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Proposition for analysis of elastic deformation in ceramic tiles using multilevel factorial design

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Abstract. The production of ceramic tiles requires specific technical properties to allow a wide application, including covering floors and walls, building furniture, and decorative items. Current methods of measuring the dimensions of large ceramic tiles seem inadequate for products that exhibit elastic deformation due to their weight affecting the accuracy and precision of measurements. This paper aims to analyze the influence of format, thickness, and typology variables on the elastic deformation of ceramic tiles. Additionally, this study provides an analysis about which products can be measured by the traditional measurement system without compromising the quality of the results. Tests to determine warpage under different support conditions were performed using a laser-equipped coordinate measuring machine. This technology provided typology, thickness and size, and elastic deformation outcomes. In addition, a multilevel factorial design was carried out using analysis of variance (ANOVA) to investigate the influence of the selected variables. The results suggest that all the studied variables affect the elastic deformation due to the weight of ceramic tiles. The effect of interactions between predictor variables is significant mainly for the largest tiles sizes. The results also show that the current measurement method is indicated for tiles smaller than 30 × 30 cm. Further studies will be conducted to develop a new compatible and reliable method to determine the dimensional characteristics of larger ceramic tiles.

Keywords: Measurement system analysis / factorial design / data dimension / ceramic tiles

1 Introduction

Ceramic tiles are versatile products due to their non-combustibility, ease of cleaning, durability, and mechanical strength [1–4]. These characteristics allow the use to cover floors and walls, countertops, panels, bathroom, and kitchen sinks, and even furniture [4].

Flatness and thin laying joints are the primary customer requirements [1]. However, some processes are responsible for influencing the dimensional characteristics of ceramic tiles, requiring effective Measurement Systems (MS) for each manufacturing step [3–5].

Considering that the product is manufactured based on natural raw materials, deviations still occur even with the controls in the process. To ensure quality, a 100% inspection is carried out after firing the tiles and discarding tiles with visual and dimensional defects [5]. Tiles of first quality are also segregated into smaller size ranges (gauges) than tolerances, which is a customer requirement [5,6].

The quality concept of ceramic tiles has evolved, making technical requirements more stringent, including dimensional requirements, which in some cases have been reduced by more than 50% of the normative tolerance [2,7]. The normative Dimensional Measurement System (current MS) evaluates size deviations (length, width, and thickness), orientation tolerance (rectangularity), and shape tolerances of straightness (straightness of sides) and flatness (central curvature, edge curvature, and warpage) [8]. The measurement takes place in a horizontal plane by comparing the ceramic tile with a calibrated standard block in the data dimension measuring device (Fig. 1) [8].

It is important to highlight that the current MS may be obsolete and inadequate to measure the planar characteristics of the large-format, low-thickness ceramic tiles produced today [4,8,9]. In addition, such a system generates measurement and classification problems, the most critical of which is the tile's elastic deformation, which occurs due to its weight, which, with the rigor of the new tolerances, can disapprove good quality tiles.

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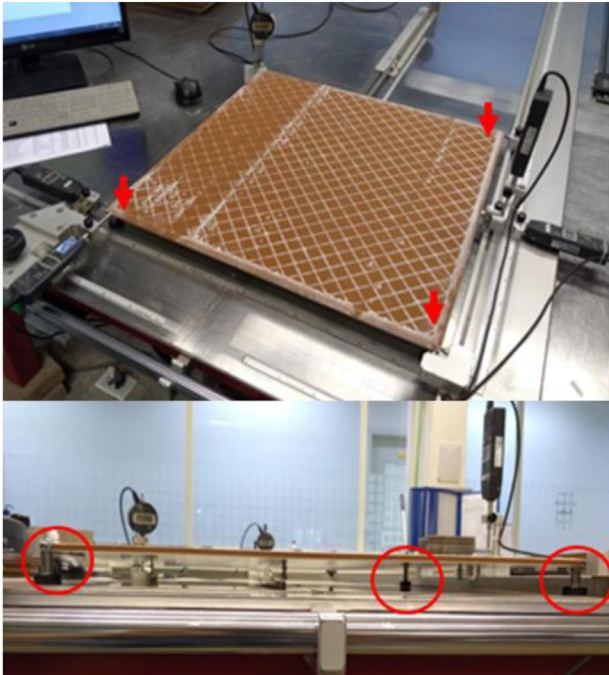


Fig. 1. Data dimension (Current Measurement System).

According to Fazio et al. [9], tiles over 60 cm already suffer deformations during the test, as they are suspended by 3 of their vertices (Fig. 1), affecting the accuracy and precision of the results. However, the Brazil Ceramic Center (CCB)¹, in its measurements, identified elastic deformation in tiles of 60 cm or less, with greater intensity in tiles with dimensions close to 60 cm of type BIIb (semi-porous) and with low thickness.

The elastic deformation of the part is considered a source of variation within an MS [9,10]. The holding system and the horizontal position of the measurement of the tiles could cause elastic deformation because this system has significant relevance in terms of repeatability and reproducibility deviations [11].

An MS must operate under stable conditions with proven quality, identifying and eliminating or reducing the sources of variation [10,12,13], so the elastic deformation of the current MS must be studied and mitigated.

Ali and Buajarern [14] proposed to determine the planar characteristics through a Coordinate Measuring Machines (CMM), considering the maximum deviations found along several points collected on the diagonals and sides of the tile, because of the deviations are not concentrated in the points defined by the standard [5]. The authors considered only the planar characteristics and used a CMM to perform the measurements of both methods (traditional and proposed), to eliminate the equipment

variation, but making it impossible to compare effectively with the traditional method.

Fazio et al. [9] compared all the dimensional characteristics using a data dimension, a conventional CMM and a portable CMM. The authors selected 10 tiles of 3 sizes smaller than 60 cm, inferring that they do not present elastic deformation. The averages of all sides were calculated, that can compensate for some deviations and approximate the values between the methods. The comparative results presented are promising, demonstrating good compatibility between the data dimension and the CMM.

Emam and Sayyed Barzani [15] proposed an alternative to the current laser process control methods, the proposed method uses cameras and algorithms to measure the tiles in the production line. The experiment was carried out in the laboratory and no in-line tests were reported and a comparison with the current method was not performed.

Sioma [16] used cameras integrated with a laser for extraction and analysis of three-dimensional images. The high volume of points collected for measurement allows a careful assessment of flatness, showing how in the analysis of flatness deviations. The study did not present a method to determine size, lateral straightness and orthogonality and did not compare with the current measurement method.

The above-mentioned studies were developed to propose a more modern, accurate and reliable method [9,14–16]. However, studies evaluating quality of measurements and when and how much elastic deformation affects measurement error are still scarce in the literature.

This study aims to analyze the influence of format, thickness, and typology variables on the elastic deformation of the ceramic tile and to determine which products can be measured by the current MS without compromising the quality of the results. This experiment is the first of three parts of a study that will evaluate the compatibility and quality of the current MS with a coordinated MS, to propose a replacement method for the traditional method that proved to be ineffective for larger-format tiles.

2 Material and methods

2.1 Variables of the study

2.1.1 Input variables and samples

In this study, measurements were performed on 16 ceramic tiles (Fig. 2) selected based on their Typologies (Type), Thickness (T), and Size (S), representing the input variables of the experiment. These variables were selected as they are stated on the packaging, enabling laboratories to make methodological decisions without the need for additional tests. Typologies BIa and BIIb were selected because they represent the largest volume produced in Brazil [17]. In addition, these typologies have the lowest porosity and density (BIa) and are the second most porous and least dense (BIIb). Typology BIII (more porous) was not selected due to the low representation in the volumes produced and the difficulty of finding tiles with low thicknesses.

¹ The CCB has been the technological entity of the Brazilian ceramic sector for 30 yr, developing standards and certifying (87.71 ± 0.25)% of Brazilian production [7]. CCB performs more than 30,000 tests annually, of which 3,600 are dimensional tests (ISO 10545-2), CCB is among the largest ceramic tile laboratories in the world.

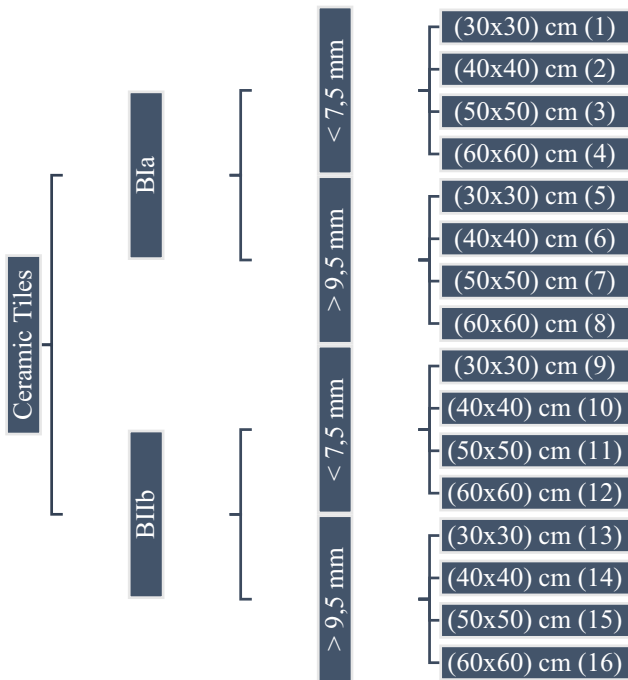


Fig. 2. Combination of levels of the input factors.

Square tiles of 30 cm, 40 cm, 50 cm, and 60 cm were used according to the measurement range of the lab's current MS and based on previous research [9] and empirical laboratory experience. The thickness was divided into two levels, thin and thick parts. The selection of thin tiles is based on the breaking strength test [18], which establishes that tiles with a thickness ≤ 7.5 mm must be cut into small formats ((20 × 20) cm), to reduce the effect curvature before rupture. The thickest tiles (>9 mm) correspond to the highest thicknesses found in products normally tested by the CCB.

2.1.2 Output variable

Elastic deformation (Ed) was selected as the study's output variable, which is the difference between the average warping results of ceramic obtained from condition 1 and condition 2. Condition 1 simulates the piece on the data dimension (Fig. 1), placing it on the supports at three vertices and the warping dial indicator at its fourth vertex.

As seen in Figure 3, condition 2 supports the piece on a panel inclined at approximately 81° with adjustable support pins to prevent the piece from moving during the measurement.

2.2 Measurement

The measurement was performed using a portable CMM, the measuring arm (Arm), and model Edge FaroArm[®] equipped with Laser, which will be calibrated before the measurements start. The tiles were measured with the proper surface uppermost, differing from the normative method, to allow data collection by the Arm.



Fig. 3. Vertical panel.

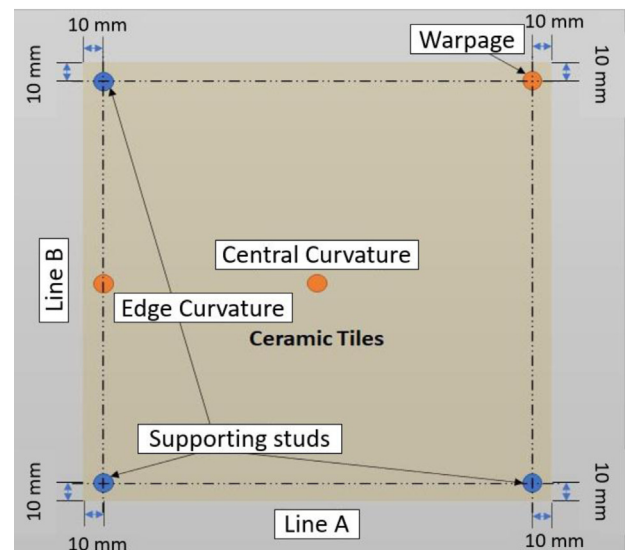


Fig. 4. Warpage measurement points.

2.2.1 Warpage test

The tiles were identified (Fig. 4) and placed on 3 supporting studs with the warpage dial gauge at the fourth vertex to stabilize the piece, simulating the normative measurement in the data dimension. The alignment of the piece was carried out in the Faro CAM2[®], a program using the plane created from the 3 points measured on the supports, the line A, and the intersection point between the A and B lines (Fig. 4). Next, the warpage was measured through the scanner, to avoid deformation by touch [14]. The same measurement procedure was performed on the inclined panel (condition 2).

2.2.2 Scanning

The tile was scanned using the Edge FaroArm[®] to evaluate the behavior of each support condition. Using the Faro CAM2[®] software, we extracted color maps from the

Table 1. Multilevel factorial design L16 plan and results.

Actual parameters			Coded parameters			Output variable (Ed) (mm)		
S	Typ	T	S	Typ	T	1 Rep.	2 Rep.	Average
(30 × 30) cm	BIa	Thin	1	1	1	-0,17	-0,17	-0,17
(30 × 30) cm	BIa	Thick	1	1	2	-0,04	-0,13	-0,09
(30 × 30) cm	BIIfb	Thin	1	2	1	-0,21	-0,18	-0,19
(30 × 30) cm	BIIfb	Thick	1	2	2	-0,08	-0,08	-0,08
(40 × 40) cm	BIa	Thin	2	1	1	-0,34	-0,29	-0,31
(40 × 40) cm	BIa	Thick	2	1	2	-0,10	-0,16	-0,13
(40 × 40) cm	BIIfb	Thin	2	2	1	-0,41	-0,48	-0,45
(40 × 40) cm	BIIfb	Thick	2	2	2	-0,27	-0,35	-0,31
(50 × 50) cm	BIa	Thin	3	1	1	-0,68	-0,61	-0,64
(50 × 50) cm	BIa	Thick	3	1	2	-0,22	-0,30	-0,26
(50 × 50) cm	BIIfb	Thin	3	2	1	-1,03	-1,03	-1,03
(50 × 50) cm	BIIfb	Thick	3	2	2	-0,62	-0,54	-0,58
(60 × 60) cm	BIa	Thin	4	1	1	-1,39	-1,42	-1,41
(60 × 60) cm	BIa	Thick	4	1	2	-0,74	-0,81	-0,78
(60 × 60) cm	BIIfb	Thin	4	2	1	-2,19	-2,27	-2,23
(60 × 60) cm	BIIfb	Thick	4	2	2	-1,26	-1,27	-1,27

point clouds. Warm colors (yellow to red) represent points above the reference plane, cool colors (light blue to dark blue) represent points below the reference plane, and green corresponds to deviations within the tolerance. The tolerance defined for the study was 0.2 mm, approximately 5% of the normative tolerance for the evaluated typologies and sizes.

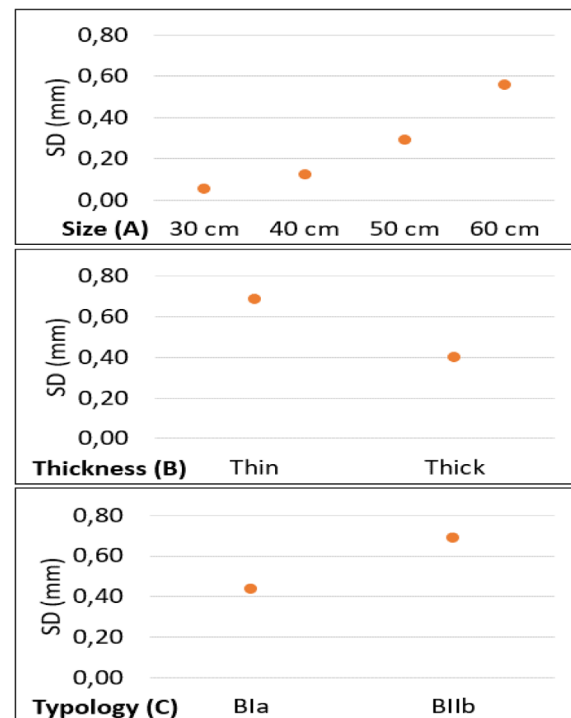
2.3 Experimental design

Based on the objective of the experimental research, which is to study the elastic deformation of ceramic tiles during the performance of the dimensional test [8], the variables Typ, T, and S were selected to plan the experimental design.

Design of Experiments (DOE) is a test or a series of tests that evaluate how variable input changes influence the output variable [19]. We used a DOE – multilevel factorial with three input variables, four levels in the variable S, and two levels in the variables T and Typ. The most appropriate experimental matrix is a Multilevel Factorial Design L16 with 16 experiments, as listed in Table 1. All measurements will be conducted randomly by the same technician, at a temperature of $(20 \pm 2)^\circ\text{C}$ and in duplicate (twice with the same tile) to avoid bias and minimize influences.

3 Results and discussion

After measuring both support conditions and calculating the average deformations, the results were analyzed and summarized in Table 1. Then we performed an analysis of variance (ANOVA) to verify the influence of the input variables individually and their interactions on the

**Fig. 5.** SD Charts.

variable output. The results on the influence of variables S (30, 40, 50, and 60), Typ (BIa and BIIfb), and T (< 7.5 mm and > 9.0 mm) on deformation are shown in the results of the standard deviations (Figs. 5 and 6), in the comparative graph (Fig. 7), results of the ANOVA analysis (Tab. 2), Tukey test (Tab. 3) and hot and cold color map (Figs. 8–11).

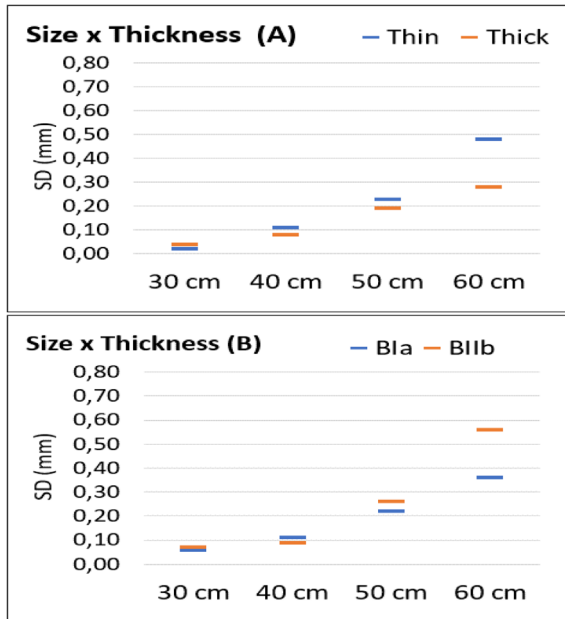


Fig. 6. SD of interactions.

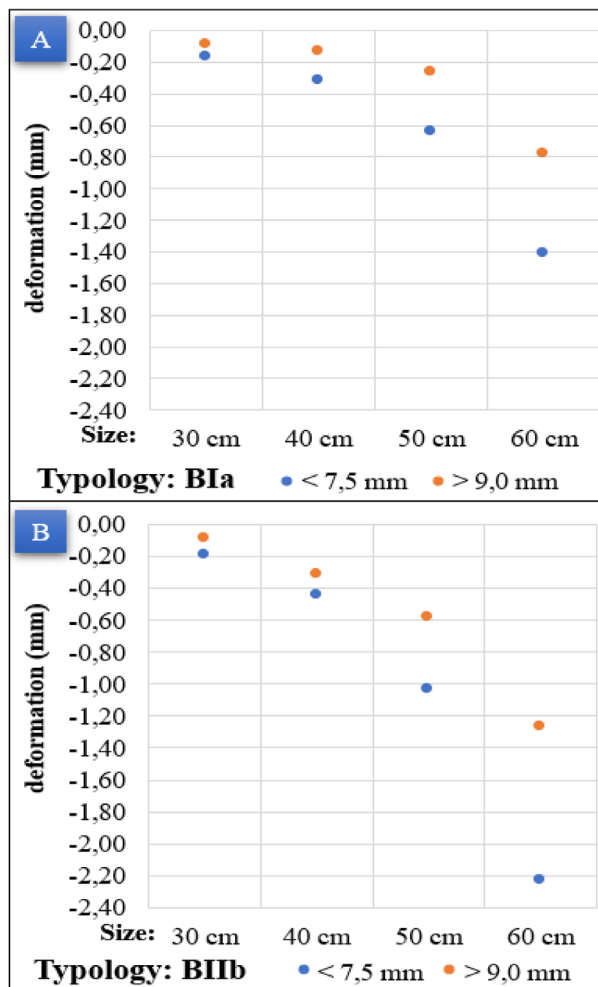


Fig. 7. Deformation of parts about shape and thickness.

Table 2. ANOVA results.

Source	DF	SS	MS	F-value	P-value
Size	3	7,86	2,608	1582,88	0,000
Thickness	1	1,08	1,082	656,36	0,000
Typology	1	0,70	0,697	423,04	0,000
Size $\times$ Thickness	3	0,61	0,202	122,43	0,000
Size $\times$ Typology	3	0,47	0,156	94,83	0,000
Thickness $\times$ Typology	1	0,02	0,019	11,33	0,004
Size $\times$ Thickness $\times$ Typology	3	0,04	0,014	8,49	0,002
Error	15	0,03	0,002		
Total	31	10,77			

As observed in Figure 5A, the results suggest that the larger the size, the higher the standard deviation. This result shows greater instability in the measurements of larger-format tiles. In Figures 5B and 5C, typology BIb and thin products present greater dispersion than BIa and thick products. With regard to format, a higher standard deviation is observed for the BIb typology and thin products in the (60 $\times$ 60) cm size (Fig. 6).

As illustrated in Figure 7, the format samples (30 $\times$ 30) cm and the thick BIa sample (40 $\times$ 40) cm have relatively low deformations, less than 0.2 mm $\cong$ 7% of the tolerance). The other samples in the format (40 $\times$ 40) cm and the thick BIa sample (50 $\times$ 50) cm have deformations between 0.3 mm $\cong$ 8% of the tol.) and 0.4 mm $\cong$ 11% of the tolerance) of ceramic tiles when they are at the limit of the normative specification. For the other sizes, thicknesses and typologies, deformations range from 0.6 mm $\cong$ 17% of the tolerance) to 2.2 mm ($\cong$ 61% of the tolerance).

These results show that increasing the format of the tile increases the deformation of the tile. In this way, typology BIa is more robust, deforming with less intensity when compared to typology BIb. The same occurs with thicker products, which deform less than thinner products.

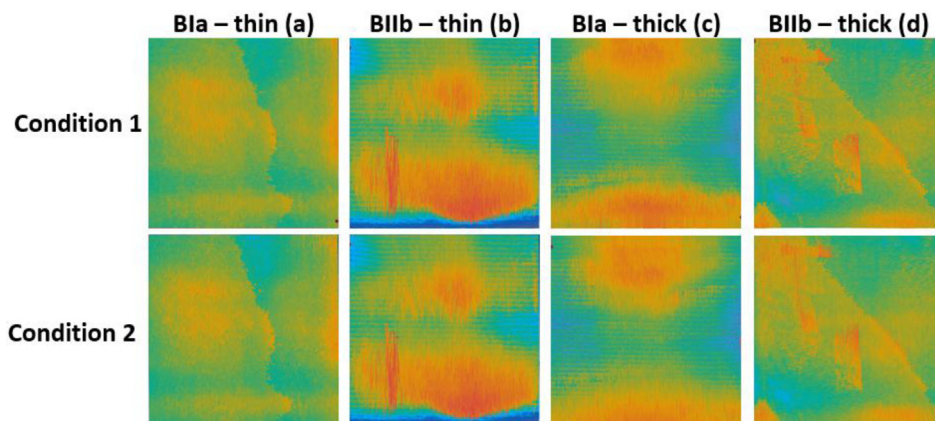
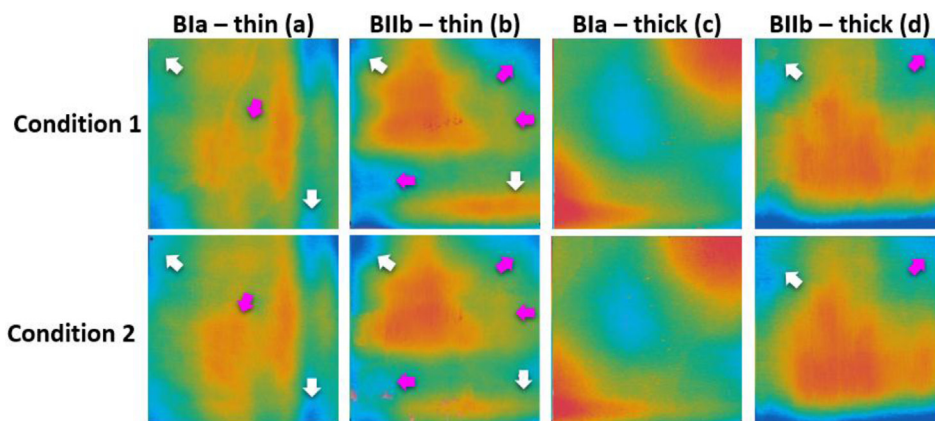
In addition, the results in Table 2 show that the p -value of thickness, shape, and typology are smaller than the adopted significance level (0.05), rejecting hypothesis H_0 at a significance level of 5%, showing that the three variables influence the deformation. A triple interaction is observed, where the three variables interact.

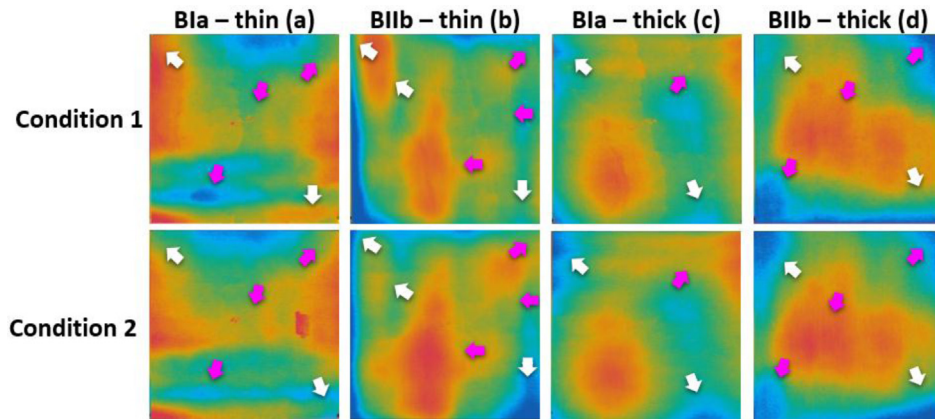
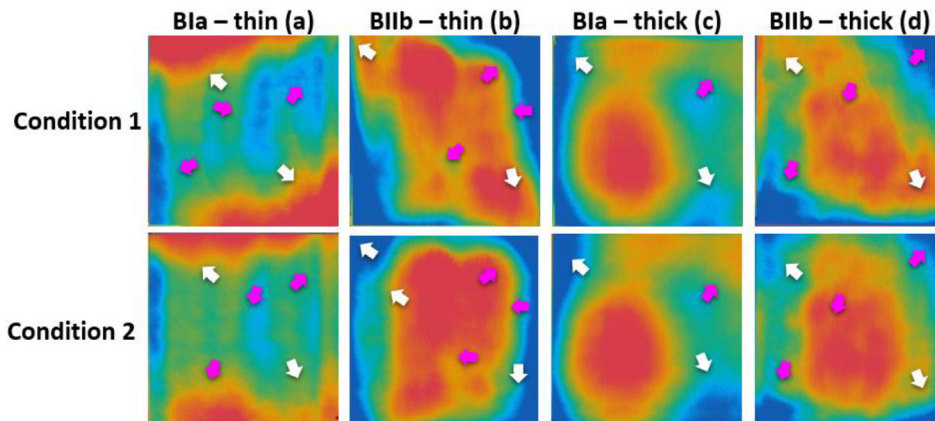
Table 3 shows the outputs of the Tukey test. There is no significant interference from thickness and typology for the smallest format, corroborating with previous analysis where the size is responsible for deformations, followed by thickness and, finally, the typology.

As compared to the color maps (condition 1 versus condition 2), there is a change in the shape of the tile. The patterns are highlighted by white arrows when the deformation left the most positive point (above) or roses when there are more negative point (below). The tiles (30 $\times$ 30) cm illustrated in Figure 8 and the tiles (40 $\times$ 40) cm in thick BIa typology (Fig. 9c) do not present a perceptible change. The tiles (40 $\times$ 40) cm are illustrated in Figures 9a, 9b, and 9d, as well as the tiles (50 $\times$ 50) cm in

Table 3. Tukey tests.

Size	Thickness	Typology	Deformation	Groups									
				1	2	3	4	5	6	7	8	9	10
(60 × 60) cm	Thin	BIlb	−2,23	****									
(60 × 60) cm	Thin	BIa	−1,41		****								
(60 × 60) cm	Thick	BIlb	−1,27		****								
(50 × 50) cm	Thin	BIlb	−1,03			****							
(60 × 60) cm	Thick	BIa	−0,78				****						
(50 × 50) cm	Thin	BIa	−0,64				****	****					
(50 × 50) cm	Thick	BIlb	−0,58					****	****				
(40 × 40) cm	Thin	BIlb	−0,45						****	****			
(40 × 40) cm	Thin	BIa	−0,31							****	****		
(40 × 40) cm	Thick	BIlb	−0,31							****	****		
(50 × 50) cm	Thick	BIa	−0,26								****	****	
(30 × 30) cm	Thin	BIlb	−0,19								****	****	****
(30 × 30) cm	Thin	BIa	−0,17								****	****	****
(40 × 40) cm	Thick	BIa	−0,13									****	****
(30 × 30) cm	Thick	BIa	−0,09										****
(30 × 30) cm	Thick	BIlb	−0,08										****

**Fig. 8.** Colors map for tiles (30 × 30) cm.**Fig. 9.** Colors map for tiles (40 × 40) cm.

Fig. 10. Colors map for tiles (50×50) cm.Fig. 11. Colors map for tiles (60×60) cm.

thick BIa typology depicted in Figure 10c. Generally, the vertices where the supports are placed (white arrows) are presented more positively, and the regions close to the center and those without support (pink arrows) are more negative.

In the other tiles (50×50) cm (Figs. 10a, 10b and 10d) and the (60×60) cm (Fig. 11), there is a significant change in the shape of the tiles due to the center of the piece and the unsupported vertex presenting results more negative in condition 1 when compared to condition 2 and the supported vertices with inverse effect, with great evidence in the piece (60×60) cm thin BIlb, which presents a convex format when in vertical support (condition 2) and horizontal (condition 1) presents the vertices supported almost flush with the center of the piece.

4 Conclusion

In this study, measurements alternating the inclination of the tile were carried out to evaluate the influence

of typology, thickness, and size on the elastic deformation of ceramic tiles. The tests were performed according to dimensional characteristics in [8]. The conclusions of the study were drawn as follows:

- The three input variables selected for the investigation process influence the elastic deformation of ceramic tiles, but at different levels.
- The size is the variable with the most significant influence on deformation (1.42 mm in the largest size), the thickness is the second one (0.8 mm in the thin tiles), followed by the typology (0.77 mm in the BIlb).
- The effect of the interaction on the input variables is significant, mainly in the larger sizes.
- The tiles tested in the horizontal plane show elastic deformation at the center and unsupported vertex, with more negative results in these regions of the piece than in the supported vertices.
- The results suggest that only tiles with sizes up to (30×30) cm of any thickness and typology can be measured by the data dimension without presenting variations in results due to the effect of elastic deformation.

- For thick tiles with sizes up to (40×40 cm), can be measured with confidence, however a complementary study must be carried out to determine from which thickness the tiles deform with less intensity.

This article provides researchers and practitioners with an indication for the development of new methods of laboratory measurement and process control, studies on new applications and improvements in process controls considering the effect of deformation. The main limitation of this study refers to the restricted number of variables selected to verify the effect on elastic deformation of the tiles. More research is needed to investigate the influence of other variables including apparent porosity, apparent relative density and bulk density, radius of curvature and some process variables. The time required to perform one test on one tile is relatively short, taking approximately 6 days for all measurement rounds. With an increase in the number of input factors in future studies, the application of a fractional factorial design could prove beneficial. Future research ought to include more factors and variables that affect the measurement of large-format ceramic tiles.

Nomenclature

Arm	Measuring arm
Bla	The lowest porosity and density (porcelain tile)
BIlb	The second most porous and least dense
CCB	Brazil Ceramic Center
CMM	Coordinate Measuring Machines
DOE	Design of Experiments
Ed	Elastic Deformation
S	Size
MS	Measurement System
T	Thickness
Typ	Typology

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