Sound parameters in mosques

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5aMU3. Sound parameters in mosques

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Unlike auditoriums, there are no defined recommendations or rules for the acoustical parameters inside mosques. Most of the existing recommendations are developed for multipurpose halls, for opera or dramatic theaters, and for structures built for organ music. But regarding mosques the elaboration of general sound parameters requires a specific understanding of the acoustical and spiritual environment expected in such structures. Newly defined acoustical parameter values with regard to mosque volumes and types will be addressed here. New treatment rules for closed or courtyard structures are introduced. Especially so-called mosque volume dependent parameters are derived. They allow optimizing the secondary structure of a mosque by considering the primary structure determined by the architecture. Such parameters deal with optimal reverberation time or intelligibility considered for all praying modes at once. Target of the research is to get standard acoustic parameter values especially applicable for mosques.

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1. INTRODUCTION

Mosques are religious structures used by Muslims for prayer, public speaking, preaching, lecturing, and Quran recitations. Good levels of intelligibility and speech audibility are required to conduct such activities. Consequently, achieving the required level of listening conditions is highly depending on how mosques interiors are designed. In catholic churches the intelligibility of sound was in the old days not so very important, because all the activity inside the church was carried out in Latin and the worshippers were asked only to repeat the prayers but not required to understand them. In a mosque, however, Quran recitation in prayer, public speaking, preaching and lecturing all require from the beginning a high level of intelligibility, since all these activities are carried out in Arabic and have to be understood by the audience.

In this work standalone acoustical quality parameters were generated for mosques according to a native understanding of the praying and spiritual need in such structures.

2. GENERAL RULES OF ACOUSTICAL QUALITY PARAMETERS

The most primary parameter which has to be sorted out is the Reverberation Time. High Reverberation Time will lead to unacceptable intelligibility levels. On the other hand, low Reverberation Time will result in what so called “Dead” spaces where spiritual ceremonies lose the attention of the worshippers. So, let us start with the following equation to formulate the relation between the Reverberation Times and Volumes of mosques [1].

$$r_R^2 = r_H^2 \times \gamma_L \, \Gamma_L^2(\vartheta) \text{......}(1)$$

Where,
γ_L – the effective front-to-random factor of the sound source
Γ_L – the directivity factor of the source (in main radiation direction ≈ 1, i.e. negligible)
r_H – the Reverberation Radius
r_R – the critical distance

It is known that

$$r_H^2 = \left(\frac{A}{16\pi}\right), \quad A = 0.163\left(\frac{V}{RT}\right)$$

Where V is the mosque’s volume and RT is the Reverberation Time. Thus by substituting in equation1;

$$r_R^2 = \left(\frac{0.163\,V}{16\,\pi RT}\right) \times \gamma_L \text{......}(2)$$

Therefore;

$$RT = \left(\frac{0.163\gamma_L}{16\pi r_R^2}\right) \times V ......(3)$$

To draw this relation it was assumed that at 1kHz, C=10 log γ_L= 2, minimum required L_{diff} is 65dB and sound power level of a Imam loud voice at 1m is 80dB. By substituting some of these quantities in the following equation 4 for the minimum required sound level at the diffuse field [2] :

$$L_{diff} = L_w + 14dB - 10\log\frac{V}{RT}dB.....(4)$$

Therefore

$$\frac{V}{RT} = 800....(5)$$

The maximum recommended RT for a 10,000 m^3 Speech hall is 1.8s [1]. Initially, assuming that 1.8 s is the no border cross line for the RT as a matter of fact for any mosque volume, thus, mosques with a volume/RT ratio of V/RT= 800 m^3/s should have a volume of no more than 1440 m^3 (1.8 s × 800 m^3/s) to maintain 65dB at the diffuse field. Accordingly, all mosques with a volume of less than 1440 m^3 can be handled pure acoustically (using only the Imam voice) without the need for a sound system. Applicable sound systems must be applied for bigger size mosques to maintain the required SPL level at the diffuse field to overcome high background noise in mosques. The critical distance for a mosque with 1440 m^3 can be calculated using the following equation [2]:

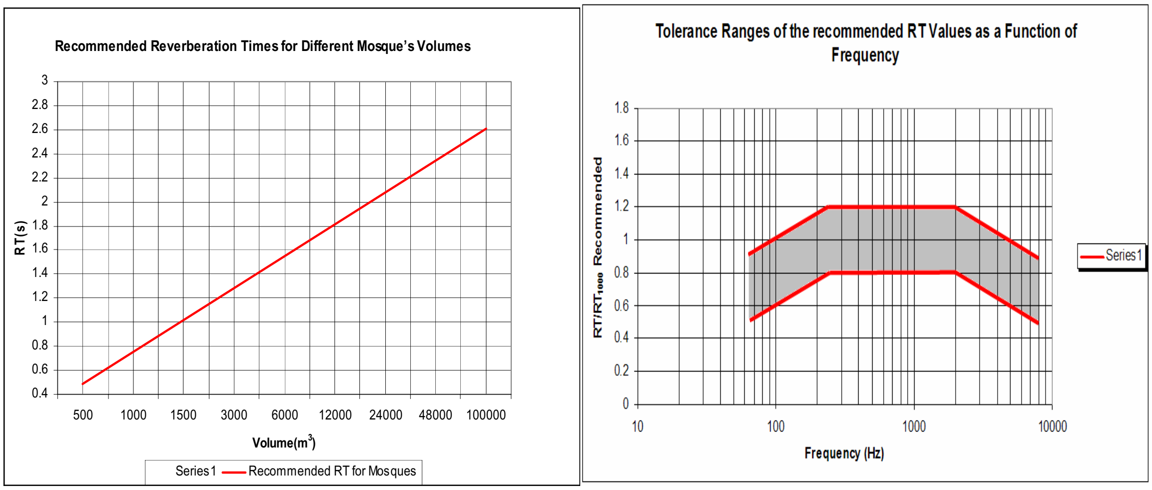
$$L = L_w - 20 \log r_R \; dB + C + 10 \log \left(\left(\frac{r_R}{r}\right)^2 + 1\right) dB - 11 dB ....(6)$$

$$65 \; dB = 80 \; dB - 20 \log r_R + 2 + 10 \log 2 \; dB - 11 \; dB ....(7)$$

Therefore

$$r_R = 2.82 \text{ m}$$

From equation 3, drawing a relation between Reverberation Time and Volume was possible at this point as shown in Figure 1a. First, the first point on the volume reverberation time relation was determined in a mosque with a volume of 1440 m^3 and critical distance of r_R=2.82 m as presented above. It was assumed that the effective front-to-random factor is 2 (at 1 KHz) for loud Imam voice and a natural increase of equivalent absorption area (*A*) coexists with increase of the mosque's volume. Increasing or decreasing the volume to draw the relationship presented in Figure 1a was found by increasing and decreasing the critical distance as it is influenced by the volume change.



(a) (b)

Figure 1. (a)Recommended RT for different Mosque's Volumes (b)Tolerance Ranges of the recommended RT as a function of frequency

In Figure 1(b) the Tolerance Ranges of the recommended RT as a function of frequency are demonstrated. The RT at frequencies less than 250 Hz degrade at a rate of 0.2 per octave. In mosques where a speech performance dominates, the effective frequency spectrum is ranging between 250 and 2000 Hz. Therefore, the contribution of frequencies lower than 250 Hz should be omitted. This will ensure the suppression of Flutter Echoes emerging at low frequencies. Also, the recommended Tolerance Ranges decrease at frequencies higher than 2000 Hz. This behaviour is enforced according to the natural sound energy loss (absorption of the air) as it travels throughout a mosque. Also, this behaviour is valid according to higher absorbing characteristic of surface materials (especially the carpet) at high frequencies

The Recommended Reverberation Time presented in the last Figure 1a was used to calculate the Articulation Loss of Consonants as a measure of intelligibility using the following equation [1].

$$AlCons\ \% = 0.652\left(\frac{r_{LH}}{r_R}\right)^2 \times RT \text{ ......(8)}$$

The relationship between the distance ratio r_{LH}/r_R and the Articulation loss level at different Reverberation Times is shown in Figure 2.

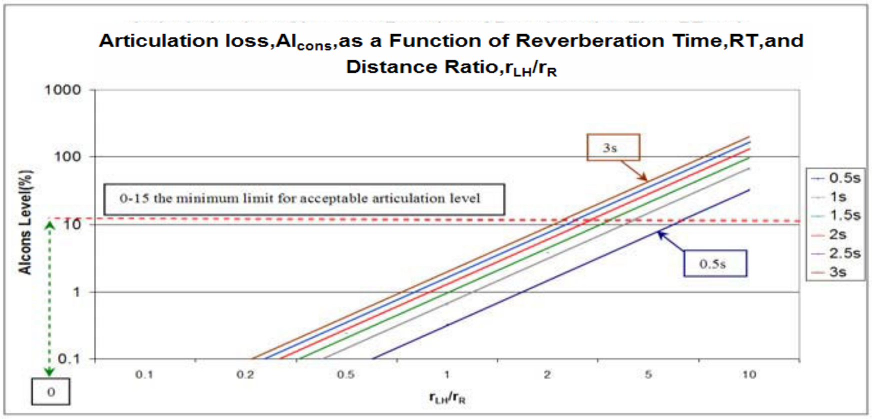


Figure 2. Recommended Articulation loss as a function of RT and r_{LH}/r_R

To maintain an acceptable level of intelligibility by means of AlCons% (a minimum of 15%) for structures with Reverberation Time between 0.5-3 s, the ratio r_{LH}/r_R ranges between 2 and 7 respectively.

Another measuring tool of intelligibility is C_{50}. Here the ratio of energy before and after 50 milliseconds in decibels is measured. Statistical Clarity of speech C_{50stat} formula as a function of Reverberation Time is shown in Eq. (9) using a statistical approach [1].

$$C_{50\,stat} = 10 \log \frac{(r_H / r_{LH})^2 + 1 - e^{\left(\frac{-0.69}{T}\right)}}{e^{\left(\frac{-0.69}{T}\right)}} \quad ......(9)$$

The relationship between $C_{50\,stat}$ and Reverberation Time for different r_{LH}/r_R ratio is shown in Figure 3 .

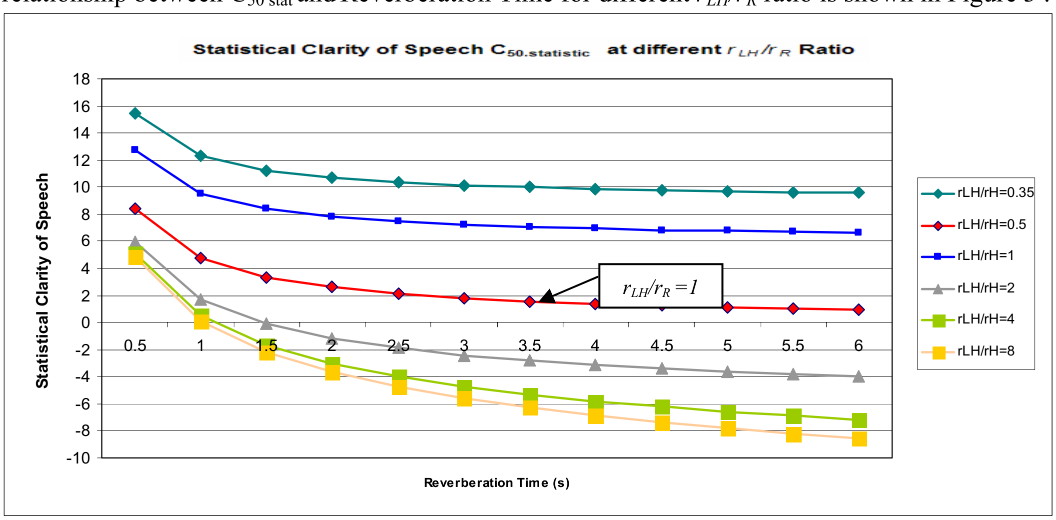


Figure 3. Statistical Clarity of speech for different r_{LH}/r_R ratio as a function of Reverberation Time

Values above the zero line depict more energy arrivals before the 50msec than after it what enhances the direct sound and increases clarity. The integration of sound arrivals within 50msec with direct sound is due to human nature of our ears. Values under the zero line depict more energy is arriving after the

50msec. This should not be the case in a sound system built for speech purposes. All arrival of sound energy between 50-80msec will be effectively integrated to reverberant sound and considered useful for musical performances.

Speech Transmission Index, STI must also be investigated, since it is one of the most popular parameters to evaluate the intelligibility. An equation that takes into consideration the contribution of the direct sound and interfering noise in the calculated STI was provided by Houtgast and Steeneken in 1980[3]. It represents the squared impulse response as a component of direct sound and reverberant field.

$$r(t) = r_d(t) + r_r(t)......(10)$$

Where

$$r_d(t) = \frac{3}{r_{LH}^2}\lambda(t)....(11)$$

$$r_r(t) = \frac{1}{r_C^2}\frac{13.8}{T}e^{\left(\frac{-13.8t}{T}\right)}....(12) \qquad \text{for} \quad t < 0$$

Equation 11 represents only the direct sound component *r(t)* obtained as the product of Delta Function (*λ(t)*) multiplied by the relative weight of the direct field $q_{t,1}/r^2_{LH}$. Here $q_{t,1}$ represent the enhancement of the direct field by the directivity index of the talker sound field and as a result of listener's directional hearing capacity. $q_{t,1}$=3 as estimated by Plomp and Mimpen [4].

Equation 12 illustrates that the reverberant field is a combination of its relative weight $1/r_c^2$ multiplied by the loss factor 13.8/T and decaying exponentially (r_c is the room's critical radius and it is influenced by the loss factor). This means that the initial value of the reverberant field is subject of the Reverberation Time (T) and the room's critical radius.

Replacing (10),(11) and (12) in the basic equation founded by Schroeder in 1981 [5] for the Modulation Transfer Function MTF give

$$m(F) = \frac{\left|\int_0^\infty r(t)e^{-j2\pi Ft}dt\right|}{\int_0^\infty r(t)dt}....(13)$$

And after including the noise factor, the final equation of MTF yields to:

$$m(F) = \frac{\sqrt{(A^2 + B^2)}}{C}\frac{1}{1+10^{((-S/N)/10)}}....(14)$$

Where

$$A = \frac{3}{r_{LH}^2} + \frac{1}{r_R^2}\frac{1}{\left[1+\left(\frac{2\pi FT}{13.8}\right)^2\right]}$$

$$B = \frac{2\pi FT}{13.8}\frac{1}{r_R^2}\frac{1}{\left[1+\left(\frac{2\pi FT}{13.8}\right)^2\right]}$$

$$C = \frac{3}{r_{LH}^2} + \frac{1}{r_R^2}$$

Here
T The Recommended Reverberation Time in (sec)
r_{LH} Talker-to- listener distance
r_C The room's critical distance
F Modulation Frequency from 0.63-12.5Hz
S/N Signal to Noise ration in dB at the listener position

To derive the STI values from the calculated MTF the following set of equations can be considered for each Octave-Band:

$$X_i = 10\log\left(\frac{m_i}{1-m_i}\right)dB \longrightarrow X = \frac{1}{14}\sum_{i=0.63}^{12.5} X_i \longrightarrow STI_{Oct} = \frac{X+15}{30}$$

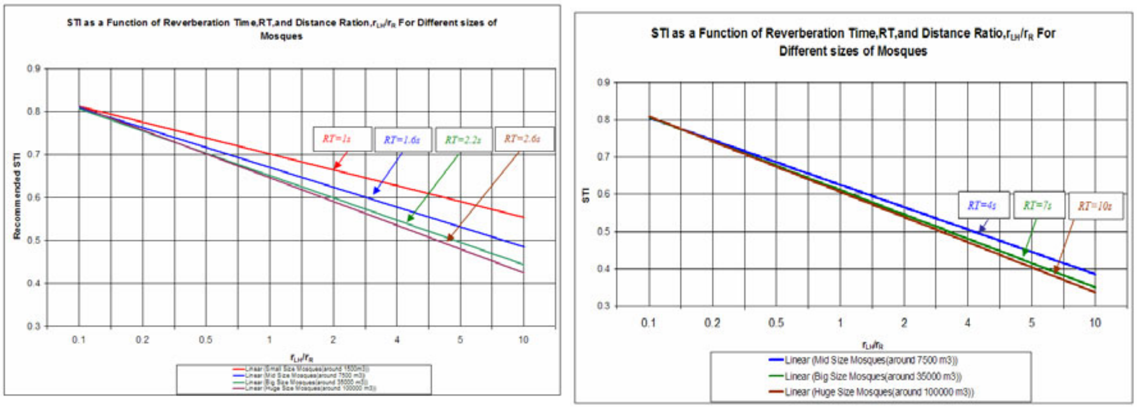
To calculate the total STI for the seven different Octave-Bands, the weighted mean of all STI_{oct} should be used to balance the influence of all Octave-Bands on the final STI value. The equation associated with this is as follows [5]:

$$STI_{total} = \frac{w_{125}STI_{125}\times w_{250}STI_{250}\times w_{500}STI_{500}\times w_{1000}STI_{1000}\times w_{2000}STI_{2000}\times w_{4000}STI_{4000}\times w_{8000}STI_{8000}}{w_{125}+w_{250}+w_{500}+w_{1000}+w_{2000}+w_{4000}+w_{8000}}$$

Where the weighting factors for each octave-Band are:

W_{125} = 0.13, W_{250} = 0.14, W_{500} = 0.11, W_{1000} = 0.12, W_{2000} = 0.19, W_{4000} = 0.17 and W_{8000} = 0.14.

Figure 4 presents the relation between the recommended STI as a function of RT and the distance ratio r_{LH}/r_c and it is concluded from equation 14. Here the recommended RT for different mosque's volumes presented in Figure 1 was used to calculate the Recommended STI values.



(a) (b)

Figure 4. (a)Recommended STI for different r_{LH}/r_R ratios for different mosques sizes(b) STI values for different r_{LH}/r_R ratios for different mosques sizes using high RT Values.

Let us assume that the recommended RT's for the different mosque's volumes have not been considered. What would be the resulting STI figures for the same Mid-size, Big-size and Huge-size mosque used to generate Figure 4a?; Giving that the associated not preferable RT's are 4,7 and 10 s for Mid-size, Big-size and Huge size mosque respectively (Here, the small-size mosque has been excluded while in such mosques high RT time values are not most likely to happen). By using the same formulas used to calculate STI figures presented in Figure 4a, the STI were acquired for the same mosques with the new RT's, see 4b.

In general, the intelligibility of the different mosques volumes decreases compared to the same volume mosques where the recommended RT values were used. The decrements of intelligibility in term of STI were evident especially as r_{LH}/r_R ratio increases. In other words, when the distance between a worshipper and loudspeakers increases compared to the associated critical distances of the used loudspeakers, STI are detected to drop more compared to STI values calculated using the recommended RT. Maintaining closer distance between worshipper and sound source will improve the intelligibility figures and makes them less dependent on mosque's volume.

In this section, general rules and recommendations for some sound parameters which matters in mosques were introduced. RT, STI, Alcons% level and C_{50stat} were calculated upon good understanding and experience of the acoustical environment needed in mosques. Some of these parameters were a function of the distance ratio r_{LH}/r_c at different Reverberation Time values to address wide range of conditions in constructed and newly constructed mosques.

3. NEWLY CONSTRUCTED MOSQUES RULES

Early cooperation between architects and acousticians should take place to avoid any acoustical complications in later phases. Moreover, cooperation in early stages will save considerable costs which might be spent to relocate walls or to change wall's materials.

The first question to answer when starting to design a mosque is: Are we dealing with a large state mosque, a community mosque or a small mosque? As the mosque volume increases, the Reverberation Time increases accordingly. In the opposite side, the increase of Reverberation Time produces a decrement of Intelligibility and Clarity of sound. These dependent relationships have to be clear to the designers of mosques. This is, also, does not mean that no big mosques have to constructed, but, if necessary, especial treatment should be implemented for walls and under the carpet in order to make this relation disproportional again.

Regarding the internal design of mosques, the acoustician should have some few more words to say. Constructional features like Roof Supporting Columns, Domes and walls must be designed in the right way; so that it behaves in favour of sound quality in such structures.

3.1 ROOF SUPPORTING COLUMNS

There is no doubt that eliminating the roof columns will improve the intelligibility especially in the areas shadowed by them. Increasing thickness of the roof and walls might be the solution of eliminating such columns and decreasing noise intrusion and consequently increasing intelligibility. It is more recommendable to use 4 in 1 columns, since sound wave can penetrate through them and decrease the shadowed areas. Circular columns help reducing the shadowed area behind them as compared to squared shape columns. Also, increasing the spacing between roof supporting columns will decrease the percentage of the shadowed direct sound. Figure 5 shows the influence of the type and spacing of different roof supporting columns kinds on the percentage of the shadowed direct sound.

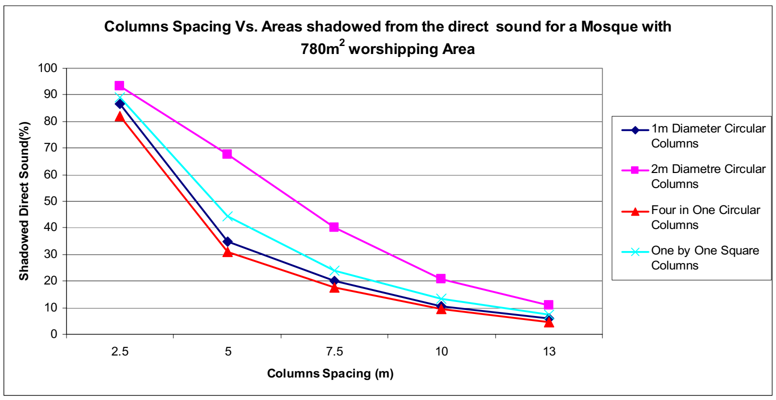


Figure 5. Relation between columns spacing and Areas shadowed from the direct sound.

3.2 DOMES

Constructing domes in mosques eliminate the need for using roof supporting columns. When the architect decides to design a mosque with a Dome, the relationship between the focusing height and the speaker's height must be carefully observed. The ratio s/r should be more than 1.1 to prevent focusing at the height of listening plane of the worshippers. Such a relation is addressed in Figure 6 to provide guidelines for architects.

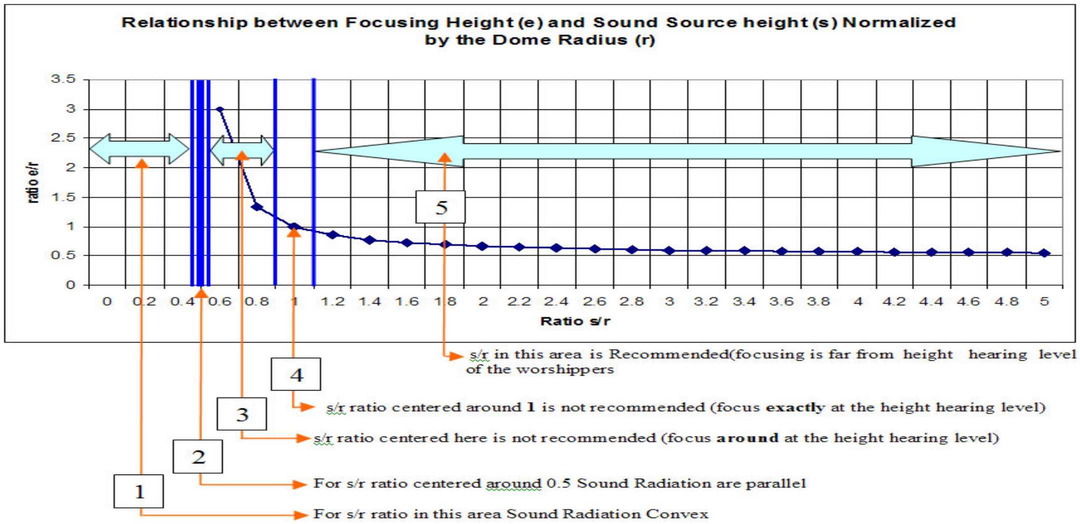


Figure 6. Relationship between Focusing Height (e)and sound source Height (s) Normalized by The dome radius (r)

While concave surfaces must be avoided especially at the back wall to prevent focusing, convex surfaces can be attached to parallel walls to diminish or decrease the possibility of flutter echoes. Also, ornaments can be added to parallel walls to scatter the sound waves and preventing it from forming fluttered sound echoes. Furthermore, lowered surfaces which are usually included within the main praying hall and represents woman worshipping area requires extended number of carrying columns which causes shadowing ,accordingly, it must be brought outside the main hall as a separate structures.This will decrease the number of roof supporting columns inside the main hall and will improve the sound parameters in areas under the lowered surface.

3.3 BACKGROUND NOISE

Background Noise (BN) is a major contributor in degrading the overall intelligibility levels in mosques. It is mainly resulted from Air Conditioning operation noise. It is highly recommended to isolate the Air Conditioning unit in a separate Technical Room. This will reduce dramatically the Background Noise level and consequently improving the overall intelligibility level. Figure 7 depicts a surveyed data of the averaged Background Noise of ten mosques evaluated using RC curves. RC curves are used to evaluate and diagnose the continuous noise from HVAC systems (Heating, Ventilation and Air Conditioning systems) according to the measured sound pressure level, Shape of frequency spectrum, tonal content and low frequency forced vibration.

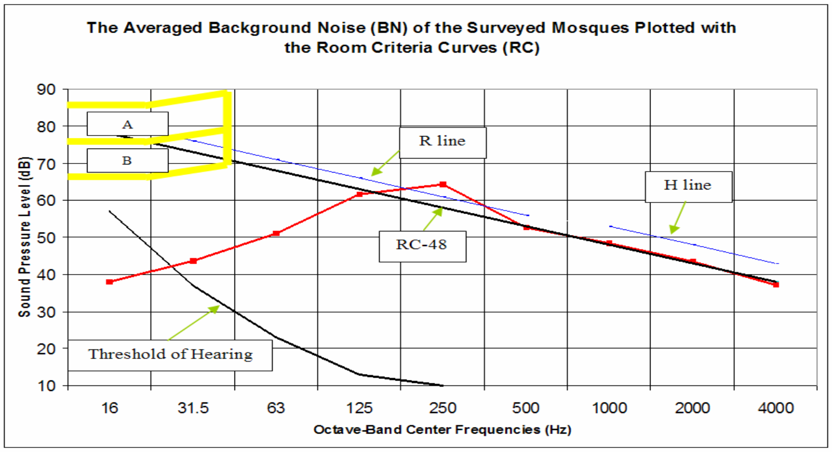


Figure 7. The averaged Background Noise of the surveyed mosques

In Figure7, It is observed that one value is above the R line. Therefore, the Background Noise represented by this curve sounds "Rumbly" and it is rated as RC-48(R). Such a rating is quit high for structures used for speech purposes and must be reduced.

Open courtyards mosques are more exposed to Environmental Noise surrounding them. In case of constructing a mosque with an open courtyard, caution must be exercised to reduce the late arrivals of sound radiated from the Minaret sound system. Also, a proper aiming and orientation of the Minarets sound systems should take place to decrease the possibilities of sound reflections from the neighbouring building and high landscape into the courtyard. Furthermore, constructing a moveable dome or glass roof to prevent the noise and late reflected sound from penetrating into the courtyard should be considered. Such a solution has drawbacks which must be considered. A noticeable increase of reverberation in the courtyard will be evident when the dome covers the courtyard or when the glass roof is constructed over it. This will form different acoustical environmental conditions which have to be treated to maintain acceptable quality of sound. Such a treatment will be introduced in the next section as treatments recommendations for constructed mosques.

4. RECOMMENDATIONS TO OPTIMISE ACOUSTICAL PARAMETERS OF CONSTRUCTED MOSQUES

Fortunately, once the internal design of a mosque is completed and can not be further modified, secondary structures can be treated to optimise the sound quality. Different recommendations of carpet treatments as a prime solution and walls materials will be presented here. Furthermore, recommendation of digitally controlled loudspeakers which enforce better intelligibility levels in such structures will be within the scope of this part.

Architecturally, mosques come in two major architectural forms. These forms are mosques with an open courtyard and as closed structures; both of which have different acoustical recommendations according to their architectural form. Let us start with the open courtyard mosque.

4.1 OPEN COURTYARD MOSQUE

An open courtyard was designed in the early days to accommodate high numbers of worshippers in communal praying. It is open to the air to expose the worshippers visually more to the sight surrounding them. From the designer's perspective, it opens an extended view of the sky to consolidate the relation between God and the worshippers during the praying ceremonies. On the other hand, such a design exposes the worshippers more to the environmental noise surrounding the mosque compared to closed structure mosque. A solution has to be developed to decrease noise intrusion into the courtyard and at the same time to maintain a good view of the sky and the geographical sights surrounding the mosque.

Electrically sliding light weight structured Domes or Transparent Roof can be considered as a prime solution, but has to be treated acoustically right to prevent high Reverberation Time and consequently low intelligibility while they are closed. Both of them are shown in Figure 8.

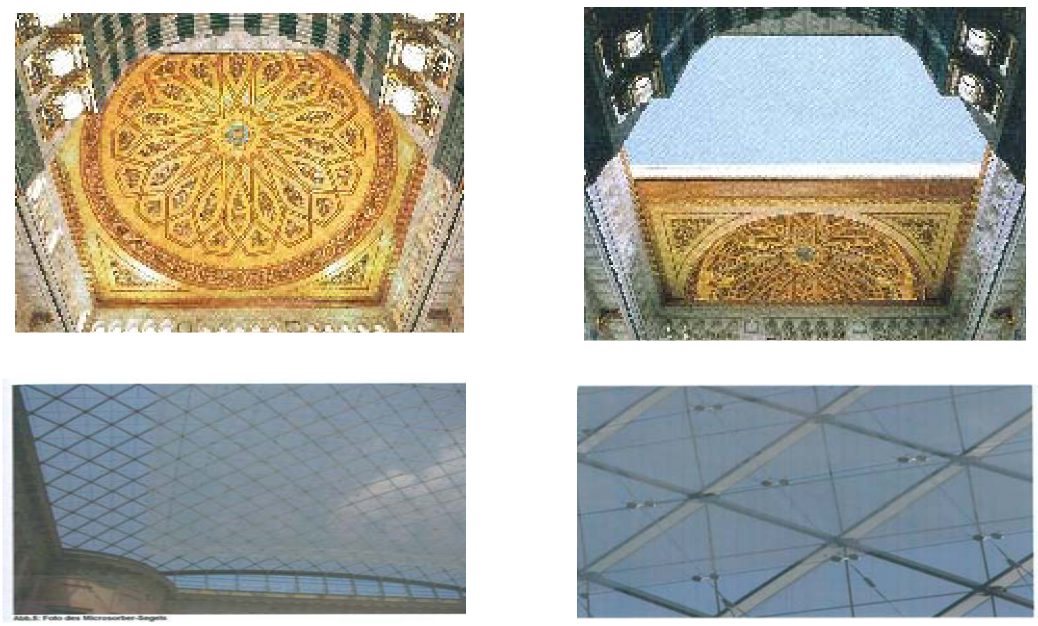


Figure 8. Sliding light weight structured Domes and transparent roof

Also, the concept of Convertible Umbrellas has been introduced as a prime solution to maintain the purposes of courtyard mentioned above. Such umbrellas were developed and implemented by SL-Rasch Stuttgart, Germany in the courtyard of the Prophet Mohammed Mosque in Mahdina, Saudi Arabia as shown in Figure 9.

Figure 9.Umbrellas implemented in the Courtyard of the Prophet's Mosque in Madinah

The absorption coefficients of the material used in this project were measured in two different set-ups in the Reverberation Chamber of the Technical University in Berlin. The results are shown in Figure 10.

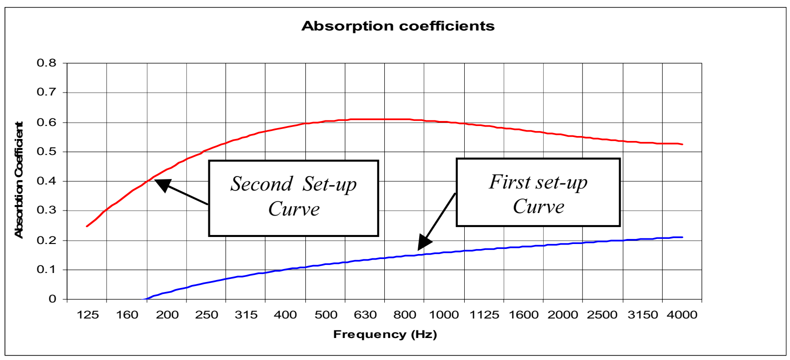


Figure 10.Absorbtion Coefficients of the material used in the Umbrellas on the ground (blue Curve)and with a air gap from the wall (red curve)

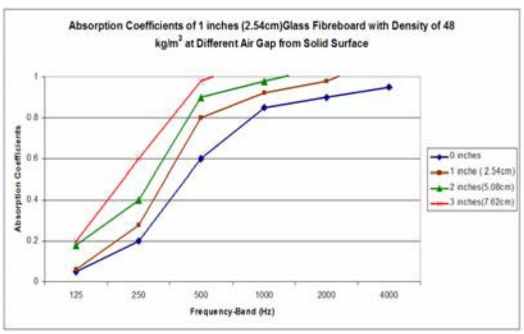
First set-up(blue curve) was to place the material on the ground . It will result in a more classical semi-linear relation between the frequency and the absorption of the material with higher absorption at higher frequencies. Hanging the material 20 cm away from the side wall will result in the second relation shown in red in figure 10. Spacing the material from the wall will boost up the absorption which will have a maximum value at the lower frequencies. Also, increasing the gap further will introduce another maximum at a lower frequency compared to the first curve and so on. The second set-up involves placing the material with a defined distance from the wall (red curve).

Material thickness, density and weight are factors which manipulate the absorption of the material. It is understood that increasing the thickness of the used material will increase its absorption, but this logic holds primarily at low frequencies. As if we were to place air cavity between the absorbing surface and the substrate, increasing the thickness of the material will result in placing its surfaces at a higher practical velocity, consequently, increasing its absorption.

Material density affects sound penetration; therefore, it affects the amount of the absorbed sound energy. The measurement results were conducted for one material with its associated density. Generally speaking, less dense materials with wide spaced fibres will give the chance for the emitted sound to penetrate back and forth through it (high flow of resistance); thus, increasing the sound absorption and vice versa. Also, increasing the weight of the absorbing material will require more energy of the incident sound to displace or move it (more absorption).

The construction of such umbrellas using the same measured material at height of 8 m, or higher, will not contribute significantly in changing the courtyard acoustics. Once the height of the umbrella from the ground floor exceeds the wavelength of the lowest frequency of interest in the speech spectrum (60Hz), the umbrella construction will not contribute significantly in manipulating the courtyard acoustics. They might only increase the Sound Pressure Level in the courtyard. One of its advantages is that it can be considered as acoustically transparent. So, putting or removing them will be harmless to the acoustical behaviour of structures (depending on their set-up).

Two different treatments can be applied for the sliding dome and transparent roof to improve their absorption. In case of the sliding domes highly absorptive glass-fibres with different thickness and with an appropriate air gap can be used to obtain the required absorption behaviour. Figure 11 shows the absorption coefficients for glass-fibres material with a different thickness and 1 inches (2.54 cm) glass-fibre with different air gap from the solid surface.



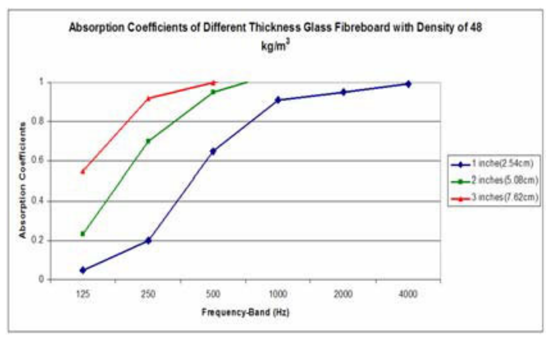


Figure 11. Absorption coefficients for (a)1 inch of glass fibreboard with different air gaps(b) for glass fibreboard with different thickness

The internals of, for example, a light weight structure dome can be stuffed with a fibre-glass material (with/without an air gap) with a certain thickness to obtain the required absorption behaviour and to seek the required results. It is clear from Figure 11 that increasing the thickness of the fibre-glass or the air gap will result in increasing the absorption especially at low frequencies.

Transparent roof like glass can be considered in the courtyard to decrease the outside noise intrusion. They can be constructed as fixed or sliding roofs. Additionally, acoustical treatments have to be associated with this solution to decrease unacceptable Reverberation Time. Constructing such roofs on the top of a courtyard gives the possibility to make a further treatment to the floor, since by having a roof the floor is protected from weather conditions like rain, snow, etc. Also, Air Conditioning can be added to the courtyard in the existence of the roof to improve its temperatures in countries where hot weather prevails.

Especial transparent micro-perforated foil can be attached to the glass with a certain air gap from the glass surface. The transparent micro-perforated foil with two different distances from the glass surface along with its absorption coefficients are shown in Figure 12. The implementation of the transparent micro-perforated foil with 100mm to the reflecting surface and 30 mm distance between foils is more adequate for mosque applications, since it is broad band absorber. In some other application where less absorbing are needed at lower frequencies a distance of 50 mm to the reflecting surface and 30 mm distance between the foil can be considered.

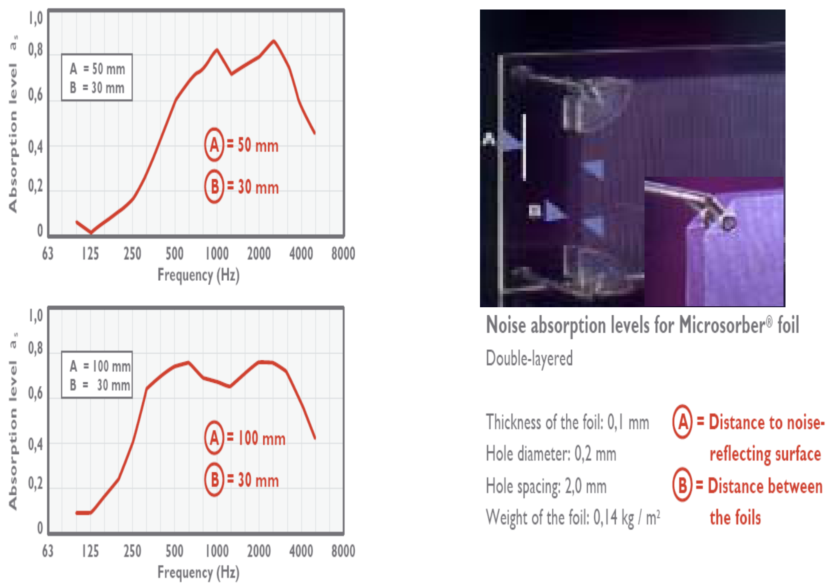
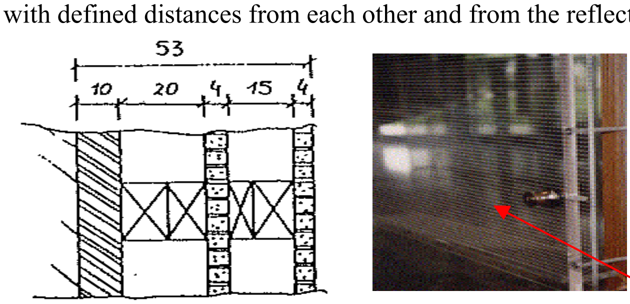


Figure 12.Micro-perforated foil with two different distances from the glass surface along with its absorption coefficients

Not only treatments of the glass roof and the floor can be implemented to improve acoustical parameters inside mosques. The merge of transparent absorbing surfaces makes it possible to "passively" treat and manipulate the internal design without changing the mosque's general overview. This can be very effective treatment solution especially in old and historical mosques and sensitive parts in modern mosques like the Qibla wall. Such a treatment would be a prime solution which satisfy the architect and will result in acoustically successful treatment. Transparent Micro-perforated Acrylic Glass can be implemented in these kinds of "passive" treatment applications. Figure 12 shows a suggested configuration of the two layers Acrylic Glass with defined distances from each other and from the reflecting wall.



Thickness of the Plate: 4 mm
Perforation: diameter of holes 0.8mm
Distance between holes 5 mm

Figure 13.The two layer glass along with its specifications.

The absorption coefficients of the above shown configuration are shown in Figure 14.

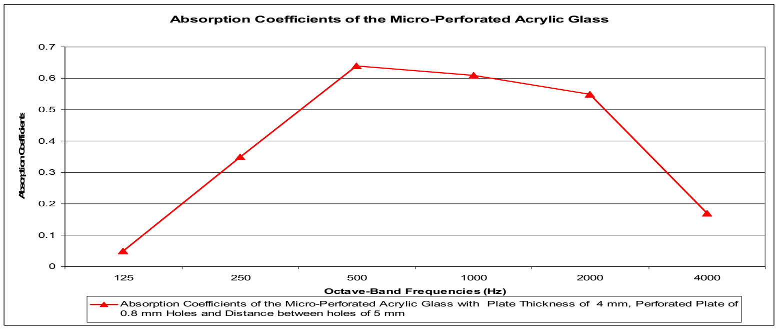


Figure 14. Absorption Coefficients of the two layer Micro-perforated Acrylic Glass.

Let us assume that the primordial Prophet Muhammad Mosque in Madinah/Saudi Arabia is still standing until nowadays. A "Transparent Architectural" approach is suggested to be implemented in the renovation of the mosque. It was decided to adopt this approach in the renovation process to preserve the same ancient materials and architectural design of the mosque.

Now, the architect decides to implement glass surface above the court yard of the mosque. This decision was taken to give the chance of implementing an Air Condition system in the courtyard. Unintentionally, the overall sound intelligibility in the courtyard benefited from such a decision by reducing noise intrusion into the mosque. Also, late sound energy arrivals which cause reduction of overall intelligibility were prevented from penetrating to the courtyard.

The influence of transforming mosques from an open courtyard to a closed structure mosques on acoustical parameters must be taken into consideration. The increase in the Reverberation Time after implementing such a roof has to be treated acoustically. The Reverberation Time of a virtual mosque after constructing the roof is shown in Figure 15.

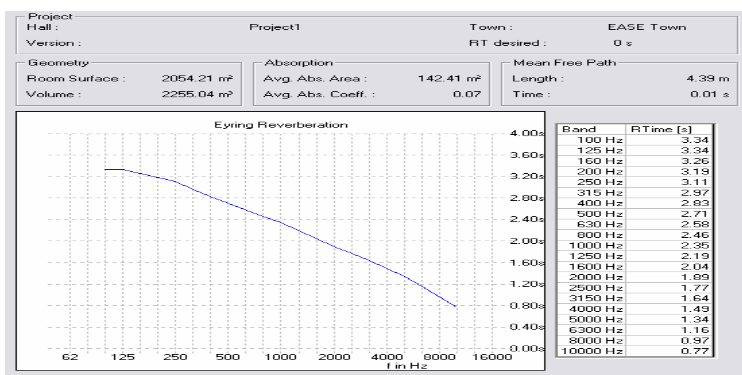


Figure 15. RT of the Prophet Mosque before treatment of the glass roof

The mosque volume is around 2200 m^3. The recommended RT represented in Figure 1 for the same size mosque is around 1.2 s. It is quite clear from Figure 15 that the mosque needs treatment to decrease its Reverberation Time to the recommended value. Different treatment approaches with one and double layer micro-perforated foil as a transparent treatment of the glass roof were implemented to the Glass roof to decrease the overall RT. The Reverberation Time after treatment is shown in Figure 16.

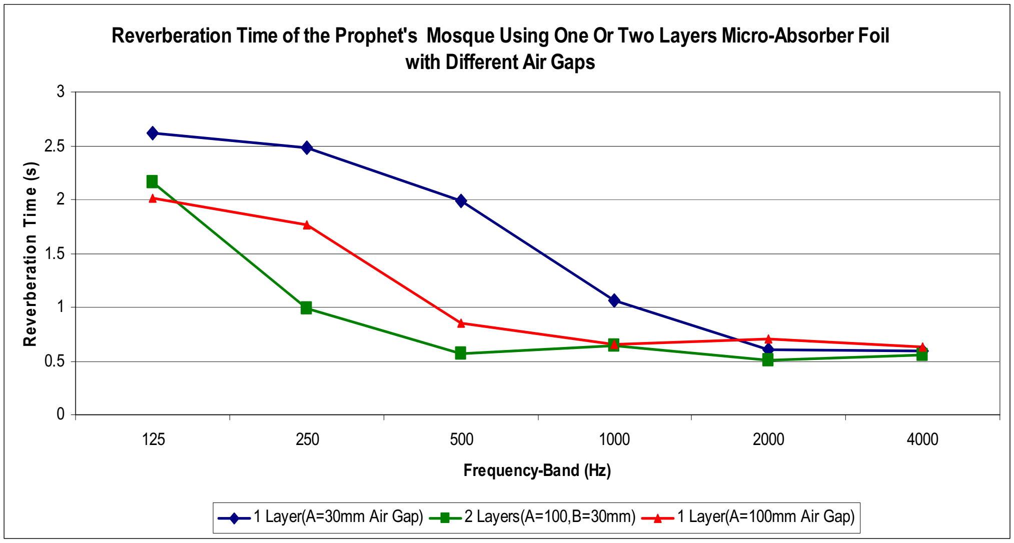


Figure 16. Reverberation Time of the Prophet's Mosque using one or two layers of the Micro-Absorber Foil with different Air Gaps after treatment

All of the three suggested treatments are within the acceptable RT values. As mentioned earlier the recommended RT for the same size mosque is around 1.2 s. To stay within acceptable treatment cost a 1 layer with 30 mm air gap will result in Reverberation Time of 1.1 s at 1 kHz.

The implementation of the Sliding Domes or Glass Roof to decrease the intrusion of outside noise must be associated with a proper acoustical treatment to decrease the Reverberation Time. Fibre-Glass stuffed in the sliding domes with an air gap or micro perforated foil attached to a Glass Roof with a proper air gap are recommended to decrease Reverberation Time and to improve the overall intelligibility levels. If further acoustical improvements are needed, the carpet could be manipulated in favour of Reverberation Time. Constructing Glass roofs on the top of a courtyard makes it possible to treat the floor, since by having a roof the floor is protected from weather impacts like rain, snow, etc.

4.2 CLOSED STRUCTURES MOSQUES

In mosques, treatments which involve manipulating the main internal design at construction's final stages might be costly and require a lot of effort. It was shown in detail in a presented paper in ASA 151st meeting in providence [6]; how efficient is the carpet treatment compared to other surfaces treatments. Usually, carpet covers large portion of the total surface area of a mosque. Consequently, a small change in its absorption behavior will make a considerable difference in term of reducing the total Reverberation Time. Additionally, increasing the thickness of the carpet or adding an additional absorbing pad under the carpet to increase its absorbing behavior at low frequencies will make it more convenient for the worshippers sitting and kneeing on the ground.

Two different kinds of carpet have shown an acceptable absorption results. Heavy Carpet on a thick pad (1.5 cm rubber pad) and Carpet Pad on 1134 g/m^3 FOAM RUBBER are the names of the two recommended carpets for their absorption behaviour. The absorption coefficient of the two materials is shown in Figure 17. The Heavy Carpet on thick pad has more absorption at the low end frequencies than the Carpet Pad and vice versa. The decision to select between the two carpets types depends on the required acoustical effect.

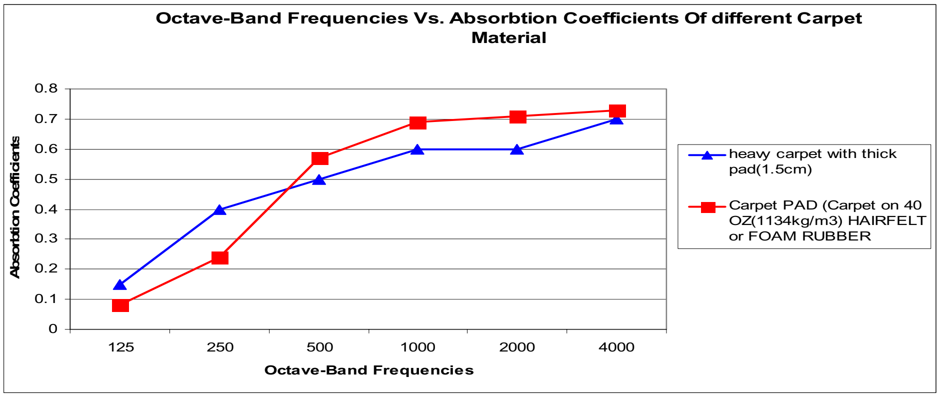


Figure 17. Absorption Coefficients of two recommended carpet material

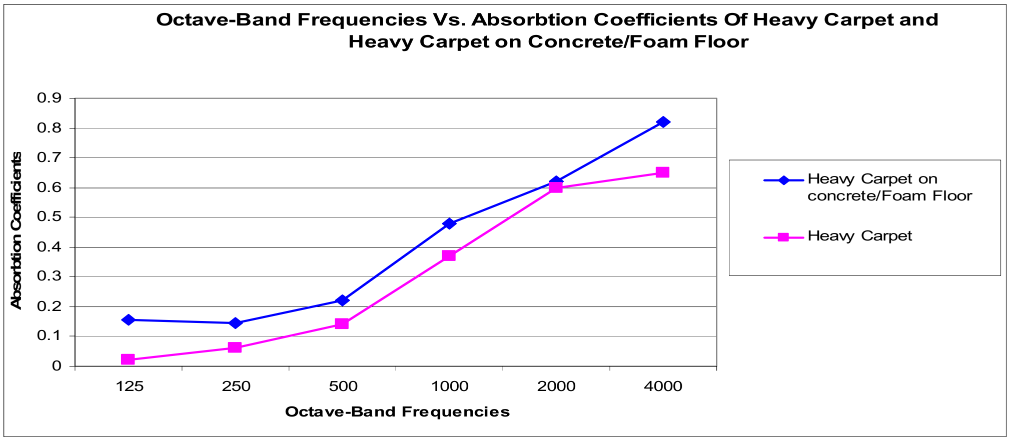
The benefit of concentrating the acoustical treatment on the floor surface by adopting an appropriate carpet or padding material under the carpet was investigated in the paper presented at the 151st ASA meeting in providence [6]. In this section a recommended carpet and padding material were pointed out. In some occasions the architect rejects even treatments under the carpet surface. Although, this treatment is very efficient and dramatically decreases the need for further treatments of other visible walls, sometimes it fails to satisfy the architect. The reasons behind this decision are different.
Some of them think that such a material is beyond the acoustical treatment budget and some others find it inappropriate and do not fit the general outlook of the mosque's interior. In this case some sort of other solution should be developed.

Usually, the surface under the carpet in any mosque is a hard reflective concrete. This concrete surface is formed from cement powder, sand and water. Sometimes, it is mixed with fine particles of stones to increase its stiffness. For acoustical purposes, a high percentage ratio of white foam bubbles to concrete can be adopted as a new concrete mixture. This light-weight structure is demonstrated in the following figures during production. Also, a cross-section view of the final concrete/foam bubbles surface is shown in Figure 18.

Figure 18. cross-section view of the final concrete/foam bubbles surface and the light-weight structure during production

The resulting mixture of concrete and foam bubbles is more absorptive compared to the concrete mixture only. The absorption behaviour of this concrete/foam bubbles surface was measured using an impedance tube in the TU Berlin acoustic lab. Figure 19 shows the absorption coefficients of such material at different Frequency-Bands and the material placed inside an impedance tube.

(a)



(b)

Figure 19.(a) Concrete/foam bubbles with and without the carpet inside the impedance tube(b)absorption coefficients of the heavy Carpet and heavy carpet on a concrete/Foam floor

The addition of the white bubbles foam to the concrete under the carpet adds to the total absorption of the mosque's floor. It will allow a certain amount of air to be located underneath the carpet; accordingly, more absorption will be added to the low end frequencies. Even though the increment is small it will make a different since the total surface area of the floor in any mosque is large. If bigger size bubbles are used more air will be placed underneath the carpet what makes it more absorptive at the lower frequencies.

5. CONCLUDING REMARKS

This work we have started with introducing new acoustical quality parameters quantities in mosques. Reverberation Time, ALcons%,STI and C_{50stat} figures were established for the first time to govern the acoustical environment in such structures.

Designing a mosque with an open courtyard is usually accompanied with complexity inside the courtyard. Contemporary covering methods like Transparent Sliding Glass Domes and Light Weight Structured Sliding Domes have been introduced along with proper and effective acoustical solutions. The pros and cons of electrically controlled umbrellas which do not have a considerable influence on the acoustical environment when placed in the courtyard were presented. Treatment of the courtyard walls can be associated with the implementation of the controlled umbrellas with Transparent Micro-perforated Acrylic Glass; this was shown to be effective and suitable in this case.

In closed structure mosques, treatment of the carpet floor compared to other surfaces was proven to be more efficient while the carpet covers large portion of the total surface area of a mosque. Also, it is more practical in a sense that it does not require deformation of important wall figures and characteristics. Manipulating the absorption of the carpet by increasing its thickness or adding an additional layer underneath it will make it more convenient for the worshippers sitting or kneeing on the floor. Two different materials have been recommended for the treatment of the carpet. A Heavy Carpet on a thick pad (1.5 cm rubber pad) and Carpet Pad on 1134 g/m3 FOAM RUBBER did show considerable beneficial results especially at low frequencies.

Another floor surface treatments alternative were discussed. When the floor treatment using thick carpet or padding material under the carpet are rejected, such a treatment can be considered. A mixture of concrete and foam bubbles was introduced to be used as sound absorber. This mixture is very light in weight and has a considerable positive acoustical behaviour

6. ACKNOWLEDGMENT

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