) and pressure rollers of different size (19), respectively. These equations were used to calculate the consolidation times for the two tablet machines using the following parameters: a radius of the pressure roller (r_1) of 88.9 mm, a radius of the mould table between two oppositely-positioned punches (r_3) of 114.3 mm, a radius of curvature of the curved portion of the flat head of the punch (r_2) of 7.9375 mm for the Manesty Beta press and a radius of the upper pressure roller (R_u) of 60 mm, a radius of lower pressure roller (R_l) of 70 mm, a radius of mould table (r_3) of 50 mm a radius of curvature of the curved portion of the flat head of the punch (r_2) of 7.9375 mm for the Korsch Pharmapress. Surface plots of the consolidation time are shown in Figures 6 and 7 for the Manesty and Korsch presses, respectively. As expected, the consolidation times for both presses decrease as the press speed increases. In addition, at a fixed angular velocity the consolidation time increases as H_d - H_t increases, i.e. as the punches travel deeper into the die cavity. Finally, the consolidation times for the

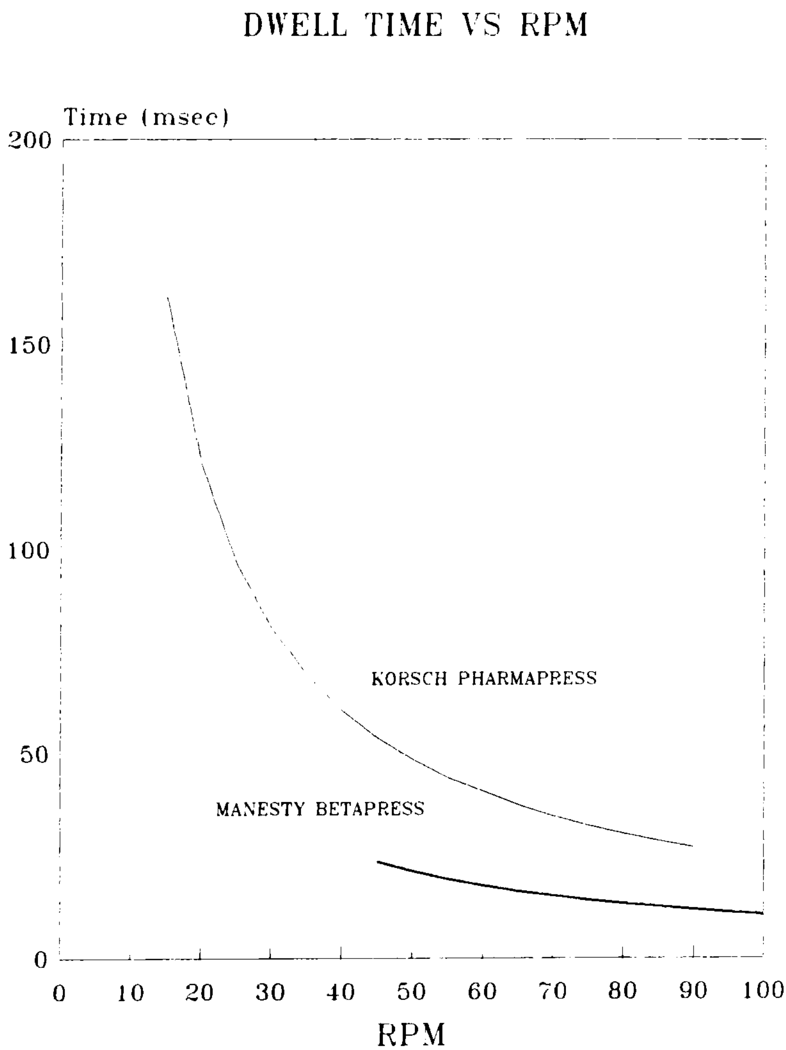


Figure 5

Dwell time for Manesty Betapress and Korsch Pharmapress.

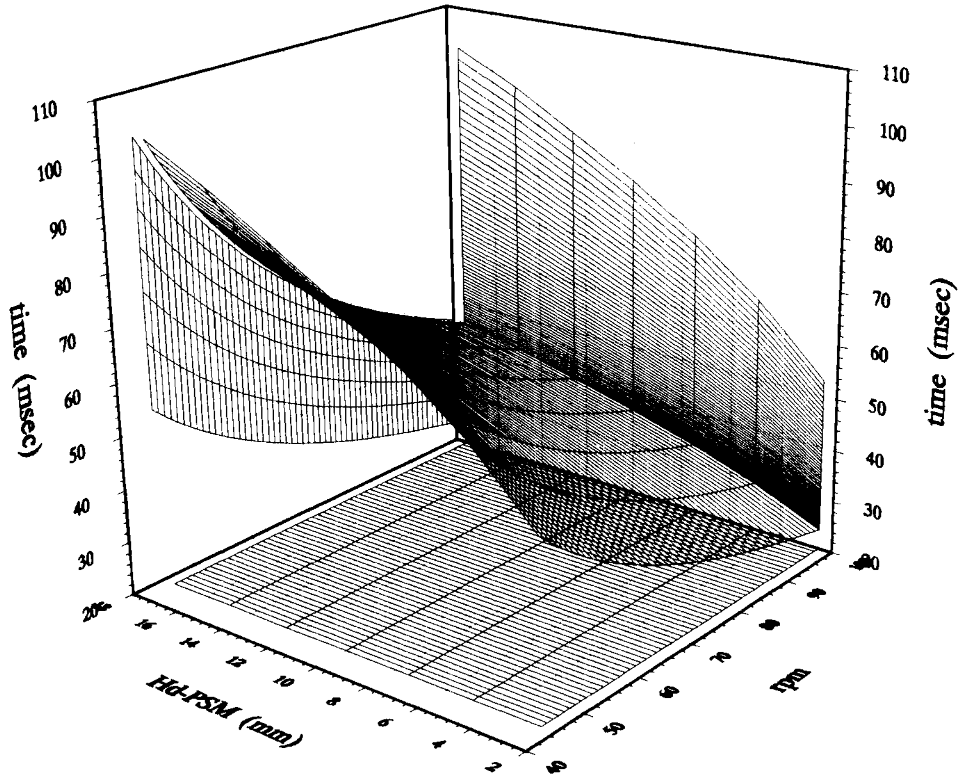


FIGURE 6

Consolidation time for Manesty Betapress using equation of punch displacement.

Korsch are approximately an order of magnitude greater than those of the Manesty. It should be noted that the estimation of consolidation time based on these equations depends not only on the dimensions of the mould table, pressure rollers and the punches but also the thickness of the resulting tablet. It is assumed the powder or granulation behaves perfectly plastic under compaction. In reality, the elastic recovery of the tablets will contribute to some error in these estimations.

The other approach taken to estimate the consolidation time is based on the dimensions of the mould table, pressure rollers and punches and their geometries. The consolidation time for the Manesty Beta press was presented in Equation (25). Instead of using the out of the die tablet thickness, this equation is

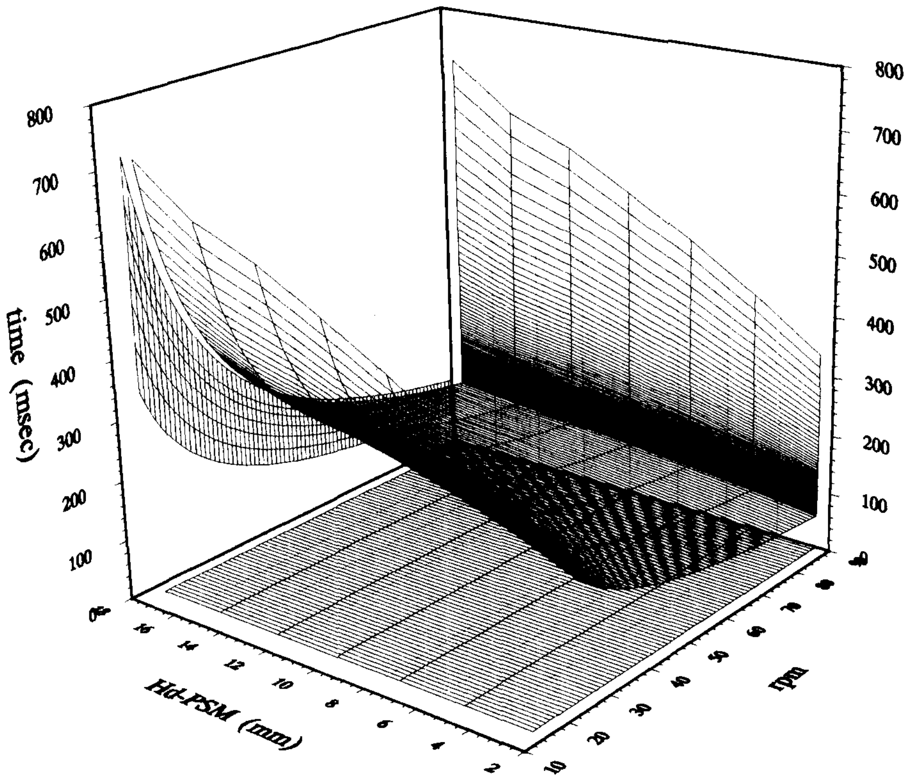


FIGURE 7

Consolidation time for Korsch Pharmapress using equation of punch displacement.

based difference in separation of the punches, H_d - PSM. The punches are separated by a distance H_d when they first contact the powder or granulation and by a distance PSM when they are a minimum distance apart. A series of values for the press speed and H_d - PSM was plugged into equation (25) to generated the plots of consolidation time. These surfaces are shown in Figure 8. The parameters used for equation (25) are the same as those used in equation (9) with the addition of the height of upper and lower pressure rollers above cam track, D_r and H respectively, and the length of punch , Lp, of 133.5 mm. These latter parameters were used to evaluate the minimum distance between punch tips, PSM. The curves in Figure 8 are similar to those in Figure 6.

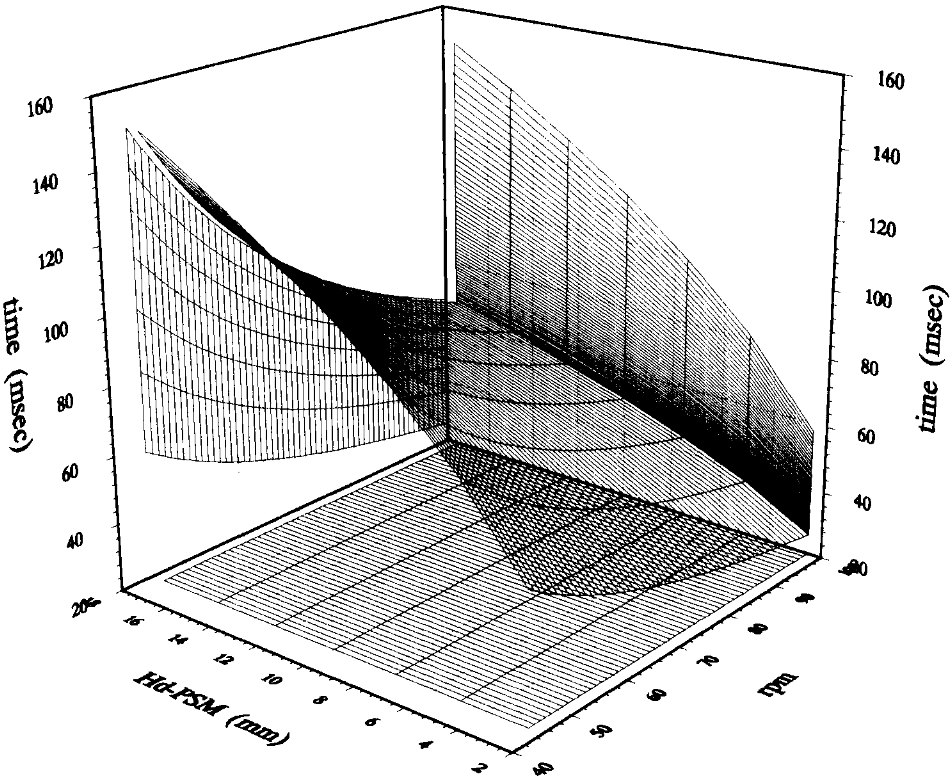


FIGURE 8

Consolidation time for Manesty Betapres using equation of separation between punch tips.

In the case where the pressure rollers are of different size, the consolidation time is given by Equation (32). To solve this equation it is necessary to know the same parameters as those used in equation (25), except the radius of the pressure roller is replaced by the radii of the lower and the upper pressure rollers, R_u and R_l , respectively. Equation (32) was used to evaluate the consolidation time for Korsch Pharmapress at different values of Hd-PSM and from 15 to 90 rpm. Figure 9 graphically represents the results of these calculations as a surface plot.

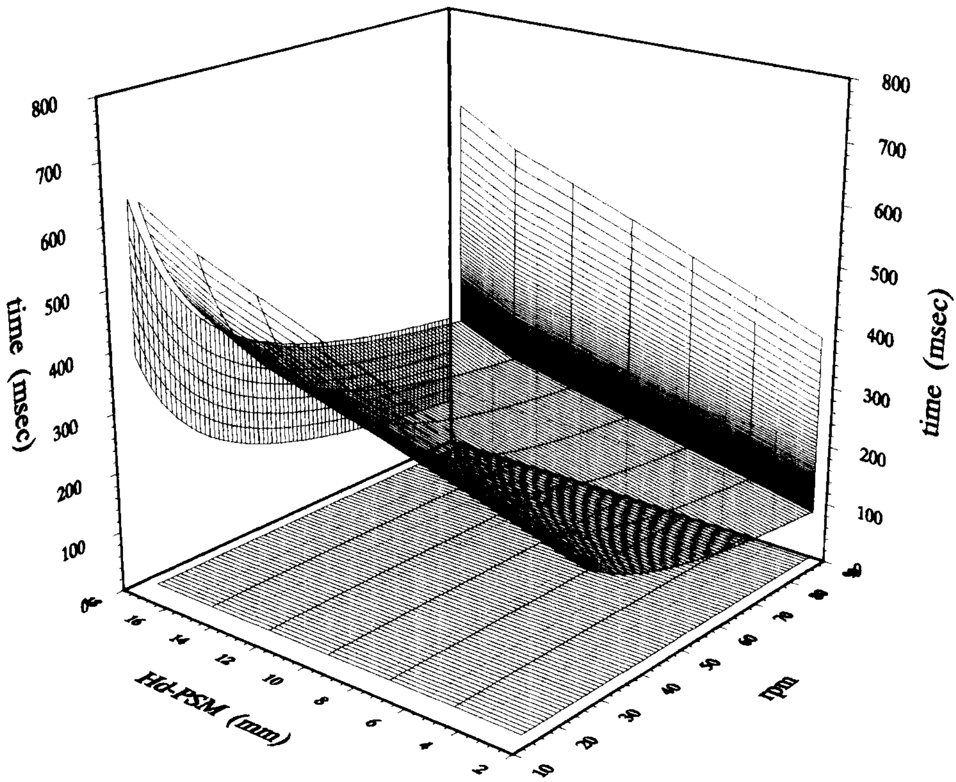


FIGURE 9

Consolidation time for Korsch Pharmapres using equation of separation between punch tips.

CONCLUSIONS

In this study, two approaches using theoretical equations were developed to estimate the consolidation times of rotary tablet machines with pressure rollers of the same size (Manesty Betapress) and of different size (Korsch Pharmapress). The estimated consolidation times can be calculated based on easy to measure tablet press parameters or tablet properties. The graphical representation of the theoretical equations indicated similar results.

The consolidation time obtained from these equations along with the dwell time provide important information regarding the time scale of the compaction event on two different tablet machines operating under various speeds and settings. This information may help explain some observed differences in the compaction behavior of tablet formulations exhibiting time-dependant mechanical properties.

A study using radio-telemetry devices to record the exact consolidation times would be advantageous in comparing experimental data with the theoretically, calculated consolidation times.

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