ON-LINE MEASUREMENT IN REAL TIME OF TILE MOISTURE AT THE DRYER EXIT BY RADIO FREQUENCY

J. C. Jarque[(1)], V. Cantavella[(1)], C. Segarra[(1)], G. Mallol[(1)], B. Cabrera[(2)], F. Gascón[(2)]

[(1)]Instituto de Tecnología Cerámica (ITC)
Asociación de Investigación de las Industrias Cerámicas
Universitat Jaume I. Castellón. Spain
[(2)]AZTECA, S.A.

1. INTRODUCTION AND BACKGROUND

The residual moisture contained in green ceramic tile bodies at the dryer exit conditions the immediate and subsequent mechanical behaviour of the tiles. To avoid breakage of these ceramic bodies and, simultaneously, to ensure uniform tile mechanical behaviour during subsequent processing, it is essential to assure low residual moisture in the bodies, which shall, in addition, be uniform and steady among the different tiles made. Obviously, to achieve this it is necessary to have a reliable on-line measurement method in real time of the residual moisture in these pieces at the dryer exit.

This on-line measurement of tile residual moisture content would enable estimating tile mechanical behaviour at the dryer exit, under constant density and compositional conditions.

Among the non-contact methods used for on-line measurement of moisture content in a solid, infrared radiation is the only non-contact measurement used in production lines in the ceramic sector. Note that the measurement made is practically superficial, since ceramic materials are opaque to infrared radiation, and a measure of the moisture of total tile volume is not obtained.

However, microwave and radio frequency instruments can measure the total tile moisture content, since penetrating measurements are involved, which are not based on reflection. For this study we have selected radio frequency, because the instrument required is simpler to install, cheaper and because unlike microwaves no electromagnetic screening system is needed.

The measurement of moisture by radio frequency is based on the measurement of the dielectric value of the product, using an electric radio frequency field. The instrument comprises a number of emitters and a receiving antenna that measures the increase in signal produced by the water found in the field of radio frequency waves (figure 1).

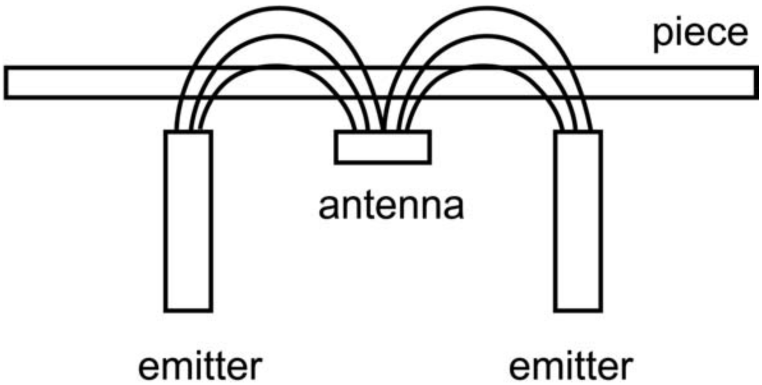

Figure 1. Scheme of radio frequency measurement

The dielectric value of the product or piece is a function of its dielectric constant (which increases considerably with water content) and of the length of the flow lines that pass through it. For this reason, it is very important to keep the distance between the instrument and the piece, and the thickness of the piece, fixed (practically constant for a given model in industrial production).

2. OBJECTIVE AND SCOPE

The objective of the present study has been, first, to examine the technical feasibility of using radio frequencies for on-line measurement of ceramic tile moisture content at the industrial dryer exit.

Secondly, after proper on-line measurement of tile moisture content at the dryer exit has been verified, it will be attempted to establish a relation between tile moisture content and mechanical strength.

3. FINE-TUNING AND CALIBRATION OF THE MEASUREMENT ASSEMBLY ON A PILOT PLANT SCALE

A Sensortech, model ST2200A, radio frequency measurement instrument was installed in the glazing line of the ITC pilot plant (figure 2). The firm Azteca supplied a series of industrial ceramic tiles, pressed under standard working conditions (9.6 mm thick, bulk density of 2060 kg/m^3 and moisture content of 5.5% on a dry basis) to perform a preliminary study in the pilot plant with the equipment. The 41x41 cm tiles (the size usually made in the line in which it was planned subsequently to perform the industrial trials) cover the 30 cm measurement field of the radio frequency equipment.

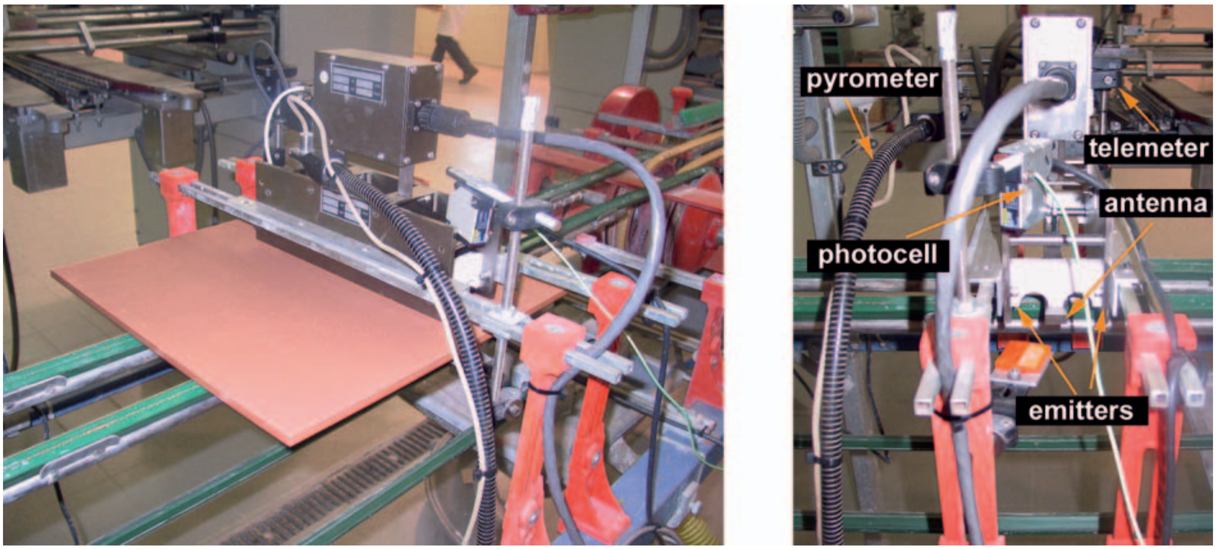

Figure 2. General view of the radio frequency instrument measuring tile moisture content at ITC

The Sensortech ST2200A instrument operates on the principle of dielectric determination. In order to measure the dielectric value of the material, it is necessary normally to place the material between two electrodes, but this instrument uses a configuration that allows setting the emitter and receiver in the same plane. Figure 2 (right) shows the receiving antenna and the two emitters. The instrument reading is a function of the value of the dielectric constant of the wet material and this reading can be related, by the relevant calibration, to tile moisture.

In order to study tile moisture measurement, in addition to the Sensortech 2200A equipment, other items were also incorporated: a pyrometer, telemeter, photocell, data-logging card and PC on which the software program was installed that collected the moisture data on-line.

The pyrometer and telemeter signal, in addition to the instrument reading, were then logged to obtain simultaneously the values of tile moisture, temperature and distance between the tile and the sensor, over time.

The photocell detected the passage of the tile, thus initiating data acquisition, saving these data to a file. This file was created from the data obtained after treating the signals with the program designed by ITC.

The following section describes the variables studied in the pilot plant before the equipment was installed in the industrial production line. The purpose of this preliminary analysis was to measure the influence of the variables (of the equipment and of the material) on the instrument in order, subsequently, to minimise their influence or take this into account.

3.1. MEASURING EQUIPMENT DISTANCE TO THE TILE

In order to analyse the influence of the distance between the instrument and the tile on the signal captured by the instrument, tests were conducted at three distances: 5, 7.5 and 10 mm. The results obtained are shown in figure 3.

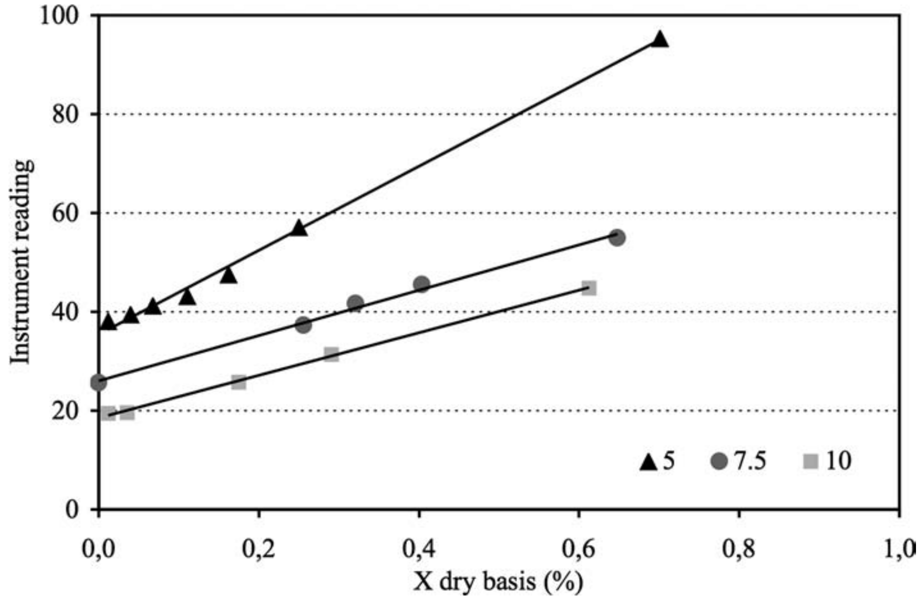

Figure 3. Effect of instrument–tile distance on the reading

It can be observed that as the equipment is moved away from the tile, the reading signal weakens, thus diminishing its sensitivity. Therefore, for the subsequent trials it was decided to place the instrument as close as possible to the tile, at about 5 mm, and to capture the reading of the tile-to-instrument distance on-line with a telemeter. This distance needs to remain constant for the moisture data obtained from the calibration to be correct.

3.2. TILE PASSAGE VELOCITY

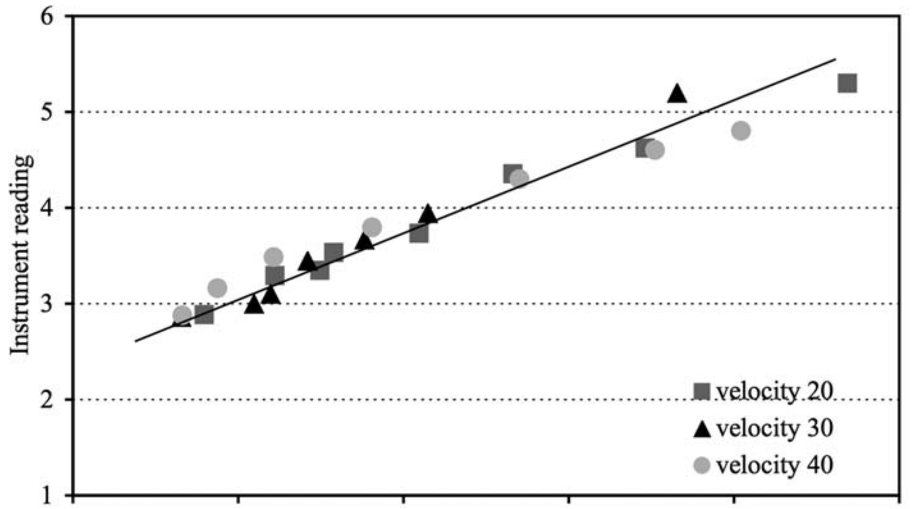

Figure 4. Effect of tile passage velocity on the instrument reading

One of the variables that could not be fixed in the industrial line was belt velocity. For this reason, it was considered advisable to study the influence that tile passage velocity could have on the reading signal by the instrument.

Three different belt advance speeds were tested. It was verified that the reading signal by the instrument hardly varied (Figure 4).

3.3. TILE TEMPERATURE AT THE DRYER EXIT

The temperature of a material is a variable that influences its dielectric constant and which, therefore, can affect the reading and calibration of the instrument. In order to analyse the influence of temperature on the measurement of tile residual moisture (<1 %), two tests were conducted at different tile temperatures. Figure 5 shows the results obtained with tiles at temperatures of 45 ºC and 75 ºC.

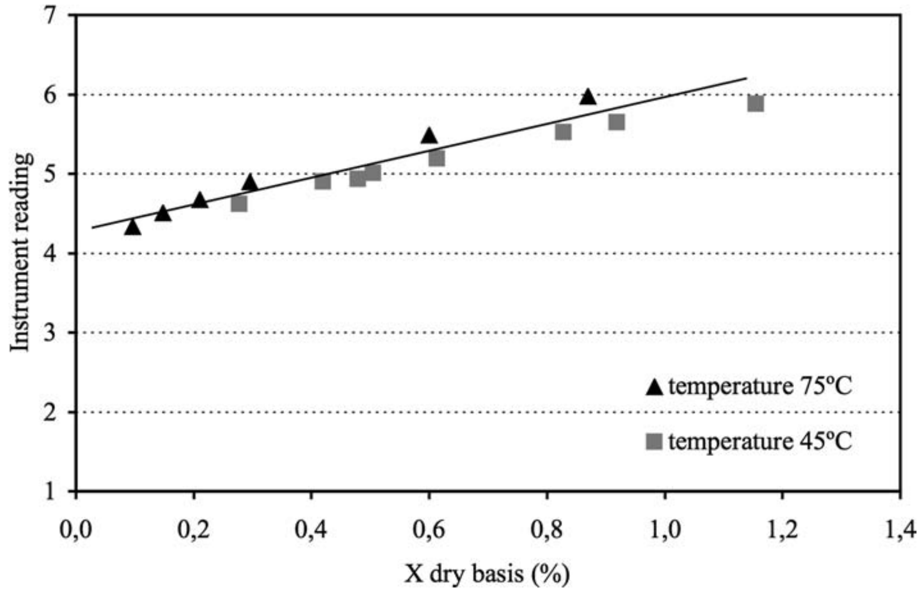

Figure 5. Effect of tile temperature on the instrument reading

The results indicate that a temperature variation of 30 ºC (which is much greater than would usually occur in usual industrial manufacture) produces a relatively small variation in the moisture values, yielding slightly higher values when the temperature is increased. If the temperature data are logged on-line during the industrial measurement, possible deviations in the measured moisture values can be corrected, even though these variations may be considered of little significance.

3.4. TILE THICKNESS

Trials were also run on industrial tiles, varying tile thickness by 1 mm. Figure 6 displays the results. They show that the instrument reading does not change with these variations in thickness.

Industrial tiles do not usually vary in thickness during continuous production; only a changeover of models might involve a drastic change in thickness. This would require recalibrating all the equipment, since a change in thickness would then also alter the distance between the measuring instrument the tile surface.

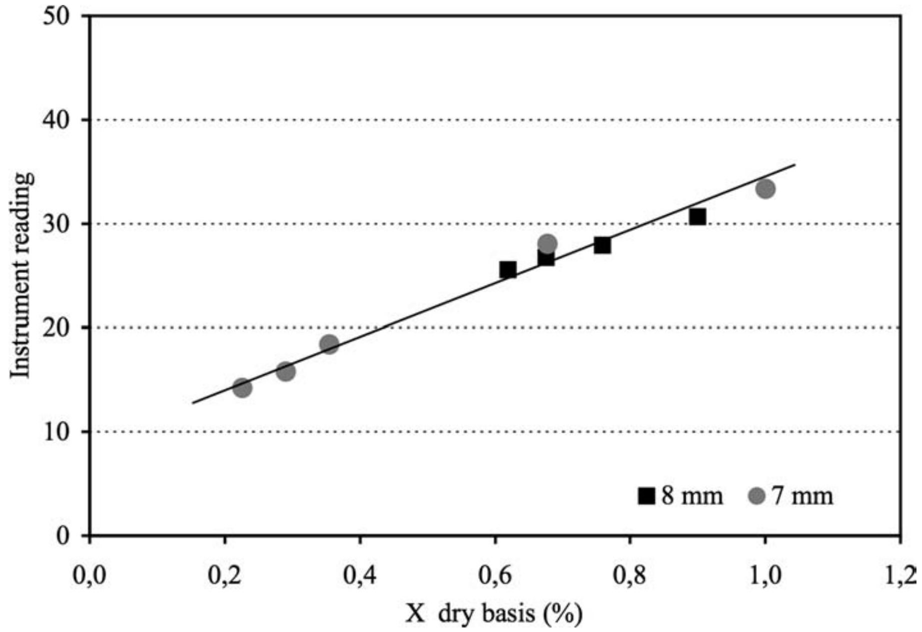

Figure 6. Effect of the variation of tile thickness on the instrument reading

3.5. TILE BULK DENSITY

In order to make tile calibre adjustments in pieces at the kiln exit, it is common practice to modify the tile bulk density values. Moreover, mismatches also sometimes occur when spray-dried powder moisture content is altered at the presses. It was considered of interest, therefore, to establish the relation of the instrument reading to tile bulk density. To conduct this study, pieces were formed with different bulk densities, and then dried to residual moisture contents between 0 and 1%.

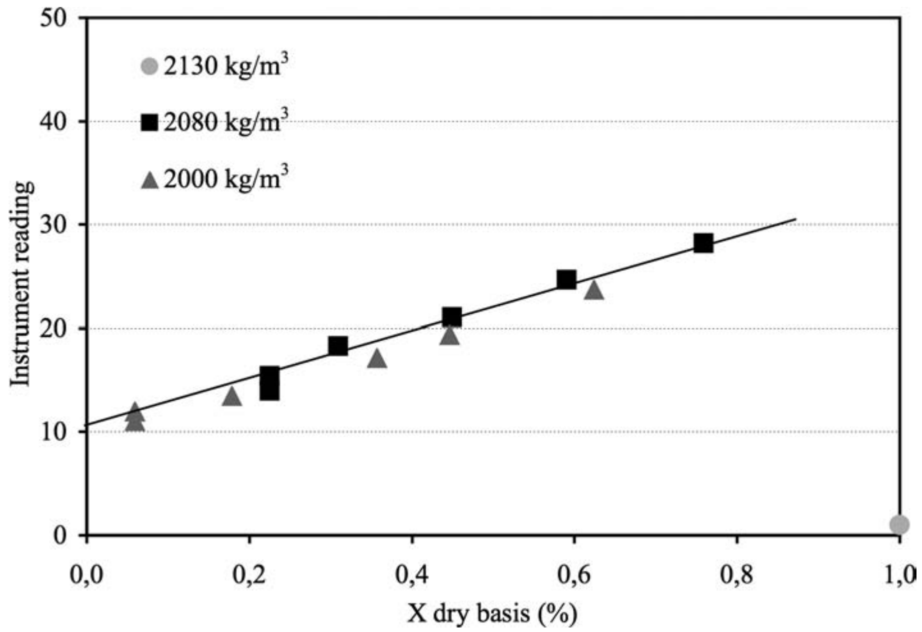

Figure 7. Effect of tile bulk density on the instrument reading

The results (Figure 7) indicate that the instrument reading signal is not sensitive to the small changes in bulk density that can take place in production.

4. INDUSTRIAL STUDY

4.1. INSTALLATION AND CALIBRATION OF THE INSTRUMENT

The equipment was installed at the exit of a horizontal dryer at Azteca. This line produces the same 41x41 cm stoneware tile that had been thermo-mechanically characterised in previous studies. The instrument was set as close as possible to the dryer exit, in a position where there would be no possible interferences in the signal measured, for example by the belt velocity inverter motors.

The instrument was set at a distance of 5 mm from the tile surface. We also installed the pyrometer, telemeter, photocell and data-logging card, together with the PC. A mechanical barrier was placed in front of the equipment, which prevented tiles from superposing themselves as they crossed the equipment.

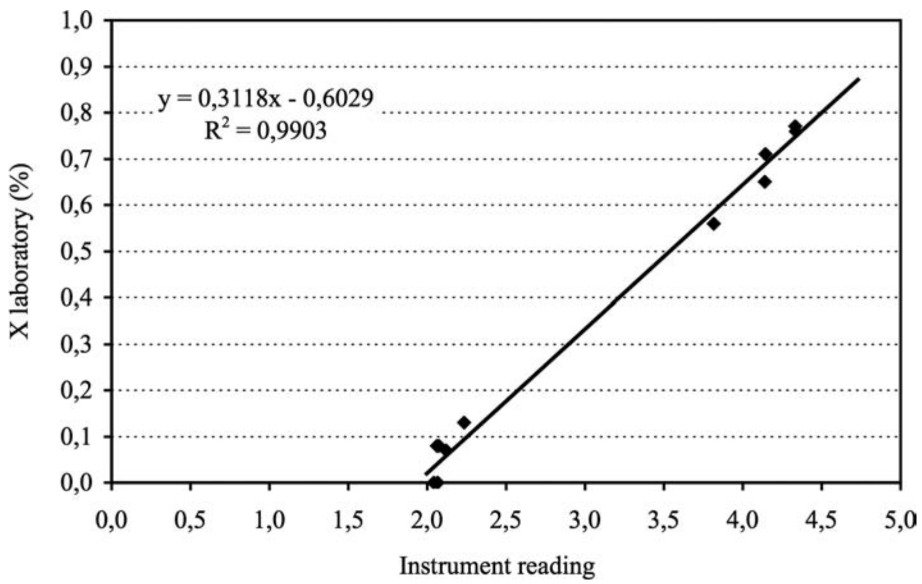

Figure 8. Calibration straight line

After appropriate installation of the instrument and the measuring equipment, the instrument was calibrated. To calibrate the instrument that measured moisture by radio frequency, tiles were taken from different planes at the dryer exit. In addition, to cover the maximum possible range of moisture contents at the dryer exit, several tiles were taken in different working conditions:

- First, in order to obtain low moisture contents, several tiles were taken immediately after a dryer stoppage; as these had remained longer inside the dryer, they were drier.
- Secondly, to obtain intermediate moisture contents, i.e. the usual working moisture contents, several pieces were taken when dryer operation was steady.

- Finally, to obtain higher moisture contents dry tiles were placed on top of tiles that had left the press, just before these entered the dryer. This yielded tiles with higher moisture content, as drying was thus slowed.

The moisture measuring instrument readings were then noted down when the tiles crossed the instrument. Immediately after taking the reading from the computer, the tiles were cut into 5 pieces and placed in hermetically sealed bags. This allowed subsequent measurement of their moisture by the difference in weight on a dry basis at ITC after drying in an oven ($X_{laboratory}$).

The resulting graph and the equation of the fit of the values of $X_{laboratory}$ (%) versus the instrument reading are shown below.

Bulk density (ρ) and thickness (e) were constant in all the sampled tiles: ρ= 2067 kg/m^3, e = 9.6 mm. Figure 8 shows that the fit obtained in the calibration straight line is very good; the fitted equation is:

$$\mathbf{X_r(\%)=0.3118\times Instrument\ reading - 0.6029}$$

Equation 1

4.2. MONITORING AND ANALYSIS OF TILE RESIDUAL MOISTURE CONTENT AT THE DRYER EXIT

For a proper study of dryer operation in regard to tile drying, in addition to the data on distance, temperature and moisture of the tile, we collected the work reports of the plant during the time the study lasted. This was done in an attempt to have the necessary additional information regarding possible alterations in dryer operation (stoppages, changes in setting temperatures, changes in entry moisture, etc.), which could explain real variations in the final moisture of the tiles.

Dryer operation was thus monitored for two months.

In a preliminary analysis of the data logged by the instrument, a data sequence was observed, which was repeated in time. The same sequence was repeated every 15 tiles, which was the number of tiles that were spread over the three planes in the dryer. For this reason, it was attempted to verify this dependence.

In order to assign the moisture corresponding to the 15 pieces located on the three planes (top, bottom and middle), we placed our hand beneath the photocell, so that the reading would give a low value (used as the signal for the start of the passage of controlled pieces) and it was thus possible to establish the position of the tiles across the three planes and in a given plane.

The following graph (Figure 9) shows the position of the 5 tiles in each of the three planes, as well as their real moisture content. The tiles corresponding to the middle plane have higher moistures and exhibit a considerable scatter in moisture. The tiles in the bottom plane have a similar scatter, albeit with lower moisture. In contrast, the tiles in the top plane do not display so much variation in moisture between each other.

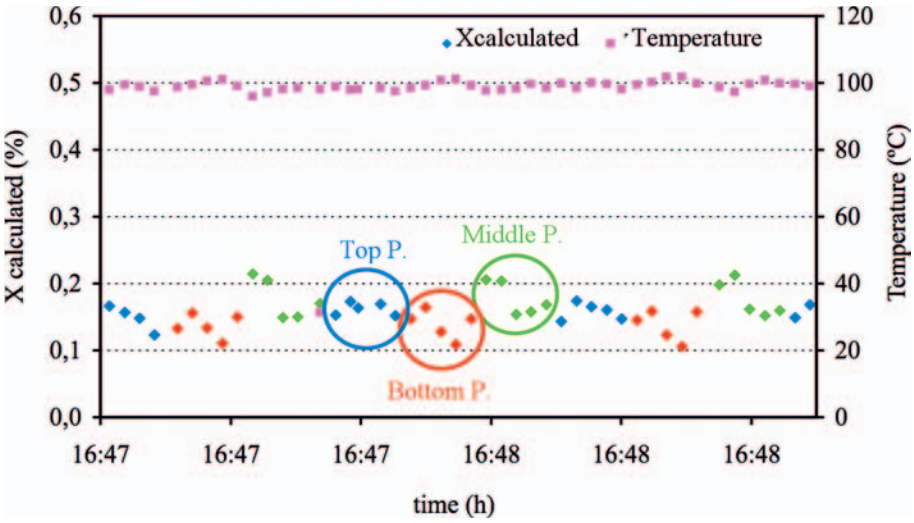

Figure 9. Assignment of tiles to the three planes in the dryer

The moisture measurements exhibit a repetition in time as a function of the plane in which they lie, i.e. the moisture measurement over time depends on the dryer plane in which the tile is dried, and on tile position in this plane.

4.3. MONITORING OVER TIME OF INDUSTRIAL DRYER OPERATION

Treatment of the data collected in the program files, together with the work reports provided by the company, enable interpreting the moisture values of the tiles at the dryer exit. The analysis of the results has been focused on the determination and analysis of the possible moisture gradients between the tiles in the dryer during steady operation and with shutdowns

The following figures show the moisture and temperature values for a selected period of time, in addition to the histogram of the moistures obtained from the statistical data treatment. The moisture that appears in the graphs is tile moisture (% on a dry basis), obtained from the data of the calibration straight line constructed for the instrument.

4.3.1. Steady operation

Figure 10 plots tile moisture and temperature during steady dryer operation for a period of two hours. The moisture values are all observed to lie in a range with an amplitude of 0.3 %.

When the statistical treatment of the data was performed (Figure 11), the frequency histogram was observed to display a Gaussian distribution. The moisture mode was between 0.24 and 0.30 %.

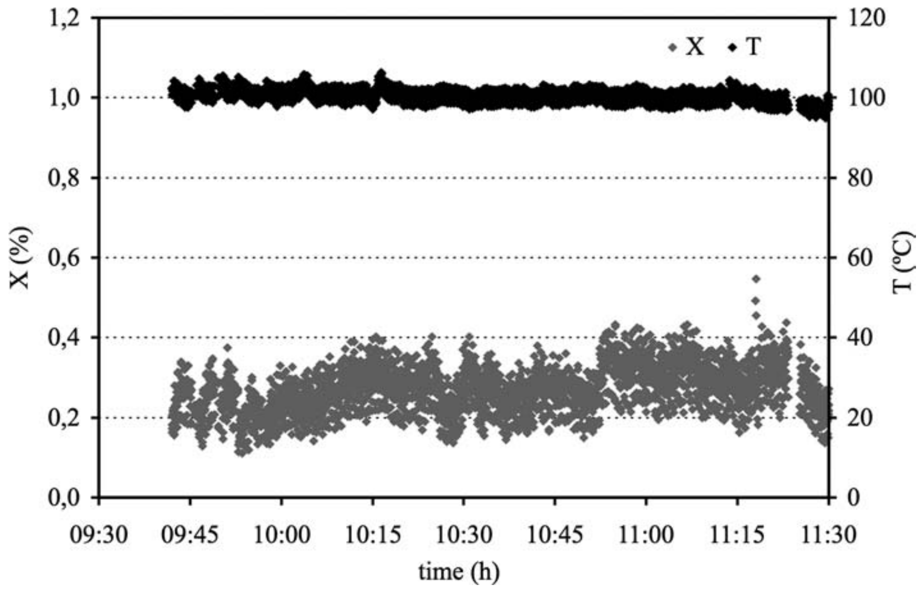

Figure 10. Tile moisture and temperature values during steady dryer operation

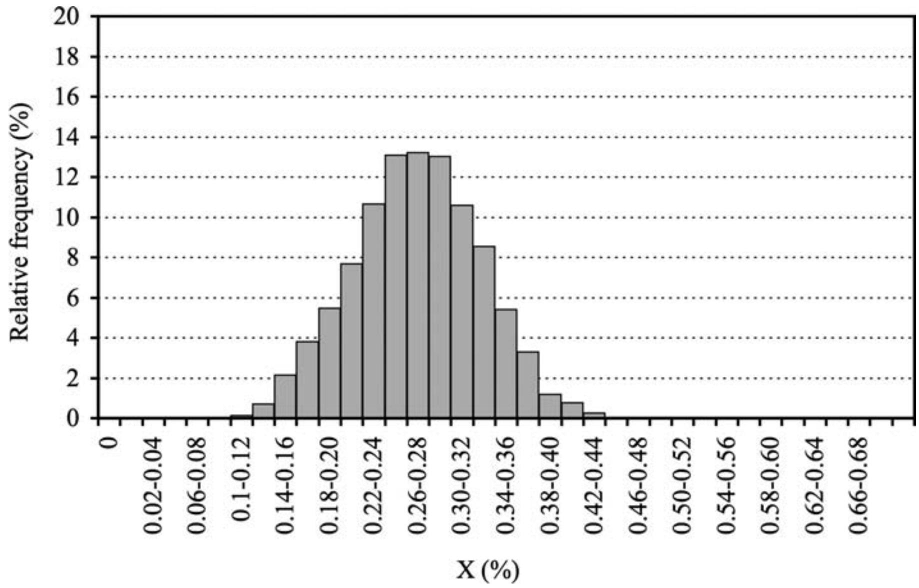

Figure 11. Histogram of tile residual moisture during steady operation

4.3.2. Operation with stoppages

After analysing the small variation in moisture of the pieces observed during steady dryer operation, we also analysed the variation in moisture during dryer stoppages.

For a better interpretation of the variation in moisture after a long shutdown, the data have been extended, taking as the time range the period corresponding to a total of three drying cycles (66 minutes). Figure 12 shows the evolution of temperature and moisture for this cycle.

The graph exhibits three zones in which the moisture displays very different values, which correspond to cycles of 22 minutes (A, B and C). Thus, the first tiles measured after the shutdown correspond to those that were held in the last module of the dryer during the stoppage. After two minutes, we measured the tiles that were in the penultimate module, and so on until completing the first cycle of 22 minutes, section A in Figure 12.

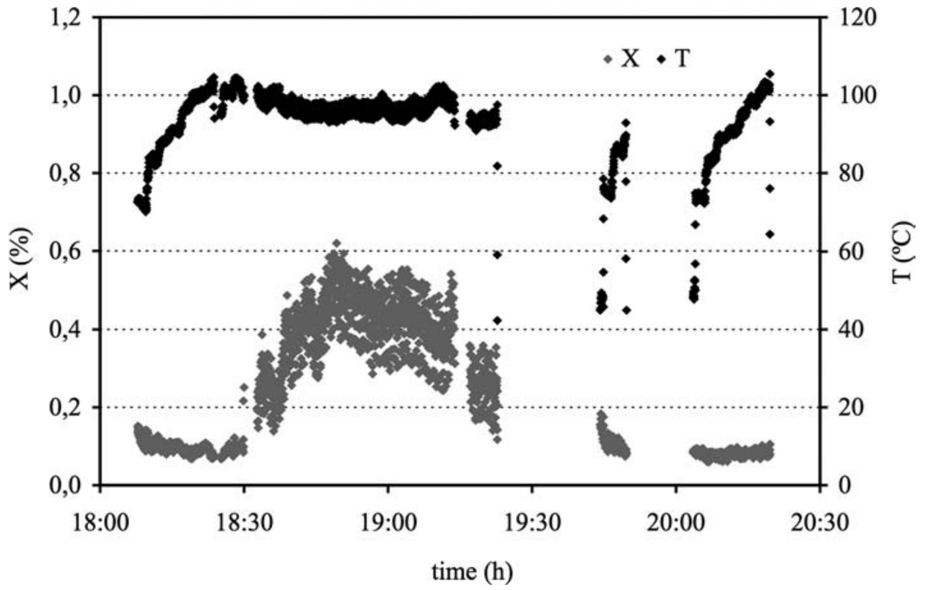

Figure 12. Tile moisture and temperature during operation with long stoppages

The three sections exhibit the following behaviour:

- Zone A: The tiles display very low moisture because they were all pieces that were inside the dryer during the shutdown and, therefore, have had a longer drying time. The initial temperature of these tiles is low, but it increases as time passes and pieces begin to exit that were in progressively hotter zones.
- Zone B: Tile moisture increases little by little until the typical mean residual moisture of steady dryer operation is reached. Tile temperature remains practically constant.
- Zone C: Dryer operation in this zone corresponds to steady dryer operation, but with slightly higher moisture values than usual.

When the moisture values of these three zones are analysed statistically, it can be observed that in zone A there is a very narrow distribution of moistures at very low values). The progressive increase in moisture corresponding to section B involves a curve with a more scattered moisture distribution. In section C, the distribution narrows again, but with higher moisture values.

Joint analysis of all the moisture values in these sections yields a bimodal frequency distribution curve, characteristic of the behaviour of tile moisture at the dryer exit after a long shutdown (Figure 13).

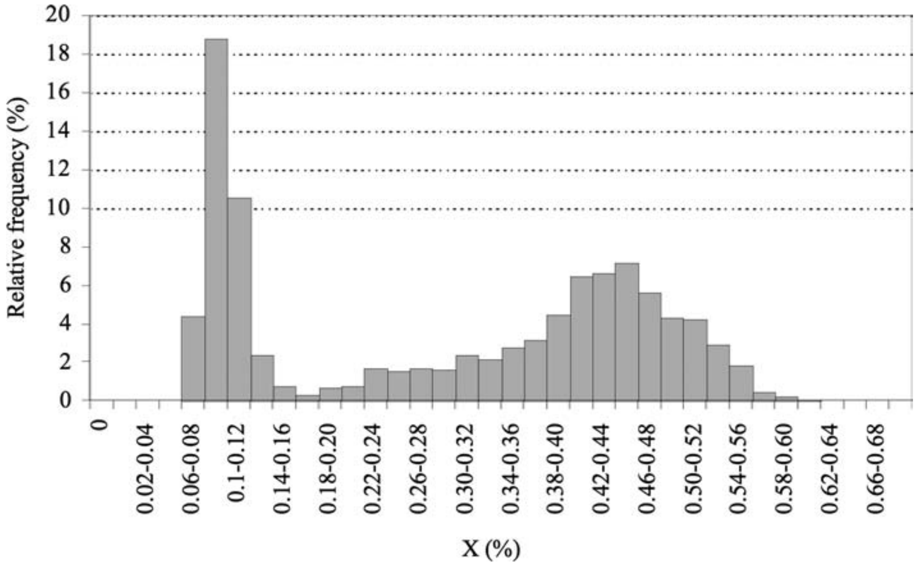

Figure 13. Histogram of overall tile moistures after a long shutdown

Note that after such a shutdown, the low moisture values do not pose a problem, but the high values (> 0.4%), together with other factors that can also appear, could lead to problems of tile breakage due to reduced tile mechanical strength.

4.4. ANALYSIS OF DRIED TILE MECHANICAL STRENGTH

4.4.1. Relation between dried tile mechanical strength and tile residual moisture

In order to undertake the second objective of the study, namely to establish a relation between tile moisture content and mechanical strength, it was necessary to measure the mechanical strength of tiles in the same production line.

As verified in previous studies, in which the mechanical behaviour of ceramic tiles during industrial drying was characterised, dried tile mechanical strength (σ_R) varies as a function of the bulk density (ρ) and pressing moisture (X_p), according to Equation 3.

$$1\text{n}\sigma_R = -14.086 + 1.054X_p + 7.222\rho - 0.477\rho X_p$$

Equation 3

However, note that for the same bulk density, the variation in mechanical strength due to the pressing moisture is insignificant in comparison to the variation undergone with tile residual moisture(X_f < 1%) at the dryer exit (Equation 4).

$$\sigma_R = \sigma_{R0}e^{-b_\sigma X_f}$$

Equation 4

Thus, for low moistures (X_f <1%) (corresponding to high strength values), small variations in residual moisture entail considerable changes in mechanical strength. The decrease in tile mechanical strength with the increase in moisture is due to the parallel decrease in interparticle bond strength with the increased spacing between the solid particles caused by the presence of thicker layers of water.

Therefore, if we assume that tile bulk density hardly changes in the industrial process, the variations in mechanical strength can directly be related to tile residual moisture at the dryer exit.

Mechanical strength was measured in steady operation in two ways:

- *Immediate measurement*: The tile was picked up at the dryer exit after crossing the moisture measuring equipment to determine its residual moisture, and its mechanical strength was measured in the bending test equipment.
- *Delayed measurement*: The tile was picked up at the dryer exit after crossing the moisture measuring equipment and placed in a sealed bag (to keep its moisture from altering). After 24 hours, the tile was removed from the bag, and its mechanical strength was measured in the bending test equipment.

Figure 14 shows the joint values obtained for mechanical strength in the delayed and immediate mode, in addition to the critical mechanical strength value $\sigma_{Rcritical}$ (value below which the company indicated that tile breakage began to become a serious problem).

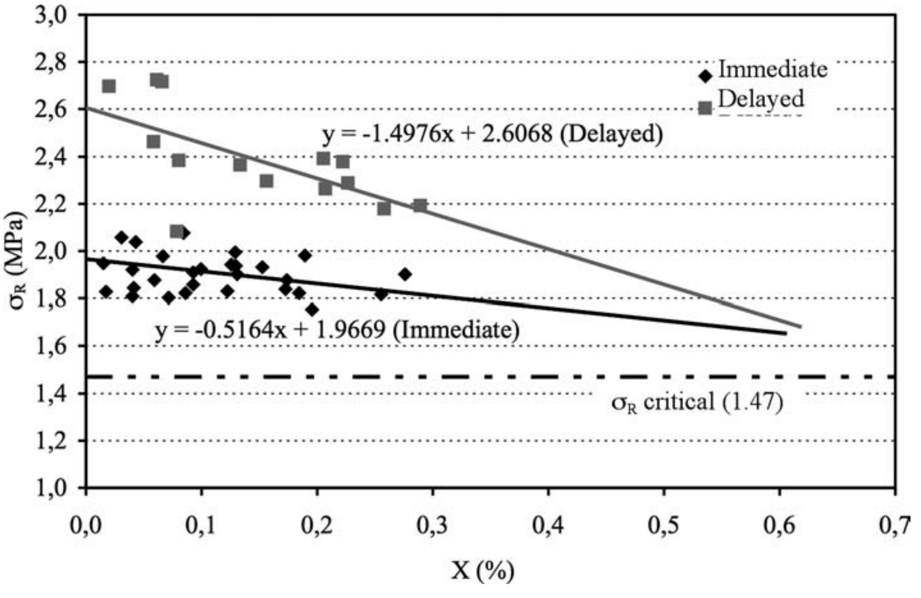

Figure 14. Comparison of mechanical strength in immediate and delayed measurement

The results show there is just a slight decrease in the mechanical strength values in the delayed measurement, when an increase in residual moisture occurs. This could be because the delayed measurement assures more homogeneous moisture throughout the tile, as was also the case with the experimental test specimens in the laboratory used to determine the dependence of mechanical strength on residual moisture (Eq. 4).

However, at the studied moistures, the mechanical strength data from the immediate measurement remained practically constant, without a decrease in mechanical strength when tile moisture increased. The reason for this behaviour could lie in the moisture gradient observed in the tile thickness in the immediate measurements, not found in the delayed measurements, in which the moisture has had time to migrate and/or to spread, giving rise to a more homogeneous distribution. Thus, although the overall moisture of the whole tile is high (0.2%), at the tile surface, where the fracture initiates in the bending test, the moisture is 0%; this then yields a mechanical strength value corresponding to that 0% moisture, and not to the 0.2% moisture.

The difference between the mechanical strength values measured in the two modes could also be influenced by the stresses that are generated inside the piece. These will be greater as heating and drying rates rise. It is quite likely that these stresses are not freed immediately at the dryer exit, owing to the nature of the material. Therefore, tile mechanical strength will increase as residual stresses relax. The tiles measured immediately have no time to relax stresses, so that they display lower mechanical strength values at the same moistures.

The results obtained allow establishing the mechanical strength from the residual moisture, depending on the type of stress to which the tile is subjected. Thus, for the study of breakage in tiles subject to bending stresses (decoration in the flexographic machine) it would be appropriate to obtain the mechanical strength values from the fit obtained in the immediate mode. The mechanical strength values obtained from the fit of the delayed measurement data could be used to analyse the fractures caused by knocks between the tiles.

4.4.2. On-line estimation of dried tile mechanical strength

Analysis of the variation in tile moisture at the dryer exit during steady mode drying and with shutdowns has confirmed the need for on-line measurement of this variable, in addition to obtaining from this, on-line, the variation in tile mechanical strength from the drying process.

Figure 15 shows, together, the values of moisture, temperature and mechanical strength of the tiles over time.

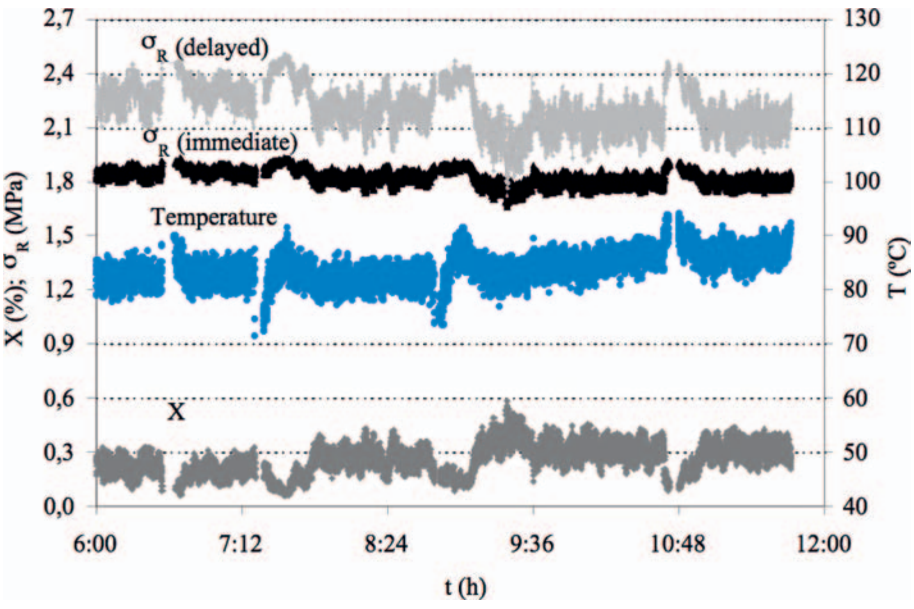

Figure 15. Values of σ_R obtained by calibration together with the X and T of the tiles at the dryer exit

The mechanical strength values have been obtained from the fits performed with the delayed and immediate mechanical strength measurements. The mechanical strength values obtained in the delayed measurements explain the problems of breakages by knocks, whereas the values obtained with the fit of the immediate measurement explain the breakages of tiles subjected to bending stresses. The great advance entailed by the results of Figure 15 is having on-line information of a property of the material, σ_R, directly related to the probability of tile breakage.

5. CONCLUSIONS

The study conducted at the ITC pilot plant and the Azteca industrial facility allows drawing the following conclusions:

- The final moisture content of the tiles exiting the dryer can be measured on-line with a radio frequency instrument, with reliable and reproducible results. The sensitivity of the instrument is sufficient to measure moisture values in ceramic tiles below 1%, and allows obtaining a calibration straight line with very good linear fit.
- The influence of certain variables on the radio frequency instrument reading has been analysed. The analysis shows that tile temperature, thickness, bulk density and speed have no significant affect on the reading. However the distance separating the tile from the instrument does significantly affect the reading, so that this must remain constant during the on-line measurement.
- The instrument operated correctly under industrial conditions, in which it was monitored for a period of two months. Analysis of the tile moisture data recorded during this period shows:
    - The scatter in tile moisture contents in steady dryer operation was small (0.2 %), and a unimodal distribution was obtained.
    - After a long shutdown (> 5 min), the moisture distribution became bimodal, and the scatter in moistures increased considerably (0.5%). One of the highest corresponded to high tile moisture values. This high moisture value could cause problems of tile breakage, owing to the reduction in tile mechanical strength.
- Tile mechanical strength was measured at the dryer exit and related to tile final moisture. This fit allows observing, on-line, the thermo-mechanical behaviour of the tiles from the final moisture data supplied by the radio frequency instrument. This can help avoid tile breakage caused by a decrease in tile mechanical strength when tile residual moisture content increases.

REFERENCES

[1] AMORÓS, J.L.; SÁNCHEZ, E.; CANTAVELLA, V.; JARQUE, J.C. Evolution of mechanical strength of industrially dried ceramic tiles during storage. *J. Eur. Ceram. Soc.*, 23, 1839-1845, 2003.

[2] JARQUE, J.C.; CANTAVELLA, V.; SEGARRA, C.; SILVA, G.; CABRERA, B.; GASCÓN, F. Comportamiento de composiciones cerámicas frente al secado en condiciones industriales. *Ediceram*, 12, 22-41, 2002.

[3] NEGRE, F.; JARQUE, J.C.; MALLOL, G.; SÁEZ, M. Determinación en contínuo y en tiempo real de la humedad del polvo cerámico por atomización. *Técnica Cerámica,* 200, 34-42, 1992.

[4] JARQUE FONFRÍA, J.C. *Estudio del comportamiento mecánico de soportes cerámicos crudos. Mejora de sus propiedades mecánicas.* November 2001 [Doctoral dissertation]