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ACOUSTICAL CHARACTERIZATION OF AUTHENTIC MATERIALS AND SYSTEMS OF HISTORICAL STRUCTURES IN ANATOLIA

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ABSTRACT

Acoustical simulation techniques are commonly used for analyzing indoor acoustic characteristics of historic structures, when in-situ measurements are found impractical. Simulations are also beneficial for rendering the acoustical effects of restoration works and to compare them to the authentic conditions. On the other hand, authenticity of simulations requires accurate acoustical characterization of the historical materials. Reverberation chamber measurements are one of the current techniques used to determine sound absorption coefficients of any type of building material. Nevertheless, such method requires large specimens, which are often difficult to acquire from historical sites. In this study, impedance tube measurements are utilized to measure samples of various sizes that are collected from the vicinity of investigated sites and to characterize systems which are reproduced from original documents. Measurements conducted on the tuff stone utilized in a Middle Byzantine Masonry Church in Cappadocia exhibit high sound absorption performance at mid-high frequencies. The stone sample from a 19th century building in İstanbul, Rami Barracks, exhibit relatively lower absorptive characteristics in comparison to tuff stone. Measurements of a cavity resonator found in the dome of Süleymaniye Mosque -a 16th century landmark inherited from Ottoman Empire-, exhibited a sound absorption peak at the vicinity of 500 Hz.

Keywords: *archeoacoustics, sound absorption measurements, cavity resonators, cappadocia*

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1. INTRODUCTION

Acoustical simulation tools help acousticians to examine indoor acoustical characteristics of rooms particularly when an in-situ measurement is found inapplicable or the acoustical design phase is being conducted. Such method especially benefits the acoustical assessments of public historical structures where there are on-going restoration works or the complete structure is not present at the time of the study, such as partially ruined structures [1]. They not only provide alternative solutions against practical challenges, but also enable further assessment of the historic soundscapes. The sonic ambience of an interior space is formed by the material and geometrical features of an enclosure both of which are often altered in the course of time. When accurate acoustical characterization of the authentic finishing materials once employed in the building is achieved, the assessment of changing acoustical qualities of an edifice in its different historic stages becomes possible.

The acoustical characterization of an authentic material, on the other hand, brings its own challenges. Collecting large specimens from the heritage site or reproduction of original acoustical systems found in the structures are often difficult. Owing to such limitations, other experimental methods emerge as an alternative. In a recent study Navacerrada et al. [2] utilized pressure/particle-velocity impedance gun on historic stone surfaces to evaluate damage on their finishing in respect to the sound absorption coefficient values measured in-situ from a close distance to the stone surface. In another study, Saccenti et al. [3] measured the normal acoustic impedance and normal sound absorption coefficients of the wood planks, sandstone and brick surfaces of a historic theater in Sicily using Laser Doppler Vibrometer (LDV). A review study covering the in-situ sound absorption coefficient measurement techniques by Brandão et al. [4] is also present.

As for the characterization of the historical acoustic systems, investigation of the acoustic clay pots in form of Helmholtz resonators is one of the recent topics. In previous research, their acoustic performances are studied throughout the world by in-situ and laboratory measurements [5-8]. Theoretically, the resonance frequency of the pots can be predicted with the well-known Helmholtz formula based on their given dimensions. Nevertheless, acoustical characterization of such clay pots found embedded into the structure is complicated as the accurate measurement of the internal shape conditions of the neck area and the internal volume of pots is difficult. A semi-empirical model investigating the internal corrections for the complex neck shape of the pots is proposed in a recent study [9]. Nevertheless, the pots investigated in our study are neckless, which is different than the samples used in the proposed model.

In the present work, impedance tube measurement is used for acoustical characterization of different stone finishes and a medieval acoustic clay pot example. The authentic materials examined in this paper are found in three architectural heritage sites in Anatolia. Those are: tuff stone of the Middle Byzantine Bell Church (Çanlı Kilise) in Cappadocia, cavity resonators found in Süleymaniye Mosque (a 16th century landmark inherited from Ottoman Empire), and lastly, stone masonry walls of a 19th century military building, Rami Barracks in İstanbul. The measured sound absorption coefficients of the materials are later utilized in acoustic simulations in which interior sound field of each structure is analyzed. Some of the samples utilized in this study are larger than a regular sample to fit inside the sample holder of the impedance tube. Therefore, measurement procedures ensuring the samples to be sealed into measurement chamber are presented.

2. METHODOLOGY

The normal-incidence sound absorption coefficients of three of the samples are all measured with impedance tube set-up (S.C.S Kundt Impedance Tubes) based on transfer function method. The measurements are performed in accordance with the ISO 10534-2: 1998 standard [10]. A large tube (Ø100mm) and a small tube (Ø28mm) setup respectively covering low (50 Hz to 1000 Hz) and high (1000 Hz to 5000 Hz) frequency measurements are utilized. The microphones and the tube are calibrated before the measurements.

The Kundt Tube method has proven to be a practical and faster method to measure absorption coefficients of sound absorbing materials than both Standing-Wave-Ratio (SWR) and reverberation chamber methods [11, 12]. Large samples that cannot be brought into reverberation chambers for sound absorption coefficient measurements are the main reason of using the Kundt Tube method in this study.

3. CASE STUDIES

3.1 Bell Church, Cappadocia

In the case of Cappadocia, there is a general problem of understanding settlement patterns of the Middle Byzantine Era. This is mainly due to the lack of any textual evidence from the region [13]. However, there is a vast range of physical study material in the form of Cappadocia's signature rock-cut structures and much fewer masonry structures which are studied in interpretative way to understand their function. One physical character of such spaces is their indoor acoustical climate. With the challenges of a remote location and the survival of a partial structure, the acoustical characteristics of Bell Church has been previously studied via acoustical reconstruction [1]. The Bell Church settlement is located on the outskirts of present-day Aksaray, Turkey. The church stands aloof from the rest of the settlement (Fig. 1).

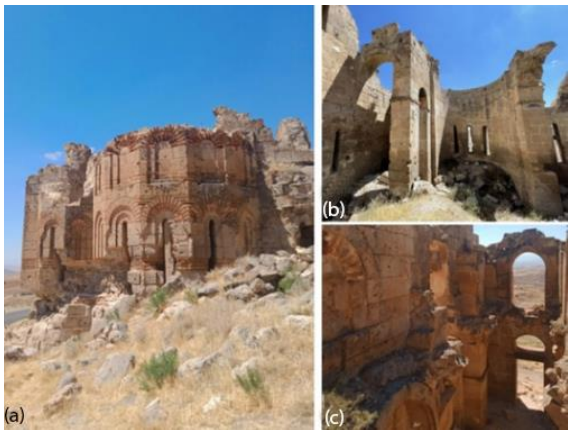

Figure 1. (a) An exterior view of Bell Church; (b) an interior view of the main church space (naos) with three apses; (c) the entrance hallway (narthex) of the church.

For the acoustical reconstruction of the church, four materials from different parts of Cappadocia (Göreme, Ürgüp, Hallaç Church and Avanos Dining Hall) and their absorption coefficients have been documented by means of impedance measurements and acoustical simulations. The samples for impedance measurements are prepared by cutting the stone for the large samples (Fig. 2a, 2c). For smaller samples, the tuff rock sample has to be filled in steel molds as it would crumble upon cutting to fit the size of the mold for the high frequency setup (Fig. 2b, 2d). Since the rock samples are porous, an acoustically transparent piece of cloth has been used on both ends of the mold to ensure that the material stays compact. The sound absorption coefficients of tuff stones from two neighboring sites, Hallaç Church and Avanos Dining Hall, are extracted via simulations based on in-situ measurements [14].

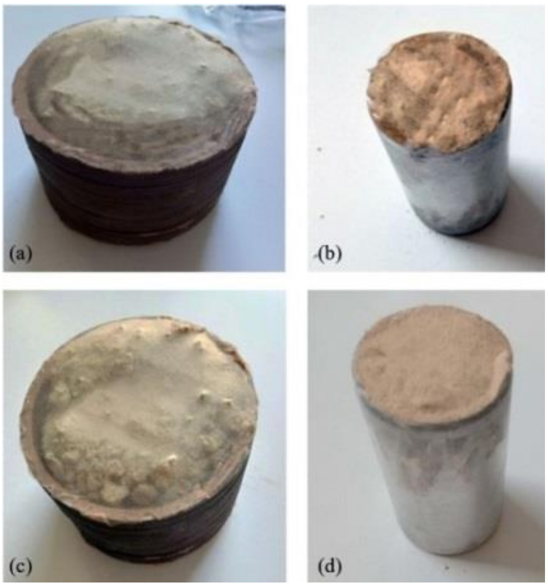

Figure 2. Göreme rock sample (a) for low frequency; (b) for high frequency setup; Ürgüp rock sample (c) for low frequency; (d) for high frequency setup.

It is essential to compare the data to see the similarities and differences between sound absorption performances of different tuff rock samples, as shown in Fig. 3. There are basically two types of rock samples that have been evaluated: soft and hard. The difference in the hardness of these rock samples is due to their different mineral composition. Previously, qualitative and quantitative chemical tests have been carried out on these rock samples, which suggest that the differences in the amounts of chemical compounds found in the samples account for different textures, porosity, and hardness of tuff stone samples [1]. After evaluating the sound absorption qualities of all four materials, the tuff stone type I (from Hallaç Church) is chosen for the application of a material in the church's acoustical models, due to the material's similar texture and hardness with that of the masonry blocks of the church on site.

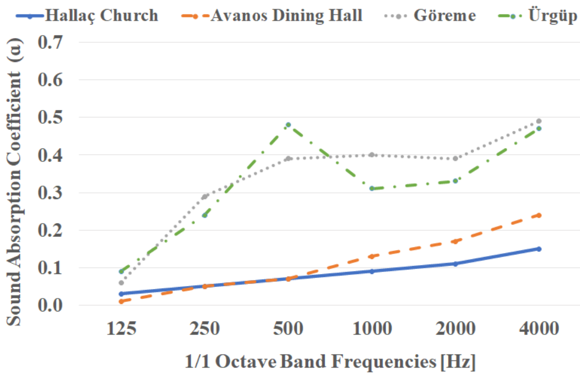

Figure 3. Absorption coefficients (α) of the materials over 1/1 octave bands from the Hallaç Church, Avanos Dining Hall, Göreme, and Ürgüp tuff stones.

3.2 Süleymaniye Mosque, İstanbul

Süleymaniye Mosque is a 16th century edifice located in İstanbul, inherited from the Classic-Era of the Ottoman Empire. The spacious interior with 75000 m^3 acoustical volume is covered with a 26 m wide central dome placed 50 m above the ground level (Fig. 4). The dome contains 224 clay pots, all of which are embedded into the dome structure on 7 levels, each level containing 32 pots with their openings facing the interior space. The pots are 50 cm in height and 30 cm in their widest diameter (Fig. 5).

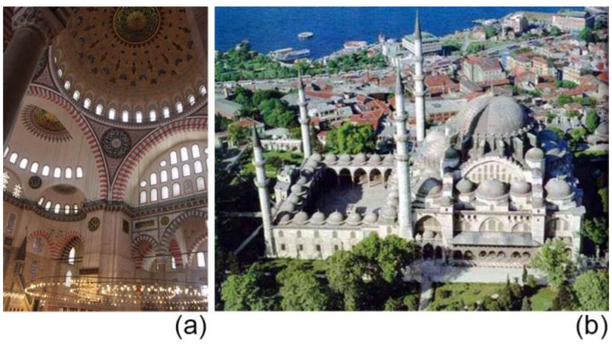

Figure 4. Süleymaniye Mosque interior (a) and outside view (b) [15].

Employment of acoustic pots in historical structures (mostly with a dome typology) is a significant case of a wider practice in Anatolia [16]. Their acoustical employment has been the center of academical debates regarding the pots' true contribution to the sound energy decay pattern of the structure, which is often related to their employment as cavity resonators owing to the resemblance of their shape with Helmholtz resonators. The 224 pots found in the central dome of Süleymaniye Mosque turned the edifice into a significant case among its contemporaries due to the abundant number of pots it contains. Apart from the pots, the interior finishing of the edifice includes stone, brick, ceramic tiles, plaster, wood and carpet with straw backing [17].

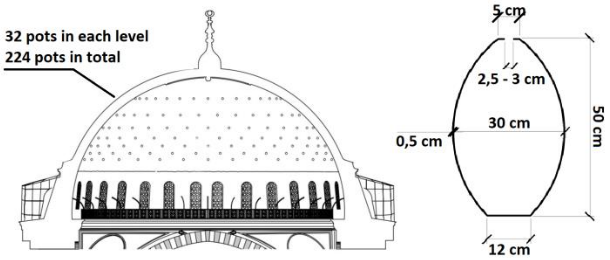

Figure 5. (On the left) Disposition of the clay pots in the central dome of Süleymaniye Mosque. (On the right) Size of the original clay pot found in the dome structure [19].

A comprehensive restoration work is held in the edifice in between 2007 and 2011. The works included the repairment of broken pots found embedded in the dome structure, aiming to regain their functionalities [16, 18]. It is also recorded that the cement-based plasters are replaced with Horasan plasters that supposedly have higher sound absorption performance. In the most recent in-situ acoustic measurements of the edifice, a decrease of 2 seconds in T30 values was observed in 500 Hz octave band [17]. In order to validate the effect of the pots in this improvement, analysis of their effective frequency range and characterization of their sound absorption performance is necessitated.

Initially, a sample clay pot based on the dimensions measured during restoration works is reproduced and impedance tube measurements are held with the new sample. The size of the pot is larger than a regular sample to be placed inside the sample holder. Therefore, a custom fitting piece is designed for a loss-free coupling between the pot and the tube. The fitting piece is composed of an MDF ring and a plaster piece which is produced based on a mock-up plaster element molded from the aperture of the pot. Potential gaps in the connection points between the pot, fitting piece and the tube are sealed. The custom fitting piece and its production steps are presented in Fig. 6.

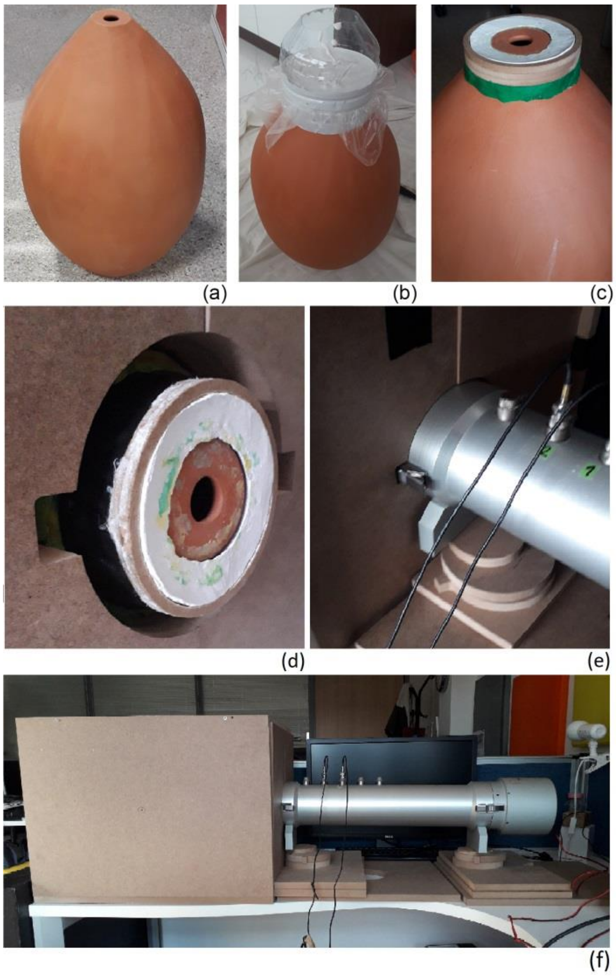

Figure 6. (a) Reproduced clay pot sample; (b) Molding process of the aperture of the pot; (c, d) Custom fitting piece; (e) Coupling of the tube with the clay pot; (f) Measurement set-up.

Three different backing configurations are used in the impedance tube measurements. In the first one, the pot is directly coupled with the impedance tube with the custom fitting piece at the aperture. In the other two set-ups, the clay pot is placed inside a custom-made MDF box. These backing configurations are gradually improved to imitate the tight placement of the pot in the steady and solid structure of the dome by providing enough isolation at the back of the pot. The 3.6 cm thick

MDF box with the interior dimensions of 40 cm x 40 cm x 51 cm is respectively filled with 5 cm thick mineral wool and sand bags. Measurements are done with a total of six setups consisting of three backing configurations coupled with two impedance tubes covering high and low frequencies. The connection details produced both for smaller and the larger tubes are provided in Fig. 7.

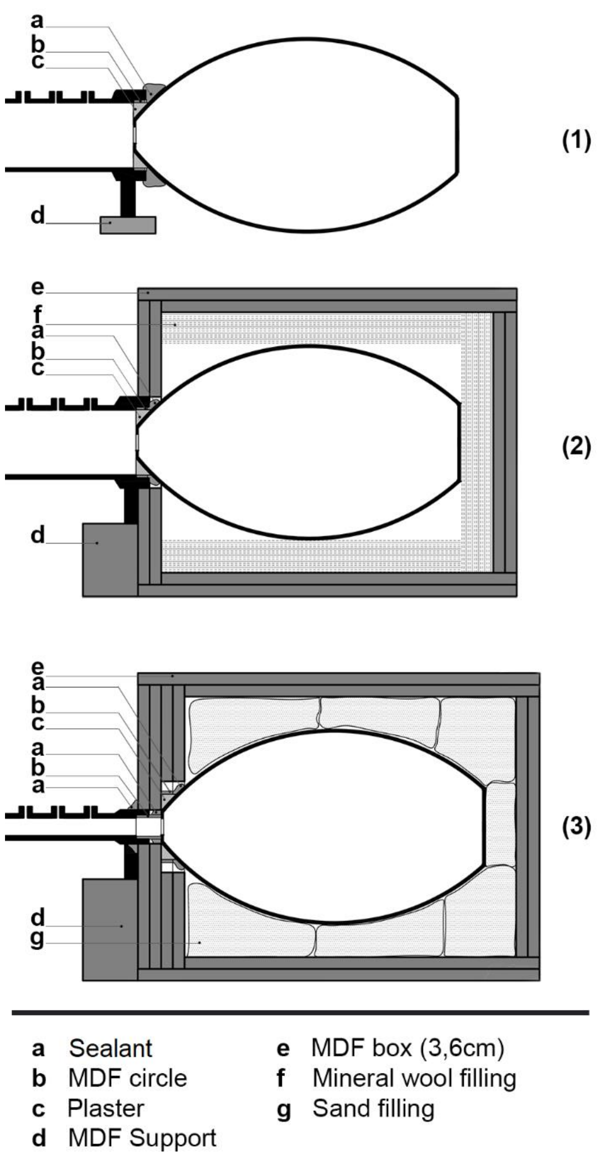

Figure 7. Backing configurations coupled with small and larger impedance tubes: (1) Large impedance tube – no enclosure; (2) Large impedance tube – mineral wool filling; (3) Small impedance tube – sand filling.

Each measurement is repeated 10 times to ensure the repeatability and reliability of the measurement results. The measured sound absorption coefficients are provided in Fig. 8. The results are discussed in the following chapter.

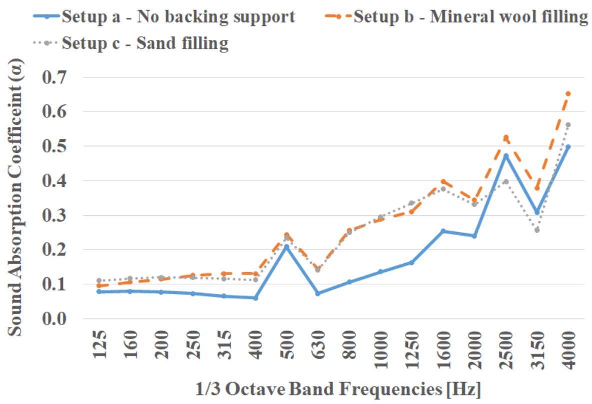

Figure 8. Absorption coefficients (α) of the acoustic clay pot over 1/3 octave band measured with the impedance tube.

3.3 Rami Barracks, İstanbul

Rami Barracks is a military complex that dates back to the 18th century. The building is arranged around a large central courtyard with a simple rectangular plan layout, on which the places are organized in two floors around the courtyard space. The structure was previously served as a basis for training and accommodation of the military personnel. In 2023, the building underwent renovation and transformed into a public library complex (Fig. 9.). Previously, the barrack contained bakery, bath, mosque, barn, warehouse, and *hünkar kasrı* (the room where the sultans stayed) [20]. In the recent restorations conducted in 2023, Rami Barracks was restored and re-habilitated as a public library. After the renovation, the existing spaces are transformed into reading and seminar rooms, workshop areas, a café, and office areas. With the changing requirements, development of the acoustical design with the use of acoustic simulation tools for the renovated structure is necessitated. For this reason, it was necessary to obtain the sound absorption coefficients of the authentic finishing materials and utilize them in the simulations.

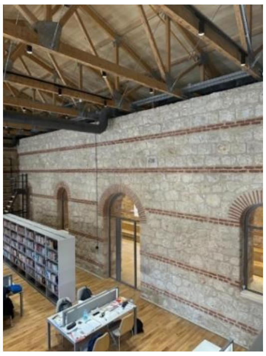

Figure 9. Rami Barrack stone masonry walls.

The primary building materials of the barracks consist of the load-bearing stone masonry walls and timber roof structure. The accurate acoustical characterization especially of the stone masonry was critical as the proper conduct of simulations largely depends on the stone finishings. Therefore, impedance tube measurements are held with an authentic stone sample obtained from the construction site. The dimensions of the sample provided by the restoration team are approximately 18 x 19 x 13 cm (Fig. 10).

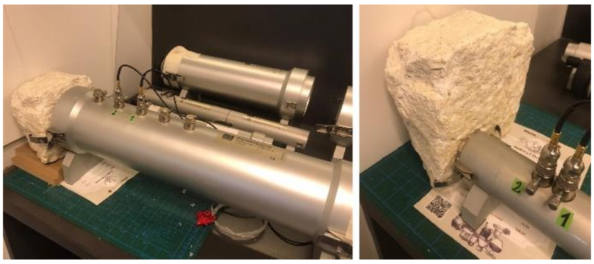

Figure 10. Impedance tube measurement setups.

The measurements are held with two locations selected from the front and rear surface of the sample to verify that the measurement results wholly represent the varying rough surface of the stone. Due to the practical difficulties owing to the rigid and hard texture of the stone, it was not possible to cut it to the precise size which would fit the tube diameter. Therefore, the large stone sample is leaned on to the impedance tube and a loss-free coupling between the sample and the impedance tube is achieved by a custom-made fitting piece similar to the one used in the clay pot measurements. The piece is composed of an MDF circle specially designed to fit inside the tube section to connect the tube with the stone sample. The gaps in connection between the stone and the MDF circle is sealed with silicone (Fig. 11).

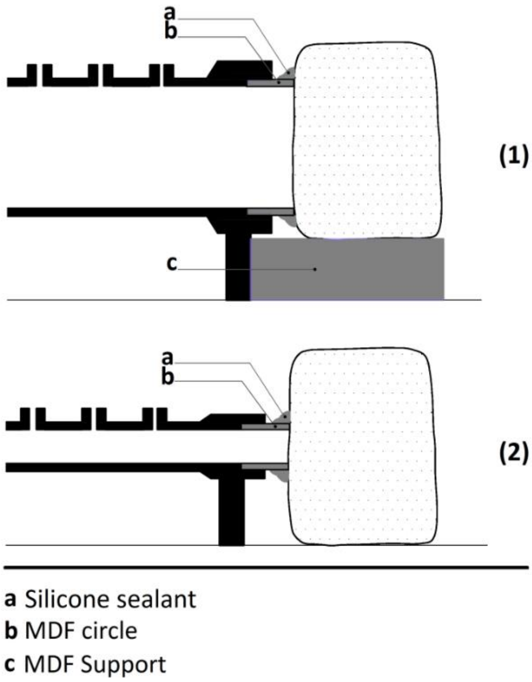

Figure 11. Connection details of the stone sample with the impedance tube: (1) Low frequency tube, (2) High frequency tube.

A total of 6 measurements -3 measurements from the front surface and 3 measurements from the rear surface- are held for each side of the stone. The sound absorption coefficient values obtained from both sides are presented in Fig. 12.

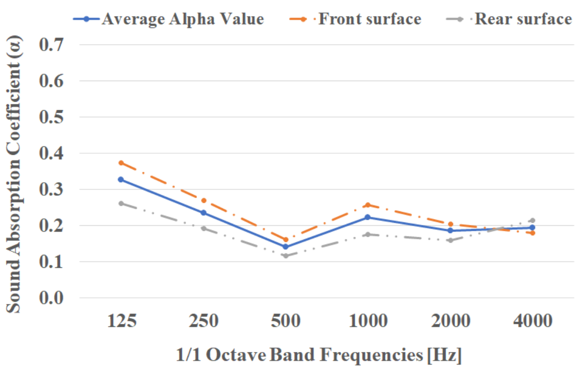

Figure 12. Absorption coefficients (α) of the acoustic stone sample from Rami Barracks over 1/1 octave band measured with the impedance tube.

4. DISCUSSION

In the previous chapter, the measurement procedures and the resultant sound absorption values of the authentic material samples are presented. In the Cappadocia case, impedance tube measurements are essential for the aural reconstruction of the partially demolished structure of Bell Church. With the combination of collecting sound absorption data via impedance tests and simulations based on field measurements, four materials are evaluated. According to Figure 3, among all the materials under study, the sound absorption values of the samples studied with the impedance tests (Göreme and Ürgüp) have an overall higher sound absorption than the materials obtained from the tuning of virtual models (Hallaç Church and Avanos Dining Hall). As part of the original study, the most suitable material is chosen to be used in the simulation of the church to document and analyze the acoustical climate of the church over its different phases.

As for the Süleymaniye Mosque case, impedance tube measurements with changing backing configurations of the measurement set-up exhibited coherent results. As shown in Figure 8, a peak at 500 Hz is noted in three of the backing configurations. At mid-high frequencies, especially after 800 Hz, an improvement in sound absorption performance is also observed which can be linked with the millimetric surface texture of the clay. Distinct discrepancies are observed between the different configuration results. When the pot is directly coupled to the impedance tube without the use of a MDF box, a lower alpha value is measured at mid-frequencies. In the other configurations in which the clay pot is placed inside the MDF box with mineral wool and sand bag filling, a higher isolation at the back of the pot is observed and the reflection of the incident planar sound wave back to the tube volume is prevented up to a certain level. In the latter configurations, sound absorption coefficients are measured slightly above 0.2 at 500 Hz octave band.

A downside of the impedance tube measurement is observed in low-cut frequency range of the tube in which the fundamental frequency of the clay pot falls within. The impedance tube measurement is incapable of identifying the fundamental frequency of the pot -52 Hz- which is calculated with the Helmholtz formula.

In the case of Rami Barracks, the sound absorption coefficients obtained from the sample exhibit relatively absorbing characteristics especially at the mid-low and mid-high frequency ranges due to the porous and textured structure of the stone surface. The high sound absorption values observed in low frequency ranges may be attributed to the thickness and porosity characteristics of the stone sample. A maximum of 0,1 difference between the alpha values of the front and rear sides are observed. Therefore, an average value of the two sides is utilized for the acoustic simulations. Employment of the actual sound absorption coefficients of the authentic stone in the simulations aided the acoustical design decisions of the new library in terms of achieving the most optimized acoustical design solution.

5. CONCLUSION

In this study, acoustical characterization of three material samples obtained/ reproduced from three different historic structures are summarized. In each case, absorption coefficients are measured with transfer function method using an impedance tube. As the sizes of the materials are larger than the ones used in a routine procedure, custom-made fitting pieces and connection details are developed on behalf of a regular sample holder. Measures are taken to ensure a loss-free coupling between the sample and the impedance tube.

It is advantageous to utilize the reliable sound absorption coefficients of the authentic finishing materials to optimize the acoustical design of the spaces or accurate examination of the current acoustic state of cultural heritage structures. In the case that in-situ measurements or reverberation room measurements are unapplicable, impedance tube measurements can be a viable solution even in the cases where only the large material samples are available for examination.

6. ACKNOWLEDGEMENTS

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