

ASSESSMENT OF CERAMIC TILE INTEGRITY USING SOUND SIGNALS IN NON-DESTRUCTIVE TESTING

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ABSTRACTRESUMEN

The ceramic tile industry faces challenges in detecting internal flaws that compromise product integrity. Traditionally, quality control relies on visual inspection and manual mechanical analysis — subjective, slow, and imprecise methods. This research proposes a non-destructive testing (NDT) method based on acoustic analysis of controlled-impact signals, acquired via microphone, DAQ board, and LabVIEW software. To validate the method, three-point bending tests (NBR ISO 10545-4:2020) were performed on 74 ceramic tiles (37 flat tiles + 37 textured tiles, 200×200×7 mm, Group BIII). Results show that partially broken tiles exhibited natural frequencies clearly deviating from the Gaussian distribution of intact tiles, and an elastic modulus factor ratio of ~3.8 vs. a mean of ~2.2 for intact specimens. The acoustic approach is viable as a rapid, low-cost complementary inspection tool for ceramic quality control.

1. INTRODUCTION

Brazil is the 3rd largest producer of ceramic tiles in the world (ANFACER, 2025). However, the sector still faces significant challenges in detecting manufacturing defects — particularly in the pressing, firing, and cooling stages. Undetected defects reach end customers, generating costly returns and reputational damage.

Current inspection methods are manual: visual inspection and in some instances the "tap test," where an operator listens to the sound of a tap performed by hand on each tile. Both methods are subjective, slow, and operator dependent. Standard NBR ISO 10545-4:2020 provides a destructive 3-point bending test as the definitive quality metric, but this is impractical for 100% production inspection.

Tests using acoustic waves can estimate various elastic properties through the propagation of longitudinal and transverse waves. Since these tests are feasible, it would not be necessary to perform conventional destructive tests, thereby reducing costs associated with sample preparation and shortening data acquisition time (Carvalho, 2020).

The adoption of automated and reliable methods to assess the integrity and condition of ceramic tiles is a growing need in the ceramic industry, which faces high rates of losses and costs associated with the late identification of defects. The application of acoustic analysis techniques as a non-destructive testing method represents a low-cost, rapid alternative for quality control.

This work proposes an automated NDT system based on acoustic analysis: a pendulum delivers a controlled impact on each tile; a microphone and DAQ board capture the sound; LabVIEW software extracts the natural frequency via Power Spectral Density (PSD). Natural frequency deviation from the normal distribution of a production batch serves as the defect indicator. Destructive bending tests on all specimens provided the mechanical ground truth for correlation.

2. THEORETICAL BACKGROUND

The sensitivity of ceramic materials to the presence of internal discontinuities and possible heterogeneities in the application of mechanical stresses makes the use of statistical tools relevant for describing results obtained from mechanically tested ceramic materials. Such tools make it possible to identify consistent results or indicate, with a certain degree of statistical precision, the existence of differences between materials, manufacturers, batches, or samples based on the results obtained. However, this evaluation does not indicate the cause of the difference between measured results (Fonseca et al., 2015).

The presence of internal discontinuities and possible heterogeneities are determined using destructive tests for the quality control of ceramic tiles (Pessanha et al., 2019). According to Samborski and Sadowski (2006), one of the greatest challenges faced by the ceramics manufacturing industry is the rapid and efficient identification of small deformations/cracks that may occur in the internal structure of tiles and that are not easily identified through visual inspection.

The tap sound shows the difference in acoustic signal between a defect-free and a defective ceramic. The main advantage of this non-destructive testing method compared to other NDT methods is its low cost. The disadvantage is that it requires high environmental isolation

requirements and appropriate — sometimes complex — mechanical structures. With this method, internal defects, external defects, and online detection can be achieved (Zhao, 2021). Regarding other methods used for detecting anomalies or defects in ceramic tiles installed on buildings, Pessanha et al. (2019) state that spectral and temporal analysis shows that the acoustic response of their prototype was better than four other non-standardized methods: sphere, wooden handle, steel bar, and threaded bar.

ASTM E 1876-22 defines a method for determining elastic modulus E from natural frequency, mass, and geometry of a rectangular specimen (Eq. 1). For suspended plates ($T = 1$):

$$E = 0.9465 \times (m \times f_n^2) / b \times (L^3 / t^3) \times T \text{ [Eq. 1]}$$

where m = mass [g], f_n = natural frequency [Hz], b = width [mm], L = length [mm], t = thickness [mm].

The flexural rupture stress σ and fracture toughness K are determined per NBR ISO 10545-4:2020 (Eqs. 2–3). These destructive parameters serve as reference for correlating acoustic results.

Mechanical tests for material characterization are associated, to a greater or lesser degree, with imprecision in obtaining the values of the measured properties (Fonseca, 2015). According to standard NBR ISO 10545-4:2020, the bending stress applied during the flexure test is calculated using Equation 2:

$$\sigma = 3FL / (2bh^2) \text{ [Eq. 2]}$$

Where σ is the modulus of rupture in flexure [Pa], F is the applied force [N], L is the span between supports [mm], b is the specimen width along the fracture [mm], and h is the minimum specimen thickness [mm].

Toughness is calculated using Equation 3 (area under the load $\times$ displacement curve up to fracture):

$$K = \int_0^{\delta_r} F(\delta) d\delta \text{ [Eq. 3]}$$

Where $F(\delta)$ is the applied force [N] and $d\delta$ is the specimen deformation.

3. MATERIALS AND METHODS

Two groups of 37 ceramic tiles each were tested: flat surface (white tiles) (200×200×7.15 mm mean, mass 490 g mean) and textured surface (blue tiles) (200×200×6.43 mm mean, mass 426 g mean), both Group BIII. Visual inspection identified one defective specimen in each group (broken edge — Specimen 37), leaving 36 nominally intact tiles per group.

Non-destructive setup:

Tiles were suspended by a thin cord and struck at the geometric center by a calibrated nylon pendulum (constant release angle). A CEM DT-8852 sound level meter captured the acoustic signal, fed to an NI USB 6009 DAQ board, and recorded/processed in LabVIEW. PSD analysis identified the dominant frequency peak (natural frequency) for each tile; digital filters removed ambient noise.

Destructive setup:

Three-point bending per NBR ISO 10545-4:2020 (span 180 mm, 4 mm rubber pad, 1 mm/min crosshead speed) using an EMIC DL10000 machine. Flexural stress σ (Eq. 2), fracture toughness K (Eq. 3), and elastic modulus E_{dest} (slope of σ - ϵ curve at $\epsilon = 0.001$ – 0.0015) were extracted for all 74 specimens.

4. RESULTS AND DISCUSSION

4.1. Sound Pressure Level

The non-destructive testing performed in this research consists of evaluating the integrity of ceramic tiles through the natural frequencies produced by impact. Mechanical properties were evaluated and correlated with tile integrity. Specimens were weighed, and their length, width, and thickness dimensions were measured; subsequently, the natural frequency value was determined through sound signals collected in the time and frequency domains. Destructive tests were then performed according to NBR ISO 10545-4:2020 to determine mechanical properties.

Maximum sound pressure ranged 88–99 dBA (textured tiles) and 89–104 dBA (flat tiles). As shown in Chart 1, the distribution is broadly Gaussian and Specimen 37 falls within the normal cluster in both groups — sound amplitude alone is not a reliable defect indicator.

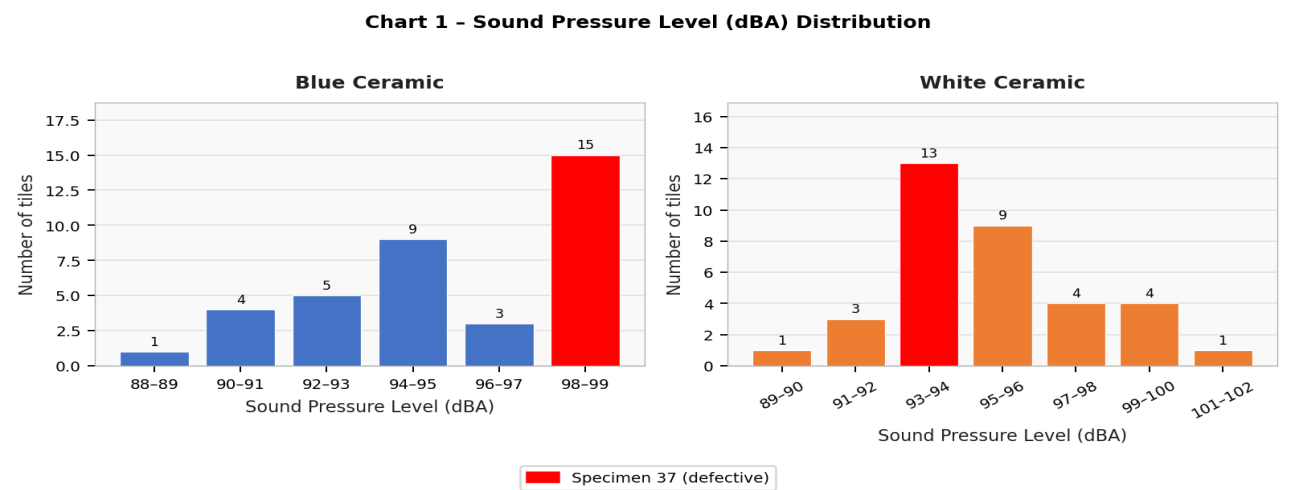


Chart 1. Sound Pressure Level distribution: a) Textured tiles (blue ceramic); b) Flat tiles (white ceramic). Red bar = Specimen 37 (defective).

4.2. Natural Frequency

Natural frequency proved a markedly better discriminator. Intact textured tiles clustered at 612–619 Hz (mean 618.9 Hz); Specimen 37 measured 632 Hz — roughly 2 standard deviations above the mean. Intact flat tiles clustered at 694–701 Hz (mean 695.6 Hz); Specimen 37 measured 712 Hz — similarly isolated at the far tail of the distribution (Chart 2). This is consistent with the edge chip reducing effective mass while local stiffness is approximately maintained, shifting the resonance upward.

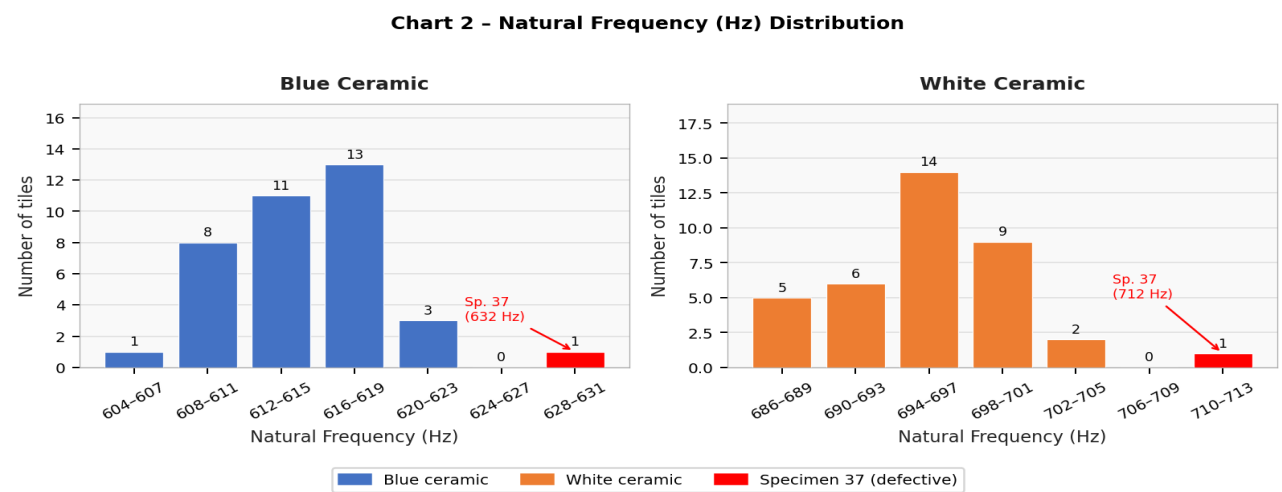


Chart 2. Natural Frequency distribution: a) Textured tiles (blue ceramic); b) Flat tiles (white ceramic). Red bar = Specimen 37 (defective). Arrows indicate deviation from Gaussian center.

4.3.Acoustic Elastic Modulus

Elastic modulus computed from Eq. 1 ranges 18–29 GPa (textured tiles) and 22–27 GPa (flat tiles). As shown in Chart 3, Specimen 37 falls within the normal band for both groups — the calculated acoustic modulus alone does not reliably separate the defective tile, because the shift in frequency is partially offset by the mass reduction caused by the broken edge.

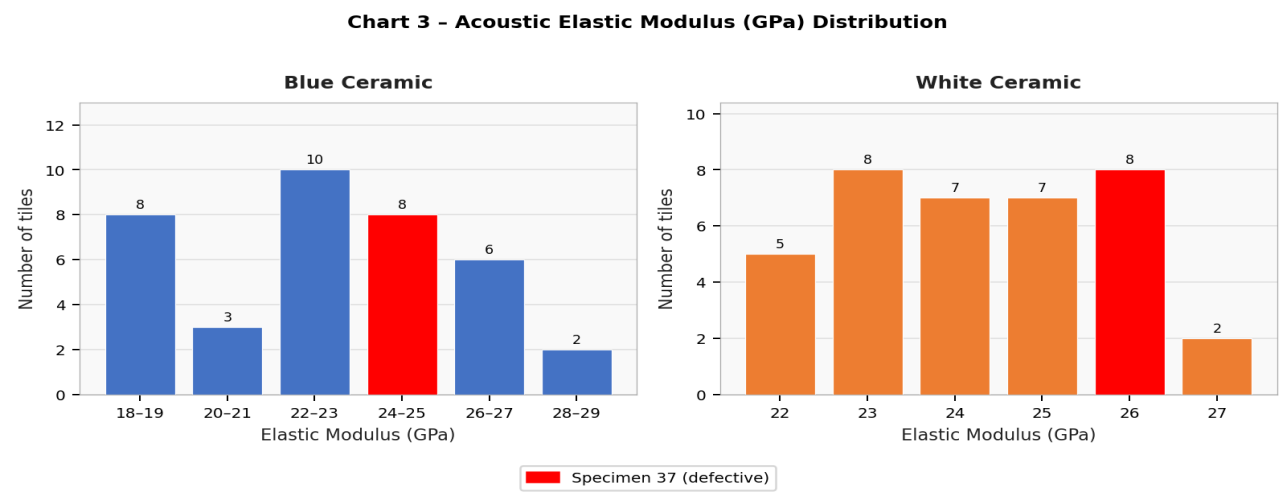


Chart 3. Acoustic Elastic Modulus (GPa) distribution: a) Textured tiles (blue ceramic); b) Flat tiles (white ceramic).

4.4. Elastic Modulus Factor

The ratio $E_{acoustic} / E_{destructive}$ ("Elastic Modulus Factor") provides a cross-method validation metric. For intact specimens, this factor clusters tightly: mean 2.28 ± 0.2 (textured tiles) and 2.19 ± 0.1 (flat tiles), overall mean 2.24. Specimen 37 shows a factor of 3.8 in both groups — 70% above the intact mean — clearly distinguishing it as an outlier (Chart 4). This consistent ratio across 72 intact tiles suggests $E_{acoustic}$ can serve as a reliable screening proxy for $E_{destructive}$, with the defect-induced frequency shift producing a proportionally large factor excursion.

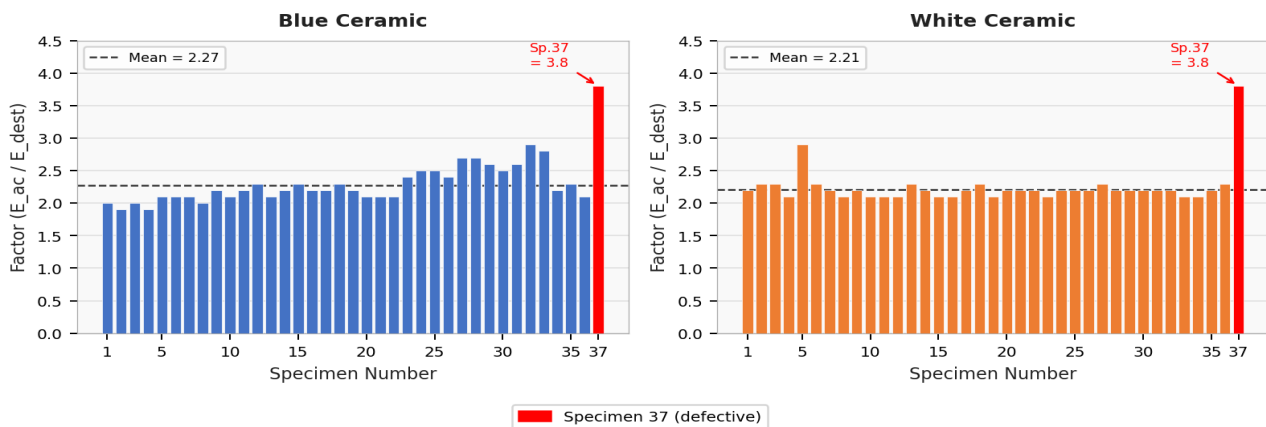
Chart 4 - Elastic Modulus Factor ($E_{acoustic} / E_{destructive}$)

Chart 4. Elastic Modulus Factor ($E_{acoustic} / E_{destructive}$) for all specimens. Dashed line = mean of intact tiles. Red bar = Specimen 37. (blue ceramic = textured tiles; white ceramic = flat tile)

4.5.Destructive vs. Acoustic Comparison

No direct mathematical relationship between acoustic and mechanical properties is established in the literature; the two methods measure fundamentally different physical responses. Table 1 compares Specimen 37 against a nearby intact specimen for each group.

Specimen	Max Stress (MPa)	Toughness (J/m ³)	Edest (GPa)
37 (textured tile — defective)	14.58	13,913	6.49
13 (textured tile — intact)	18.67	15,651	11.63
37 (flat tile — defective)	11.78	16,594	11.41
07 (flat tile — intact)	16.94	21,491	12.02

Table 1. Mechanical properties: defective vs. representative intact specimens.

The textured defective tile shows clearly lower stress (~22% reduction) and toughness (~11% reduction) compared to the intact reference, consistent with structural compromise from the manufacturing defect. For the flat tile, stress and toughness are near the group mean, supporting the hypothesis that Specimen 37 flat tile sustained a transport (non-process) chip that does not penetrate the structural cross-section. Fracture mode patterns confirmed no observable difference between defective and intact specimens in either group.

Chart 5 plots maximum stress vs. natural frequency for all specimens. Specimen 37 (textured tile) occupies the lowest-stress, highest-frequency position — a clear outlier. Specimen 37 (flat tile) shows anomalous frequency with near-average stress, consistent with a surface chip.

Chart 5 - Maximum Stress vs. Natural Frequency

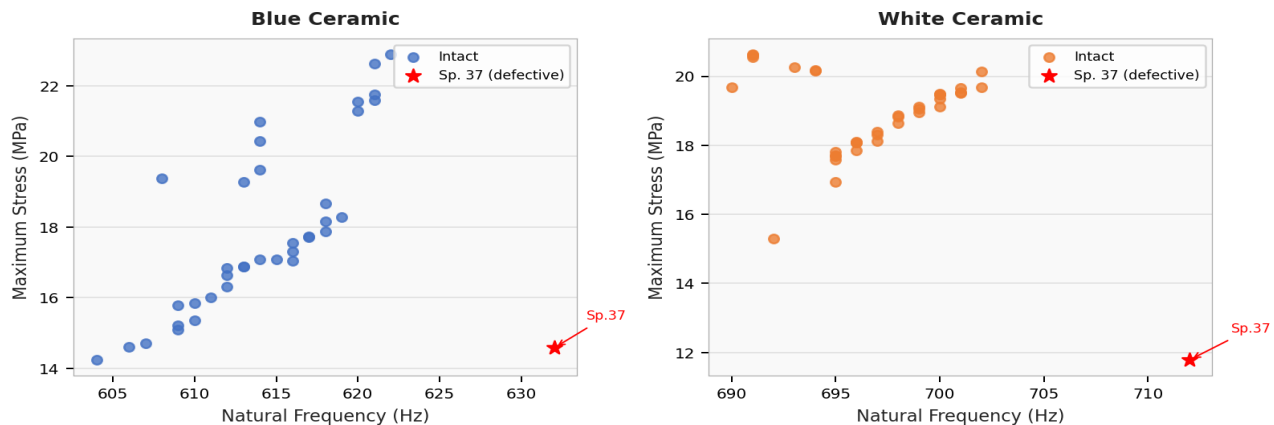


Chart 5. Maximum flexural stress vs. natural frequency. Star = Specimen 37 (defective). (blue ceramic = textured tiles; white ceramic = flat tile)

4.6. Fracture Pattern

Figure 1 illustrates the fracture mode for Specimen 37 (defective) and a representative intact specimen. No qualitative difference in crack propagation pattern was observed, indicating that the edge defects detected acoustically do not alter the bulk fracture mechanism under three-point bending.

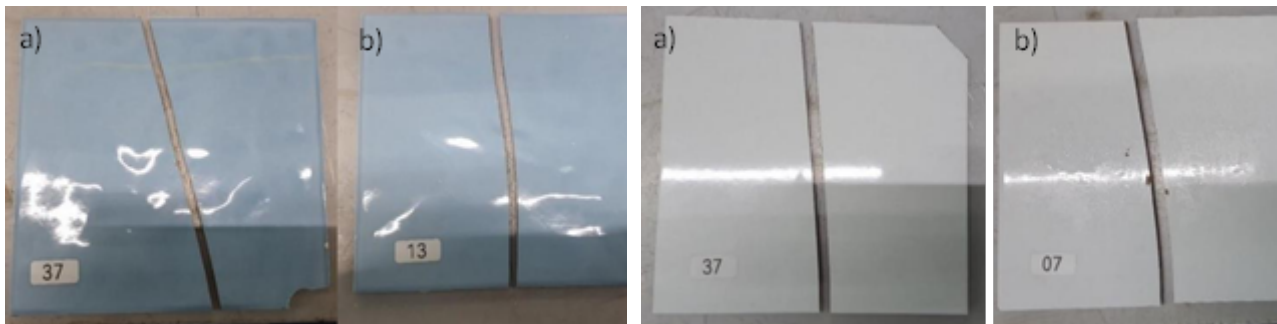


Figure 1. Fracture surfaces: Blue a) Textured tiles defective (Specimen 37); Blue b) Textured tiles intact; a) White Flat tiles defective (Specimen 37); White b) Flat tiles intact.

5. CONCLUSIONS

This work demonstrates that controlled-impact acoustic analysis is a viable, low-cost method for detecting structural defects in ceramic tiles:

- Natural frequency is the most sensitive acoustic indicator: defective Specimen 37 deviated ~2 standard deviations from the intact group mean in both tile types.
- Sound pressure amplitude alone is not discriminating — defective tiles fell within the normal distribution range.
- The Elastic Modulus Factor ($E_{\text{acoustic}}/E_{\text{destructive}} \approx 2.24$ for intact tiles) increases to ~3.8 for defective tiles — a robust, cross-validated anomaly flag.

- No direct quantitative relationship between acoustic and destructive mechanical parameters exists; the method is proposed as a complementary screening tool, not a replacement for standardized testing.

Future work should: expand sample size; include tiles with internal cracks (invisible visually); test tiles across different water-absorption groups; and explore machine-learning classification using PSD features for production-line automation.

6. REFERENCES

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