TECHNICAL REPORT

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INVESTIGATION ON THE PRESENCE OF DETACHMENTS OF GLAZED CERAMIC TILE PANELS BY MEANS OF NON DESTRUCTIVE ACOUSTIC MAPPING

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SUMMARY

1 THE PROGRAM

In the framework of a cooperation between Laboratório Nacional de Engenharia Civil – LNEC (Lisbon, PT) and the CNR-Institute of Acoustics "O. M. Corbino" – CNR_IA (Rome, IT) a program of non destructive experimental tests on artistic facades covered by glazed ceramic tiles has been planned.

Glazed tiles represent a legacy of Portuguese culture, to whose safeguard both cultural and scientific institutions pay particular attention.

The principal aim of this program is to evaluate the effectiveness of acoustic diagnostics employing the ACEADD (ACoustic Energy Absorption Device), developed at CNR_IA for revealing detachments in frescoes, for the evaluation of degradation in glazed ceramic tile facades. In particular the validation of the method and the evaluation of its reliability with respect to the degradation problems of tiles has been achieved.

Different typologies of defects may affect ceramic tiles panels and, as far as detachments are concerned, different levels of degradation may occur. Large area detachments involving a certain number of tiles, still holding together, but showing a lack of adherence to the wall represent the commonest macroscopic phenomenon. In some cases individual tiles may be fractured and only a fraction of a tile may be detached, while the remaining part is still holding firm to the wall. Finally delaminations of the glaze, detached from the bisque, represent the finer defect but also the most destructive one since it may lead to the loss of the layer that carries the image and thus the artistic and decorative value of the heritage.

The target of the CNR_IA was focused on the assessment of the value of the acoustic method for this particular typology of artifacts, by means of comparison between the said method and the *martelletto* evaluation carried out by LNEC researchers. The results collected during the present project represent the first application of the ACEADD diagnostics on ceramic facades, while it was validated and employed on

frescoes. Furthermore, since the method regards *in situ* measurements of acoustic quantities, technical aspects related to reproducibility of the measurement and to the influence of environment characterizing quantities were analyzed.
The target of LNEC was focused on the method potential evaluation for the determination of defects on tile panels, mainly in an early stage of degradation process in order to prevent the fall of relevant parts of tiles.

2 IMPORTANCE OF THE PORTUGUESE AZULEJO HERITAGE

2.1 A historic overview

From its origin in the Middle East and flourishing in the Islamic world, glazed tiles spread to Spain and Portugal and subsequently to Italy, the Low Countries and most of Europe.
Introduced to Portugal from the Moorish and Andalusian factories of Granada, Seville and Manises, azulejos (as glazed ceramic tiles are called in Portuguese) started being produced locally in the 16th century and developed as a preferred means of finishing architectural surfaces a century later, when they became ubiquitous in palaces, churches, gardens and bourgeois houses. The prevailing cobalt blue painting over a white tin glaze, that is so readily associated with the baroque architecture of Portugal and Brazil, developed when that colour combination became fashionable under the influence of Ming porcelain brought to the country by the Portuguese ships that made the China trade route.
Originally applied as in other countries, as a decorative and protective finishing, the use of azulejos in Portugal took a new facies in the mid 17th century, when they started being closely integrated with architecture in a characteristic way by which the architecture of volumes cannot be understood without considering together the treatment of surfaces, see Fig.1 (a) Igreja de Jesus, Setúbal. By the early 18th century, at the peak of the blue period (called in Portugal “the cycle of the Masters”) azulejo panels represented often memorable events and thus the walls “talked” graphically to their viewers, in a way that may be likened to the Renaissance frescoes in Italy. At this time architects used azulejos with an unerring easiness that surprises us today and the glory of many heritage sites rests the more on its azulejos, as the exterior architecture is simple and unassuming (Fig.1 b and c).

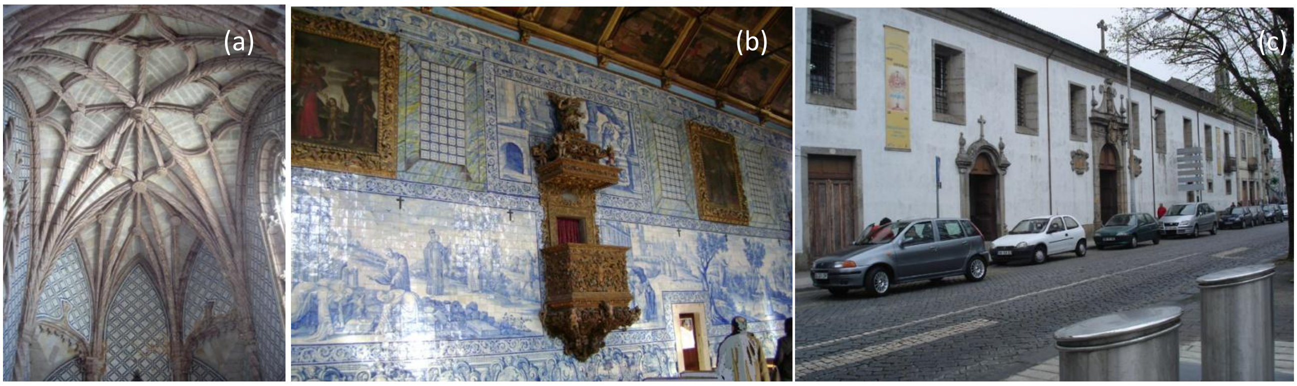
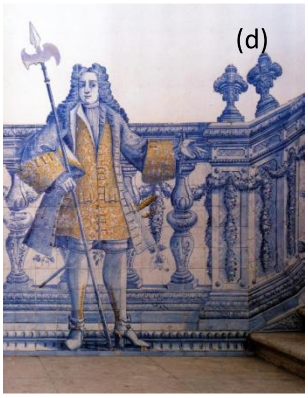


Fig. 1: Integration of glazed tile ornamental coverings into architectural structures.



Later in the century a new fad by which domains were populated by azulejo personae and animals spread and rooted. The aristocracy populated the stairs of their palaces with make-believe armed guards or servants inviting guests in (Fig.1 d Paço dos Arcebispos, Santo Antão do Tojal). Children and animals observed from behind stair balusters (all painted in tile panels) while simulated street goers peeped to gardens from closed barred gates. The inextricability of Portuguese azulejos and architecture is nowhere more evident than in this trompe l’oeil world [4].
Eventually demand in Portugal grew so much that it could not be met locally, and tiles of specified design were actually imported to the country from Holland.

Portugal, on the other side, never exported except to its own overseas possessions, mostly to Brazil, and so Portuguese azulejos remain a national feature. Thus, it is not surprising that azulejos are an important theme in Portugal and studies on their conservation are easily recognized as of national interest and relevance.

2.2 Some relevant forms of decay

Azulejos are a durable architectural finishing, as proven by centuries-old panels that are still virtually undamaged. However, whole tiles or groups of tiles may be lost by detachment from the supporting walls. Detachments of this kind may be caused by a number of factors but, once a single tile comes loose, its expansions and vibration will tend to contribute to the detachment of adjoining tiles in a process that will, if not counteracted, result in the collapse of large areas. Thus, it is common to find detached areas in which tiles are held solely by their lateral adhesion to other tiles, often also detached from the wall in an alarming example of precarious equilibrium.

Azulejos also suffer from the inherent weakness of being a layered material in which the outer glazed layer can readily detach from the ceramic substratum when shear forces arise in the interface. Such is the case when the thermal expansion coefficients of both glaze and bisque are not finely attuned [1]. During the cooling phase after the last firing, whenever the bisque contracts more than the glaze, shear tensions may lead to local or widespread delamination (Fig.2 (a) and (b)).

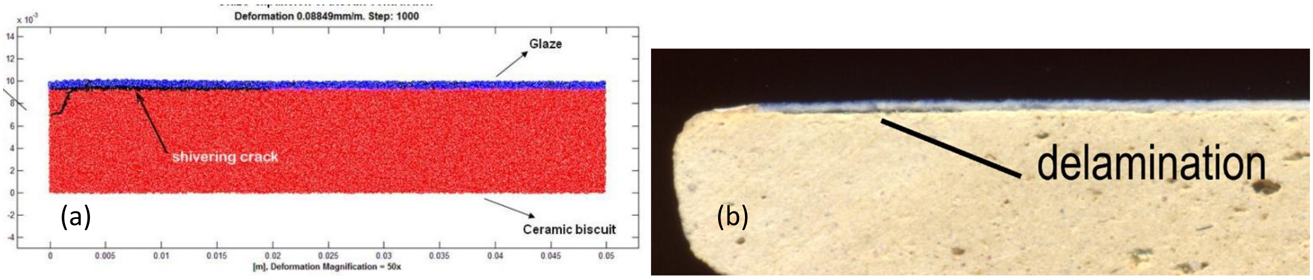


Fig.2: Delamination between clay bisque and glaze, (a) numerical model and (b) real sample.

This phenomenon, actually a manufacturing defect, is called "shivering" and often causes no alarming outside signals, rather it lays in waiting. When water moistens the biscuit, it will be able to penetrate in the open spaces under the glaze resulting from delamination, causing a characteristic bubble that breaks away leaving a lacuna wherefrom the process of detachment later progresses. Cases are found nowadays where well over a third of the glazed surface has been lost [1] in a decay process that is in progression and will inevitably lead to the loss of whole panels of heritage value (Fig.3).

Detachments from the wall can often be detected by a process of knocking each tile with the fingers (similar to the Italian *marteletto* method). Delaminations caused by shivering, however, are not detectable and even when evident because of an ongoing loss of glaze, it is not easy to assess the remaining areas to check whether they are sound.

Fig.3: Generalized decay of an interior panel (Igreja de Jesus, Setúbal).

3 LNEC: THE HOSTING INSTITUTION AND THE COOPERATION WITH CNR_IA

Laboratório Nacional de Engenharia Civil (LNEC) in Lisbon, Portugal, is a public research institute encompassing virtually all branches of civil engineering and related areas. Present workforce is of about 600 employees, of which around 300 have education at university level and 150 are LNEC Researchers. These must pursue a scientific career similar to that of university teaching staff.

LNEC carries out research, including planned research of a strategic nature, developed on the basis of research lines considered as essential due to their interest in the European and National contexts. LNEC also carries out consultancy activities on a contract basis in structural engineering, geotechnics, hydraulics, environment, transportation, housing, building materials and components aiming at the quality and safety of works, at the protection and rehabilitation of the natural and built heritage and at the technological modernisation and innovation.

The modern and sizable testing facilities at LNEC are available not only to its own staff but also to external researchers and research teams to develop projects within the scope of LNEC research programs. Such projects often include the participation of LNEC researchers as partners or coordinators. The present cooperation between CNR-IA and LNEC was integrated by a common interest for innovative testing technologies within one of LNEC's planned research projects aimed at identifying the forms of azulejo decay and develop preventive and remedial solutions.

4 THE ACOUSTIC DIAGNOSTIC METHOD: ACEADD

ACEADD device reveals detachments in multilayer structures, in particular in those structures having non homogeneous surface characteristics. Detachments can been revealed by measuring acoustic energy absorption coefficient since it was proved to be a good indicator of the presence of detachments. The ACEADD device identifies anomalous absorption process through a non contact 2D scan over the surface of interest, in *back reflection* geometry, providing acoustic images of the surface under test in which detached areas are discriminated from non damaged areas. Indeed, the physical principle upon which the diagnostic method is based assumes that a portion of a structure that is detached from its support, with a volume of air behind, behaves like an acoustic absorber resonating at characteristic frequencies while a portion of the same structure showing good adherence behaves as a total reflecting system due to the difference of acoustic impedance between air and structure constituent. The scheme in Fig.4, even if recalling the fresco representation, illustrates the interaction between acoustic wave excitation and the structure; a synthetic description of the relevant physical quantities involved in the interaction is reported.

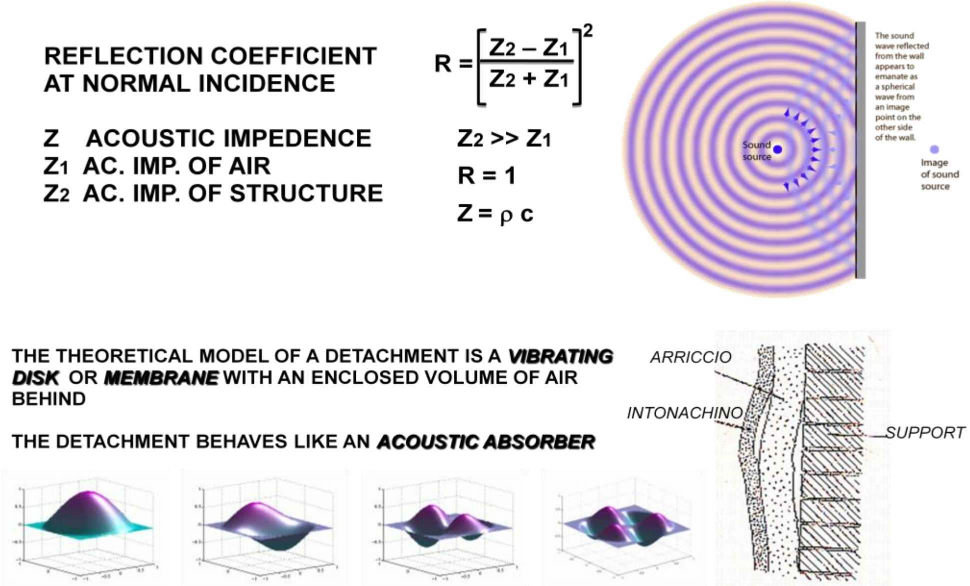


Fig.4: Scheme of the interaction between acoustic wave and the structure under study.

The method employs a specific algorithm, the Cepstrum algorithm, to allow a direct extraction of the impulse response, and it was validated in laboratory tests by means of fresco models with artificial detachments, realized by the Opificio delle Pietre Dure (Florence), and on real frescoes by means of *in situ* measurements in Rome and Florence [2,3]. Till now no test was carried out on glazed ceramic tiles nor mosaics, structures that even different from frescoes are affected by similar problems.

The results presented in the present report refer to the first attempt to study the response of tiles to a proper acoustic excitation and its impulse response characterization.

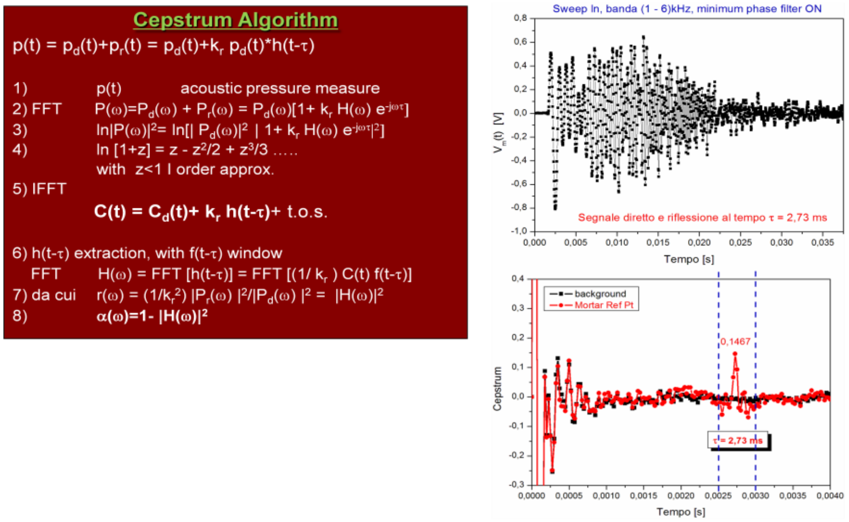
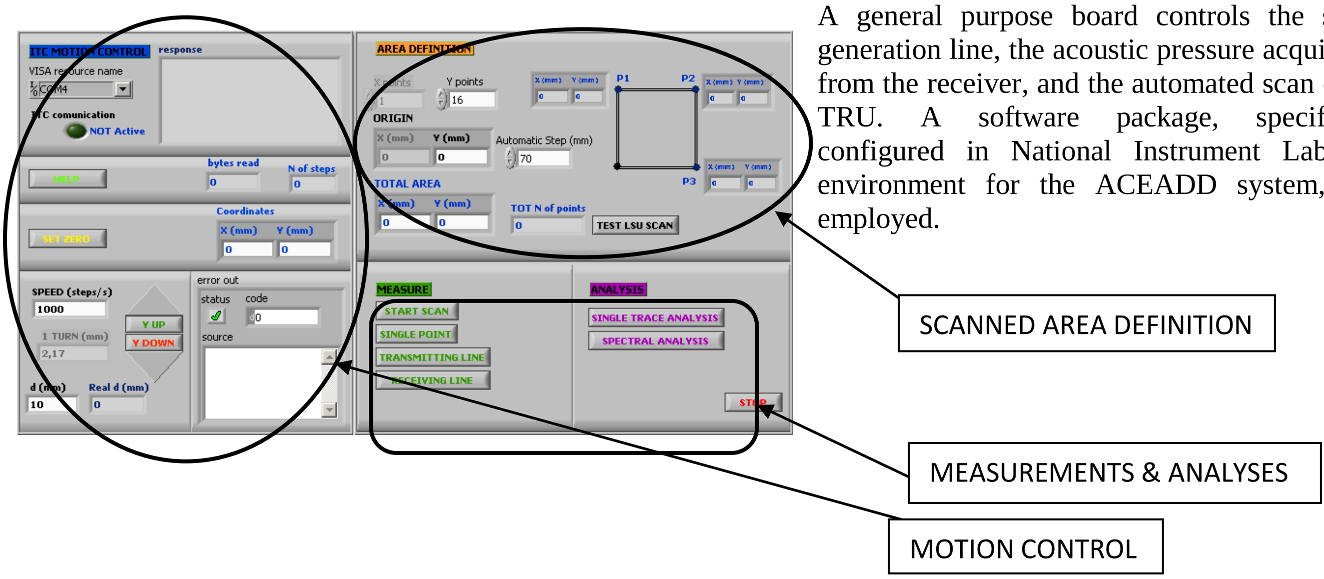


Fig. 5: Cepstrum algorithm.

The system employed in this work is the CNR_IA laboratory prototype equipped, in this case, with the Linear Scan Unit LSU, suitable for many different configurations of the site. The Transmit-Receiving Unit TRU is composed of a full range acoustic source S and an omnidirectional receiver M mounted in a co-axial configuration and placed at normal incidence with respect to the surface. Standard working distance was set to about 40cm from the surface (Fig.6).

Fig. 6: The ACEADD system illustrating the linear scan unit and the transmit-receiving unit.

A general purpose board controls the signal generation line, the acoustic pressure acquisition from the receiver, and the automated scan of the TRU. A software package, specifically configured in National Instrument LabView environment for the ACEADD system, was employed.



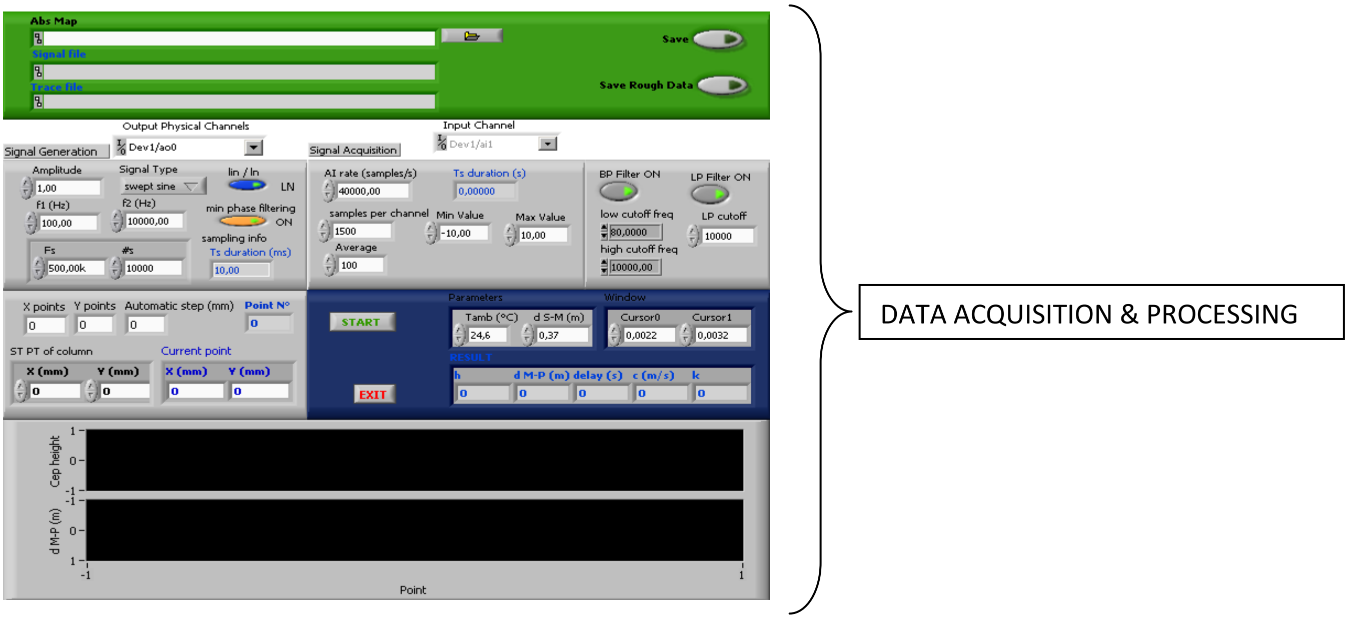


Fig.7: LabView SW package for ACEADD measurements.

A Mikromec Multisens logger, equipped with temperature and relative humidity probe, completed the system allowing the environmental parameter monitoring, required for the elaboration of impulse response values.

5 THE WORKING PLAN

The activity was planned, as reported in the following chart, including an initial check of the entire system, a preliminary set of measures to study the response of the specific structure to acoustic excitation, and finally the completion of a defined protocol suitable for acoustic mapping.

ACEADD PROTOCOL & MEASURING PROCEDURE			
TESTS	**FUNCTIONS UNDER TEST**	**IN SITU MEASUREMENTS:**	
LABORATORY TESTS:	LSU functionality	PRELIMINARY ACTIONS:	Surface Image
	Signal Generation		System Positioning
	MIC acquisition		Alignment System-Surface
	Scan functionality		Analysed AREA Definition
	Mapping		
		PRELIMINARY TESTS:	Background NOISE evaluation
			FREE-FIELD analysis
			Absorbed Frequencies analysis
			Frequency Band definition
			Timing evaluation
			Reference Points determination
			Reproducibility evaluation
		ACEADD MASUREMENTS:	MAPs: Detachments from support
			MAPs: Delaminations & Defects of glaze
ANALYSIS:			
	Evaluation of the dispersion of reflection peak values		
	Range of Absorption percentage for wide band excitation		
	Range of Absorption percentage for high frequency band excitation		
	Elaboration of Absorption Maps for wide detachments and for delaminations		
	Frequency analysis		

Tab.1: Working plan.

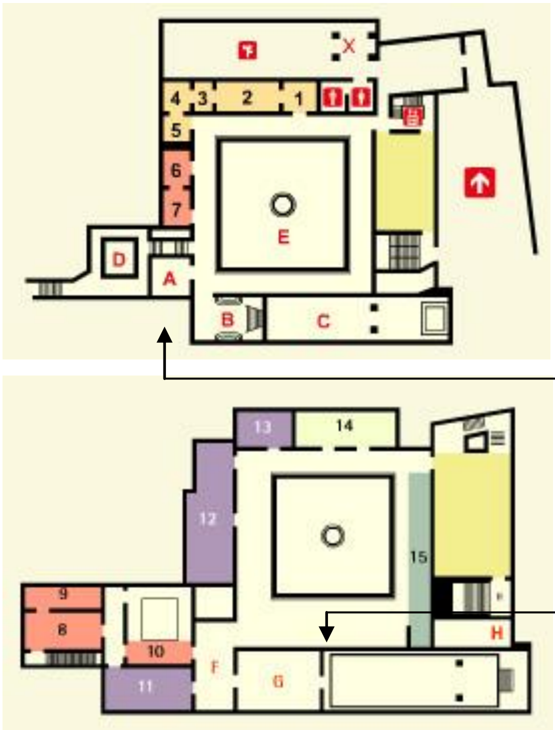
It is worthwhile to note that only an initial part of the planned analyses was carried out, while a more complete approach to data interpretation will be reserved to more technical publications.

6 THE LOCATION

The Madre de Deus Convent is a Portuguese National Monument situated in Xabregas, on the western area of Lisbon. The Convent was originally built between 1509 and 1516 and houses nowadays the National Azulejo Museum. The 16th century construction was affected by the earthquake of 1755 and the present building is a combination of 16th to 18th centuries architecture, with decoration motifs that span to the late 19th century.

Fig.8: Madre de Deus Convent.

The work presented is this report was carried out at two locations within the old conventual building: i) the assessment of glaze detachments from the wall used as test subjects two panels at the older 18th century church, scheduled for a future conservation intervention and presently used on a temporary basis to house part of the extensive reserves of the museum inventory; and ii) the top level of the cloister, whose walls are covered with low set panels obviously affected by moisture and depicting extensive loss of glaze, attributable to a manufacturing defect, probably shivering.



MNAz - GROUND FLOOR MAP
A - D. Leonor's Chapel
B - Chapterhouse / lower choir
C – Church
D - The small cloister
E – Cloister

first location
for Tiles Acoustic Mapping @ MNAz

MNAz - FIRST FLOOR MAP
F - Saint Antony's Chapel
G - Choir
H – View of Jerusalem

second location
for Tiles Acoustic Mapping @ MNAz

Fig.9: Locations at the National Museum of Azulejo where in situ measurements were carried out.

7 THE EXPERIMENTAL PROGRAM

In order to assess the reliability of the method, few important tests were required with supporting the analyses of acoustic mapping. The principal aim was the characterization of the environment, and the characterization of the electronic chain both through transmission and receiving lines. This was realized carrying out Noise evaluation, performing acquisition in passive configuration (i.e. transmission not active), and Free-Field evaluation, performing acquisition in active configuration with the system far from reflecting targets (with respect to the acquisition time window). These tests were relevant in order to reproduce the best conditions to make the Cepstrum processing work properly. Once these tests were completed a certain number of acoustic maps were realized, as reported in the following table.

ACEADD *IN SITU* MEASURING PROCEDURE		
PRELIMINARY TEST:	NOISE	Background evaluation
	FREE-FIELD	Background evaluation
	Reproducibility test	Sensitivity to random components
	Alignment procedure reliability	
ACEADD MASUREMENTS: Detachments from support	**MAP NMA1** [100-10k]Hz	[13L × 18PTs], 50mm step; 234PTs
	MAP NMA2 [100-10k]Hz	[24L × 21PTs], 50mm step; 504PTs
	MAP NMA3 [100-10k]Hz	[31L × 16PTs], 70mm step; 496PTs
Delaminations & Defects	**MAP NMA4** [5-20]kHz	[20L × 39PTs], 10mm step; 780PTs
	MAP NMA5 [5-20]kHz	[17L × 21PTs], 10mm step; 357PTs
	MAP NMA6 [5-20]kHz	[6L × 13PTs], 10mm step; 78PTs

Tab. 2: Scheme of ACEADD measurements.

For the validation of the acoustic method some maps obtained by means of *martelletto* evaluation were realized by LNEC researchers. The comparison will be described in the following sections.

7.1 The experimental results

ACEADD diagnostic method was developed by CNR_IA for fresco surfaces and only recently the response of the acoustic device from other typologies of surface have been explored. Thus, some comments regarding the structure of the objects under study can be useful for the comprehension of their acoustic behavior. Frescoes, mosaics and glazed ceramic tile panels can all be seen as multilayer structures, but each of them differentiates from the others for peculiar aspects.

Fresco structure shows a superficial structure that can be considered a *2D continuum*, while the in depth profile shows a discrete organization of plaster layers (support, *arriccio*, *intonachino* with the uppermost pictorial film). This is not the case of glazed ceramic tile panels that, at least in principle, present also in plane discrete and periodic organization of unit elements, the tiles. The in depth profile is similar to frescoes, but for the differences of materials (in particular thickness of layers, mass, density, porosity and physical properties of support, bisque and the upper glaze). Thus tile could be seen as the *2D unit cell* of the structure, but when we deal with detachments different situations may occur. A single tile can be detached losing also the bonding to its neighboring tiles so that it can be seen as isolated element, or a number of neighboring tiles may be detached from the support but still present a good bonding between them, and in this case they behave like a uniform large area with a quite significant mass to excite. On the other hand a tile can be cracked and separate fragments may present different adhesion states. In the end, delaminations of the glaze represent the limiting case where small masses and very thin layers are involved.

Thus in principle we must pass through different levels of defect analysis, being able to discriminate problems and interpretative planes from let’s say multi-tiles detachments, single-tile and sub-tile detachments, up to thinner delaminations. Employing ACEADD diagnostics this target can be accomplished by the employment of acoustic excitation of the structure with a suitable frequency band (and power transmission) for defects discrimination.

Another aspect deriving from these notes regards the choice of mesh size in the final matrix. While for fresco’s *2D continuum* a reasonable surface mesh size is determined by the maximum spatial resolution achieved by the experimental system, for tile panels a reasonable mesh size can be determined also by tile size, and a proper choice can be a fraction of tile size so defining the minimum number of points for the tile’s status to be properly represented. Thus, considering some observed fracture profiles, the mesh unit cell and relative matrix step can be

$$step = \frac{tile\ size}{2}$$

4 pts per tile, pts centered in each quadrant

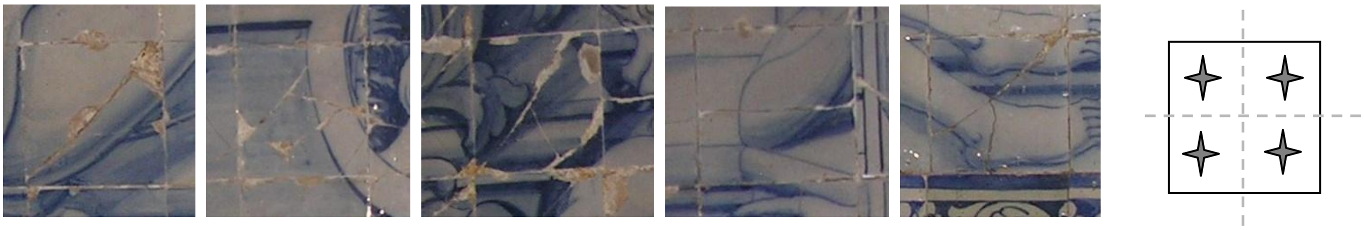


Fig.10: Fracture profiles in single tiles, and acquisition points arrangement for single tile.

Instead of achieving the maximum spatial resolution allowed by the device, this criterion reduces the number of points in the final map, calibrating this last with respect to a representative picture of the analyzed surface avoiding redundancy, and reducing the acquisition time as well. In this case alignment and position reproducibility become crucial, thus laser beam assisted alignment procedure was applied.

For glaze delaminations and defects, the previous criterion does not allow an adequate detailed analysis of the surface thus a smaller mesh size is preferable down to 10mm or less, even if an integration over a wider linear size area is expected.

In the acoustic absorption maps, described in the following sections, different step sizes were employed. For wide detachments mapping 50mm and 70mm step (this last according to the above mentioned criterion) were used. For detecting delaminations and small surface defects 10mm step was used.

7.2 Repeatability of measurements

An accurate determination of the acoustic diagnostics potentiality requires an evaluation of repeatability of measurements, thus a part of *in situ* tests was oriented to assess this feature. The test was performed carrying out four independent acquisitions of two selected vertical lines on the analyzed panels, taken in a few days time spread. For each repetition the system was re-configured, i.e. LSU re-positioned, TRU re-assembled, to account for random error, while the measurement procedure, the system and the references for tile alignment were kept unchanged. These tests were performed in the first location in NMAz, where the environmental parameters were quite stable. For this reason differences due to environmental changes could not be appreciated. For the analysis the *mean value*, the *standard deviation*, and the *standard uncertainty* of the replicate measurements were calculated. A summary of the analysis is reported in Annex 1 and 2. Even though this represents only a first stage evaluation of repeatability, that must be studied once the transfer function and the absorption coefficient for each point are extracted, it can be assessed that the dispersion of values referred to the reflection peak in the Cepstrum trace is comprised in less than 3% relative standard uncertainty for most points. The system position as well can be properly reproduced.

7.3 Levels of interpretation of experimental data

Assuming that in most cases an a priori knowledge of the surface acoustic behavior is not possible or required, a first level to interpret data can be based on the dispersion of impulse response values in a defined area of interest. Since the results of replicate measurements range around less than 3% of peak value, as observed in the previous section, one may expect that good adherence areas present a quite restricted range of values. While a wider range of values can be expected from rather heterogeneous areas. Thus the first interpretative level may be restricted to a comparison of *dispersion of values of data set* representing an area of interest with respect to a standard data set from particularly good surface, regardless of in plane points arrangement. Nevertheless particular attention, at this level of interpretation, has to be paid to the typology of wave excitation, in particular to the extension of frequency band. Since a wide band sine sweep signal is usually employed, the more extended is the band, the more likely is the acoustic absorption. Since in NMA1, NMA2 and NMA3 the excitation presented a quite wide frequency band (100Hz to 10kHz) the probability to excite many different modes of vibration is very high, while the chance to directly discriminate deterioration degrees is lower and an accurate frequency analysis becomes compulsory. For these maps, Fig.11, the overall values of absorption gather around 50-55%, indicating that the employed excitation is able to excite some characteristic modes in the whole scanned areas.

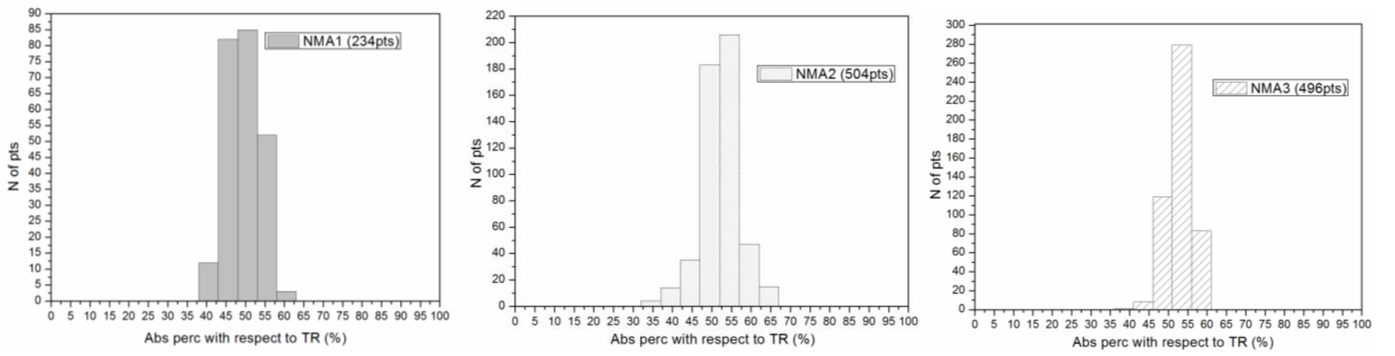


Fig.11: Dispersion of absorption percentage values in NMA1, NMA2, NMA3.

The employment of an acoustic excitation tuned to specific and restricted frequency band makes the analysis more direct and significant even at this stage of interpretation, as is the case of NMA4, NMA5 and NMA6 (5kHz to 20kHz), as shown in Fig. 12. In these maps a certain number of points present total reflection (i.e. normal modes not excited) with absorption percentage very close to 0%. Little amount of acoustic energy absorption is anyhow present, having a number of points with about 30% of absorption. In this case a discrimination between points with glaze coverage and points without glaze (where the glaze is lost and the bisque is exposed) becomes fundamental. In principle these points can be discriminated since their absorption coefficients showing different features. This aspect will be the object of further analyses.

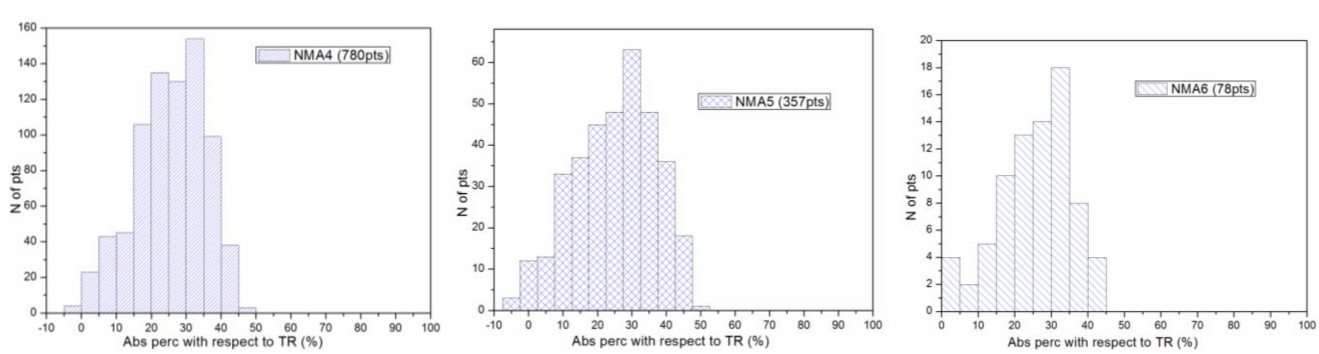


Fig.12: Dispersion of absorption percentage values in NMA4, NMA5, NMA6.

A second level is represented by acoustic mapping of absorption, for which different approaches are possible. A detailed analysis of these approaches is beyond the aims of this report, for which the simpler mode for displaying data was chosen in sections 7.4 an 7.5.

The last and most significant level of interpreting data is represented by frequency analysis for which the absorption coefficient vs frequency is extracted for each point. A sequence of absorption map with respect to characteristic frequencies gives information about the scale of the structure excited, as expressed in section 7.1. Wide detached multi-tile areas can be excited and may show absorption at lower frequencies (<1kHz) while delaminations, if excited, may show absorption at high frequencies, in our case due to source limited response towards the upper tail of frequencies in the audible range (20kHz) depending on the thickness of air cavity.

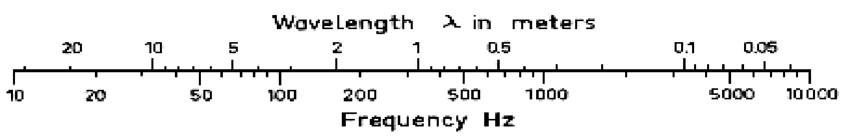
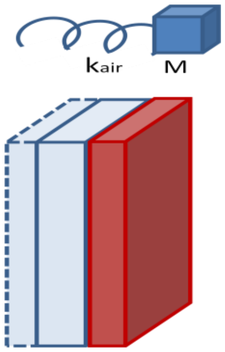


Fig.13: Wavelength to frequency conversion for the speed of sound in air of 343 m/sec.

The representation of the real system (tile-cavity-wall or glaze-cavity-bisque) is not a simple matter due to the heterogeneity of the structure, the variety of bonding conditions and constituent materials of both glaze and bisque, and burning temperature. All these characteristics influence the values of important elastic parameters and the acoustic behavior[6]. For simplicity the theoretical model of an absorbing panel, with a cavity of air between the panel and the wall, can be used for both detachments and delaminations excited by a sound wave impinging on them at normal incidence, in order to evaluate expected resonance frequencies. The system is schematically represented by a *mass-spring* model, where the *mass* is that of the panel and the *spring* represents the elastic action of air inside the cavity. In this model the section of the cavity equals the area of the vibrating panel. The energy absorption is maximized when the system resonates since the transformation of acoustic energy into mechanical energy reaches its maximum and also its transformation into heat.



$$k_{air} = \rho_0\, c_0^2\, S/d$$

$$f_0 = 1/2\pi\ [k_{air}/M]^{1/2}$$

$$f_0 = c_0/2\pi\ [\rho_0 /(\rho_s\, d)]^{1/2}$$

The fundamental frequency of the harmonic oscillator depends on the action of the elastic constant of air-spring and the mass of the panel, ρ_0 is the density of air, c_0 is sound velocity in air, ρ_s is the panel surface density, and d is the cavity thickness. The values of the fundamental frequency for a variety of cases can now be evaluated, Tab. 3, on the basis of experimental data on samples analyzed at UFPA-Universidade Federal do Parà [5] In particular sample P5 was taken as representative even if data show a wide range in composition, porosity, density and thickness both of bisque and glaze (the values are reported in Annex 3).

Material	Density	Sound speed long	Layer thickness	Cavity thickness	Panel+Air cavity
(*)	ρ (kg/m3)	cL (m/s)	σ (m)	d (m)	f0 (Hz)
Tile [P5]	**1,75E+03**	3505	**1,00E-02**	0,001	**4,69E+02**
Glaze [P5]	**7,25E+03**	3850	**3,00E-04**	0,0001	**4,21E+03**
Air	1,292	343			

(*) P5 refers to a sample analyzed at UFPA[5].

Tab.3: Estimated values of fundamental frequency for tile panel and glazed layer.

Air cavity (m)	f0 Tile (Hz)
9,00E-04	4,94E+02
8,00E-04	5,24E+02
7,00E-04	5,61E+02
6,00E-04	6,06E+02
5,00E-04	6,63E+02
4,00E-04	7,42E+02
3,00E-04	8,56E+02
2,00E-04	1,05E+03
1,00E-04	1,48E+03
5,00E-05	2,10E+03
1,00E-05	4,69E+03

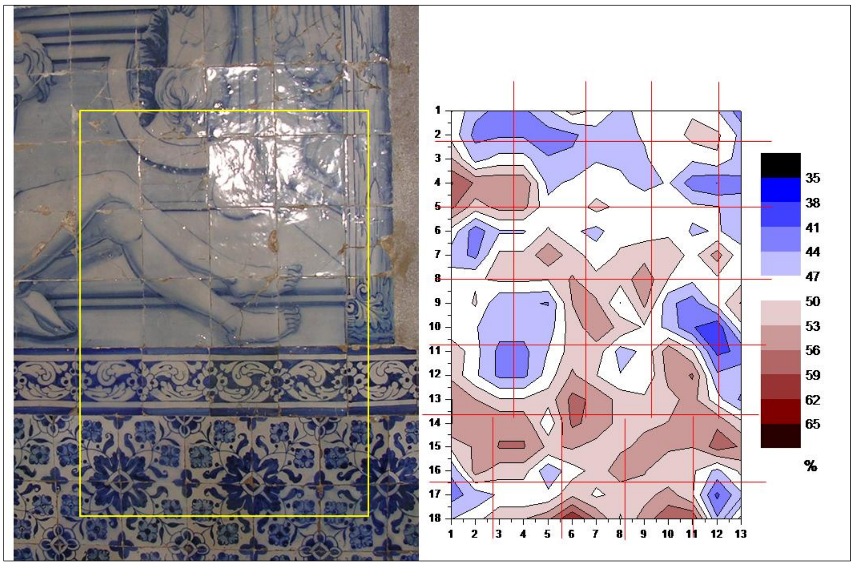
Air cavity (m)	f0 Glaze (Hz)
1,00E-04	4,21E+03
9,00E-05	4,44E+03
8,00E-05	4,70E+03
7,00E-05	5,03E+03
6,00E-05	5,43E+03
5,00E-05	5,95E+03
4,00E-05	6,65E+03
3,00E-05	7,68E+03
2,00E-05	9,41E+03
1,00E-05	1,33E+04
5,00E-06	1,88E+04

Tab.4: Fundamental frequency for tile panel (10mm thick) and glazed layer (0,3mm thick) for different thickness of air cavity.

For different thickness of air cavity the values for tile panel or glaze panel (referred to P5 sample) were calculated and are shown in the following table, Tab. 4. It can be easily noted that tile detachments with an enclosed volume of air behind, of less than 1mm, present resonance frequencies less than 1kHz, while delaminations of the glazed layer present resonance frequencies in the range 5kHz up to the limit of the acoustical device (and human perception) around 20kHz. Thus the impulse frequency bands employed are suitable for excitation of normal modes for both detachments and delaminations.

A detailed frequency analysis is beyond the aim of the present report and it will not be presented here.

7.4 Detachments



Concerning wide detached areas, three acoustic maps were realized at the Museo Nacional do Azulejo hosted in the Madre de Deus Convent. The site in which they were detected is the first location, in a room closed to visitors, described in section 6. The figures exposed in the present section present three maps showing details of the analyzed areas and relative tile network, giving some references for map alignment. In these maps an extended color scale was used, since the percentages of energy absorption are distributed in a narrow range indicating an overall excitation of modes for the frequency band (0,1÷10)kHz.

Fig. 14: NMA1.

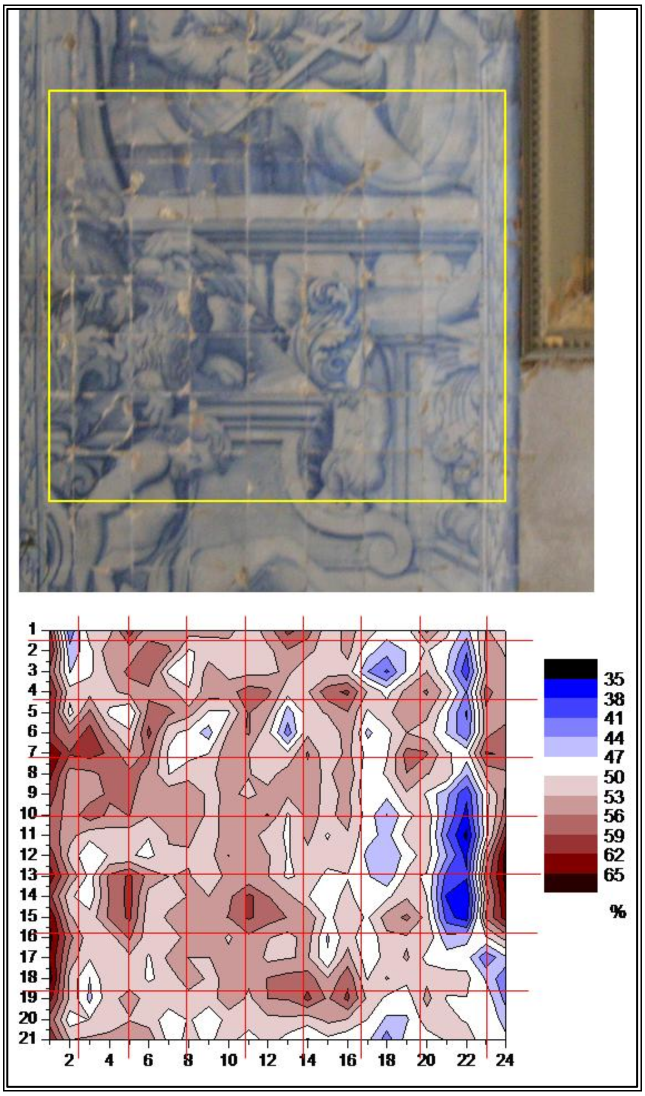
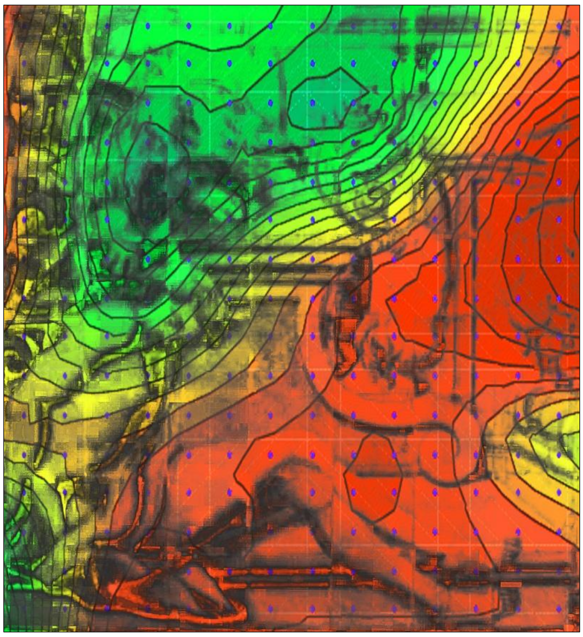


Fig. 15: NMA2.



A map corresponding to areas of the maps NMA1 and NMA2 was also produced by using a percussion technique similar to the *marteletto*. As respects to azulejos, the percussion technique must now be revised. Basically, the idea is that when a tile is detached it looses surface contact with the wall, forming a resonance chamber. When hit sharply, the sound perceived will vary according to the acoustic resonance of the system thus formed. If this is considered as a rectangular box whose dimensions are the fixed square size of the tile and its distance from the wall, then the resonant frequency will be lower as the detachment distance increases. In practice the situation is much more complex- a totally detached tile that is still in full contact with the wall will return a “non-detached” sound. On the other side, tiles are usually detached in large patches of many azulejo units and thus hitting any tile of the group will actually excite the same resonant volume but at a different spot, accounting for the tonal differences.

Fig. 16: Map detected by *martelletto* technique.

Detachment maps of azulejo panels may be achieved by deciding on a 1 to 5 scale of decreasing perceived frequency and judging the sound returned when hitting any single tile in a given manner. The results must, however, be interpreted in the following way:

i) a tile marked “1” is very likely fully attached, but it may conceivably be detached and still totally in contact;

ii) tiles marked “2” to “5” are detached and those with a higher “detachment rating” are either further away from the wall, or else they mark the center of a large detachment area.

Figure 16 shows the graphic result of an assessment of an area of the panel shown in Figure 15, in which green corresponds to an assessment of “1” = “fully attached” and red corresponds to an assessment of “5” = “detached and furthest away from the wall”.

The maps in Figures 14 and 15 cannot be compared directly with Figure 16, since the first two are obtained with a measure of a specific physical quantity, the acoustic absorption coefficient, that must be put into relation with the presence of resonant cavities in the specimen. The map in Figure 16 already contains an interpretative analysis about the degree of deterioration (from 1 up to 5) the surface presents together with the application of a smoothing operator.

Figure 17 shows a quite wide area presenting isolated points with good adherence in a general vibrating structure. An area presenting more stable conditions appears on the right half of the map, while an extended vertical region of high absorption appears in the centre, corresponding to the contour of the cross bottom. The left hand vertical line is not very reliable due to border effects decreasing the signal at the receiver. For the three maps realized by means of acoustic energy absorption a frequency analysis is compulsory since they present an integration over a very wide band, decreasing the discrimination capability of the method.

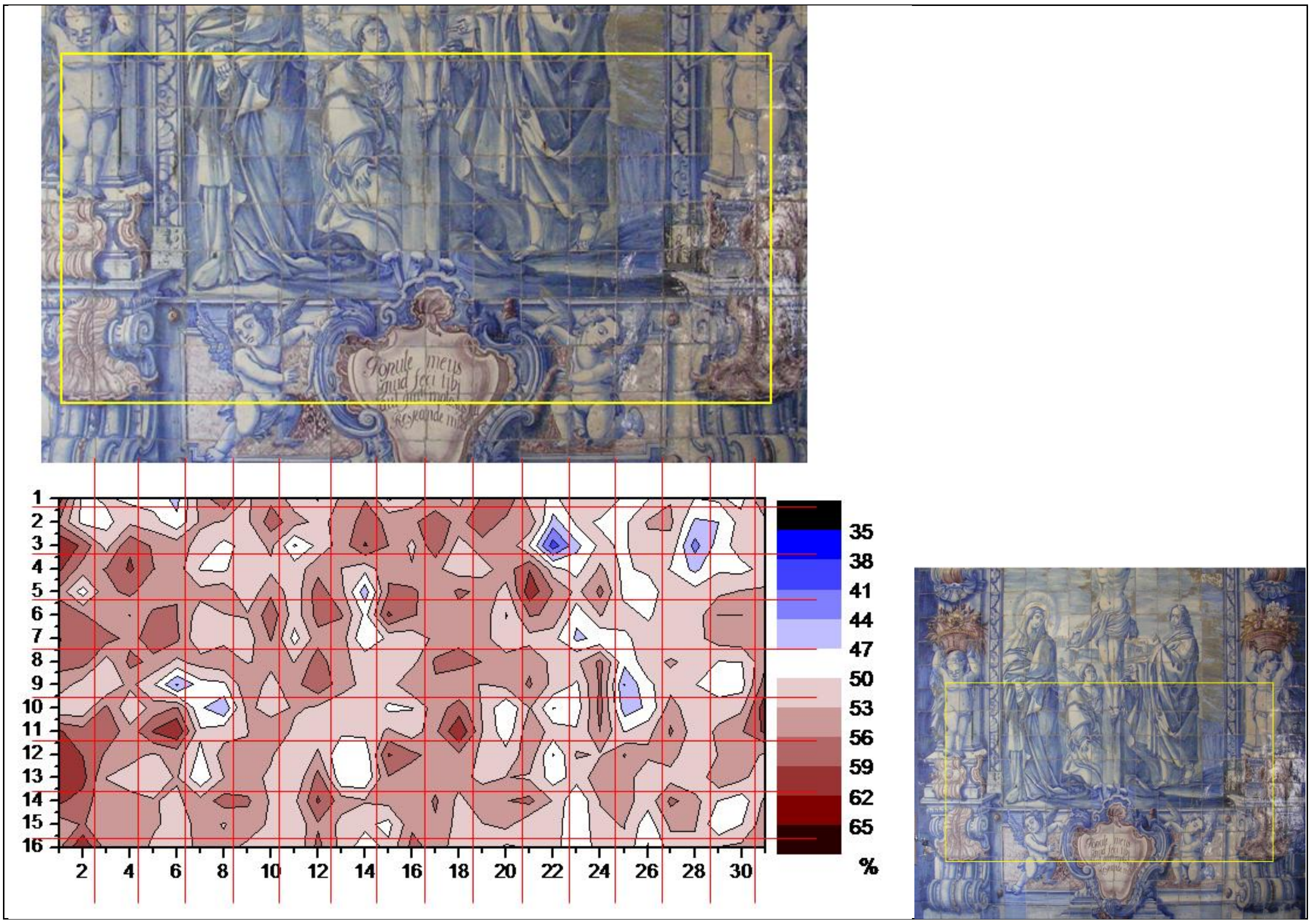


Fig. 17: NMA3.

7.5 Delaminations

The following figures refer to the maps obtained in the second locations in NMAz (upper cloister) in order to verify if delaminations of the uppermost glazed layer can be detected by the ACEADD apparatus. In the following images the photo of the analized area is highlighted in yellow, while on the acoustic maps the separation between adjacent tiles are marked in red. A deep analysis about delamination is beyond the aims of the present report, since the resonant frequencies of glaze layer has to be carefully investigated. Anyway a recursive behavior seems to be present and to identify single tiles. Inside single tiles the uncovered bisque is not identified at this stage, while it could be identified by means of frequency analysis, showing an absorption coefficient vs frequency curve different from narrow resonance peak, whose shape is characteristic of cavity resonance absorption.

In Fig. 19 NMA5 represent the acoustic map of a single sound tiles; the map shows a quite well defined squared area where a difference in acoustic behavior seems to divide the tile along its diagonal. At the top and at the bottom some absorbing areas appear to delimitate the tile.

In Fig. 20 NMA6 shows a very restricted area with a non flat surface due likely to production defects. As for NMA4, the acoustic behavior seems to differentiate two halves of tiles across the diagonal, showing an higher absorption in the upper part, above the defects clearly visible.

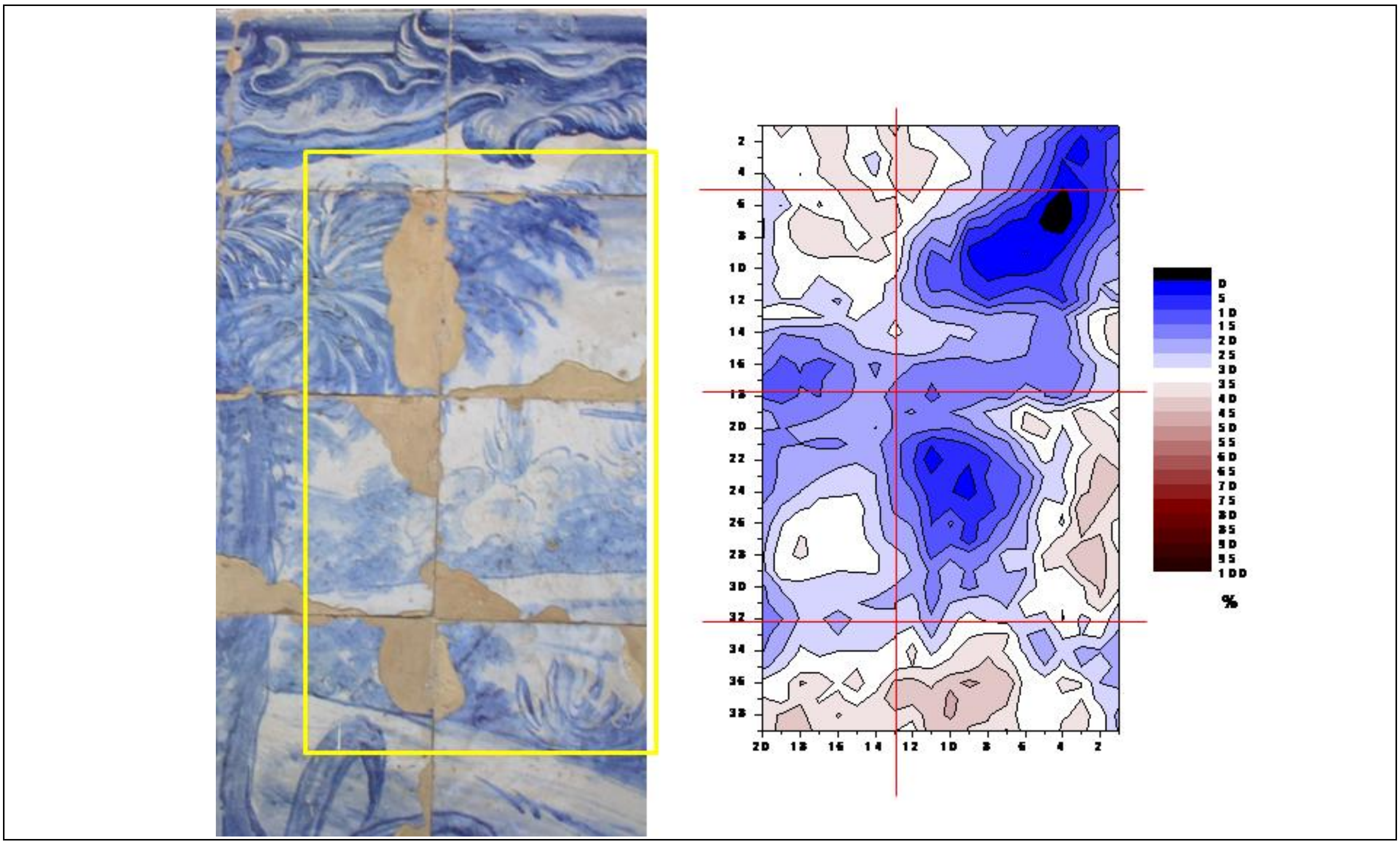


Fig. 18: NMA4.

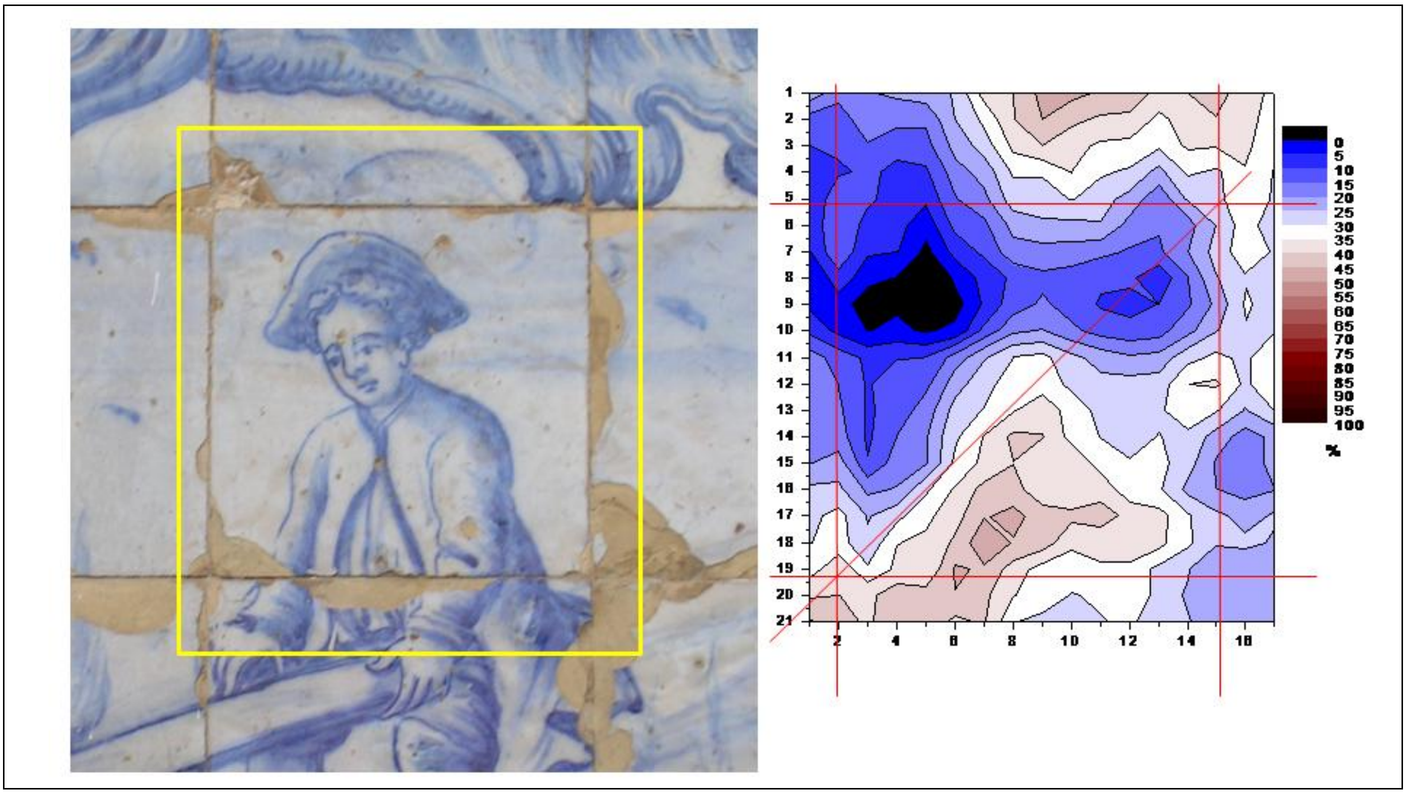


Fig. 19: NMA5.

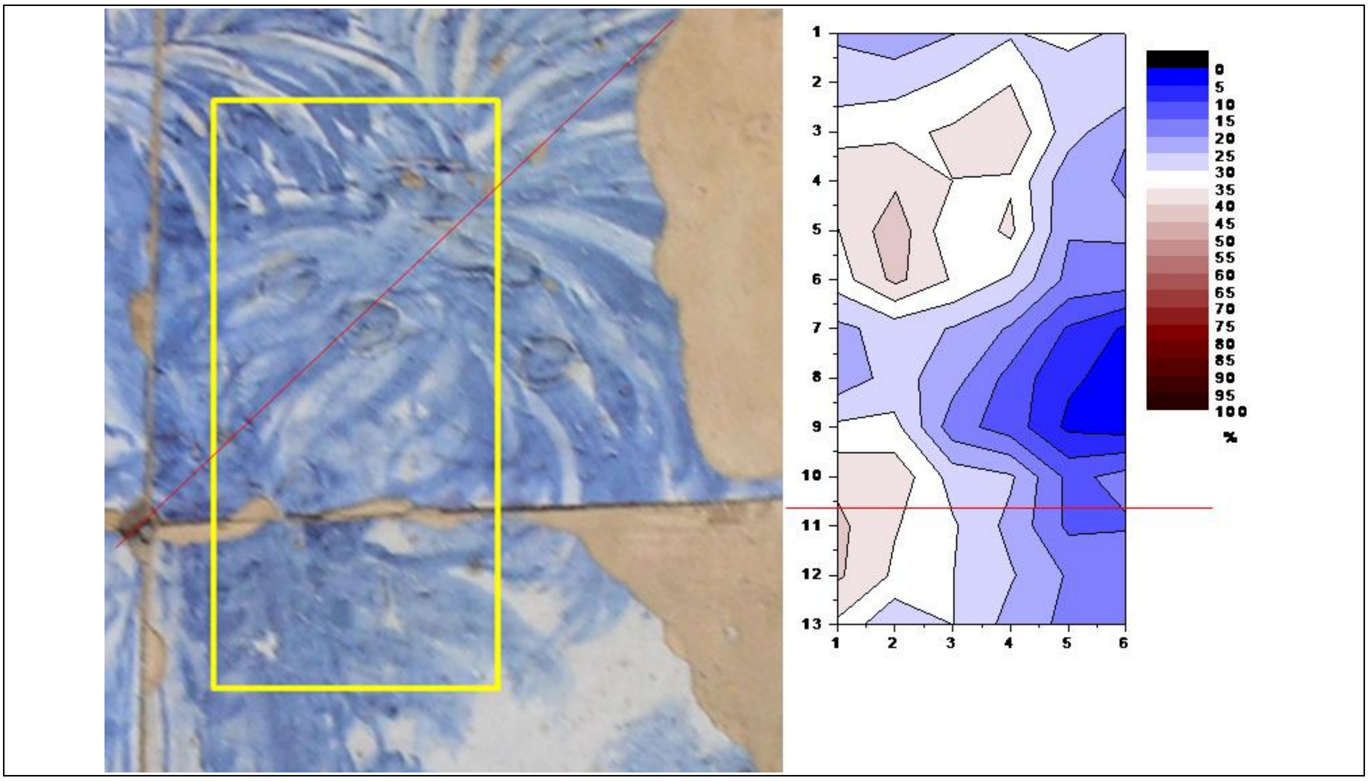


Fig. 20: NMA6.

8 EVIDENCE AND FUTURE DEVELOPMENT

At present, the experimental data analysis cannot be considered complete enough to give clear indication about all the aspects connected to the reliability of the acoustic absorption method for tile diagnostics. Repeatability tests return rather promising results allowing us to be confident about the capability of the method to detect relatively small variation in surface acoustic behavior (less than 3% of absorption percentage). Laboratory test on known specimens, provided by LNEC, will confirm the soundness of these elements. An estimation of resonance frequencies for tile detachments and for glaze delaminations confirmed the suitability of the excitation impulse employed in the measurements to excite both kinds of resonant cavities.

As specified in the previous sections, only a frequency analysis and the realization of maps for narrower frequency bands will definitely assess the potentiality of the ACEADD method for this kind of specimen. Among all the maps presented in the present report NMA4, NMA5 and NMA6, realized with a high frequency content incident impulse, offer a better discrimination between low and high resonance frequency and, therefore, between tile detachments and glaze delaminations. Even though the measuring procedure included few aspect requiring a better understanding of their implications (such as spatial resolution and matrix step, and the existance of high frequency limit for the sound source), the application to delaminations show interesting results, and this part of the study represents the major interest of LNEC researchers, partner of this work. Indeed, at present there is not a valid method to detect glaze delamination at an early stage of the degradation process (before bubbling is apparent and some glaze is lost), thus an assessment of ACEADD diagnostics suitability could be very important.

On the basis of the experimental data and of a reciprocal interest of CNR_IA and LNEC, the following aspects were outlined for a further development in the framework of future cooperation:

- Realization of laboratory test on known samples, provided by LNEC, presenting glazed layer delaminations (to be executed at the CNR_IA);
- Field work by LNEC at the same delaminated working areas analyzed with ACEADD using a different technology (thermography) aiming at obtaining results that may be used for the comparative assessment of the acoustic method;
- Optimization of an ACEADD device configuration suitable for glazed layer delamination detection, employing only high frequency source (this configuration can present reduced assembly dimension);

- Study of metrological aspects of the method, in particular referred to the evaluation of uncertainty budget according to the international standard JCGM 100:2008 (***Evaluation of measurement data — Guide to the expression of uncertainty in measurement***) and JCGM 101:2008 (***Evaluation of measurement data — Supplement 1 to the"Guide to the expression of uncertainty in measurement" — Propagation of distributions using a Monte Carlo method***).

9 CONCLUSIONS

The present report describes an investigation realized in cooperation between CNR_IA (Rome) and LNEC (Lisbon) including *in situ* determination of acoustic energy absorption coefficient from surfaces covered by glazed ceramic tiles. This investigation represents the first experimental study realized on glazed ceramic tiles by means of the acoustic energy diagnostic device, developed and patented at the CNR-IA. The experimental data analysis, though not complete, and considerations about the physical principles allow us to be confident about the potentiality of the method to reveal surface variations of energy absorption due to the presence of resonant behavior in tiles panels, both in the low frequency range (likely due to tile detachments, even if only frequency analysis will discriminate between different possible sources of resonance absorption) and in the high frequency range (more suitable for glaze delaminations). The problems affecting the glazed layer seems to be more urgent, for the prevention of glaze loss, thus additional investigations matching the interests of the Portuguese partner may constitute the basis for future cooperation.

ACKNOWLEDGEMENTS

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I would like to thank the Director of the ***Portuguese National Tile Museum (Museu Nacional do Azulejo-MNAz)***, *Maria Antónia Pinto de Matos*, who gave me the opportunity to access the museum and to materialize this study. I appreciated the positive attitude of MNAz in cooperating with the scientific community and the multidisciplinary approach. Thanks to the staff of MNAz, in particular to *Alexandre Pais* and *Lurdes Esteves* for their support and hospitality, allowing me to experience the MNAz as an uncommon laboratory of extraordinary richness and beauty.

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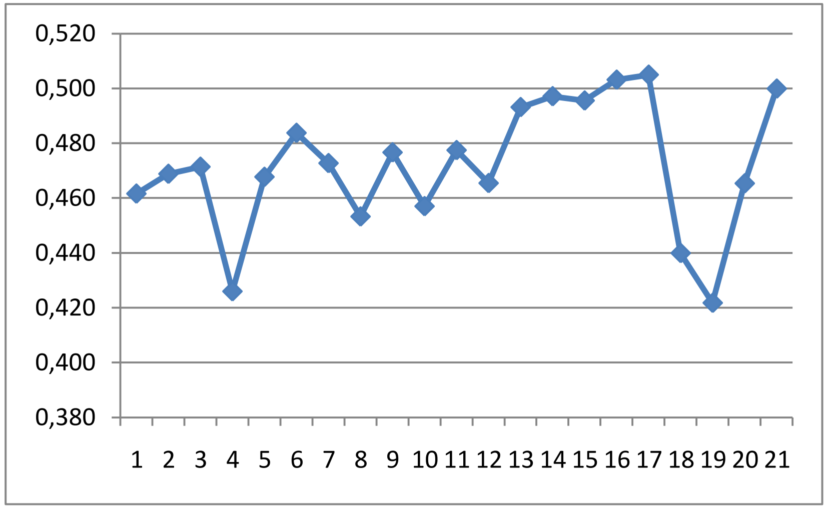
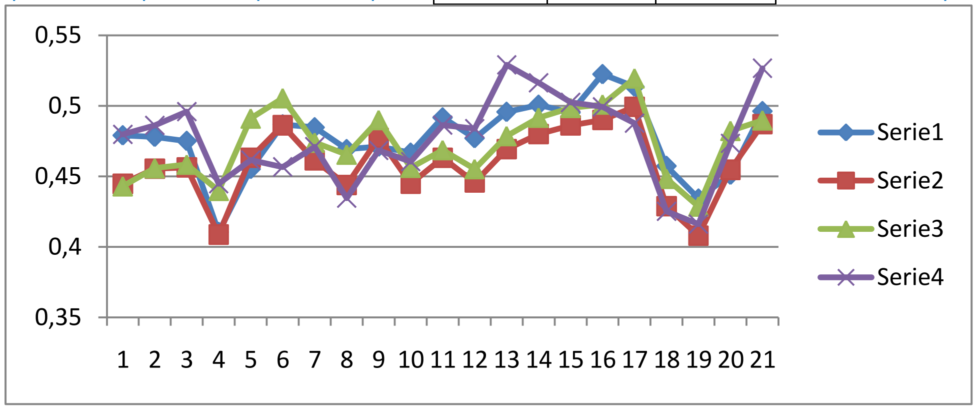
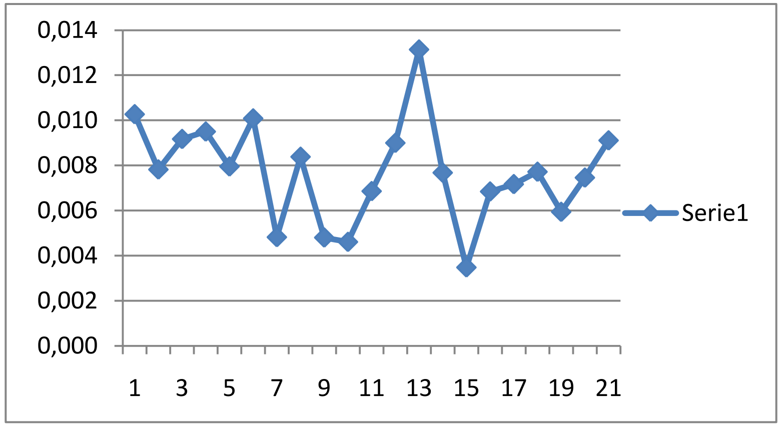
rip0	rip1	rip2	rip3	mean	std dev	std unc	rel std unc	perc
0,47902	0,44461	0,44297	0,47967	**0,462**	**0,021**	**0,010**	0,022	2,2
0,47795	0,45536	0,45576	0,48609	**0,469**	**0,016**	**0,008**	0,017	1,7
0,47504	0,45632	0,45832	0,49584	**0,471**	**0,018**	**0,009**	0,019	1,9
0,41051	0,40869	0,43975	0,44483	**0,426**	**0,019**	**0,010**	0,022	2,2
0,45517	0,46314	0,49098	0,46147	**0,468**	**0,016**	**0,008**	0,017	1,7
0,48674	0,48617	0,5054	0,45661	**0,484**	**0,020**	**0,010**	0,021	2,1
0,48466	0,46127	0,47391	0,47093	**0,473**	**0,010**	**0,005**	0,010	1,0
0,46919	0,44378	0,46544	0,43452	**0,453**	**0,017**	**0,008**	0,018	1,8
0,47102	0,47714	0,48992	0,46839	**0,477**	**0,010**	**0,005**	0,010	1,0
0,46669	0,44481	0,45608	0,46033	**0,457**	**0,009**	**0,005**	0,010	1,0
0,49164	0,46312	0,46861	0,48635	**0,477**	**0,014**	**0,007**	0,014	1,4
0,47702	0,4456	0,45518	0,48384	**0,465**	**0,018**	**0,009**	0,019	1,9
0,49562	0,4693	0,47856	0,52899	**0,493**	**0,026**	**0,013**	0,027	2,7
0,50063	0,47987	0,49159	0,51627	**0,497**	**0,015**	**0,008**	0,015	1,5
0,49517	0,48607	0,49854	0,50232	**0,496**	**0,007**	**0,003**	0,007	0,7
0,52233	0,48997	0,50094	0,49925	**0,503**	**0,014**	**0,007**	0,014	1,4
0,51349	0,49925	0,51943	0,48759	**0,505**	**0,014**	**0,007**	0,014	1,4
0,45732	0,42882	0,44828	0,42513	**0,440**	**0,015**	**0,008**	0,018	1,8
0,43418	0,40799	0,42866	0,41613	**0,422**	**0,012**	**0,006**	0,014	1,4
0,4511	0,45463	0,48225	0,47333	**0,465**	**0,015**	**0,007**	0,016	1,6
0,49611	0,48704	0,4897	0,52658	**0,500**	**0,018**	**0,009**	0,018	1,8
rip0	rip1	rip2	rip3	**mean**	**std dev**	**std unc**	rel std unc	perc

mean





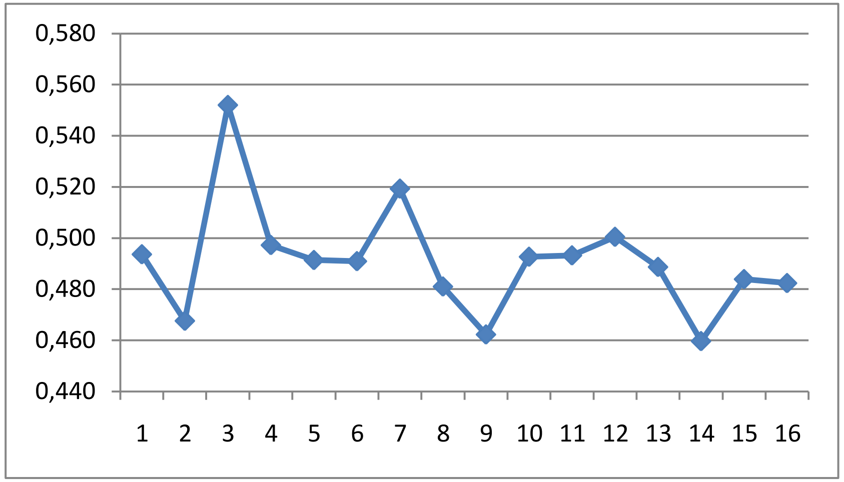
std unc

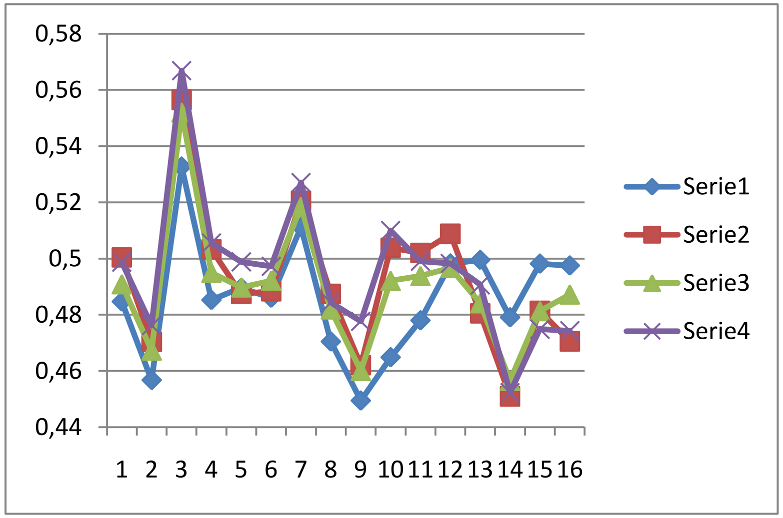


Annex 1 Ref.: NMA2; L15

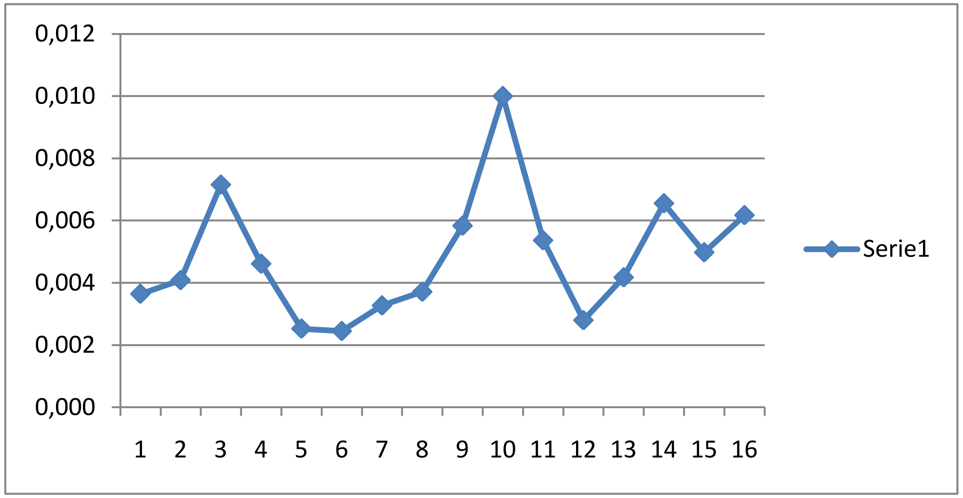
rip0	rip1	rip2	rip3	mean	std dev	std unc	rel std unc	perc
0,48466	0,50038	0,49086	0,49869	**0,494**	**0,007**	**0,004**	0,007	0,7
0,45672	0,47037	0,46725	0,47619	**0,468**	**0,008**	**0,004**	0,009	0,9
0,53268	0,55644	0,55206	0,56687	**0,552**	**0,014**	**0,007**	0,013	1,3
0,48522	0,50327	0,49493	0,50555	**0,497**	**0,009**	**0,005**	0,009	0,9
0,48956	0,48746	0,48973	0,4988	**0,491**	**0,005**	**0,003**	0,005	0,5
0,48601	0,48838	0,49214	0,49723	**0,491**	**0,005**	**0,002**	0,005	0,5
0,51118	0,52049	0,51849	0,52706	**0,519**	**0,007**	**0,003**	0,006	0,6
0,47044	0,48744	0,48191	0,48436	**0,481**	**0,007**	**0,004**	0,008	0,8
0,44941	0,46207	0,45999	0,47769	**0,462**	**0,012**	**0,006**	0,013	1,3
0,46483	0,50383	0,49205	0,51	**0,493**	**0,020**	**0,010**	0,020	2,0
0,47796	0,50203	0,49378	0,49908	**0,493**	**0,011**	**0,005**	0,011	1,1
0,49819	0,50877	0,49663	0,49826	**0,500**	**0,006**	**0,003**	0,006	0,6
0,49948	0,48049	0,48409	0,4907	**0,489**	**0,008**	**0,004**	0,009	0,9
0,47903	0,45098	0,45646	0,45227	**0,460**	**0,013**	**0,007**	0,014	1,4
0,49814	0,48141	0,48129	0,47487	**0,484**	**0,010**	**0,005**	0,010	1,0
0,49748	0,47054	0,48722	0,47428	**0,482**	**0,012**	**0,006**	0,013	1,3

mean





std unc



Annex 2 Ref.: NMA3; L11

Density bisque	Density bisque+glaze	Thickness bisque	Thickness glaze	Thickness total	Density glaze (g/cm3)	Sample [Ref.5]	Mass bisque	Mass glaze	Mass bisque+glaze	Tile size 14cm x 14cm
ρb (g/cm3)	ρb+g (g/cm3)	db (cm)	dg (cm)	db+g (cm)	ρg (g/cm3)		mb (g)	mg (g)	mtot (g)	mglaze/mtot
1,93	2	0,858	0,052	0,91	3,16	P1	324,56	32,16	356,72	0,090
1,5	1,97	0,52	0,38	0,9	2,61	P2	152,88	194,63	347,51	0,560
1,56	1,73	0,61	0,285	0,895	2,09	P3	186,51	116,96	303,48	0,385
1,66	1,64	0,639	0,111	0,75	1,52	P4i	207,91	33,17	241,08	0,138
1,76	2,11	0,532	0,193	0,725	3,07	P4ii	183,52	116,31	299,83	0,388
1,58	1,75	0,97	0,03	1	7,25	P5	300,39	42,61	343,00	0,124
1,61	1,65	0,759	0,266	1,025	1,76	P6	239,51	91,97	331,49	0,277
1,61	1,66	0,811	0,039	0,85	2,70	P7	255,92	20,64	276,56	0,075
1,64	1,72	0,858	0,042	0,9	3,35	P8	275,80	27,61	303,41	0,091
1,54	1,66	0,801	0,049	0,85	3,62	P9	241,77	34,78	276,56	0,126
1,42	1,78	0,812	0,048	0,86	7,87	P10	226,00	74,04	300,04	0,247
1,87	2,2	0,655	0,025	0,68	10,85	P11	240,07	53,15	293,22	0,181
1,71	1,75	0,818	0,067	0,885	2,24	P12	274,16	29,39	303,56	0,097
1,38	1,4	0,621	0,029	0,65	1,83	P13	167,97	10,39	178,36	0,058
1,63	1,83	0,798	0,062	0,86	4,40	P14	254,95	53,52	308,46	0,174
1,59	2,15	0,878	0,022	0,9	24,50	P15	273,62	105,64	379,26	0,279
1,77	1,9	0,971	0,019	0,99	8,54	A1	336,86	31,82	368,68	0,086
1,64	1,7	1,069	0,031	1,1	3,77	A2	343,62	22,90	366,52	0,062
1,72	1,74	0,601	0,059	0,66	1,94	F1	202,61	22,48	225,09	0,100

Tile Thickness cavity1E-3m; Glaze Thickness cavity 100,0E-6m

Surf density bisque (g/cm2)	Surf density bisque+glaze (g/cm2)	f0 (Hz)		Surf density glaze (g/cm2)	Sample	f0 (Hz)
1,66	1,82	459,95		0,16	P1	4844,45
0,78	1,77	466,01		0,99	P2	1969,11
0,95	1,55	498,67		0,60	P3	2540,09
1,06	1,23	559,49		0,17	P4i	4769,45
0,94	1,53	501,69		0,59	P4ii	2547,19
1,53	1,75	469,06		0,22	P5	4208,39
1,22	1,69	477,14		0,47	P6	2864,43
1,31	1,41	522,37		0,11	P7	6047,17
1,41	1,55	498,72		0,14	P8	5227,82
1,23	1,41	522,37		0,18	P9	4657,95
1,15	1,53	501,52		0,38	P10	3192,55
1,22	1,50	507,32		0,27	P11	3768,26
1,40	1,55	498,60		0,15	P12	5066,91
0,86	0,91	650,47		0,05	P13	8521,69
1,30	1,57	494,62		0,27	P14	3755,06
1,40	1,94	446,07		0,54	P15	2672,76
1,72	1,88	452,43		0,16	A1	4870,19
1,75	1,87	453,76		0,12	A2	5740,50
1,03	1,15	579,03		0,11	F1	5794,31

Annex 3: Resonance frequency evaluation.