A DISCUSSION ON THE ACOUSTICS OF SÜLEYMANİYE MOSQUE FOR ITS ORIGINAL STATE

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Keywords: *Süleymaniye Mosque, room acoustics, reverberation time, historical plasters, sound absorption coefficient*

ABSTRACT

Süleymaniye Mosque (1550-1557) is an inspirational edifice for many fields such as architectural acoustics and materials science. In its original state, the mastery of acoustics within the Mosque is a common belief. Due to the scarcity of knowledge on its authentic acoustical features, comprehensive studies are needed to assess the acoustical conditions of the Mosque in relation to its architectural elements and interior finishing materials contributing to those features. In the context of this study acoustical simulation that relies on recent field tests are carried on. The combined interpretation of the overall architectural and acoustical data exhibited the presence of very high reverberation time values, especially at low frequencies, for the current state. As the previous field tests presented the unoccupied condition of the Mosque, the acoustical simulations are performed initially to discuss some activity patterns for the occupied state, and later to experiment the effects of historical lime-based plasters on the acoustics of the Mosque. Considerable improvement in the sound field of the main prayer zone are observed due to the replacement of current cement-based plasters with the historical lime-based ones, collected from some other structures of the same era. The results pointed out the necessity of further investigations on historical lime-based plasters in terms of their acoustical performances and raw materials characteristics in order to scientifically prove their contribution to the acoustical features of Süleymaniye Mosque and to re-achieve its original acoustical comfort conditions.

INTRODUCTION

Süleymaniye Mosque (1550-1557), designed by the architect Sinan, constitutes the central structure of one of the biggest mosque complexes of the Ottoman Empire (Figure 1). It is still an inspirational edifice for many fields such as architectural aesthetics, construction technologies, architectural acoustics and material science. In its original state, the mastery of acoustics within the Mosque is a common belief while there are many complaints about its acoustical performance at the present time. Due to the scarcity of knowledge on the authentic acoustical features of Süleymaniye Mosque, comprehensive studies are necessitated to assess the acoustical features of the Mosque in relation to its architectural elements/components and interior finishing materials.

Figure 1.Süleymaniye complex - an old gravure.

Süleymaniye Mosque underwent various restorations in years [1], and the acoustical conditions within the Mosque after some restorations are tested by real-size field measurements in previous researches [2,3,4,5,6]. However, none of the field test results reflect the acoustical conditions of the Mosque in its original state. This study aims to assess the original acoustical conditions of the Mosque in terms of natural sound by using computer aided simulation technique and field test data obtained in previous studies [5]. The knowledge on its original finishing materials, main geometric and architectural features at interior are considered during the simulation analyses to evaluate the effects/contributions of these features on acoustical conditions in the Mosque.

ARCHITECTURAL FEATURES AND MATERIAL REVIEW

The structural elements of the main structure are composed of domes, arches and flying buttresses (Figures 2-4). The mosque is covered centrally by a single dome which is supported on two sides by semi domes. The two semi domes align with the direction of the mihrab. Five smaller domes at both sides that shelter the side aisles complete the superstructure. The loading coming from the main dome is being transferred to the half domes through the arches and pendentives, and then to the vertical structural elements, such as walls/columns and footings. The arch walls and dome rim are decorated with number of windows, which also lighten the weight of the structure.

The inner plan of the mosque is a rectangle measuring 63 m by 69 m (Figure 2). Main dome rests on 4 “elephant feet” and 32 footings on a circular wheel with a diameter of 26.20 m. The height from the foundation to the impost is 33.70 m. The inner rise of the dome is 14.05 m, and thus the height of the dome from the ground to the keystone is 47.75 m [7]. The middle and corner domes on aisles have a diameter of 9.90 m and the smaller ones between them have a diameter of 7.20m. Except for the elephant feet, there are eight columns carrying secondary arches. Corner domes are supported by arches in between elephant feet and exterior shell walls while the remained ones in between corner domes sit on arches each of which is supported by two columns on two rows. Pendentives are used as the structural transition elements to smooth the central dome, secondary half dome and arch connections as well as the connections between superstructure and walls/columns (Figure 3). Muqarnases/stalactites are also used as transition elements in column heads, in the skirting of half domes and enhance the sound diffusion in mostly curvilinear and concave transition planes by fragmenting the surfaces into much smaller pieces [8].

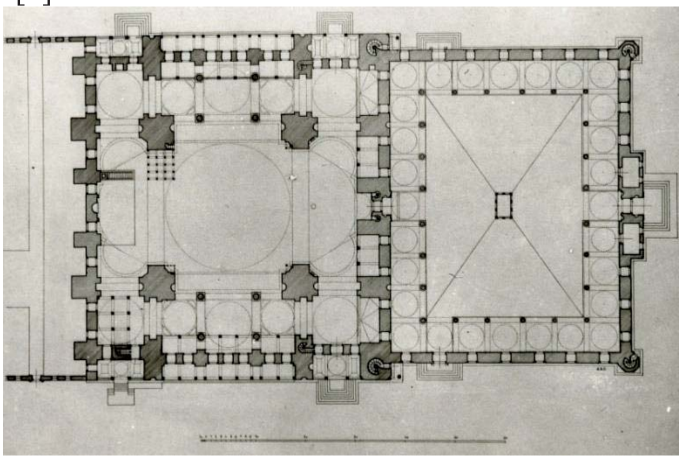


Figure 2. Süleymaniye Mosque plan [1]

Figure 3. Interior view of domes and pendentives in Süleymaniye Mosque

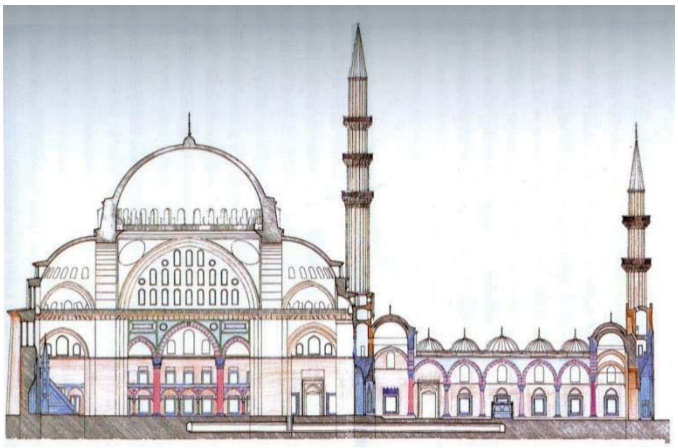


Figure 4. Süleymaniye Mosque, section view [9]

The richness of materials applied within Süleymaniye Mosque, with different regions of source and construction techniques, is an extensive research subject. In its original state the basic interior materials could be summarized as stone, brick, ceramic tile and pots, plaster, paint, glass, wood and carpet. The interior walls are faced with stone-clad surfaces. The ceilings of the pulpits and the royal box, the domical superstructure, and the pendentives are painted. In contrast to painted domes and pendentives in lower zones the stone-clad surfaces left relatively bare. Piers carrying the main dome and suspension arches are of cut limestone while the inner faces are painted as of Hereke conglomerate and Proconnesian marble. Columns are of Egyptian porphyry (red sparrow eye). The historical brick dome masonry superstructures are plastered in multi-layers, and then decorated with gold foiled pen carvings. The mihrab and the minbar (pulpit) are of carved white marble and stained glass windows on the sides [9].

Lime, brick crumbles, fine sand, gypsum, linen and straw are the basic ingredients of plaster layers and seams. Linen is added in the mixture of dome plasters. In accounting registers of Süleymaniye Mosque construction (scrapbook number 108) [10], it is declared that for plaster finish of dome (Beray-i sıva-i kubbeha-i cami'-i şerif) 134 scale of linen is purchased. Floor finish of the mosque is carpet with straw backing which are collected from the finest straws grown in Nile delta - as stated in original documents [10]. Carpets had originally been woven in Egypt and Aydın-Tire. Wood in interior is mostly used for flat ceilings, doors, window frames and furniture. Only the two windows on each side of "mihrab" have "kündekari (a specific type of historical wood joining work)" wooden work shutters [9].

Another feature of Süleymaniye Mosque in its original state is the use of "Sebu (clay pot)" cavity resonators for the control of excessive low frequency sound content. In accounting registers of Süleymaniye Mosque construction (scrapbook number 88, paper 19/a), it is declared that each for 2 akce's 255 "Sebu"s (clay pots in function of a cavity resonator) are purchased (Baha-ı Sebu, beray-ı kubbe-i cami'-i şerif) [10]. In several investigations it is stated that 64 of these pots are located on a circular disk at the central dome, which have a length of 50 cm and neck width of 2 to 6 cm [11,12]. On the other hand, in 2007-2011 restorations it is declared –in press- that 256 pots with 45 cm length and 15 cm mouth, open towards the interior space are detected [13]. Except these explanations, however, no reliable data, technical report or proof was mentioned in the literature on their existence at the central dome and their contribution to the acoustics of the Mosque.

ACOUSTICAL SIMULATIONS

Technological developments provide new opportunities for the estimation of acoustical properties of a space virtually by using computer simulations. The purpose of acoustical simulations in this research is: (i) to compare the acoustical features of the Mosque in occupied conditions and unoccupied conditions of the Mosque in current state, and (ii) to examine the acoustical features of the Mosque in (assumed) original state based on some acceptances. The simulation models representing the current state of the Mosque for its unoccupied condition is based on the field test approximated model [5] while its occupied condition is based on the full occupancy of the Mosque during a Friday's sermon. The original acoustical features of the Mosque are examined based on an assumption that the interiors were repaired wıth the lime-based plasters with pozzolanic additives which are compatible with the historical ones belonging to the same era. Such a simulation analysis is expected to offer an insight into the

probable acoustical conditions in original state of the Mosque.
Simulations are carried by ODEON Room Acoustics Software version 12.12. The 3D acoustical model of Süleymaniye Mosque that reflects its current status is generated by joint use of AutoCAD-2D and SketchUp-3D modelling software; in reference with the latest measured drawings achieved in Archives of the General Directorate of Pious Foundations [1]. In the process of modification of the geometry, the graphical model is preserved in great detail in order to maximize the effects of domes and scattering surfaces, while keeping the limits of minimum surface dimensions dictated by the software (Figure 5). The simplified model made up of 3-D face elements is comprised of 38478 plane surfaces. Acoustical model is then imported into ODEON. Ray tracing is used majorly in sound path analysis and checking waterproofness of the model (Fig.6). In calculation parameters number of late rays is defined to be 329283 and the impulse response length is set to 15000 ms. Estimated acoustical volume of the mosque is approximately 120000 m³.

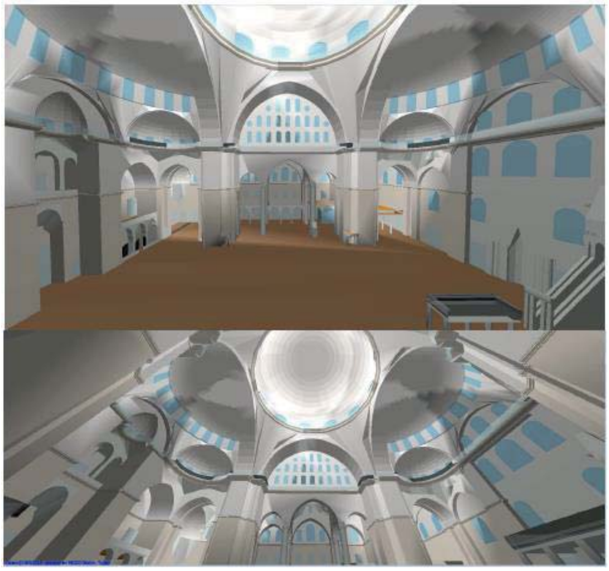


Figure 5.Interior 3D Open-GL views of modelled Mosque

The sound absorption coefficient data of people on prayer area applied in simulations -reflecting occupied state of the mosque- are taken from previous laboratory tests on Mosque congregation [14]. An omni-directional source is defined in front of mihrab at 1.50 m representing the “imam” in standing position. Twenty two receivers are distributed throughout the prayer zone as of standing prayer positions. Relevant acoustical parameters, specifically T30, are then calculated considering the occupied and unoccupied conditions as well as sound absorption coefficients of interior finishing materials for the current and original states. Sound absorption coefficients of current/existing materials are assigned in adjustment to the field test results held in 2013 [5]. Specifically, the sound absorption coefficients of interior plasters in current state are calculated to be in the range of 0.05 and 0.07 for the mid frequency range while the sound absorption coefficients of the historical lime-based plasters are accepted to be 0.23 and 0.29 in the mid frequency range [15, 16].

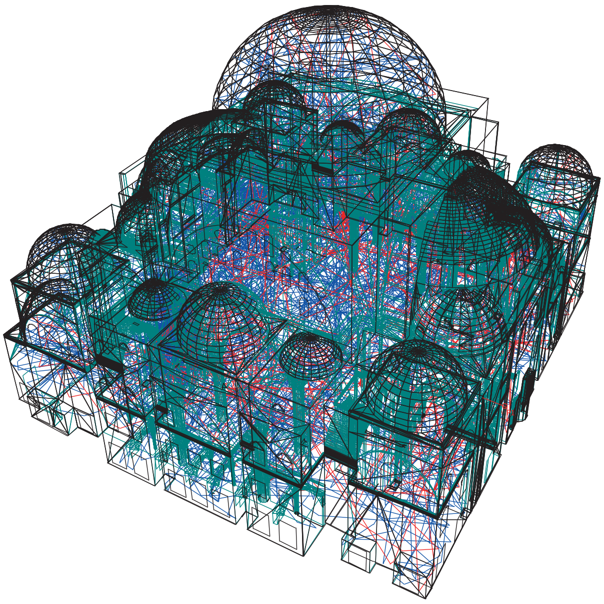
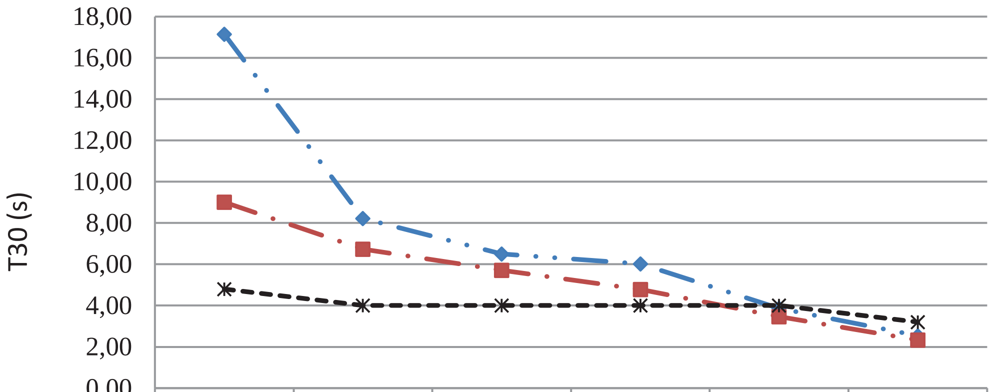


Figure 6. Süleymaniye Mosque, ODEON ray tracing view

RESULTS

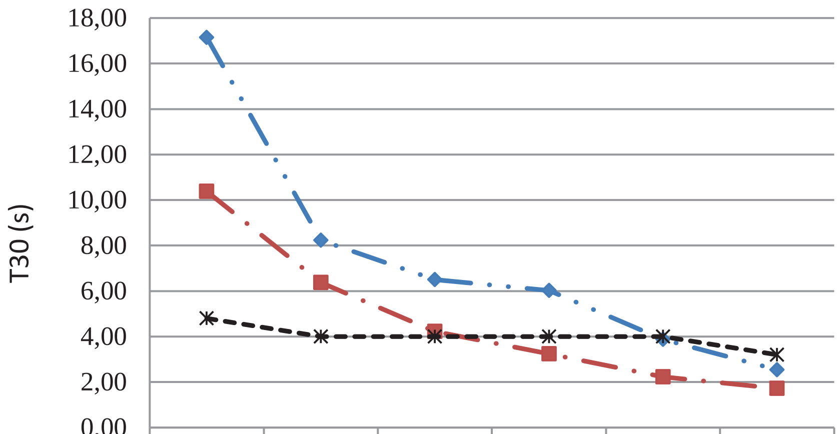
The T30 results of the simulation analyses for the comparison of the occupied and unoccupied conditions in the current state are summarized in Figure 7. The T30 values estimated for the original state of the Mosque, where the current plastered surfaces are assumed to be repaired with the interior plasters compatible with the original/historical ones, are presented in Figure 8, in comparison to the current state.



	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Unoccupied	17,15	8,23	6,50	6,02	3,87	2,54
Fully-occupied	9,01	6,74	5,71	4,78	3,46	2,33
Criteria	4,80	4,00	4,00	4,00	4,00	3,20

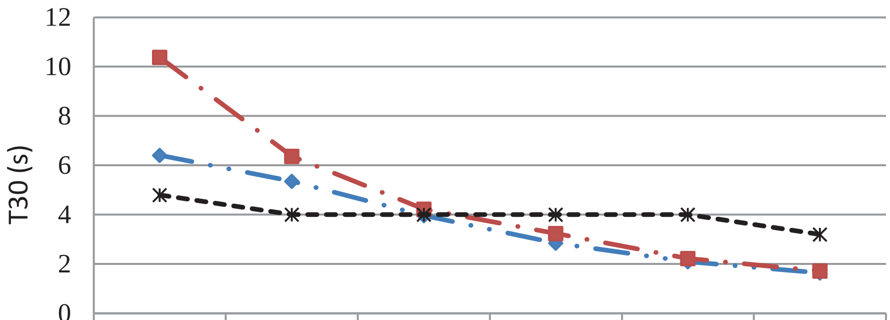
Figure 7. The simulated T30 results in 1/1 octave bands for unoccupied and fully-occupied conditions of the current state of Süleymaniye Mosque in comparison to the upper limit of acceptable T30 values given in the literature [4,17]

The occupied and unoccupied conditions for the original state of the Mosque are compared in terms of simulated T30 values in Figure 9. In all charts, the simulation data achieved are evaluated according to the accepted values (criteria values) recommended for mosque spaces in the literature [4,17].



	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Current plasters	17,15	8,23	6,50	6,02	3,87	2,54
Historical plasters	10,38	6,37	4,22	3,24	2,23	1,72
Criteria	4,80	4,00	4,00	4,00	4,00	3,20

Figure 8.The simulated T30 results in 1/1 octave bands for the current state and assumed original state of Süleymaniye Mosque in unoccupied conditions in comparison to the upper limit of acceptable T30 values given in the literature [4,17]



	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Fully-occupied	6,41	5,35	3,97	2,85	2,09	1,64
Unoccupied	10,38	6,37	4,22	3,24	2,23	1,72
Criteria	4,80	4,00	4,00	4,00	4,00	3,20

Figure 9.The simulated T30 results in 1/1 octave bands for unoccupied and fully-occupied conditions ,of the (assumed) original state of Süleymaniye Mosque in comparison to the upper limit of acceptable T30 values given in the literature [4,17]

The simulated results that reflect the current status of the Mosque indicate long reverberation times within the Mosque in its unoccupied condition (Figure 7). For speech frequencies (500Hz, 1000Hz, 2000Hz), the simulated T30 results in the range of 3.87s and 6.50s are determined to be far above the recommended T30 limit of 4.8 s, and in broadband T30 limit of 2.8 s for the mosques having a similar volume with Süleymaniye Mosque [4,17]. The simulated T30 results obtained for the fully-occupied situation seems to get closer to the recommended and broadband limits while still indicating long reverberation times within the Mosque. Especially 125 Hz is determined to be a very critical frequency in terms of the intelligibility of speech due to the very long T30 values of 17.15s and 9.01s for unoccupied and fully-occupied situations, respectively. Even worse acoustical failures should be expected, in fact, when electro-acoustic system is on.

The simulation analyses for the (assumed) original state of the Mosque in unoccupied situation presented considerable decreases in T30 values in comparison to the current state. For instance, the decreases in 7s at 125 Hz, in the range of 2-3s at mid frequencies (500-1000Hz) and in the range of 1-2 s at high frequencies (4000-8000Hz) are estimated in T30 values. That significant reduction in simulated T30 values is only due to the replacement of existing plasters with the more sound absorptive historical lime-based plasters. The acoustical model reflecting fully-occupied original state presents, expectedly, less reverberant conditions. In short, the estimated T30 values, in case that historical lime-based plasters are used seem to be satisfactory for the frequencies 500 Hz and above according to the acceptable T30 criteria defined for a mosque in given volume. The estimated T30 values for the frequencies below 500Hz seem to get closer to the acceptable values.

DISCUSSION ON ORIGINAL ACOUSTICAL FEATURES OF SÜLEYMANIYE MOSQUE

The basic parameters in room acoustics affecting natural speech/sound are the volume of the main space and its geometry. It is known that, the dimensions and basic geometrical features of Süleymaniye Mosque have not been altered until today. The dominating form of the Mosque is the central dome which is supported by semi-side domes. Acoustical focusing effects of dome can be prevented to some extent, in the case that the lower end of the diameter/circumference of the dome section is located at much higher than the receiver/prayer ear height. In Süleymaniye Mosque even the focusing zone of the biggest central dome is located 20 m above the prayer plane/floor. This indicates that Süleymaniye Mosque domes are designed so delicately that the first order high reflections and/or acoustical foci and echoes are minimized.

Sinan in his Mosques applied Sebu (clay pot) technique, which enables acoustical asymmetry within the dome by scattering the sound and enlarging dome reflection zone. By that, much even distribution of sound within the prayer zone could be provided. Sebu forms are similar to that of amphoras, which have a short neck and a backing volume. Sebu technique in statics enables to lessen the load of the dome, while in acoustics they function as Helmholtz resonators. These elements can scatter sound to some extent and especially at low frequencies (63 Hz – 250 Hz) they are narrow band volume absorbers [18]. The numerous applications of these pots with various sizes would widen the frequency bandwidth that they are effective. Thus, it could be predicted that such an application in the original state of the Mosque, to some extent, have possibly healed the excessive low frequency sound content. Together with Sebu voids, the fragmentation of parallel surfaces in both section and plan scheme of the Mosque by architectural elements such as mahfil's, niche's and surface treatments such as muqarnas, kündekari and glazed ceramics have provided sound scattering in a wide frequency spectrum, so that an even distribution of sound throughout the prayer zone is obtained.In spaces with excessive volume as in Süleymaniye Mosque, the expected long reverberation times have to be controlled by increasing the sound absorptive surface area. As absorption increases, reverberation time decreases (RT_{SABINE} = 0.161 [volume/absorption area]). The absorption area of the overall space for each frequency is calculated, firstly, by the multiplication of sound absorption coefficient of each interior finishing surface at a certain frequency and the corresponding surface area and, then, by summing up all individual absorption area. In Süleymaniye Mosque shiny and tight stone wall, column and elephant feet surfaces compose the reflective area. The absorptive carpet floor surface is not sufficient to tolerate the long reverberations that occur in this large volume; so additional absorptive surfaces are required. The sound absorption coefficients of applied stones within Süleymaniye Mosque can be predicted for the current and original states as given in the range of 0.01-0.10 in the literature [4]. The unknown is the sound absorption coefficient data of original/historical plasters with or without paintings that are renewed in several restorations. These plasters are applied at dome, arch and mostly upper wall surfaces, and compose a very large surface area of 19000 m^2. The influence of these plasters on reverberation times would be noteworthy.

The use of "porous soft horasan mortar with linen and hemp fiber ingredients" at dome and wall surfaces in Sinan's Mosques has been mentioned in researches [3]. It has also mentioned that "in restorations the replacement of historical mortar and plasters, which are good absorbers at low to mid frequency range, with tight and stiff cement based plasters are accused for excessive reverberation times observed especially at low to mid frequencies at most of the historical Mosques" [3]. The use of natural fibers as an ingredient in historical plasters, in fact, is considered to be a significant information in terms of acoustical performance of historical plasters, and need to be investigated with further studies. An experimental research on sound absorption coefficients of multi-layered lime plasters with pozzolanic additives used in the historical baths belonging to the Ottoman Period presented that historical plasters at dry air has 8.5 times higher sound absorption capacity (for 500 Hz – 1000 Hz) than that of today's cement based repair plasters. Moreover, noise reduction coefficient (NRC; average sound absorption coefficient at 250 Hz, 500 Hz, 1000Hz and 2000 Hz) of historical lime-based plasters are 14 times higher than that of cement-based repair plasters.

According to the simulation results for unoccupied condition, the replacement of cement based repair plasters with historical ones ended up with a drop of 2 s in T30 value at 500 Hz and a drop of 7s in T30 value at 125 Hz. The fully-occupied state of the Mosque with the application of historical plasters provided the upper limit of criteria above 500 Hz, and it is much closer to the limits below that frequency. Those results indicate that if the historical plasters could have been survived till now or if the Mosque underwent repairs with the plasters compatible with the historical ones, the acoustical conditions would be much suitable for the function of Mosque in today.

For an even distribution of reverberation over frequency, the sound absorption of materials in octave bands should be well balanced. Carpet is an absorptive material after mid frequency range (1000 Hz to 8000 Hz), unless it has at least 5-10cm height platform underneath. In records of construction documents of Süleymaniye Mosque such a platform is not mentioned [10]. This means the original carpet's sound absorption performance would be similar to that of today's carpet for low frequencies, and not much of a difference is expected from high frequencies in reference to some other research on carpet effects [19]. Carpet is still significant in terms of providing positive absorption area for intelligibility (of consonants). One other significant information is that in its original state straw is laid underneath carpet of Süleymaniye Mosque [9, 10] which would provide an improvement in absorption of mid frequency sound content. Apart from those in occupied case, the presence of people and their compactness would improve sound absorption.

Being located in a courtyard of a big complex (külliye) surrounded by walls together with a thick and strong exterior shell of domes and walls, Süleymaniye Mosque is very well isolated from any environmental noise that might be present in its time. It is also hard to talk about any traffic or industrial noise as in today's, and any noise sourced from mechanical equipment that were not existent in the past. Thus, the intelligibility of speech within the Mosque should have been least masked or distorted in its original state.

CONCLUSION

A trial on the estimation of original acoustical features by using acoustical simulation techniques have signalled the importance of inherently good sound absorption characteristics of historical lime-based plasters on the control of acoustical environment in Süleymaniye Mosque. The results pointed out the necessity of further investigations on the acoustical properties of historical lime-based plasters belonging to the Ottoman Period and their raw materials characteristics contributing to the acoustical features of the historical mosque structures. The studies on the acoustical performance of historical plasters applied in Süleymaniye Mosque dome and upper shell structures have vital importance for the development of compatible repair plasters as well as the improvement of current acoustical conditions in the Mosque.

It can also be stated that Sinan has taken many precautions for the sake of acoustics in Süleymaniye Mosque, such as:

- position of the Mosque in a courtyard protecting itself from environmental noise
- the particular geometrical configuration of its multi dome superstructure and interrupted square plan-layout with elements such as mahfil's and piers for avoiding fluttering echoes and room modes,
- sound scattering elements such as muqarnas, 'kündekari' and glazed surfaces for even distribution of sound at high frequencies through the prayer zone, and
- use of sound absorptive lime based plasters to achieve high sound absorption beneficial to frequencies in relation to the articulation of speech.
- due to the scarcity of knowledge on the use of sebu technique in the Mosque and acoustical performace of this technique, further analyses are required on the topic.

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