STUDY OF THE DYNAMICS OF THE PRESSING CYCLE AND ITS INFLUENCE ON CERAMIC TILE COMPACTION BY FITTING AN INDUSTRIAL PRESS OUT WITH SENSORS

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ABSTRACT

In order to study the effect of the pressing cycle on end bulk density of the piece, the following operating variables were modified:

- Feeding system (configuration and velocity)
- Lower ram (moment of descent)
- Upper ram (supplemented)
- Hydraulic circuit (maximum pressure value)

determining the value of the main operating variables at every moment.

A non-destructive system has been developed allowing bulk density of ceramic ware to be established in real time, determining its relationship to the values of the main compaction process variables.

As a result of the study, each and every press parameter can be monitored, which can be acted upon industrially, determining their influence on overall bulk density (dimensions) and zone bulk density (wedging) of the compacted piece at the very moment of pressing.

1. INTRODUCTION

The most widespread forming method used in ceramic tile manufacture is unidirectional dry pressing in hydraulic presses. This operation allows bodies to be obtained, from a suitably conditioned powder, which on processing yield ceramic wall and floor tiles [1].

At the end of the 70's, market demands relative to final product quality favoured implementing an important technological evolution that entailed replacing friction presses by hydraulic ones, which were much stabler in service. This change did not go together at that time with a great increase in measurement and control devices for the new equipment, possibly owing to their being considered unnecessary as a result of the substantial rise in quality and productivity as a result of the new conception of press operation.

Currently, the evolution towards larger sizes and more complex models, as well as the market's growing quality demands, require greater control over the whole production process, and specifically, of body forming. Current technology in industrial control and instrumentation [2], allows continuous measurement and control of the technologically interesting variables of the raw materials fed into the press [3-5], and of the press itself [6].

2. OBJECTIVES AND SCOPE

The current relationship between bulk density of the piece and the values of the variables of the equipment (hydraulic press) during the compaction process, is wholly empirical. Control of the operating variables is manual, while the different courses of action undertaken depend on subject assessments of their values.

This study was undertaken to measure the values of the main pressing operation variables, using elements suited to the characteristics of the process, and establish the relationships between operating variables and bulk density of the pressed piece.

3. SELECTION OF THE VARIABLES TO BE MEASURED AND THE MEASURING DEVICES USED

The following variables were measured:

- Hydraulic pressure (P_h)
- Position of the feeding system (L_c)
- Velocity of the feeding system (v_c)
- Position of the travelling frame (L_t)
- Position of the lower ram (L_p)
- Specific pressure in the cavity (P_c)
- Moisture content of the spray-dried powder fed into the press (X)

measurements were performed using the following measuring devices:

- Hydraulic pressure in the circuit was determined with a diaphragm-actuated strain-gauge transducer.
- The position of the feeding system was determined with an electromagnetic transducer. This transducer concurrently allows the velocity of the feeding system to be determined.
- The position of the travelling frame was measured with a potentiometric displacement transducer.
- The position of the lower ram was determined with an inductive displacement transducer.

- The pressure distribution in the cavity was determined with five strain-gauge force transducers located inside the upper ram.
- Moisture content of the spray-dried powder was measured by infrared apparatus.

The electric signals supplied by the transducers were led to amplifiers of a digital control data acquisition system. Given the high speed of the compression cycle, the data capture rate was 4800 measurements/s.

The use of these sensors enables information to be gathered regarding the different actions the press performs during the pressing cycle. Figure 1 shows the values of the measured variables all together.

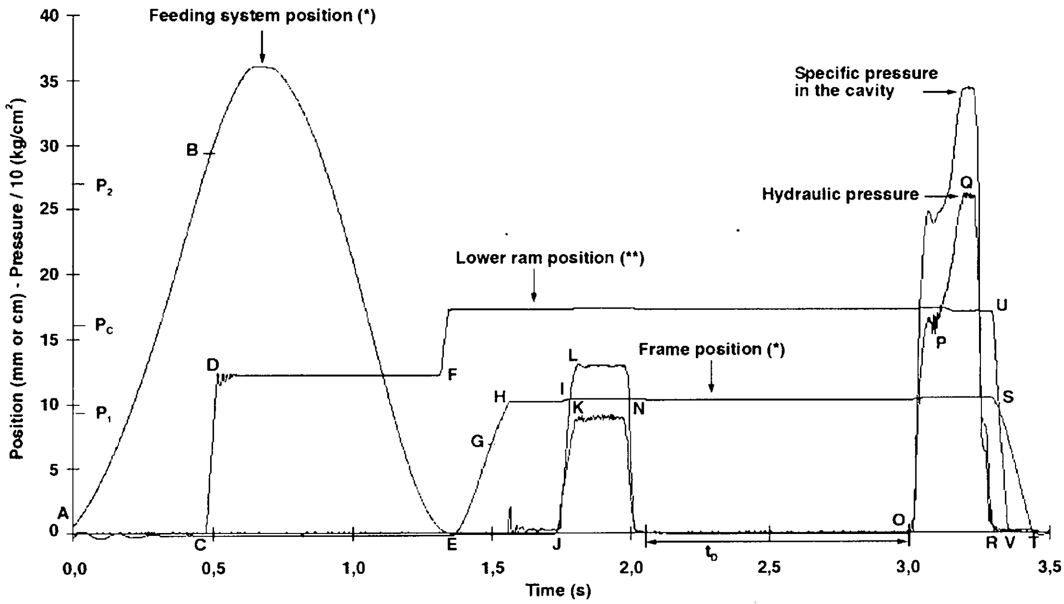

Figure 1. Full pressing cycle (***)

(*) in cm
(**) in mm
(***) in this schematic the direction of the displacements has not been taken into account, considering them all positive.

The cycle commences with filler advance (A) when the frame and lower ram are at their highest position, with null pressure in the main hydraulic circuit and therefore also in the cavity.

When the feeding system lies at a certain point above the cavity (B), the first descent of the lower ram (C) starts and cavity-filling begins. The velocity of the ram's descent (slope of CD travel) is very high and it quickly reaches the end point of its first fall (D), which will determine the thickness of the fed spray-dried powder bed.

Once the filler has ended its travel (E), a second fall of the lower ram (F) takes place, which prepares the spray-dried powder for compaction, and the frame starts descending. When the hydraulic circuit is prepared, first pressing commences, increasing pressure in the circuit (JK), inside the cavity (JL), and the frame descends (IN).

On ending the first pressing (P_1), pressure in the hydraulic circuit and in the cavity drop, while the frame rises slightly owing to the effect of the side shock absorbers (N). Deairing time (t_D) starts at this moment, allowing entrapped air to escape from the cavity.

After deairing, second pressing starts (O). The climbing travel shows two clearly separate regions: one in which pressing is direct, that is, pressure is supplied by the hydraulic power system (OP) and a second region from the peak value of the hydraulic power system onward, where pressure is supplied by a multiplier unit (PQ), until second pressing (P_2) ends. The pressure recorded by the force sensors, corresponding to its force in the cavity, exhibits the same form.

On reaching the maximum pressure programmed for second pressing, pressure drops in the main hydraulic circuit (QR) and the frame rises (ST), starting piece discharge with the rise of the lower ram (UV). The piece is thus compacted for discharge from the cavity by the filler on charging in the following pressing cycle.

One of the applications of this kind of diagram lies in establishing the synchronism of the movements. This enables the duration of the different steps to be exactly determined, thus allowing the pressing cycle to be optimized.

4. EXPERIMENTAL

4.1. MODIFIED VARIABLES

In order to study the influence of the different operating variables on bulk density of the compacted piece, a series of experiments was designed, which involved modifying one variable and determining bulk density of the piece, in these conditions.

Four experiments were performed for each modified variable, in an intent to cover the field of regulation of the press. In those cases where it could not be covered, the usual work range was covered. Maximum hydraulic pressure during second pressing was held constant at 200 kg/cm^2 (according to the Bourdon tube gauge with which the press was fitted out), except in those manoeuvres which involved modifying this value.

The values of the following variables were modified:

✓ of the feeding system: distribution of the separators and velocity

✓ of the lower ram: moment of first descent

✓ of the upper ram: placing of supplements between the travelling frame and the upper ram

✓ of the hydraulic circuit: maximum hydraulic pressure

4.2. SAMPLING AND DATA PROCESSING

Ten pieces were taken for each value of the modified variable, in which bulk density was determined by mercury intrusion [8] in five zones, corresponding to the location of the force sensors in the upper ram.

The maximum values of hydraulic pressure and average moisture content value during the sampling period were recorded for each piece.

5. RESULTS AND DISCUSSION

5.1. EXPERIMENTS CARRIED OUT ON THE FEEDING SYSTEM

The position and velocity of the system feeding spray-dried powder into the press cavities were determined. Figure 2 depicts these variables. At the outset, the filler starts by accelerating (zone A), the velocity is then kept approximately constant (zone B), until deceleration starts (zone C), before maximum displacement is reached (D).

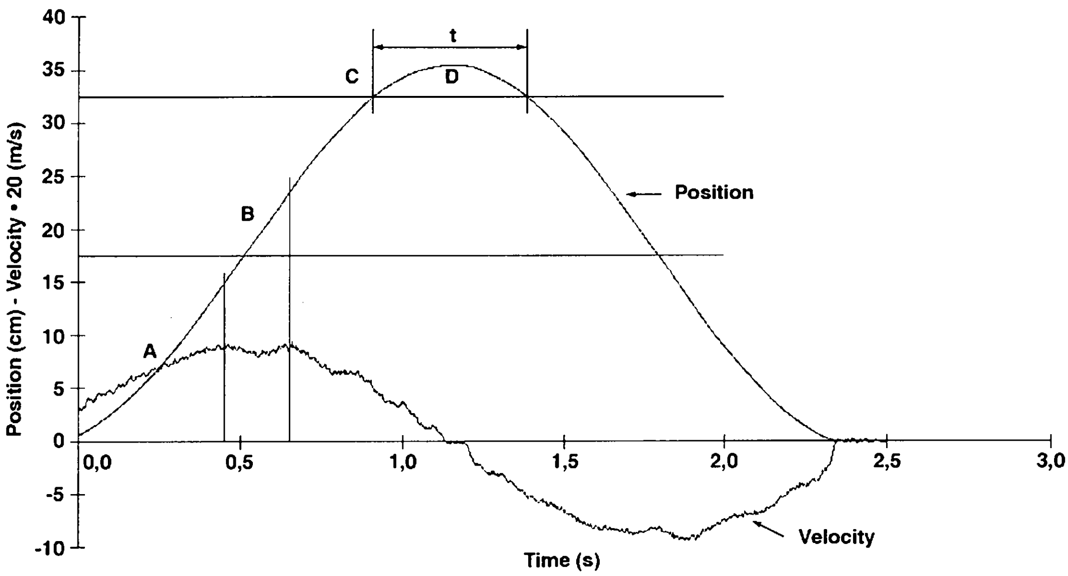

Figure 2. Position and velocity of the filler during charging of the cavity.

The return movement exhibits the same zones as the advance. The velocity of the filler therefore only remains constant over a minor part of its travel. The location of this part will depend on how its movement is programmed. These graphs allow the duration and synchronism of the filling step to be determined with great accuracy.

An extremely important parameter that can be computed from these graphs, is the dwell time of the filler over the cavity. This variable will determine, at constant flow of the spray-dried powder, the amount of powder poured into the cavity, which will in turn determine bulk density of the piece.

5.1.1. Distribution of the reglets in the filler

The filler accessories called "reglets" involve transverse parts that are located in the powder feeding system and enable its total usable surface to be divided into independent compartments with regulatable surfaces.

5.1.1.1. Manoeuvres performed

Four manoeuvres were performed that involved changing the inter-reglet spacing. Figure 3 illustrates the configuration of the feeding system for the four manoeuvres performed. In the first two, the total number was maintained whereas one reglet was added to the four initial ones in the following two manoeuvres.

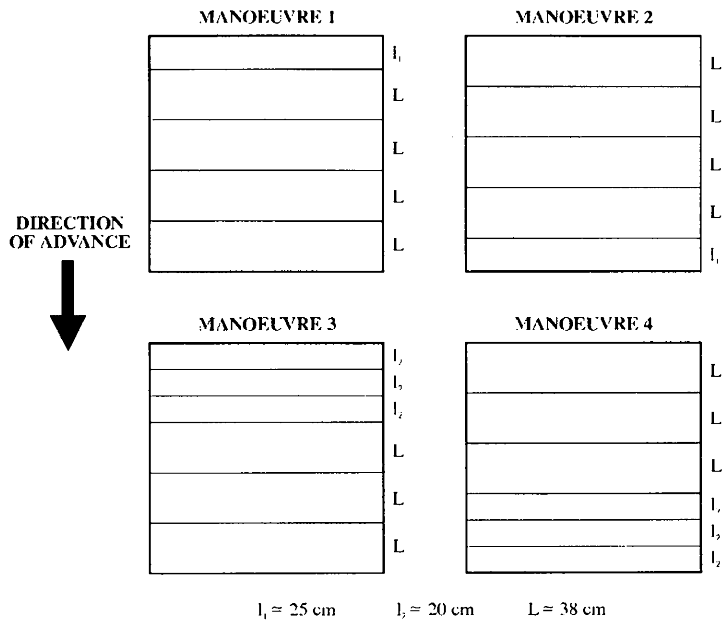

Figure 3. Filler configuration in the four manoeuvres.

5.1.1.2. Presentation and interpretation of results

When a greater number of reglets cross a certain zone, the amount of spray-dried powder poured into it will decrease and so will bulk density in all likelihood. The number of reglets that cross each area during cavity filling was determined. These values, together with the bulk density values of each zone have been detailed in Table 1.

Figure 4 illustrates these results. Increasing the number of reglets crossing a given zone is observed to decrease zone bulk density.

The data plotted fit straight lines, one for the central and rear zones, and another, parallel but with a lower ordinate at the origin for the front zone. The fact that both straight lines are parallel, indicate that the effect of the reglets is of the same intensity throughout the piece.

The lower ordinate at the origin of the front zone indicates the influence of dwell time and/or level of charge of the feeding system in this zone, as both parameters are lower than in the other areas. For the same manoeuvre, compaction at the centre of the piece is higher than at the rear (Table 1). This is because the greater number of reglets crossing the rear zone more than compensate for the differences in charge times.

5.1.2. Velocity of the feeding system

The press used in this study has two different programmable velocities for the feeding system, a fast and a slow one. These two speeds can be combined during the filler travel.

5.1.2.1. Manoeuvres performed

Four experiments were designed, dividing the whole filler travel into four stretches, programming one velocity in each (Table 2). Figure 5 shows the values of the filler positions, for the four manoeuvres effected.

Table 1. *Number of reglets crossing each zone in each manoeuvre and zone compaction*

ZONE	Manoeuvre	No. of reglets	Dap (g/cm^3)
Front	1	2	2.052
	3	2	2.041
	2	4	2.034
	4	6	2.025
Centre	1	4	2.090
	3	4	2.087
	2	6	2.069
	4	8	2.069
Rear	1	6	2.082
	2	7	2.070
	3	8	2.074
	4	9	2.061

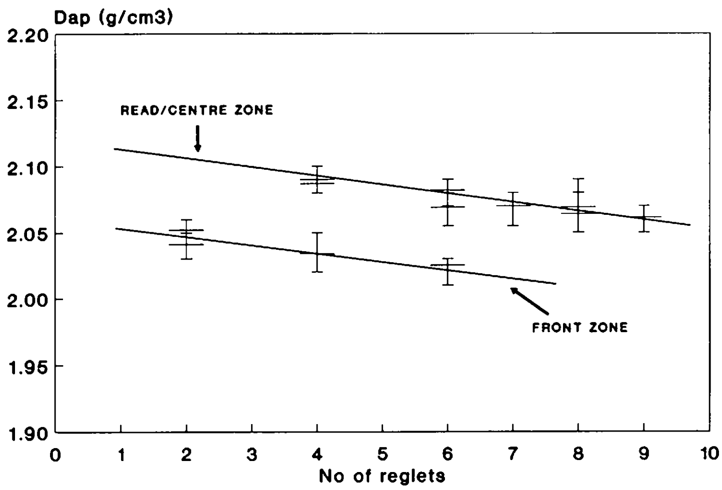

Figure 4. *Bulk density in each zone of the piece in function of the number of reglets crossing it.*

Table 2. *Velocity levels in the experiments programmed*

EXP No.	ADVANCING STRETCH		RETURN STRETCH	
	START	END	START	END
1	slow	slow	slow	slow
2	fast	fast	fast	fast
3	slow	slow	fast	fast
4	fast	fast	slow	slow

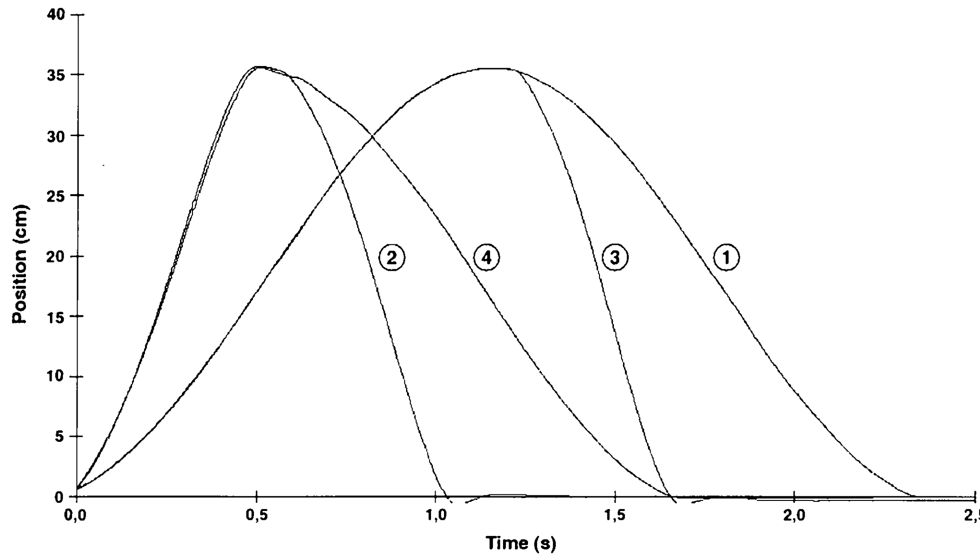

Figure 5. Feeding system position in the four manoeuvres.

5.1.2.2. Presentation and interpretation of results

The dwell time of the filler over the cavity, average and overall bulk densities were determined for each manoeuvre. These values are listed in Table 3.

Figure 6 plots overall bulk density of a piece, in function of filling time. It shows that compaction tends to increase on raising filling time.

Increasing dwell time of the filler over the cavity entails a greater amount of spray-dried powder being poured into it. Therefore, on increasing the amount of powder, overall bulk density of the piece rises slightly.

It can be observed, on analysing the compaction results of manoeuvres 3 and 4 (Table 3), that although compaction distribution varies, the overall bulk density value of the pieces is quite alike. Actually, filling time in both manoeuvres is similar, although the combination of velocity levels differs.

Filling time (for a spray-dried powder with constant technological characteristics and pressing pressure) is going to influence overall bulk density of the piece, and therefore its final dimensions.

5.2. EXPERIMENTS ON THE LOWER RAM

The purpose of the lower ram is to delimit the height of the spray-dried powder fed into the cavity, accommodate it inside the cavity, limit the thickness of the piece jointly with the frame, and discharge the compacted ware.

The travel of the lower ram during the pressing cycle is depicted in Figure 7, in which the position of the feeding system and that of the lower rams are shown in time, during cavity filling.

Table 3. Zone and overall bulk density (g/cm³) of the piece and cavity-filling time (s)

ZONE	MANOEUVRE			
	1	2	3	4
FRONT	2.077	2.039	2.052	2.057
CENTRE	2.091	2.069	2.072	2.080
REAR	2.065	2.062	2.071	2.058
OVERALL	2.075	2.054	2.063	2.062
Filling time (s)	1.28	0.58	0.95	0.89

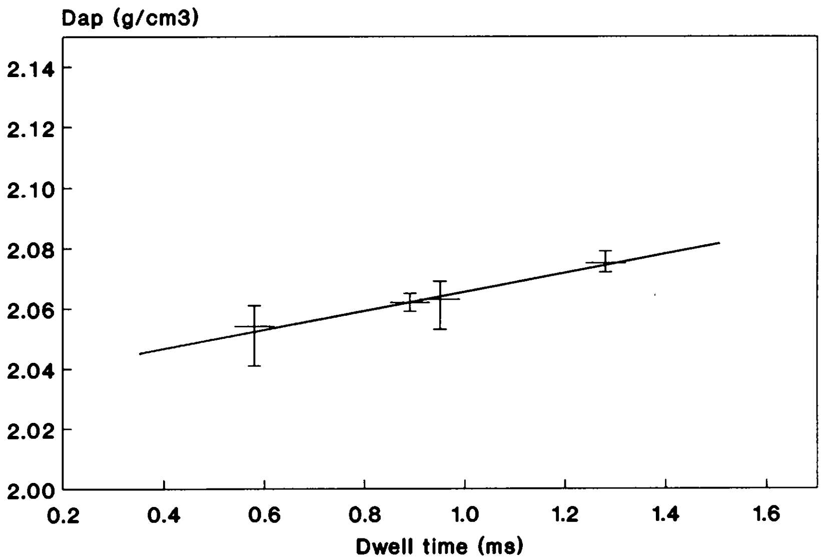

Figure 6. Effect of filler dwell time over the cavity on overall bulk density of the piece.

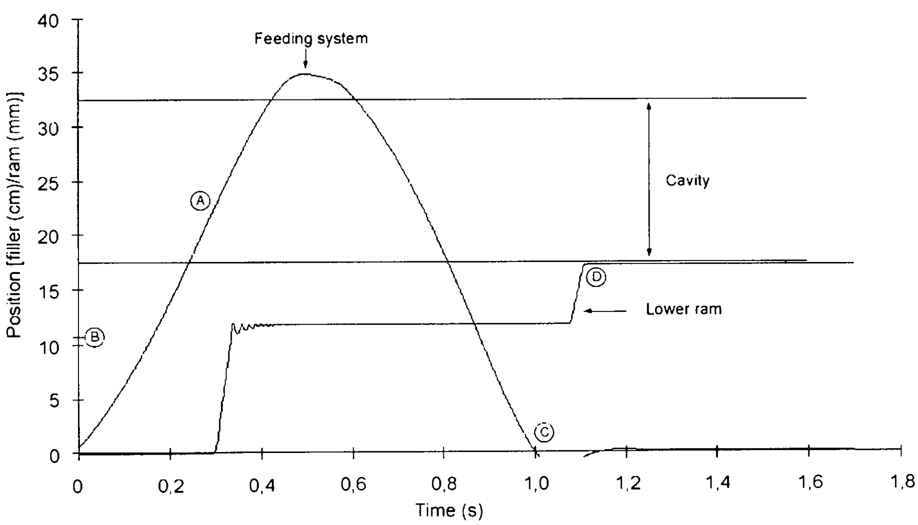

Figure 7. Filler and ram positions during filling.

When the filler reaches a certain position (A), the lower rams are observed to commence their descent, reaching their rest position in this first fall at point (B). Once the feeding system has ended its travel (C), the lower ram descends again (second fall (D)). This new fall keeps a partial vacuum from arising in the cavity with the impact of the upper ram on the powder bed, when compaction of the piece starts. The position of the cavity has been placed on the ordinate axis so that it can be exactly established at which point of it the feeding system lies, when the lower rams fall.

5.2.1. The lower ram's moment of descent with regard to the position of the feeding system

5.2.1.1. Manoeuvres performed

The point at which the lower ram starts to descend was modified, covering the full range that press regulation allows, and keeping the descending velocity constant.

Figure 8 depicts the lower ram and filler positions, for the manoeuvres performed. Ram descent is observed to undergo progressive delay.

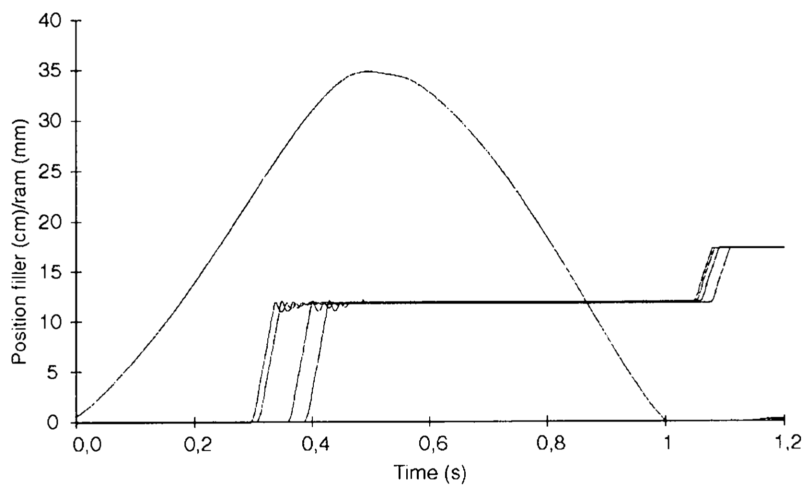

Figure 8. Position of the lower ram and feeding system in the manoeuvres performed.

5.2.1.2. Presentation and interpretation of results

Table 4 lists the point in the piece at which the filler lies when the lower ram starts to drop as well as the average density values, for each zone and manoeuvre.

Table 4. Average compaction values (g/cm^3) per zone and distance (cm) travelled by the filler over the cavity when the lower ram starts falling.

ZONE	MANOEUVRE			
	1	2	3	4
REAR	2.067	2.068	2.060	2.044
CENTRE	2.054	2.081	2.069	2.099
FRONT	2.041	2.042	2.059	2.090
Distance (cm)	4.0	5.7	10.3	12.6

In the following, the equations are derived allowing filler dwell time over each point of the cavity to be computed. To calculate this time, the following assumptions are made:

1. Ram fall velocity is very high.
2. Filler velocity over the cavity is assumed to be constant.
3. When spray-dried powder falls, transverse movement is much greater than horizontal movement, the latter being virtually negligible.

A situation is assumed as described in Figure 9, in which the feeding system has travelled a distance (P), from the beginning of the cavity, when the lower ram drops. From the point of view of cavity filling, there will be two clearly differentiated zones:

- The points lying between cavity beginning and the point of ram fall (X_1), for which filling starts at this instant.

- The zones located beyond the ram fall point (X_2), at which filling does not commence until the filler reaches them.

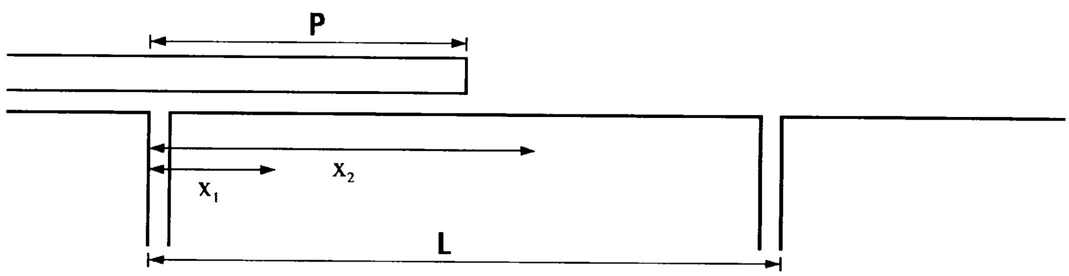

Figure 9. Schematic of cavity filling.

For the zone located between cavity beginning and ram fall point, charging time starts with ram fall and ends when the filler crosses back over it again on its return travel. Filling time (t_1) for any point in this zone (X_1) will be:

$$t_1 = \frac{2(L-P)}{v} + \frac{(P-X_1)}{v} \qquad \textbf{(1)}$$

where (v) is filler velocity.

Filling time (t_2) for any point (X_2) located beyond the feeding system position, at the moment of charging the lower ram, will be:

$$t_2 = \frac{2(L-X_2)}{v} \qquad \textbf{(2)}$$

Figure 10 plots filler dwell times over each zone in function of its position, for the different manoeuvres. Bulk density in each zone of the piece has been plotted in Figure 11 in function of the lower ram fall point.

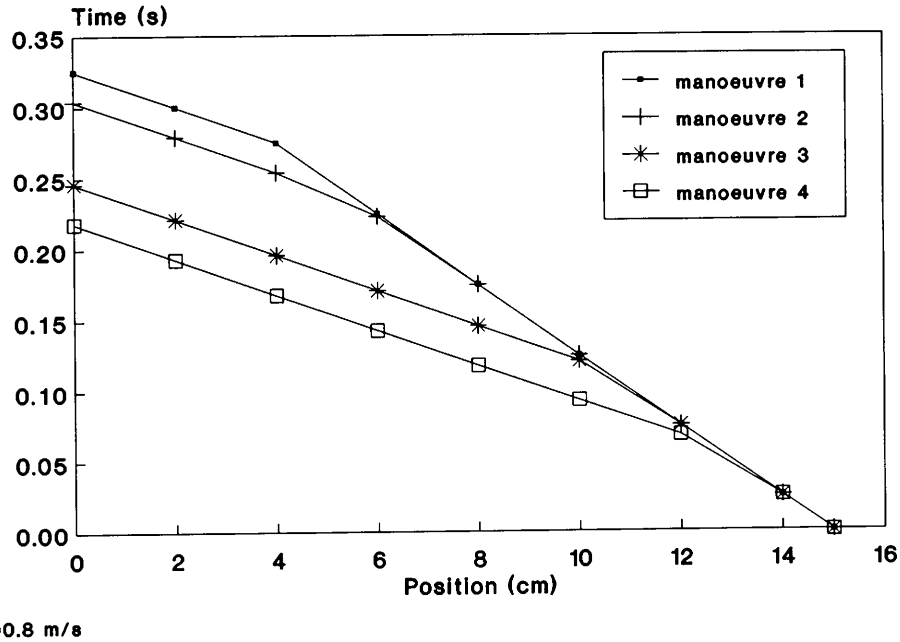

Figure 10. *Dwell times of the feeding system over the cavity, in function of its position over it, for each manoeuvre.*

At the rear of the piece, on holding back the fall point of the lower ram (increase of P), in respect of the feeding system position, filler dwell time over this zone is observed to decrease (Figure 10), so that bulk density should also drop, as indeed it does (Figure 11).

For the zones located in front of the fall point, filling time is independent of this moment (Figure 10), this parameter only taking into account that compaction in these zones should remain constant. However, from the time the rams fall, the filler fills the cavity, and it must be assumed that as it advances, it progressively deposits a smaller amount of spray-dried powder. Therefore, the closer the approach to ram fall point, the higher bulk density will be. Thus, in the front zone, when ram fall is delayed, bulk density increases (Figure 11).

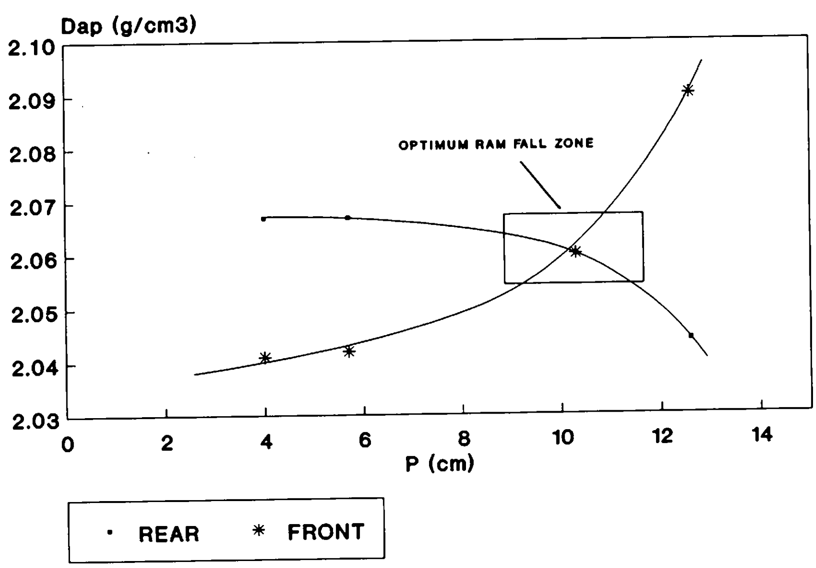

Figure 11. *Bulk density of the front and rear zones in function of the fall point of the lower ram.*

Bulk density of the centre zone of the piece will be conditioned by the predominance of the above effects, as the feeding system has in some manoeuvres already gone beyond this zone, while others have not yet been reached at the moment of ram fall.

The following inferences may be drawn from this manoeuvre:

- The moment of lower ram fall has a greater influence on bulk density at the front of the piece than at the rear.

- Holding the fall point back increases bulk density in the front zone of the piece, and to a lesser extent, lowers it at the rear. There is therefore an optimum ram fall zone, which in a plot like that of Figure 11, corresponds to the point of line intersection Dap = f(P).

5.3. EXPERIMENTS PERFOMED ON THE UPPER RAM

The upper ram is the part that transmits hydraulic pressure to the spray-dried powder bed. Therefore, pressure distribution in the cavity and homogeneity in the distribution of bulk density in the piece will to a great extent depend upon its mechanical characteristics.

Five force sensors were placed in one of the upper rams (four at the corners of the piece and one in the middle). Figure 12 shows the pressure measured by these sensors in a compression cycle. Pressure distribution is observed to be inhomogeneous in the piece, varying from zone to zone.

5.3.1. Collocation of supplements between the travelling frame and upper ram

An intent is made, by ram supplementation (collocating metal wafers), to modify force distribution in the cavity, in order to compensate for the differences in bulk density of the pieces.

5.3.1.1. Manoeuvres performed

Metal supplements of 5x20 cm of different thicknesses were progressively placed at the side of a piece. Figure 13 depicts the value of the pressure measured by one of the force sensors located in the supplemented zone, in the four manoeuvres performed.

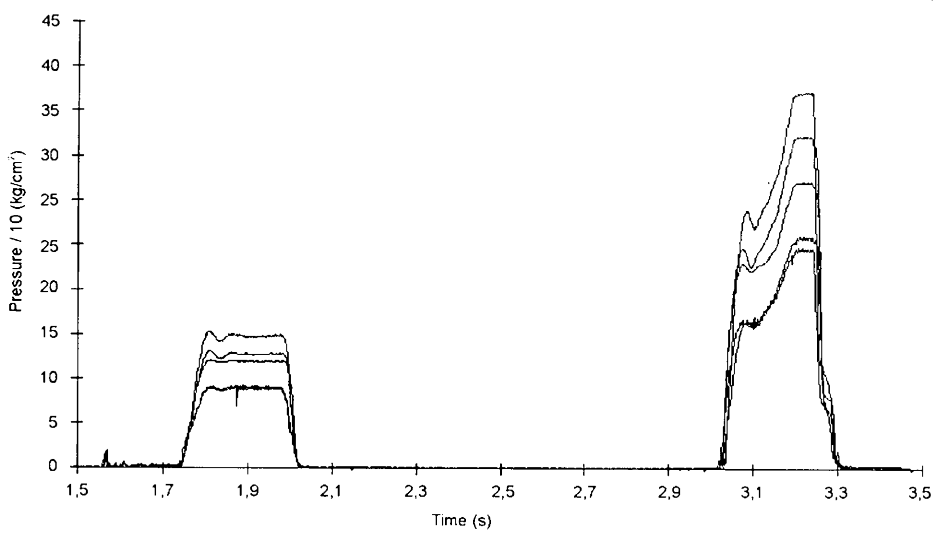

Figure 12. Pressure distribution in the piece travelling a compression cycle

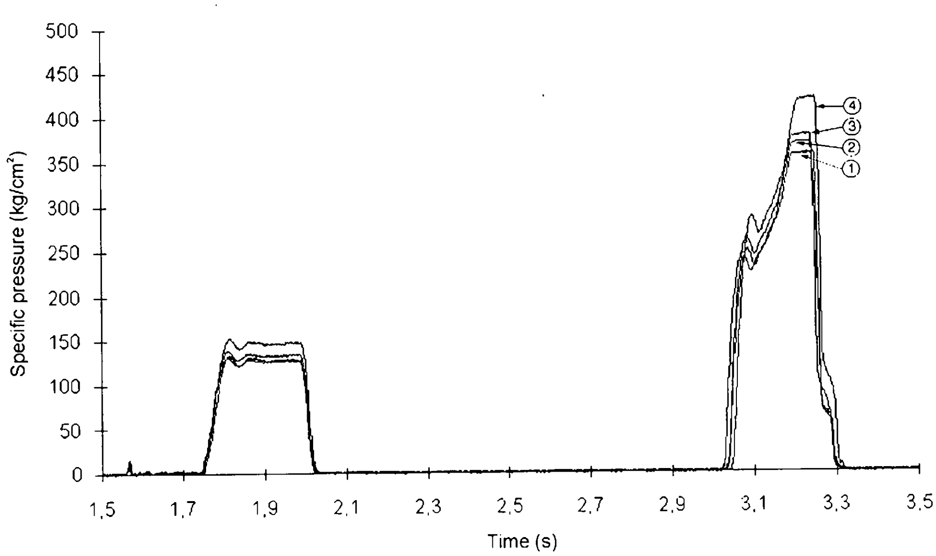

Figure 13. *Evolution of the specific pressure in the supplemented zone during the manoeuvres performed.*

5.3.1.2. Presentation and interpretation of results

Table 5 details the specific pressure values measured by the force sensors in each zone. The different zones of the piece were differentiated as follows: supplemented, centre and unsupplemented. The same table also lists the average bulk densities in these zones for each manoeuvre.

Table 5. Specific pressures (kg/cm^2) and average bulk densities (g/cm3) in each zone for each manoeuvre.

MANOEUVRE S	ZONE		
	UNSUPPL.	CENTRE	SUPPL.
1	335 2.070	382 2.075	385 2.085
2	299 2.057	390 2.082	408 2.098
3	269 2.054	422 2.095	446 2.115
4	267 2.049	416 2.087	477 2.118

It can be inferred from the values in Table 5 that supplementing a particular ram zone unequally affects bulk density values of the piece in all the zones studied. Figure 14 is obtained on plotting the bulk density value of each zone in function of the thickness of the supplement.

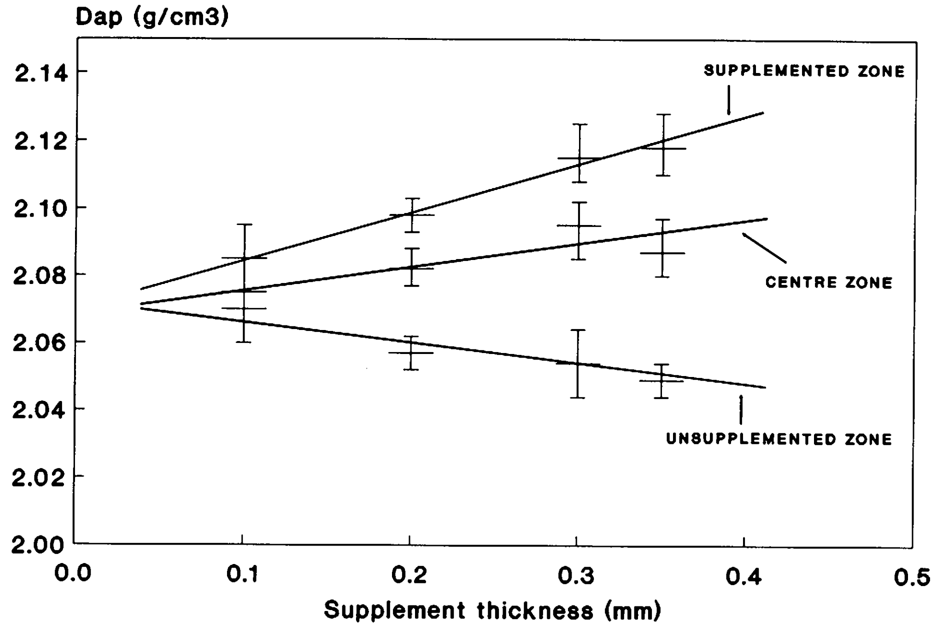

Figure 14. *Compaction variation in each zone in function of the thickness of the supplement used.*

On increasing the thickness of the supplement, bulk density of the supplemented zone rises. In the centre zone compaction rises although to a lesser extent than in the supplemented part, whereas in the unsupplemented zone bulk density of the piece drops.

The trend is linear and the slope of the straight lines is precisely the variation in bulk density caused per unit supplement thickness.

As no changes are observed in terms of the duration of the different compression cycle steps, the presence of the supplements appears to raise the velocity of force application in the supplemented zone, and lower it in the unsupplemented one. Thus, for the same hydraulic pressure application time, a higher maximum value for specific pressure is reached in the supplemented zone.

5.4. EXPERIMENTS ON THE HYDRAULIC CIRCUIT

5.4.1. Maximum hydraulic pressure

The maximum hydraulic pressure reached in the compression cycle is related semilogarithmically to overall bulk density of the piece. This datum confers decisive importance on this value in the forming process.

5.4.1.1. Manoeuvres performed

Different compression cycles were designed, modifying maximum hydraulic pressure. This parameter was measured with a strain sensor and the usual Bourdon tube gauge, with which most hydraulic presses are fitted out.

Table 6 details certain average maximum pressure readouts from the gauge (P_M) and the average maximum pressure values recorded by the sensor (P_S).

Table 6. Gauge and sensor pressure readouts

Gauge pressure P_M (kg/cm^2)	140	150	170	200	230	260
Sensor pressure P_S (kg/cm^2)	182	188	201	246	277	305

5.4.1.2. Presentation and interpretation of results

Figure 15 plots gauge maximum pressure values in function of sensor-measured pressure values, in the different manoeuvres performed.

The data in Table 6 and the above plot allow the inference that the sensor-measured average pressure is greater and proportional to the gauge readout, for any assigned pressure in the range used in these experiments.

This could be because gauge response speed may not be sufficiently high to reflect the actual variation in hydraulic pressure. However, the pressure sensor used has a greater response speed and is more suitable for use in processes in which pressure variation rates are high, as in a compression cycle (1000 (kg/cm^2)/s).

There is a difference between measured pressure and assigned pressure (Table 6). At the average pressure climb rate of 1000 (kg/cm^2)/s, this pressure is reached in 40 ms, that is, a very short time, which requires measuring systems with high-speed response.

Figure 15 also shows some uncertainty regarding the true value of the pressure exerted. This variation in hydraulic pressure values may entail a modification in bulk density of the piece, and will take place in apparently stationary press operating conditions: feeding, moisture content of the spray-dried powder, maximum pressure, etc.

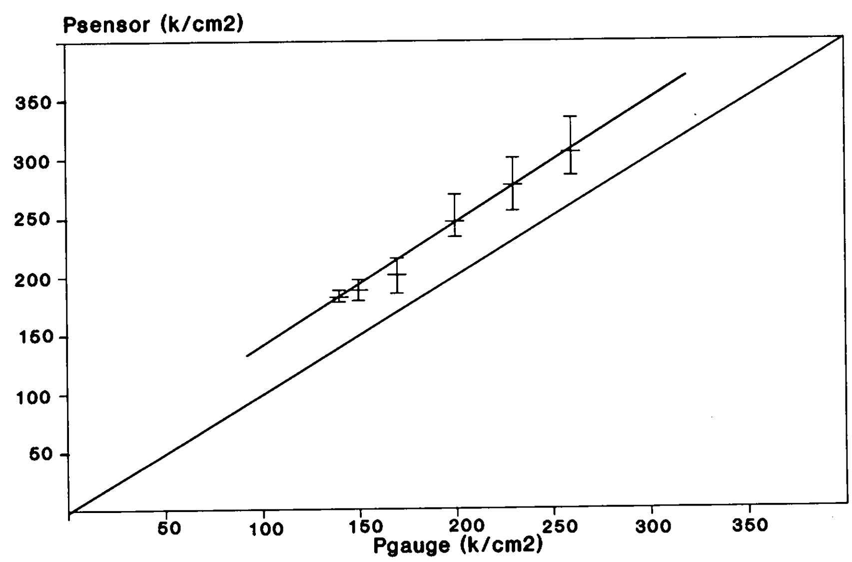

Figure 15. Maximum gauge pressure versus sensor-measured maximum pressure.

6. GENERAL CONCLUSIONS

As the conclusions relative to the effects of each piece compaction manoeuvre are to be found in the different sections of the study, this section contains the general conclusions drawn from the study.

1) The measuring devices used have allowed the evolution of the main operating variables of the pressing cycle to be monitored, studying their synchronism and establishing their relationship with bulk density of the piece.

2) The response speed of the hydraulic pressure measurement system currently being used is not fast enough to accurately detect the values of this variable during the compression cycle.

3) The main modifications in the bulk density distribution values were obtained in those manoeuvres in which the operating conditions of the feeding system and the lower ram were changed.

4) With the control system designed (by incorporating sensors) it is possible to optimize the pressing cycle in operating synchronism and time, in order to obtain maximum productivity and quality in ceramic tile.

7. RECOMMENDATIONS

1) Replacing the current hydraulic pressure measurement system with another having a faster response speed, more suitable for the compaction process.

2) Fitting out the presses that require it, with devices measuring the position of the feeding system and the lower rams, allowing these to be monitored and controlled.

3) Designing a control loop, which by measuring maximum hydraulic pressure and spray-dried powder moisture content as control variables, taking into account the compaction diagram of each composition, allows the bulk density values of the piece to be held within narrow tolerance limits.

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