PORCELAIN TILE BEHAVIOUR UNDER CUTTING. RELATIONSHIP WITH RESIDUAL STRESSES

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1. ABSTRACT

In recent years, the ceramic tile industry has developed products with enhanced technical performance and aesthetic qualities, such as porcelain tile. The porcelain tile manufacturing process differs, among other things, from that of porcelain in the duration of the firing cycle, the former having much faster firing cycles (40–90 minutes compared to 15–20 hours). The rapid cooling in the industrial kiln can lead to the generation of residual stresses as a result of the thermal gradient that establishes itself throughout the tile and the tile's viscoelastic behaviour at high temperature. These stresses influence tile mechanical strength and, probably, its behaviour during cutting when the tiles are installed, which materialise in breakage and undesired cutting tracks.

This study was undertaken to examine the influence of residual stresses on porcelain tile behaviour under cutting. To do so, two samples of glazed industrial porcelain tiles that exhibited different behaviour under cutting were selected. Using these industrial tiles, cutting tests were performed and the macroscopic residual stresses were determined by the strain relaxation incremental slotting method (SRSM). The influence of the cooling rate on the arising residual stresses and their effect on tile cutting were also studied.

For the porcelain tile with appropriate cutting behaviour, the residual stress profile in the body was symmetrical and could be fitted by just using the second-degree Legendre polynomial. This was the expected behaviour for homogenously cooled ceramic materials (same cooling rate at the proper surface as at the rib). For pieces with inappropriate cutting behaviour, it was necessary to use more terms of the series, which suggested that cooling had not been homogeneous.

With regard to the influence of cooling, the temperature range in which residual stresses were generated was determined and it was verified that pieces with a greater level of stresses exhibited worse cutting behaviour.

2. INTRODUCTION

The excellent technical performance and aesthetic qualities of porcelain tile [1-3] have allowed this product to be used in a multitude of applications including ventilated façades, indoor and outdoor floorings, urban paving and, more recently, wall and ceiling cladding [4-5].

Porcelain tile mechanical properties stem from the reduction of tile porosity during firing by liquid-phase sintering [6]. This gives rise to tiles with a complex microstructure made up of an abundant quantity of glassy phase which, beside the remaining porosity, contains residual crystalline phases, such as quartz, and newly formed crystalline phases, such as mullite and calcium albite [7].

Porcelain tile installation requires the performance of cuts, insertions, and drilling and, sometimes, the tiles are not cut as intended or they may even break, during or after cutting, whether by dry or wet cutting (Figure 1). These problems have not been observed in other types of ceramic tiles such as earthenware wall tiles and glazed stoneware tile, suggesting this is a specific porcelain tile problem.

Figure 1. *Defective cuts in porcelain tiles. Left: manual cutter; right: insert made with a radial cutter*

These problems are customarily associated with the presence of residual stresses in ceramic tiles. Such stresses can be of two types: the mismatch in body–glaze fit, in which stresses are generated as a result of different thermal expansion between the body and the glaze [8-9], and thermal gradient stresses. The latter are due to a great quantity of liquid phase that is generated in the tiles, together with the high cooling rate, which produces strong thermal gradients across the tile thickness. The different cooling rate that is established between the tile surfaces and the interior of the tile leads to the generation of residual stresses in the finished product [10-12].

Since cutting problems occur in both glazed and unglazed porcelain tiles, this study focuses on the thermal gradient stresses that develop in the body. In the first part of the study, the residual stresses of porcelain tiles with and without cutting problems were determined. In the second part, the influence of cooling on the residual stresses of the body was studied in order to relate their magnitude to porcelain tile cutting behaviour.

3. EXPERIMENTAL

3.1 MATERIALS

The following materials were used to perform the study:

- Industrial fired glazed porcelain tiles. Two samples of tiles were used. The first (POR-B) exhibited appropriate behaviour under cutting according to information provided by the manufacturer, while in the second (POR-M) problems had been detected during dry cutting with a radial cutter. Some characteristics of these tiles are detailed in Table 1.
- Industrial red-firing earthenware wall tiles. As this material customarily exhibited no cutting problems, it was used as a reference.
- Porcelain tile composition made up of 30% kaolinite, 50% albite, and 20% quartz.

Characteristic	Tiles displaying appropriate behaviour under cutting (POR-B)	Tiles displaying inappropriate behaviour under cutting (POR-M)
Body thickness (mm)	8,80	8,90
Glaze+engobe thickness (mm)	0,29	0,23
Bulk density (g/cm^3)	2,333	2,371
Water absorption (%)	0,9	0,1

Table 1. *Characteristics of the industrial fired porcelain tiles.*

3.2. TEST OF BEHAVIOUR UNDER CUTTING

A laboratory test was fine-tuned to evaluate ceramic tile behaviour under cutting. The test is based on the three-point bending method with a view to simulating the behaviour under cutting with a manual cutter of the "Rubi" type. Different configurations were tested, including the force application mode and notch length and depth. Finally the configuration shown in Figure 2 was chosen, as it allowed qualitative differentiation of tiles that exhibited appropriate and inappropriate behaviour under cutting.

To perform the test, test pieces with a 15×15 cm surface area were used, in which a notch was made in the proper surface with a variable nominal depth (between 0,2 and 0,4 mm) and 0,5 mm width. The length of the notch reached the end of the piece and was 150 mm. Figure 2 shows the disc with which the notch was made.

To carry out the test, the pieces were placed with the proper surface upwards symmetrically on a circular steel rod. The force was applied on the top of the piece at both ends by means of a bridge with a separation of 13 cm. The bridge did not exert the force on the total width of the piece, this only being applied at the edge, specifically in an area 3 cm long. This arrangement favoured crack initiation from the notch and allowed crack deviation in the area where no force was applied to be determined.

Five tests were conducted for each piece. These tests enabled the average distance at which the crack departed from the track marked by the notch, the breaking strength, and the maximum strain that the piece exhibited to be determined.

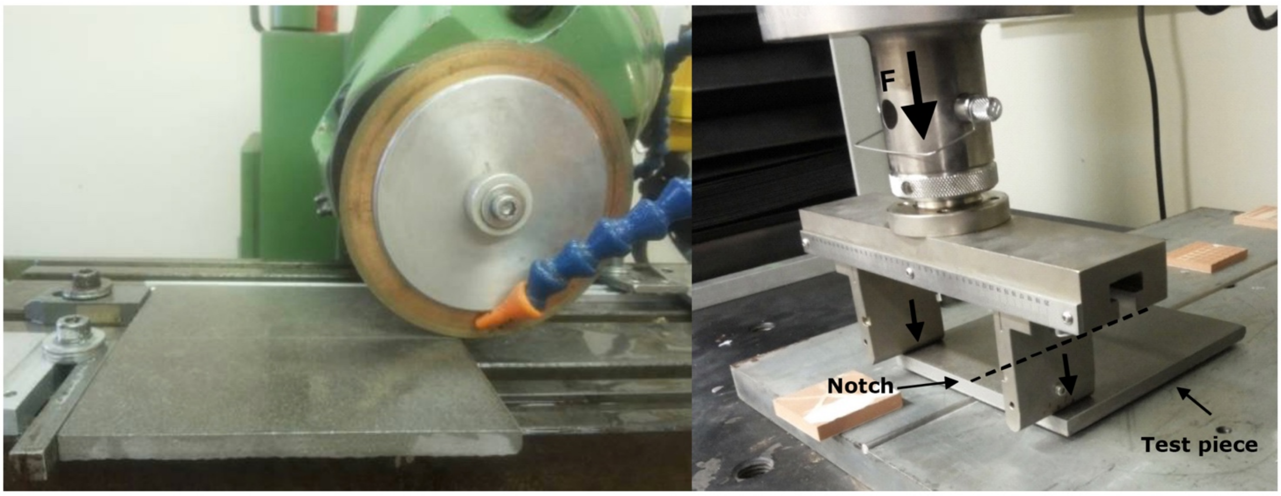
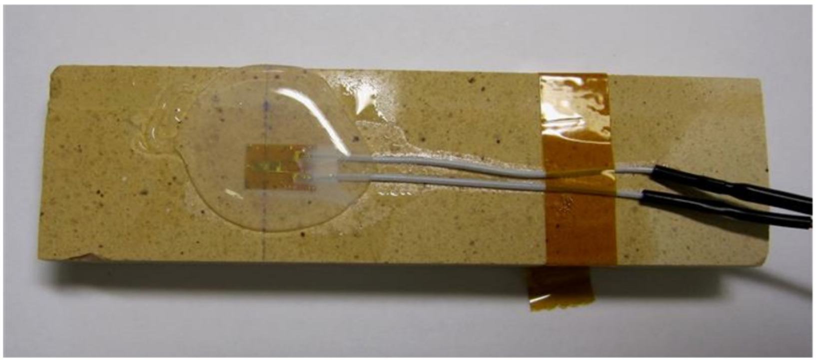


Figure 2. *Disc cutter used in notching (left) and set-up used to cut the pieces (right).*

3.3. MEASUREMENT OF THE RESIDUAL STRESSES

The residual stresses in the body produced by the thermal gradient were measured by the strain relaxation slotting method (SRSM). The method consists of gluing a strain gauge to the bottom of the piece (Figure 3 (top)) and then making slots of increasing depth (a_i) from the proper surface, measuring the strain recorded by the gauge (ε_g) (Figure 3 (bottom)). The tested pieces were prisms of 2×8 cm surface area.



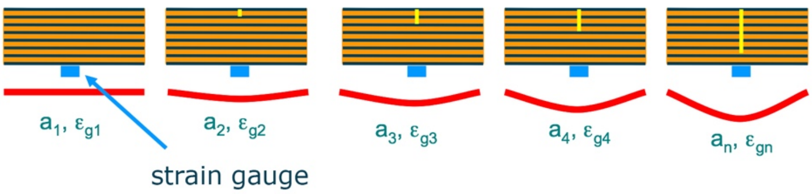


Figure 3. *Detail of the gauge (top) and representation of the SRSM method (bottom).*

In order to be able to calculate the residual stress profile, it is necessary to know the relationship between $\varepsilon_g(a_i)$ and the stress at each point inside the piece. For this, it is useful to use the free strain (ε_f) concept, which is the strain that a point in the piece would have if it were not subjected to any type of stresses (under very slow heating or cooling conditions). Free strain can be written as a function of ζ:

$$\zeta = \frac{2z}{h} - 1 \qquad (1)$$

where z is the position throughout the test piece thickness h.

It is quite common to break down $\varepsilon_f(\zeta)$ into a linear combination of certain basis functions $\varphi_k(\zeta)$ defined in the range [-1,1]. In the calculations made, Legendre polynomials $P_k(\zeta)$ were used as basis functions:

$$\varepsilon_f(\zeta) = \sum_{k=0}^{\infty} \lambda_k P(\zeta) \qquad (2)$$

From this equation, and from the linear elasticity relations, the stress profile of a homogeneous material can be expressed as:

$$\sigma_r(\zeta) = -E\sum_{k=2}^{\infty} \lambda_k P(\zeta) \quad (3)$$

in which σ_r is the residual stress and E the elastic modulus of the material. Note that in Equation (3) only the Legendre polynomials of degree equal to or higher than 2 are involved. This is because the polynomials of order 0 and 1 are related to elongation and curvature, respectively, which are cancelled out for homogeneous materials. For materials made up of more than one layer (for example, glazed tiles), the polynomials of order 0 and 1 are not cancelled out, and each layer has its own elastic modulus, which is why Equation (3) becomes somewhat more complex in this case.

From Equations (1), (2), and (3), the strains recorded in the test can be related to the residual stress profile, which requires the obtainment of the "calibration factors" λ_k. These factors were theoretically obtained by subjecting a computational representation of the notched test piece to a stress profile given by each Legendre polynomial considered and calculating the resulting strain in the position of the strain gauge from the finite element method.

4. RESULTS

4.1. TESTS CONDUCTED ON INDUSTRIAL TILES

Table 2 details the results obtained in the behaviour under cutting tests of the three types of ceramic tiles: porcelain tiles POR-B and POR-M, and earthenware wall tile AZ. Figures 4 and 5 show images of the tiles after testing.

It may be observed that the AZ test pieces exhibited appropriate behaviour under cutting, even at a reduced notch depth (0,2 mm), from the image in Figure 4 (left) and from the high value of the distance at which the crack deviated (Table 2). With regard to the POR-B porcelain pieces (Figure 4 (right)), it may be observed that the behaviour under cutting was not as good as in the AZ piece, a notch of 0,3 mm depth being needed for appropriate cutting.

Characteristic	POR-B		POR-M				AZ
Notch depth (mm)	0,2	0,3	0,20	0,25	0,30	0,40	0,2
Crack deviation distance (mm)	112	150	-	70	107	109	150
Fracture force (N)	1856	1443	2050	1720	1640	1480	450
Fracture strain (mm)	0,30	0,26	0,35	0,29	0,27	0,25	0,27

Table 2. *Characteristics obtained in the cutting test.*

In the POR-M pieces tested at low notch depth (0,2 mm, fracture was inappropriate and occurred by means of two divergent cracks that started from the proximity of the notch (Figure 5a). Increasing the notch depth improved the cut, yielding a single crack that followed the notch track reasonably closely. It may be observed that as notch depth increased, the distance at which the crack deviated decreased. However, even with a notch of 0,4 mm the fracture did not follow the notch to the end (Figure 5d).

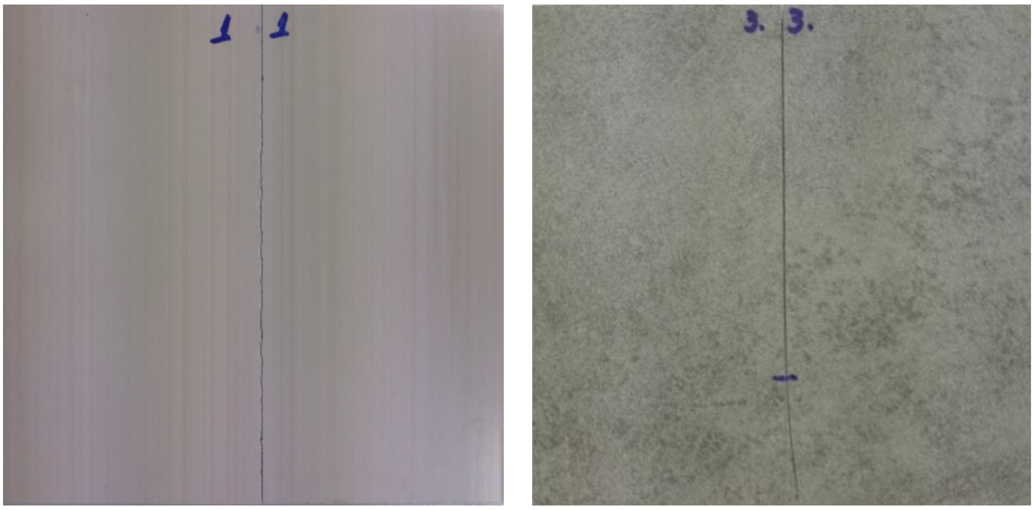


Figure 4. *Behaviour under cutting of piece AZ (left) and piece POR-B (right). Notch depth: 0,2 mm.*

These results matched the manufacturers' observations, though a greater number of tiles need to be tested in order to confirm that the test method reproduces, albeit qualitatively, the behaviour under cutting of porcelain tile.

Figure 5. *Behaviour under cutting of piece POR-M at different notch depths: a) 0,2 mm; b) 0,25 mm; c) 0,3 mm; and d) 0,4 mm.*

The residual stresses due to thermal gradients of the industrial test pieces were then determined, with a view to determining whether there was any relationship between these stresses and test piece behaviour under cutting.

Although, as indicated above, the SRSM method could theoretically be applied to materials with multiple layers, in practice the thinness of the engobe and glaze layers leads to considerable errors in the determination of the residual stress profile.

Taking this into consideration, the residual stresses were also determined for an unglazed POR-B tile. This test piece was referenced POR-B*.

Figure 6 (left) shows the strain measured by the strain gauge as a function of notch depth for the POR-B and POR-B* pieces. It shows that, for the two pieces, the strain increased with notch depth; positive strain values indicate that the piece was acquiring a concave curvature. The strain data of the body test piece (POR-B*) were fitted quite well using only the Legendre polynomial of degree 2 (as a homogeneous material was involved), whereas for the glazed piece (POR-B) the polynomials of degree 0, 1, and 2 were used, for the reasons set out above. The results indicate that, in both cases, test piece cooling had been quite homogeneous.

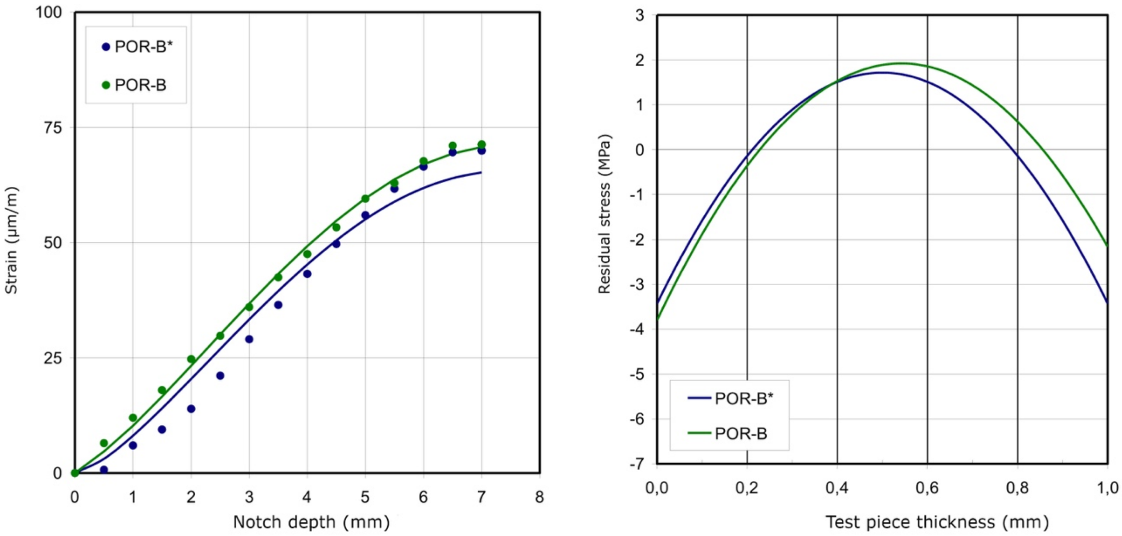


Figure 6. *Experimental strain and fit of the POR-B and POR-B*pieces (left). Residual stress profile of the POR-B and POR-B* pieces (right).*

The stress profile throughout the piece thickness is shown in Figure 6 (right). In this figure the stress is plotted as a function of the transverse cross-section of the pieces, the value 0 and 1 representing the bottom (rib) and the top (proper surface) surface of the piece, respectively. In both cases the profile was very similar, and it displayed negative stresses (compression) at both surfaces and positive stresses (tension) in the centre. These results indicate that the application of the SRSM method for the calculation of the residual stresses of glazed pieces did not lead to any great error, at least for test piece POR-B.

Figure 7 shows the values of the residual stresses of the POR-B and POR-M pieces. The magnitude of the stresses in both pieces was similar. However, to fit the experimental strains of piece POR-M it was necessary to use the Legendre polynomials of degree 0, 1, 2, 3, and 4. This indicates that test piece cooling had in all likelihood not been homogeneous so that a more complex stress profile was obtained. Thus, piece stress appeared to change from compression to tension near the proper surface, which could lead the cutting fracture to deviate.

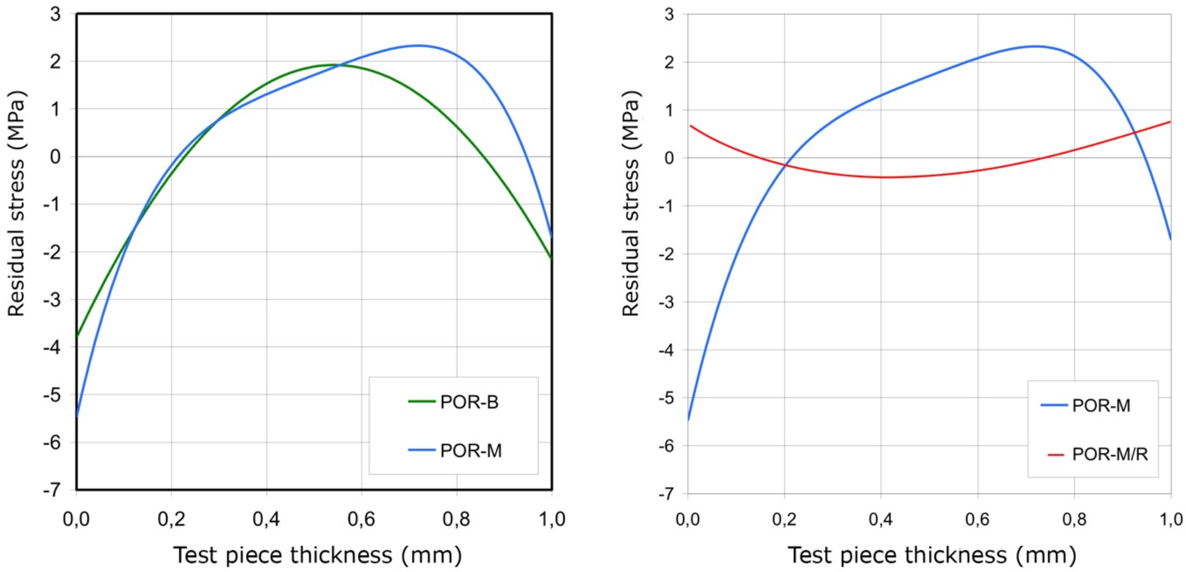


Figure 7. *Residual stress profile of the POR-B and POR-M pieces (left), and of the original and refired POR-M piece (right).*

A test was performed to verify whether the residual stresses measured by the SRSM method stemmed from the cooling stage in the kiln. To do so, test piece POR-M was refired in a laboratory kiln, this being referenced POR-M/R. The following firing cycle was used: heating at 5 °C/min to 1170 °C, dwell at 1170 °C for 6 minutes and cooling inside the kiln at 5 °C/min. The main characteristic of this firing cycle was the very slow cooling rate, aimed at minimising the temperature gradient throughout the piece thickness and hence the residual stresses. The results are shown in Figure 7 (right), in which it may be observed that the refired piece displayed a practically flat stress profile. This outcome indicates that the presence of a thermal gradient throughout the piece thickness during cooling was one of the sources of the residual stresses in the porcelain tile pieces.

4.2. INFLUENCE OF COOLING ON RESIDUAL STRESSES

In this section, the porcelain tile composition was used to study the range of temperatures in which residual stresses were generated during cooling. The literature indicates that these stresses are generated at temperatures above 700 °C, at which porcelain tile displays viscoelastic behaviour [13]. Consequently, only temperatures above 700 °C were studied.

To conduct the tests, test pieces of 2 x 8 cm and 7 mm thick were pressed, which were fired in an electric laboratory kiln at body maximum densification temperature (1220 ° C) for 6 minutes. The heating rate was 25 °C/min in every case. The cooling was modified as follows:

- Cooling E-STD: fast cooling consisting of withdrawing the test pieces from the kiln when the residence time at peak temperature ended, placing them in the device shown in the Figure 8 and cooling the pieces by blowing ambient air into the device.
- Cooling E-L: slow cooling inside the kiln (10 °C/min) from peak firing temperature to room temperature.
- Cooling E-1000, E-900, and E-800: similar to cooling E-L down to, respectively, 1000, 900 and 800 °C. At this temperature, the test pieces were withdrawn from the kiln, placed in the device shown in the Figure 8, and cooled by blowing ambient air into the device.

Figure 9 (left) shows the 5 types of cooling used.

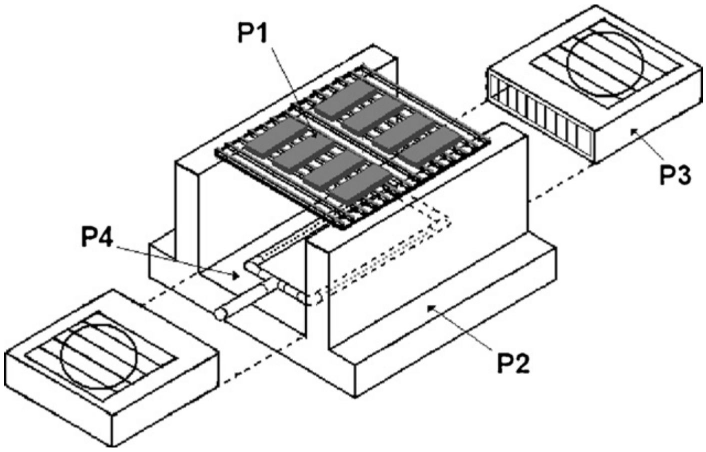


Figure 8. *Scheme of the device used to accelerate cooling. P1: perforated refractory slab; P2: refractory support; P3: fans; and P4: compressed air blower.*

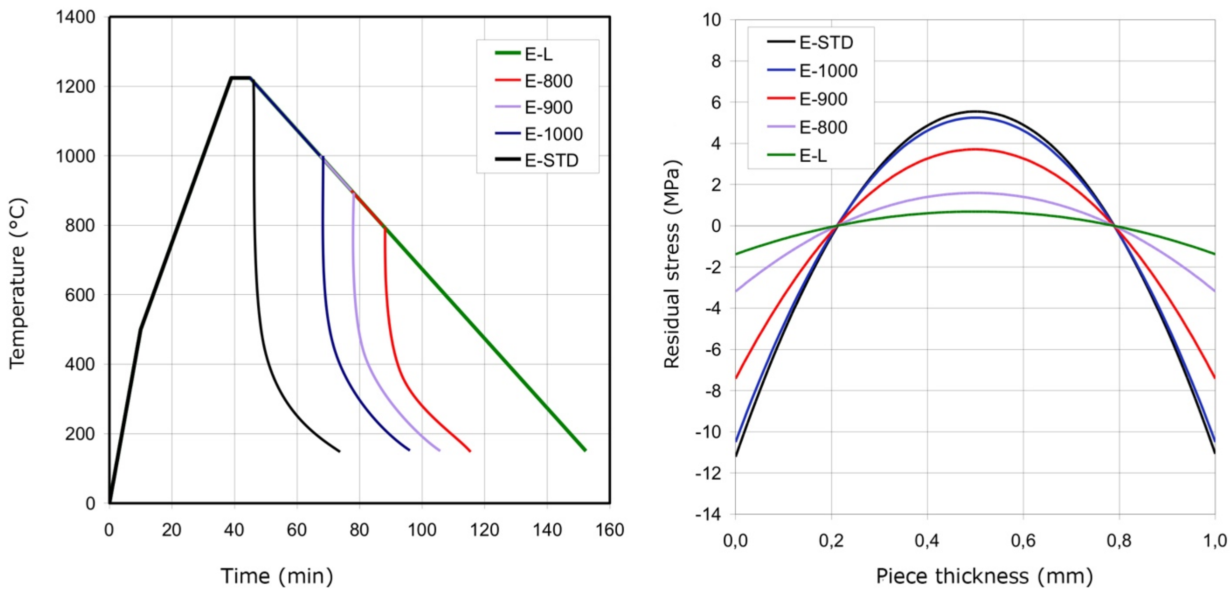


Figure 9. *Tested cooling rates (left) and residual stress profile at different cooling rates (right).*

Once the pieces had cooled, their stress profile was determined by the SRSM method. The experimental strain data were fitted quite well, only using the Legendre polynomial of degree 2, which gives rise to symmetrical stress profiles. The stress profiles are shown in Figure 9 (right). The following may be observed:

- All the pieces exhibited compression stresses at their surfaces and tension inside the pieces.
- The type of cooling noticeably influenced the stress profile, such that, as the cooling rate increased, so did the magnitude of the arising stress.
- Slow cooling (E-L) gave rise to a practically flat stress profile, whereas fast cooling (E-STD) produced the greatest residual stresses.
- The stress profiles of cooling E-STD and E-1000 practically coincided, which indicates that slowing the cooling between peak temperature and 1000 °C did not significantly influence the arising stresses.
- Most of the residual stresses were generated by fast cooling between 1000 and 800 °C. At temperatures below 800 °C, residual stresses were also generated when cooling was fast, but their magnitude was much smaller. These results are consistent with those obtained by other authors [14]

Finally, tests on behaviour under cutting were conducted in the device shown in Figure 2. To perform the test 16 test pieces of 15×15 cm were fired using the firing cycle indicated above, and then cooled either slowly (E-L) or rapidly (E-STD). In firing with fast cooling, the cooling rate was decreased to 10 °C/min between 600 and 300 °C to keep the low thermal shock resistance of the tiles in this temperature range from interfering with their behaviour under cutting owing to microcrack formation at the edges of the quartz particles. Table 3 details the results obtained and Figure 10 shows the appearance of two of the test pieces after the test.

It was observed that when cooling was fast and there were residual stresses, the percentage of pieces with an inappropriate cut was high, accounting for 75% of the tested pieces. However, when cooling was slow, the percentage of pieces that were cut inappropriately was only 6%. These results clearly show the relationship between behaviour under cutting, cooling rate, and residual stresses caused by the thermal gradient in porcelain tile pieces.

	E-STD		E-L	
	Appropriate fracture	Inappropriate fracture	Appropriate fracture	Inappropriate fracture
No. of tiles	4	12	15	1
Percentage	25%	75%	94%	6%

Table 3. *Results obtained in testing behaviour under cutting.*

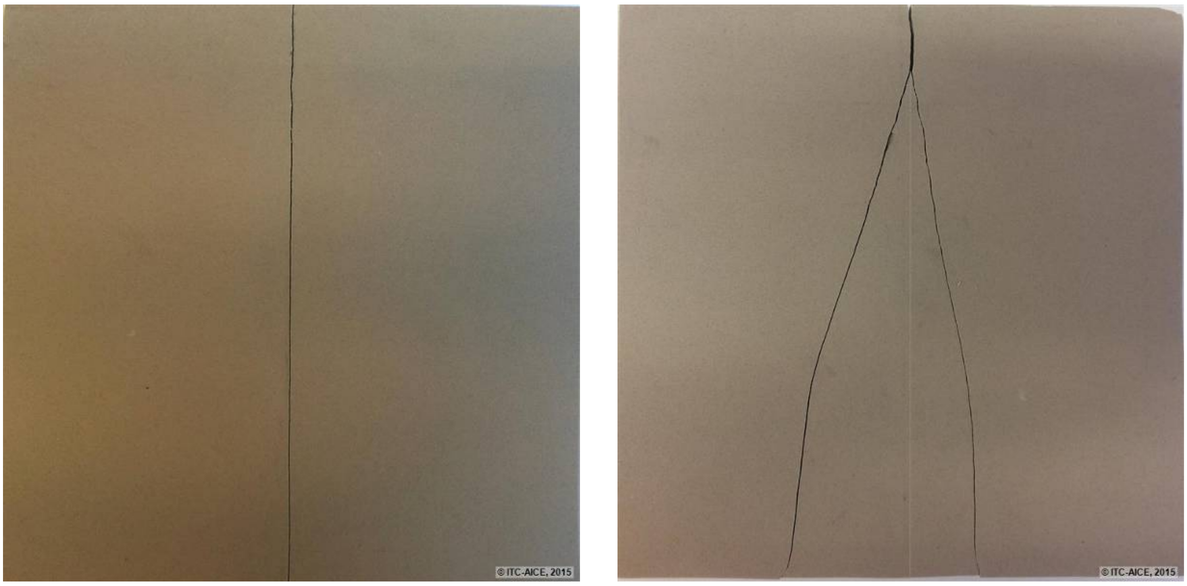


Figure 10. *Images of the test pieces with appropriate (left) and inappropriate (right) fracture.*

5. CONCLUSIONS

The following conclusions may be drawn from the study:

A test method was designed, based on the 3-point bending method, which allows the behaviour under cutting of industrial porcelain tile to be qualitatively differentiated. However, a greater number of tiles need to be tested to validate the method.

It was verified that for the tile with appropriate behaviour under cutting, the strains that developed as a result of increased notch depth in the test pieces could be fitted by just using the Legendre polynomial of degree 2, whereas for the tile with inappropriate behaviour, it was necessary to use a greater number of terms. This suggests that in the former case cooling had been more homogeneous than in the latter case.

The refiring of industrial tile test pieces using slow cooling reduced the level of stresses, which confirmed that thermal gradient stresses were generated during the cooling stage in the industrial kiln.

Laboratory tests in which the cooling rate was modified showed that thermal gradient stresses, in the tested composition, took place mainly in the temperature range between 1000 and 800 °C.

The performance of cutting tests on test pieces cooled in the laboratory demonstrated the relationship existing between the magnitude of the residual stresses and the cooling rate.

ACKNOWLEDGEMENTS

Project co-funded by IVACE and the European Regional Development Fund (ERDF), within the ERDF Operational Programme in the Valencia Region 2007–2013.

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