STUDY AND AUTOMATIC CONTROL OF THE CERAMIC TILE EXTRUSION OPERATION

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ABSTRACT

The ever-larger tile sizes demanded by the market, the higher quality requirements, and the increasingly similar installation to that of pressed products make it necessary to narrow the tolerance limits of final extruded tile size in order to maintain the product's competitiveness.

The results of this study show that, though mixing water has a great influence on drying shrinkage, it hardly affects extruded tile firing shrinkage. This indicates that control of the water added in the extrusion process is indispensable in order avoid variations in drying shrinkage and, thus, to assure good dimensional stability of the end product.

1. INTRODUCTION

The present level of understanding regarding the forming operation of extruded ceramic tiles does not allow this type of product to meet the same dimensional stability requirements as those of pressed tiles. This entails two serious disadvantages for extruded products: on the one hand, it limits tile size (the largest extruded tile size is usually 330x330 mm, whereas pressed tiles can easily reach up to 600x1200 mm) and, on the other, extruded tile installation requires having wider joints which, from a commercial and aesthetic viewpoint, tends to leave extruded tiles at a disadvantage compared with pressed tiles.

The literature indicates that the variables governing ceramics forming by extrusion (extrusion pressure, plasticity of the compositions, moisture content of the plastic masses, etc.) determine the behaviour of the pieces during the rest of the production process (drying, decoration, firing, etc.), as well as their end properties and dimensions. However, no studies establishing the relationships between the variables of the extrusion stage and end product properties in the extruded tile manufacturing process were found in the literature.

Extruded tile manufacture begins with the milling of the raw materials, generally in pendulum mills, to the desired particle size. The resulting powder is subjected to a batch wetting process in a large-capacity mixer, in which the moisture content is increased to approximately 0,16 kg water/kg dry solid. The powder is then continuously conveyed on belts to the extruder hoppers. The materials are continuously fed from these hoppers to the extrusion group mixer, in which the necessary water is proportioned for the powder to reach a moisture content of 0,17 kg water/kg dry solid. The resulting plastic mass is introduced into a vacuum chamber from which the extrusion auger advances it to the extrusion die in which the tile column is given the desired thickness. A cutting system, with several metal blades, then defines the width and length of the green tiles.

The variability of the batch wetting process itself, caused by changes in raw materials moisture content, weighing inaccuracies, changes in environmental conditions, segregations, etc., makes it difficult for all the batches processed in the mixer to attain the same moisture content. This makes it necessary to have routine mixing water controls in order to make sure that this variable remains constant. The operator usually performs discontinuous moisture content measurements on the feed belt and regulates the water feed flow rate to the mixer in order to attempt to keep the moisture content of the plastic mass constant. At the same time, extruder consumption, mixer consumption, and extruder die pressure are periodically verified, since these variables are directly related to the consistency of the mass.

For example, if the materials feed has a higher moisture content than the desired moisture content and the water flow rate is not changed, the moisture content will exceed the setting value of 17% and consumption, measured as motor power intensity, of both mixing and extrusion, will decrease, since a lower mass consistency will oppose less resistance to mass flow. Faced with this situation, the operator must act to reduce the water content since, otherwise, as the dimensions of the green tiles remain constant owing to the presence of an automatic cutter adjustment device, the change in mixing water will lead to a change in drying shrinkage, set out further below, which will result in a dimensional change of the end product. If the change in water content is too great, the variation in fired tile size can put the process outside the tolerances of the working calibre.

2. OBJECTIVE

The present work pursued two aims. First, to study on a laboratory level the influence of the mixing water on the different properties of the formed bodies, basically their drying shrinkage and firing shrinkage, with a view to identifying the maximum variation range that this variable could be allowed to display in order to maintain a targeted dimensional stability in the end product. Secondly, to analyse the tile extrusion stage on an industrial level in order to validate the laboratory results and to implement an automatic mixing water addition control loop that would keep the end size of the fired tiles within a pre-established variation range.

3. MATERIALS AND METHODOLOGY

The work was conducted with a composition of the type customarily used in manufacturing single-fired extruded stoneware tile. The study of the influence of the mixing water on the behaviour and properties of unfired and fired pieces was carried out on parallelepiped test pieces formed in a laboratory extruder with different mixing water contents.

The tests conducted to characterise the behaviour of the formed test pieces are described below [1]:

- Determination of the consistency of the plastic mass by measuring the force needed to introduce a punch with a conical end into the test pieces.
- Determination of the mixing water by, first, drying the test pieces at room temperature for 24 hours, followed by drying in an oven at 110ºC to constant weight.
- Measurement of drying shrinkage and dry bulk density by means of the mercury displacement method.
- Firing of the test pieces in a laboratory kiln at a peak temperature of 1200ºC.

- Measurement of linear shrinkage and fired bulk density by the mercury displacement method.
- Determination of water absorption by measuring the weight gain of the fired test pieces after immersion in boiling water for two hours.

The industrial trials were carried out in an industrial extruder (see scheme in Figure 1) used for manufacturing extruded ceramic tiles of different sizes. The extruder consisted of an auger coupled in series to a preceding screw mixer.

The extrusion system under study was equipped with a data logging system in which the electric signals that corresponded to different variables of the extrusion process, measured with instruments already fitted in the machine, were centralised, as well as others that were specifically installed for the study. In particular, the electric signal from the pressure transducer located in the extruder die, extruder and mixer motor intensity, extrusion and mixing speed, and the speed of the conveyor belt powder feed to the system were measured. A proportioning pump, which allowed the flow rate of the water input to the mixer to be accurately regulated, and an electromagnetic flow meter for measuring this flow rate were also added to the instruments.

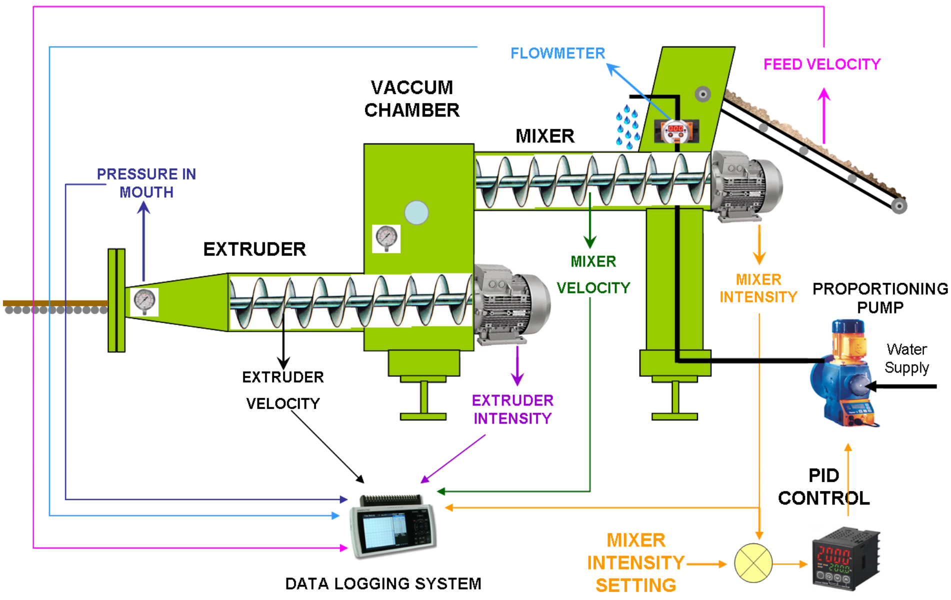

Figure 1. Schematic illustration of the industrial extruder used in the study and instruments fitted to measure the variables.

In the last part of the study, using the foregoing results, an automatic control system was implemented for regulating the quantity of water added in the mixing to keep the mixing intensity steady. This was done by installing a PID controller which, using a mixer intensity setting, acted on the installed proportioning pump, modifying the water feed flow rate and thus keeping mixing intensity constant [2].

4. EXPERIMENTAL RESULTS

4.1. Influence of mixing water on test piece properties

The variation of drying shrinkage, consistency, linear shrinkage and water absorption with mixing water content is plotted in Figure 2. The variation of dry bulk density and fired bulk density of the test pieces with mixing water is shown in Figure 3. It may be observed that, in every case, the variation of test piece properties as a function of mixing water fitted a straight line in the studied range.

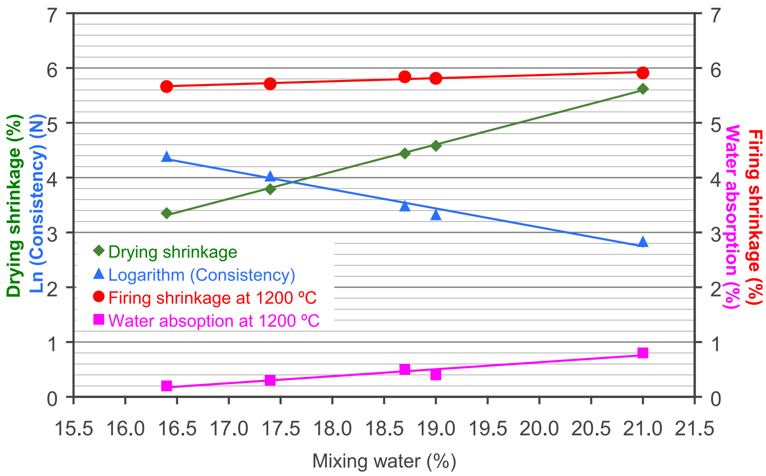

Figure 2. Variation of drying shrinkage, firing shrinkage, consistency and water absorption with mixing water.

As may be observed (Figure 2), the increase in mixing water led to a significant reduction in the consistency of the plastic mass. In effect, at the working water contents, an increase in paste moisture content led, fundamentally, to a rise in so-called 'shrinkage water', this being the water that is located between the solid particles of the plastic mass, which separates them to a greater or lesser degree, depending on the quantity of water. In this sense, as a greater water content reduces the friction between solid particles, the consistency of the plastic mass decreases with relation to a deformation. The same occurred with the increase in the drying shrinkage of the material observed in the tests. A greater spacing between the particles, owing to the existence of a greater quantity of inter-particle water, led to greater shrinkage when that water was removed.

The reduction in consistency of the plastic mass when moisture content increased in turn facilitated plastic flow in the extruder, reducing the pressure in the extruder die and thus the compactness of the unfired pieces (Figure 3).

The greater porosity of the unfired pieces at high moisture contents, related to the reduction in dry bulk density, decreased fired bulk density and increased linear shrinkage of the fired pieces. Finally, the greater porosity of the fired pieces raised water absorption as the mixing water was increased.

It may be observed that the mixing water hardly affected the firing shrinkage of the pieces; however, it influenced drying shrinkage very significantly. This indicates that the differences in tile sizes (calibres) stemmed mainly from the variation of drying shrinkage produced by swings in the mixing water.

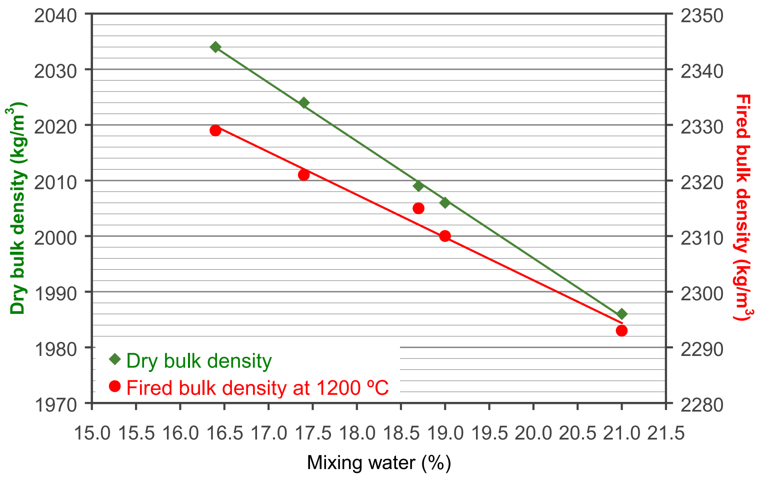

Figure 3. Variation of unfired and fired densities with mixing water.

The experiments performed showed that, of the dimensional changes that took place during the extruded tile manufacturing process, the variation of drying shrinkage with mixing water was greater than the variation of firing shrinkage. As figure 2 shows, increasing the water content from 16,5% to 21% only raised the linear shrinkage of the pieces by 0,2% (from 5,7% to 5,9%); in contrast, drying shrinkage underwent a variation of 2,2% (from 3,4% to 5,6%).

Size	Green size (mm)	Dry size (mm)	Fired size (mm)	Firing shrinkage (%)	Mixing water (%)
- 1,5 mm	722,5	696,5	663,5	3,7	17,2
NOMINAL	722,5	698,0	665,0	3,5	16,8
+1,5 mm	722,5	699,5	666,5	3,3	16,4

Table 1. Calculation of the allowed maximum variation of mixing water in order to keep end product size within the same calibre. (Tolerance of ± 1,5 mm).

Therefore, though linear shrinkage in firing was the dimensional change of greatest magnitude, it depended very little on water content, whereas drying shrinkage was the parameter that most influenced the dimensional stability of the fired pieces. The drying shrinkage and mixing water of an industrial piece with a nominal fired length of 665 mm, and two pieces with sizes corresponding to the limits of the working calibre (tolerance of ±1.5 mm) are calculated in Table 1. The table shows that only a maximum variation of ±0,4% in the mixing water can be allowed in order to keep the size of the pieces in the same calibre, hence the importance of this variable in process control.

4.2 Automatic extrusion control

In view of the results obtained on a laboratory scale, it was decided to implement a control loop on an industrial level like the one described in section 3. After a series of preliminary trials in which the system operating parameters were optimised with regard to both data logging and the adaptation of the controller parameters, experiments were carried out on an industrial scale to evaluate the operation of the implemented automatic control loop. These experiments allowed comparison of automatic with conventional (manual) operation control of the extrusion process. In both situations, the trials consisted of monitoring the different process variables using the fitted instruments and obtaining the end size distribution of the fired pieces formed during the analysed time [3].

4.2.1. Selection of the control variable

Although the laboratory-scale trials showed that mixing water content was the variable to be kept constant during the extrusion process, in industrial practice, it is very difficult to measure this variable continuously. Although certain studies report the usefulness of infrared moisture content sensors for measuring this variable on particulate materials, and even on ceramic bodies obtained by pressing [4], there is no evidence of the validity of these instruments for making moisture measurements on bodies obtained by extrusion or on powders with water contents above 15%. Preliminary experiments highlighted the difficulty of determining the moisture content of freshly extruded bodies for various reasons (surface drying, ambient humidity, light reflections, etc.). It was, therefore, decided to use a control variable that was more readily measurable but that was directly related to the water content of the mass. The possible remaining control variables included pressure in the extrusion mouth, extruder intensity, and mixer intensity.

In order to select the control variable, a series of industrial trials were conducted that allowed the changes in the water feed flow rate to be correlated with the other variables. These trials consisted of producing a step change in the water flow rate and recording the resulting variation in the other system variables. The evolution of pressure, mixer intensity, and extruder intensity for one of these experiments is plotted, on adapted scales, in Figure 4.

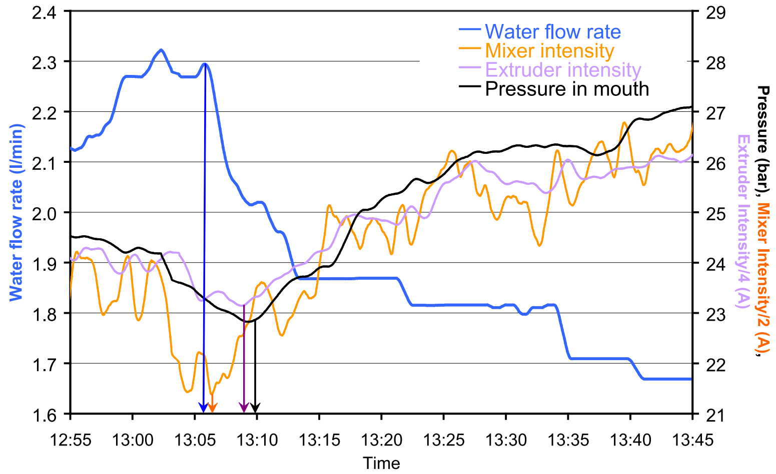

Figure 4. Evolution of process variables with relation to a step change in the water flow rate.

The blue arrow indicates the start of the step and the other arrows indicate the moment at which each measured variable changed its trend as a result of the step produced in the water flow rate. In view of this graph, it may be noted that extruder intensity and pressure were variables that swung less than mixer intensity, which could have been due to the greater heterogeneity of the plastic mass in the mixer and to its small dimension. Indeed, though the plastic mass had been subjected to a preliminary vacuum stage that provided it with its consistency and definitive homogeneity in the body of the extruder, during mixing there is a great amount of air between the agglomerates making up the plastic mass. This made the mixing dynamics more oscillating than the extrusion dynamics. Despite the greater smoothness of the pressure and extrusion intensity signals, their response to the change in flow rate was slower than that of mixer intensity. Thus, when the flow rate decreased, mixing intensity began to rise (owing to the increased consistency of the mass) in hardly a minute after the change, whereas extruder intensity took about 3 minutes and pressure about a minute more than extruder intensity. It was decided, therefore, to use mixer motor intensity as the control variable, performing a previous filtering and taking the precaution not to increase response time excessively.

4.2.2. Conventional (manual) control

The evolution of the mixing intensity and water feed flow rate to the mixer for a full production day, working in manual mode, is plotted in Figure 5. It may be observed that, at the start of the day, manual control by the operators of the facility managed to keep mixing intensity at about the pre-established setting value of 56 A. However, after 11:00 h the control actions performed, based on the discontinuous measurements made by the operators, did not allow the mixing intensity to be situated at the setting value.

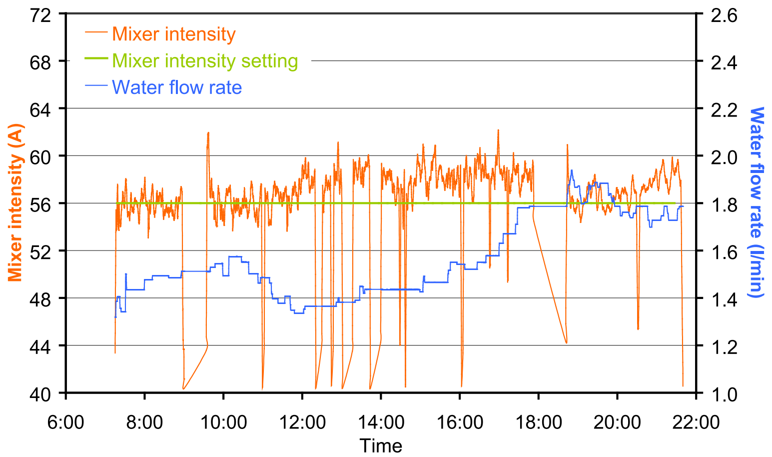

Figure 5. Evolution of mixer intensity and water flow rate for a complete production day with the manual system.

Only after 7 hours continuous production was it possible to establish the initial working conditions again, albeit only for a short time, as may be observed, since after 20:00 h mixing intensity increased again despite the control actions performed by the operators.

After monitoring the operating variables at extrusion level, the classification data were taken of the fired tile sizes for the analysed time. The resulting tile size distribution is plotted in Figure 6. It may be observed that this distribution, in addition to not having an average size centred in a given calibre, displayed a variability that exceeded the required calibre tolerance (3 mm) of the end product. That is, even if one had a production with an average size centred in one calibre, the scatter produced by the production process control mode itself would not allow assurance of the same calibre for all the resulting tiles.

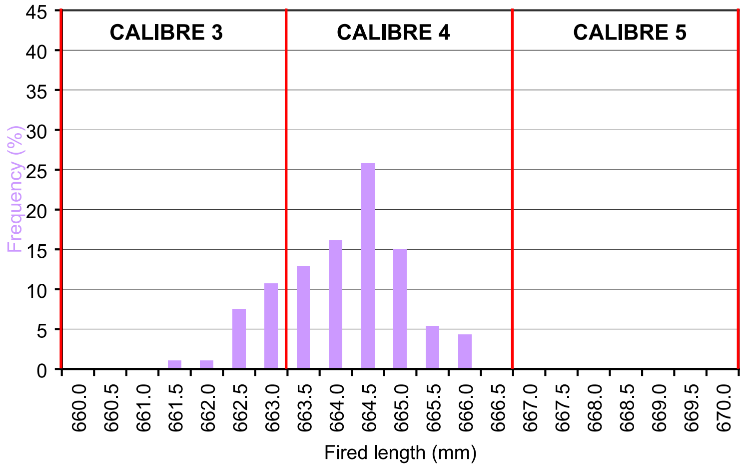

Figure 6. Tile size distribution for the period analysed with the manual control system.

4.2.3. Automatic Control

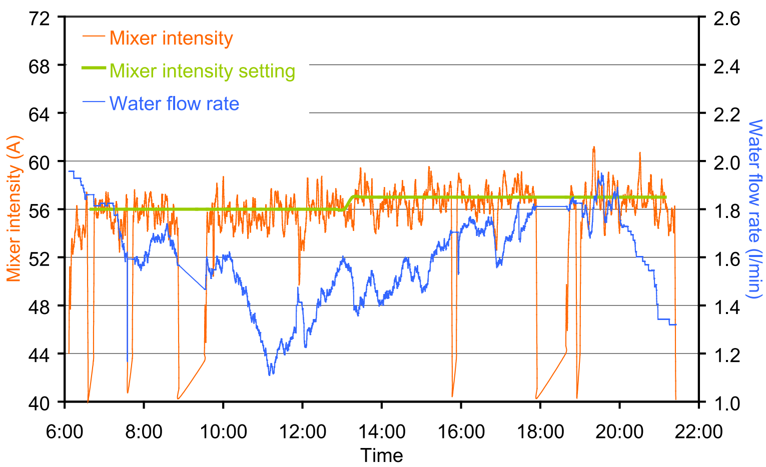

Figure 7. Recorded signal of mixing intensity, setting, and variation of the added water flow rate with automatic control.

The evolution of mixer intensity and water flow rate for a complete production day, working in the automatic mode, is plotted in Figure 7. Initially, system start-up took place manually from 6:00 h to 7:00 h, until optimum operating conditions were achieved. After this, all control actions to keep the mixing intensity constant were performed continuously and automatically.

For operational reasons, set out further below, at about 13:00 h a modification of the intensity setting took place. It may be observed that, unlike what happened under manual control when the control actions were performed discretely and discontinuously, the control action in the automated system adapted much more accurately to process needs. The system managed to hold the mixer intensity setting, even when a slight change was made to its value, at which the water feed flow rate was appreciably modified (from 1,9 l/min to 1,1 l/min).

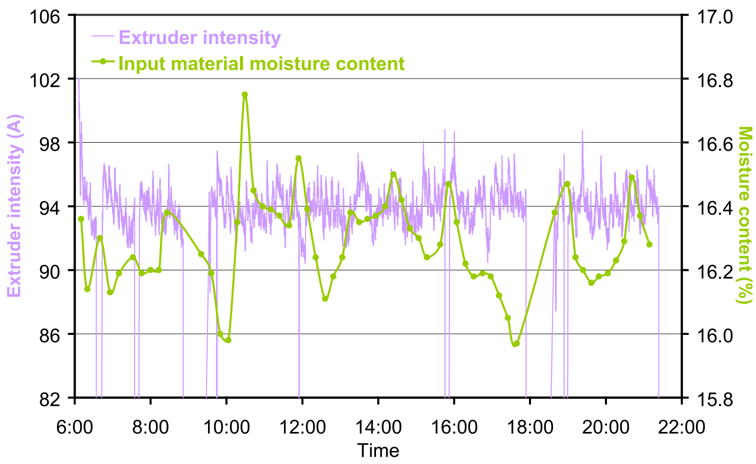

Figure 8. Evolution of extruder intensity and mass moisture content at the mixer entry with automatic control.

In order to evaluate the effect of the control system on the process, the moisture content of the mass at the mixer entry and the extruder intensity during the same period of time as that shown in Figure 7 were monitored The results are depicted in Figure 8. It may be observed that at about 10:30 h an important increase occurred in mass moisture content at the mixer entry, from 16 to 16,8%, in response to which the control system lowered the water feed flow rate from 1,6 to 1,1 l/min (Figure 7).

As a result of this control action, mixer intensity remained at about the setting value, while extruder operation was optimum at all times. Figure 8 shows that the control actions allowed extruder intensity to be maintained within a margin of variation of ±2 A throughout the entire time. Extruder motor intensity and the extruder die pressure recorded by the pressure gauge during the studied period have been plotted together in Figure 9. The two signals are observed to be proportional, which explains the observations performed on the basis of the laboratory tests. That is, a reduction in the moisture content of the plastic mass raised consistency, which translated into a rise in extruder intensity and increased pressure recorded in the extruder die.

It should be noted that changes in mixing, extrusion, or feed rates lead to changes in the dynamics of the process, which require adjustment of the mixing intensity setting as a function of these changes. Thus, for example, when working in the automatic mode, if the feed rate rises, the quantity of materials that the mixer needs to process is greater, leading to increased mixing consumption.

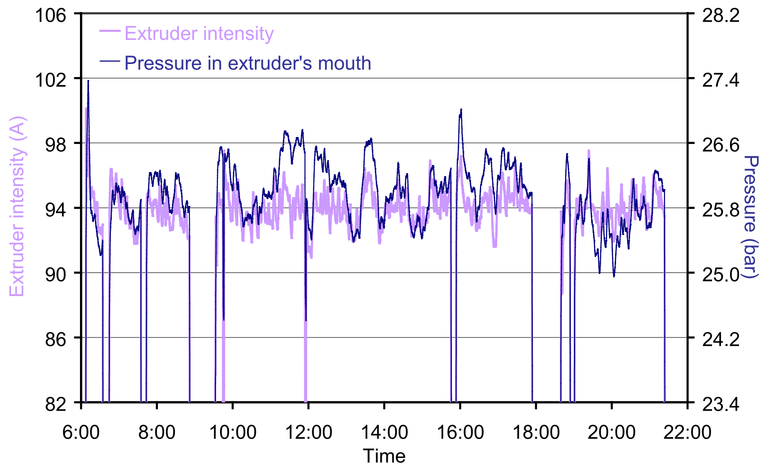

Figure 9. Intensity recorded in the extruder together with the pressure signal in the extruder die with automatic control.

In response to this increased consumption, the control system injects a greater water flow in order to attain the pre-established setting value, the plastic mass thus acquiring a higher moisture content than the targeted content. This means that, if the quantity of materials fed to the mixer is increased, it is necessary proportionally to raise the mixing intensity setting.

The evolution of the materials feed rate, extruder rate, and mixer rate, for the analysed period of time in the automatic mode, expressed as a working frequency of the respective driving motors, is plotted in Figure 10. It may be observed that, for production reasons, at about 12:00 h an increase in the materials feed rate occurred.

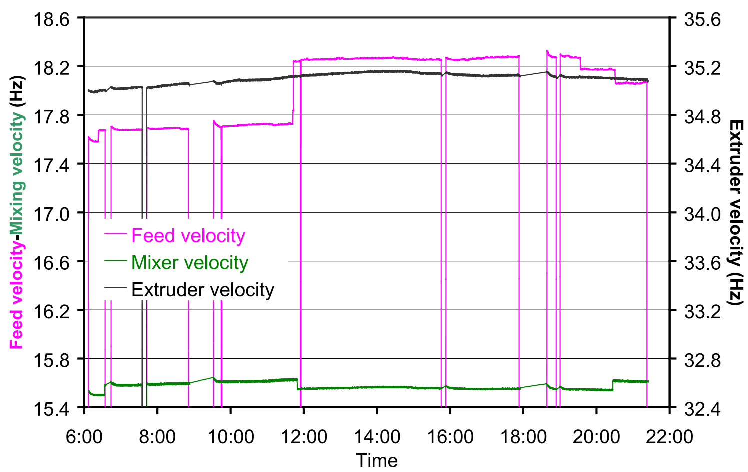

Figure 10. Evolution of the feed, mixing, and extrusion rates during the period of time analysed in the automatic mode.

In order to offset this increase in velocity, it was necessary to raise the mixing intensity setting in 1 A, as may be observed in the graph in Figure 7.

Finally, the frequency histogram of the size distribution of the tiles formed during the period of time analysed is depicted in Figure 11. It shows that, unlike what occurred during the period of time analysed in the manual mode, all tiles were within the desired calibre. The tile size distribution was slightly shifted towards the left, within the centre calibre tolerance, which indicates that the mixing intensity setting must have been slightly higher than that programmed in the PID controller from the outset.

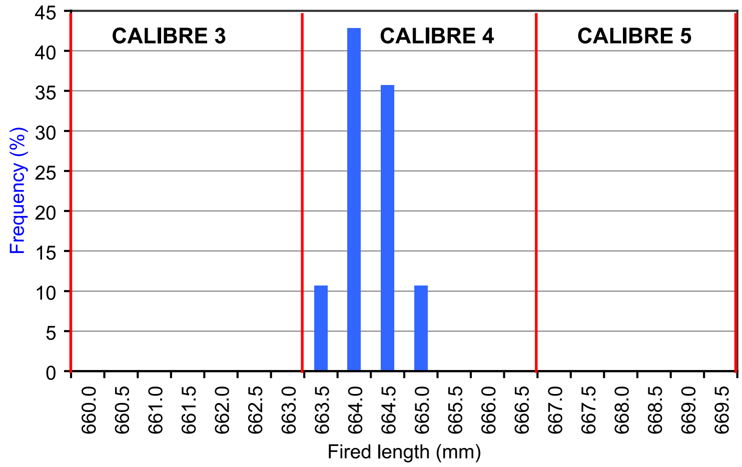

Figure 11. Tile size distribution in the period of time analysed with the automatic control system.

In spite of this it may be concluded that the control system allowed the scatter in tile size distribution to be reduced from the ±2,25 mm obtained with manual control to just ±0,75 mm. That is, with relation to a calibre tolerance of ±1,5 mm, the control system enabled the scatter of the distributions to be reduced to half this tolerance.

5. CONCLUSIONS

The mixing water of the plastic mass is a key variable in the ceramic tile extrusion process because it directly affects the dimensional changes that the tile undergoes during processing.

The variations in drying shrinkage related to changes in the water content of the plastic mass are the main source of the defects associated with lack of tile dimensional stability.

An automatic control loop of the extrusion operation was implemented which, by acting on water proportioning in the mixing, allowed extrusion intensity to be kept constant. It was verified that, for this measurement to be efficient in keeping tile end size steady, in addition, the materials feed to the mixer must be kept constant or the mixer intensity setting must be judiciously modified.

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