MEASUREMENT AND CONTROL OF MAXIMUM PRESSURE IN THE CAVITIES OF A DIE FOR CERAMIC TILE MANUFACTURE

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ABSTRACT

In this study, a measurement system in real time was developed that provides the maximum pressure applied in every cavity of an industrial die for ceramic tile manufacture during each pressing cycle. The experiments conducted demonstrate the importance of measuring the maximum pressure in each cavity in order to control the dry bulk density of the bodies obtained in the same pressing cycle.

The study was completed with the implementation of a control system that, acting in an individualised form on the position of the first drop of each of the die risers, keeps the maximum pressure applied in every cavity constant and assures consistent bulk density of all the processed bodies.

1. INTRODUCTION

Numerous bibliographic references show that the dry bulk density of ceramic bodies is one of the most important variables in the entire ceramic tile manufacturing process, since it affects the other process variables and determines most of the properties of the end product [1] [2].

The method currently used by most ceramic tile manufacturers for average bulk density control pursues a twofold objective. On the one hand it seeks to assure the consistency, over time, of the average bulk density of the processed tiles and, on the other, to ensure that all the tiles obtained in a given pressing cycle have the same average bulk density [3]. The first objective is achieved by modifying the maximum pressure of the pressing cycle, based on measurements of the spray-dried powder moisture content and wet bulk density of the bodies. The second objective is traditionally achieved by the incorporation of thin metal sheets of different thickness between the punches and the punch-carrier plate. The distribution of the pressures applied in the different die cavities is thus modified, enabling the average bulk density reached in each body to be controlled when the pressing cycle concludes.

Although bulk density control by regulating maximum pressing pressure, based on the variations of spray-dried powder moisture content, is a procedure that can nowadays be fully automated [4], control of the average bulk density distribution of the tiles obtained in the same pressing cycle is still performed discontinuously by hand. This approach, therefore, does not at present allow consistent bulk density of all the bodies obtained in each pressing cycle to be assured.

Various devices have appeared on the market in recent years that attempt to correct the differences in bulk density between tiles formed in the same pressing cycle. On the one hand, there are the so-called isostatic dies in which the risers do not rest directly on the die block but lie on a common oil chamber, which serves to offset pressure differentials that can appear between the different cavities. This type of die has not yet found much acceptance because of its great mechanical complexity and the fact that pressure regulation is performed at the expense of generating differences in the average thickness of the tiles.

On the other hand, dies with mobile risers are also now being marketed [5]. These dies exhibit the singularity of, individually, being able to modify the position of the first drop of each riser, which allows the quantity of powder fed into each cavity and, hence, the effective pressure that is really applied on it to be modified. This system has the advantage of not creating differences in thickness between the tiles and of being mechanically less complex than the isostatic dies. However, to date, control is manual and requires the action of a worker who, on the basis of routine measurements of body bulk density, regulates the setting positions of the risers in order to equalise the bulk densities.

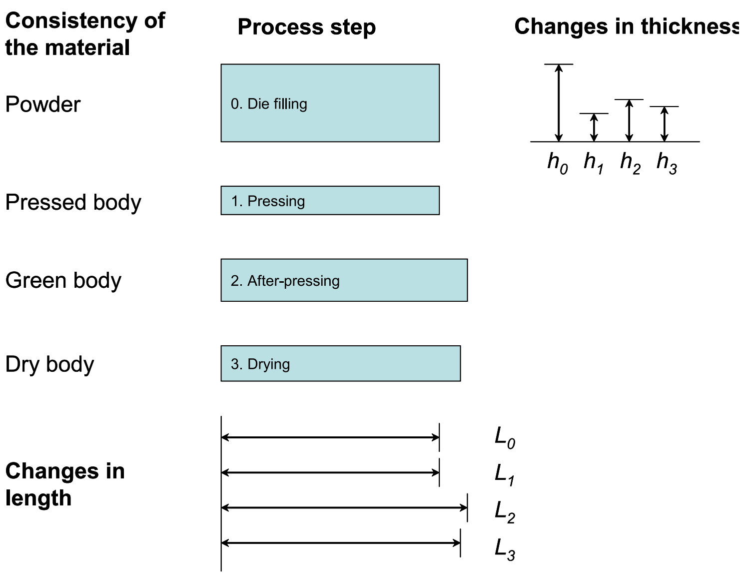

Figure 1. Dimensional changes undergone by a powder bed in the pressing and drying stages.

The average dry bulk density of pressed tile bodies depends, for the same chemical composition of the spray-dried powder and particle size distribution within the usual working margins, on the maximum pressure applied on to the powder and powder moisture content. The relationship between these three variables constitutes the so-called compaction diagram of a composition.

Although the compaction diagram is widely used in controlling the pressing operation, it does not allow the operation of the charge regulation systems by the mobile risers to be properly understood, since it does not enable the effect of other variables that, in addition to moisture content and pressure, take part in the pressing operation to be identified, such as density of the powder bed after cavity filling, initial powder bed thickness, and final thickness of the body. In order to establish the relationship between the dry bulk density of the body and these variables, it is necessary to take into account the different dimensional changes that the spray-dried powder bed undergoes, from press cavity filling to drying, once it has acquired body consistency after forming.

During cavity filling, which corresponds to step 0 of the process described in Figure 1, the dimensions of the powder bed (thickness, h, and length of sides, L) are directly related to the volume of the cavity itself (h_0 and L_0). In pressing, powder bed compaction increases progressively until a maximum compaction D_1 is reached, corresponding to a thickness h_1 and length L_1. After-pressing expansion, S_2, then occurs and the subsequent thermal treatment in drying leads to shrinkage, S_3. These dimensional changes may be calculated from equations 1 and 2.

$$S_2 = \frac{1}{3}\left(\frac{V_2 - V_1}{V_1}\right)$$

Equation 1

$$S_3 = \frac{1}{3}\left(\frac{V_3 - V_2}{V_2}\right)$$

Equation 2

where V_1 is the volume of the pressed body, V_2 the volume of the body after expansion, and V_3 the volume of the dry body.

The dry bulk density of the body after drying may be calculated from equation 3.

$$D_3 = \frac{M_3}{V_3}$$

Equation 3

where M_3 is the mass of the dry body, which may in turn be calculated from equation 4, based on the moisture content on a dry basis of the spray-dried powder at the moment of forming (W_0) and on the mass of powder initially contained in the cavity, M_0.

$$M_3 = \frac{M_0}{1 + W_0}$$

Equation 4

Combining equations 1, 2, 3 and 4 and taking into account that the volume of the body after pressing can be calculated as $V_1 = h_1 L_1^2$ (assuming a square size), and that bed initial density is $D_0 = M_0 / (h_0 L_1^2)$, one obtains equation 5.

$$D_3 = \frac{D_0}{(1 + W_0)(1 + 3S_2)(1 + 3S_3)} \frac{h_0}{h_1}$$

Equation 5

Considering equation 6 and defining the ratio of powder compressibility, ϕ, as the quotient between bed initial thickness and final thickness of the formed body, equation 5 can be simplified to equation 7.

$$K(W_0, P_1) = \frac{1}{(1 + W_0)(1 + 3S_2)(1 + 3S_3)}$$

Equation 6

$$D_3 = K(W_0, P_1) D_0 \phi$$

Equation 7

Since after-pressing expansion depends on powder moisture content and pressing pressure and (though it can be demonstrated that drying shrinkage is practically independent of pressure) drying shrinkage also depends on moisture content, K is a parameter that varies both with spray-dried powder moisture content and the maximum pressure applied during pressing (P_1).

In accordance with equation 7, the density of the dry body can be modified by acting on bed initial density or on the powder compression ratio. However, in industrial practice, it is only feasible to act on the compression ratio, since bed bulk density, a parameter that depends fundamentally on spray-dried powder composition and flowability, is hardly controllable.

For example, under given operating conditions, a simple way of increasing the compression ratio is by increasing powder bed initial thickness before pressing, keeping the final thickness of the body constant. This is achieved by increasing the powder mass fed into the cavity, thanks to the increased travel of the first drop of the riser, and by raising the pressing pressure to reach the targeted final thickness. The greater pressure required to reach the same final thickness as under the initial conditions is the pressure that increases the dry bulk density of the body.

$$D_3 = M \ln P_1 + N$$

Equation 8

The foregoing concepts are included in equation 9, which is obtained by combining equation 7 with the equation that represents the compaction diagram of the composition for a given moisture content (equation 8). Equation 9 relates the different variables involved in the pressing operation: maximum pressure, powder moisture content, bulk density and initial thickness of the powder bed, and tile final thickness.

$$P_1 = \exp\left(\frac{K(W_0, P_1) D_0 \phi - N}{M}\right)$$

Equation 9

where M and N are the characteristic parameters of a compaction diagram, which depend on spray-dried powder moisture content.

The solution of this equation is relatively complicated if the dependence of parameter K on moisture content and pressure is taken into account. However, for the usual ranges of pressure variation under industrial conditions, it may be assumed that after-pressing expansion only depends on moisture content. Under these conditions, equation 9 adopts the form of equation 10, according to which, at a constant moisture content, if it is desired to keep the final thickness of the body constant, an increase in bed initial thickness will require an increase in pressing pressure, which will in turn lead to an increase in bulk density. In contrast, if bed initial thickness is increased but the pressing pressure remains constant, in order to obey the equality defined by equation 10, it will be necessary to increase the final thickness of the body.

$$P_1 = \exp\left(\frac{K(W_0)D_0\phi - N}{M}\right)$$

Equation 10

Applied to a die with several outputs, this concept implies that the pressure applied by the press will be distributed in the different cavities as a function of bed initial thickness and density, the initial thickness in each cavity being the variable that allows the pressure applied in every cavity and, thus, the bulk density of the dry bodies to be regulated.

For example, in a hypothetical die of mobile risers with two outputs, the other variables being equal, the same initial thickness of the powder bed in both cavities would assure the same maximum pressure. In contrast, in accordance with equation 10, a decrease in bed initial thickness in a given cavity will entail a relative reduction of the pressure applied in that cavity, at the expense of an increase in pressure in the other cavity. This mechanism, which enables pressure differentials in the cavities to be generated, is what is used in practice, applied in reverse form, to offset the differences in density in the dies of mobile risers.

2. OBJECTIVE

The purpose of this study was to determine the technical feasibility of measuring the pressing pressure in each cavity of a die of mobile risers and to use this variable as a control variable in a regulation system, based on the individualised modification of the quantity of spray-dried powder fed into every cavity, which would enable the maximum pressure applied in all cavities to be kept constant.

3. MATERIALS AND METHODOLOGY

The study was conducted with a spray-dried powder composition customarily used for the manufacture of glazed porcelain tile. Using the methodology described elsewhere [6], the compaction diagram of this composition was obtained, which is represented by equation 11.

$$D_3 = (-5{,}9W_0 + 166{,}8)\ln P_1 + (44{,}7W_0 + 892{,}9)$$

Equation 11

The industrial trials were carried out in an industrial hydraulic press for the manufacture of porcelain tile bodies with a nominal fired size of 33x33 cm. The press was equipped with a penetrating die with 4 outputs, with a charge regulation system by means of mobile risers and an automatic control loop of the maximum pressing pressure, based on the variations of spray-dried powder moisture content.

In order to measure the pressure in each cavity, a cylindrical duct was machined in one side of the top punches of the die, similar to that used for filling the punches, which connected the isostatic chamber of the punch with the outside. A pressure transducer was located at the end of this duct, which determined the pressure existing in the ensemble consisting of the oil chamber and the measurement duct.

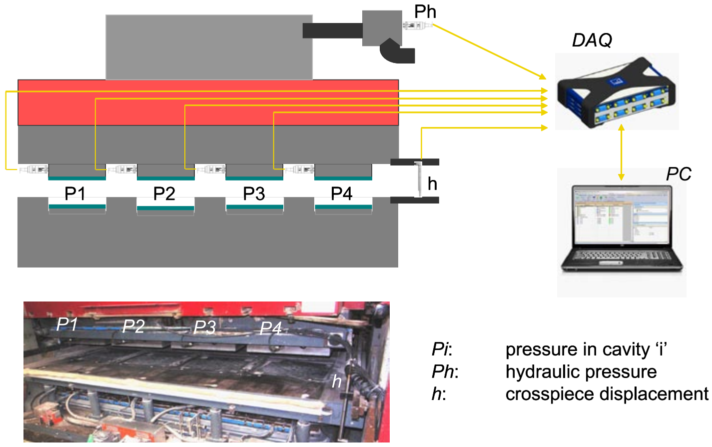

Figure 2. Instruments installed in the press used in the study.

The set of instruments (see Figure 2) was completed with a position transducer that provided information on the displacement of the press crosspiece and a fifth pressure transducer installed in the hydraulic circuit. All the signals generated by each of the transducers were recorded by a high-speed data logging card that allowed sampling at a maximum frequency of 1,25 MHz.

Using a specially developed computer application, the pressure–position values were thus recorded throughout each pressing cycle and the maximum pressing pressure corresponding to each cavity was obtained. Control algorithms were implemented on this application that would allow the position of the mobile risers of the die to be regulated in order to equalise the maximum pressure in every cavity.

4. EXPERIMENTAL RESULTS

4.1. Validation of pressing pressure measurement in the press die cavities

After determining optimum sampling conditions by means of a series of preliminary trials, operations were performed to validate the developed measurement system. These operations consisted of acquiring, during several pressing cycles, the pressure values in the die cavities in order to compare them with the pressure values provided by the pressure transducer installed in the hydraulic circuit of the press.

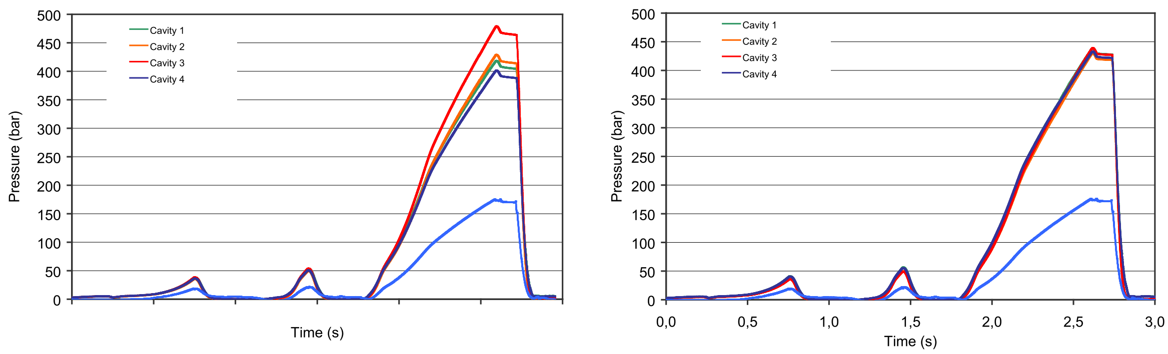

Figure 3. Evolution of the pressure recorded during a pressing cycle without charge correction (left) and a pressing cycle with charge correction (right).

The variation of the pressure in the die cavities and in the hydraulic circuit of the press during two complete pressing cycles is depicted in Figure 3. During the cycle corresponding to the graph on the left, the system correcting the position of the first drop of the mobile risers remained deactivated, giving rise to a very heterogeneous pressure distribution, with a maximum pressure difference between the cavities of 78 bar. During the cycle shown on the right, the mobile riser correction was activated, which led to a much more uniform pressure distribution with a maximum difference of only 8 bar between the cavities. It is interesting to note that, though the action of the correction system of the first drop modified the pressure distribution in the cavities, the average value of these pressures was hardly modified (134 bar in the first cycle as opposed to 135 bar in the second cycle), since the maximum pressure applied in the hydraulic circuit of the press was the same in both cases (175 bar).

As may be observed in Figure 4 (left), which corresponds to an enlargement of the final part of the last pressing in the first pressing cycle, the relationship between the pressure measured in the cavities and the pressure recorded in the hydraulic circuit of the press was very good. In effect, even the light thrust spike, recorded in the circuit pressure when the maximum pressure was applied, was perfectly reflected in the pressure measurement in all the press die cavities.

The validity of the pressure measurements in the cavities is demonstrated in the graph in Figure 4 (right), which shows the variation of the average pressure in all the cavities versus hydraulic circuit pressure. It may be observed that the experimental data satisfactorily fit a straight line that passes through the origin of the coordinates, in accordance with equation 12, which was obtained on applying a balance of forces to the press.

$$P_{cavity} = \frac{S_{cylinder}}{S_{tiles}} P_{circuit}$$

Equation 12

where $S_{cylinder}$ is the inner cross-section of the hydraulic cylinder of the press and S_{tiles} the total surface pressing area.

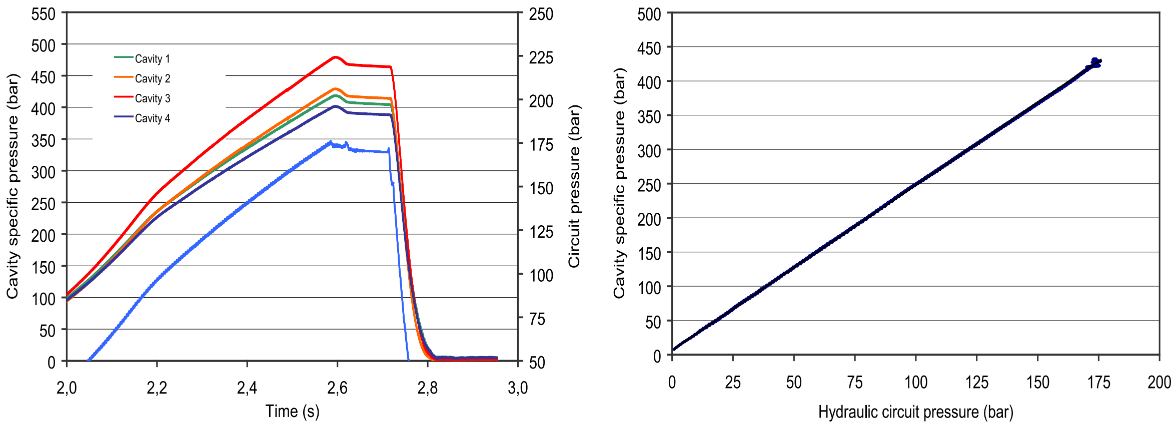

Figure 4. Evolution of the pressure recorded in the final part of a pressing cycle (left) and relationship between hydraulic pressure and specific pressure (right).

4.2. Effect of the pressure measured in the press die cavities on the bulk density of the bodies

In order to evaluate the effect of the specific pressure recorded in the press die cavities on the bulk density of the pressed bodies, the mercury displacement method was used to determine the average dry bulk density of all bodies formed in the pressing cycles analysed in section 4.1. The dry bulk densities of each body and maximum pressures recorded in every cavity are detailed in Table 1. It may be observed that the bulk density values are directly related to the maximum pressure applied in each cavity. In the pressing cycle conducted without the charge correction, the pressure applied on the powder contained in cavity 3 was 78 bar higher than that applied on that in cavity 4. As a result, the bulk density of the body processed in the former cavity was 26 kg/m^3 higher than that of the body processed in the latter. The same observation was valid for the other two cavities in the die.

When the correction by the mobile risers was performed, the bulk density values in the different cavities were observed to be much more similar, the maximum difference only being 4 kg/m^3. This highlights the positive effect on the pressure distribution of the modification of the initial height of the powder bed in each cavity.

	Uncorrected cycle				Corrected cycle			
Cavity	1	2	3	4	1	2	3	4
Riser (mm)	0,00	0,00	0,00	0,00	0,22	0,28	0,51	0,00
P_1 (bar)	418	429	479	401	438	430	439	433
D_3 (kg/m^3)	1952	1962	1971	1945	1961	1962	1962	1957
$\Delta P_{1\ max}$ (bar)	78				8			
$\Delta D_{3\ max}$ (kg/m^3)	26				4			

Table 1. Maximum pressure and bulk density recorded in each cavity.

After these first operations, the data logging program was configured to continuously record the evolution of the maximum pressures and to evaluate their effect on bulk density under different conditions.

The evolution of the maximum pressures corresponding to the four die cavities during 15 minutes' production is shown in Figure 5. During this period, the pressed tiles were collected under three different operating conditions, referenced in the graph as A, B, and C, with a view to determining their bulk density and size after firing.

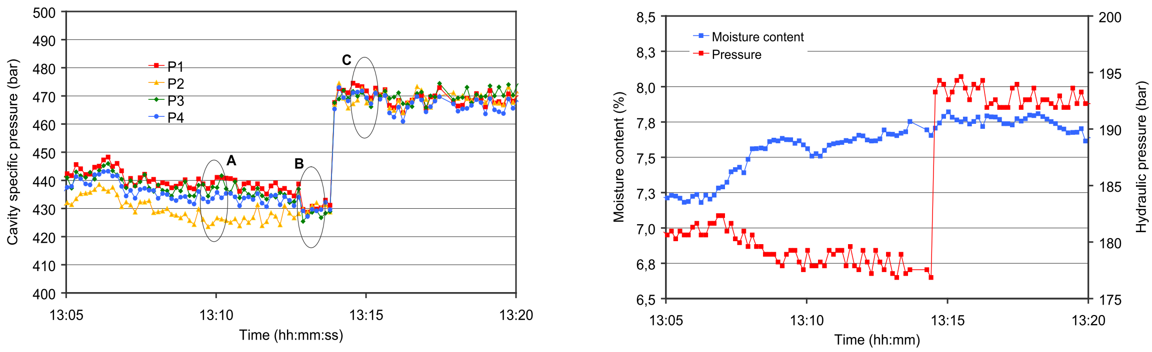

Figure 5. Evolution over time of the recorded maximum pressures (left) and spray-dried powder moisture content (right) during 15 minutes.

Condition A refers to a situation in which the press was working with the activated correction system, but configured such that the pressure applied in cavity 2 was slightly lower than that in the other three cavities. In condition B, the position setting of the first drop of riser 2 was manually modified with a view to making the pressure distribution uniform and, in condition C, the position settings of situation B were held while the pressing pressure was increased to produce a change in body bulk density.

As may be observed, when the experiment period was initiated, the recorded average pressure in the press die cavities progressively decreased as a result of the hydraulic pressure regulation performed by the automatic dry bulk density control system installed in the press. This control action was produced by the rise in spray-dried powder moisture content observed between 13:05 h and 13:10 h (see Figure 5 (right)).

Condition	A				B				C			
Cavity	1	2	3	4	1	2	3	4	1	2	3	4
Riser position (mm)	0,07	0,00	0,05	0,04	0,13	0,00	0,08	0,07	0,13	0,00	0,08	0,07
P_1 (bar)	439	425	437	436	429	432	429	430	470	470	471	471
D_2 (kg/m^3)	2090	2090	2088	2088	2099	2099	2099	2099	2116	2117	2117	2116
D_3 (kg/m^3)	1940	1940	1938	1938	1941	1941	1941	1941	1957	1958	1958	1957
L_4 (mm)	335,1	334,3	334,9	335,0	335,3	335,1	335,1	335,3	335,5	335,5	335,6	335,6
Calibre	4	3	4	4	4	4	4	4	5	5	5	5
$\Delta P_{1\,max}$ (bar)	14				3				1			
$\Delta D_{3\,max}$ (kg/m^3)	2				0				1			
$\Delta L_{4\,max}$ (mm)	0,8				0,2				0,1			

Table 2. Maximum pressure, wet bulk density, and fired size of the tiles processed under different operating conditions.

The maximum pressure, wet bulk density, and size of the tiles after firing are listed in Table 2 for the three evaluated operating conditions. Together with these variables the table also details the position of the drop of each mobile riser, taking as reference the position at the moment of pressure application; the dry bulk density, calculated by taking into account the powder moisture content at the moment of collecting the tiles; and the tile calibres.

Under condition A, owing to the lower pressure applied on the powder in cavity 2, the size of this tile after firing was smaller than that of the other tiles, for which the recorded maximum pressure was practically the same. As a result of this behaviour, the tiles processed in cavity 2 were of lower calibre (calibre 3) than the other three (calibre 4). It may be noted that, though there were obvious differences in pressure between the cavities, it would not have been possible to detect the observed differences in size from the wet bulk density measurements performed in the plant. In effect, at a variation of the applied maximum pressure up to 14 bar, which led to a difference in size of 0.8 mm, this being practically the tolerance of a calibre that, for this size, is usually set at 1 mm, the measured differences in wet bulk density did not exceed 2 kg/m^3. This indicates that the recorded maximum pressure measurement in the die cavities may even be more accurate than the bulk density measurement by mercury displacement itself. In fact, though the mercury displacement method has a maximum accuracy of ±4 kg/m^3 [7], the installed pressure sensors allowed the pressure recorded on the powder to be determined with an accuracy of ±2 bar which, according to the compaction diagram, for a given powder and moisture content would be equivalent to ±1 kg/m^3.

In situation B, the travel of risers 1, 3 and 4 was decreased, which allowed the initial thickness of the powder bed in these cavities to be reduced with respect to the initial thickness of the powder bed in cavity 2. This operation led to uniform pressure distribution in all cavities, the maximum pressure deviation between the cavities being only 3 bar. As a result, the size of the tiles processed in cavity 2 increased significantly and all pressed tiles could be classified as calibre 4.

It may be noted that, despite the slight decrease in pressing pressure in the hydraulic circuit to offset the increased moisture content (from 7,5% to 7,8%), in view of the average value of all the bodies, the wet bulk density (D_2) in situation B (2099 kg/m^3) increased slightly with relation to A (2089 kg/m^3), precisely because of this increase in moisture content. In contrast, dry bulk density (D_3) remained practically constant (1939 kg/m^3 compared to 1941 kg/m^3), thanks to the action of the automatic pressure regulation control system. This highlights the fact that wet bulk density is not the most appropriate variable for performing pressing control.

Finally, in situation C, when the pressing pressure was raised, the uniformity of the pressure distribution achieved in situation B was still maintained. However, owing to the increased bulk density of the processed bodies, tile size after firing was slightly larger, these all being calibre 5.

4.3. Industrial applicability

In view of the good results obtained in the foregoing experiments, it was decided to leave the pressure measurement system running during an entire production lot of 3500 m^2. In this period of time, the positions of the mobile risers were regulated by hand on the basis of the pressure measurements made in the cavities.

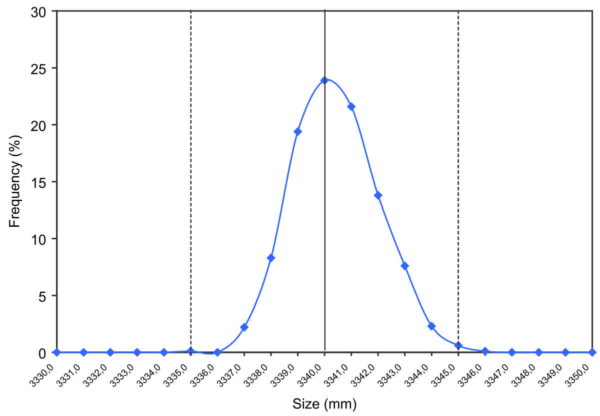

Figure 6. Size distribution in a production lot.

The control actions were performed with a frequency of about 30 minutes, based only on pressure deviations between the cavities of more than 5 bar. The automatic pressure–moisture content control system ran parallel to the control actions. After the tiles had been formed and fired, the complete lot was sorted in an industrial selection machine. This yielded the tile size distribution shown in the graph in Figure 6.

The figure shows that all produced tiles were grouped together in the same calibre (1 mm tolerance), the maximum difference in resulting size being 0.7 mm. These results highlight the great usefulness of pressure measurements for controlling the pressing operation and they open up the doors to the possibility of future automatic control of pressure distribution in the press die, based on automatic correction of the riser position in each pressing cycle.

5. CONCLUSIONS

- A measurement system in real time was developed that is able to record the evolution of pressing pressure in the die cavities of an industrial press.
- It was verified that there was a direct relationship between the pressure recorded in the die cavities and the other characteristic variables of the pressing operation.
- The pressure measurements in the die cavities were shown to allow pressing operation control to be performed very accurately, which contributed to suppression of the defects associated with differences in average bulk density between the die cavities.

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