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OPTIMIZING THE ACOUSTIC CONDITION OF A PYRAMIDAL-CEILING MOSQUE BASED ON SIMULATION

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ABSTRACT

This study aims to optimize the acoustic condition of a pyramidal ceiling mosque utilizing a simulation approach. The simulation was done using I-Simpa, simulating the room acoustic parameters of 15 m x 15 m x 5 m and a 5 m roof height of a mosque. The optimization was accomplished by varying the occupancy level and using absorbent materials. The best acoustic condition was defined as having a high level of speech intelligibility (C-50 > -2 dB) yet the longest possible reverberation time, especially at 500-4000 Hz. The simulation indicates that the speech intelligibility value increases with the number of filled rows, both with and without sound-absorbing material. On the other hand, the reverberation time is unaffected by the number of filled rows and is extended by using sound-absorbing materials. Hence, without sound-absorbing ceiling material, optimal conditions are attained when the mosque is fully occupied. Meanwhile, using sound-absorbing materials on the mosque's ceiling establishes optimal acoustic conditions for all occupancy levels. It demonstrates that using sound-absorbing materials improves the acoustic quality of the pyramidal-ceiling mosque.

KEYWORDS:
Mosque; optimization; room acoustics; simulation

INTRODUCTION

According to LEED, one of the requirements that a sustainable building must satisfy is acoustics [1]. Simulating the room's acoustics or acoustical design during the design phase is a way to satisfy these requirements [2]. A good acoustic condition can be achieved during the design phase through acoustical design [3]. An optimal building design that satisfies the comfort requirements for its intended use can also be obtained [4].

Mosques are the primary worship venues for Muslims, where most of their activities involve sound, such as praying, speaking, listening and understanding sermons, as well as reciting the Quran [5]. However, some mosques are built while emphasizing on the aesthetics, which result in poor acoustics [6]. This is demonstrated by the common use of hard and reflective materials like marble, tiles, and glass because of their aesthetic value and ease of maintenance [7]. Several studies have found out that absorbing materials can enhance a mosque's acoustic quality [8], [9].

A previous study has demonstrated that excessive reverberation time contributes to mosques' poor acoustic performance [10]. Another significant issue in mosques is the decrease in speech intelligibility brought on by high reverberation times [7]. The mosque needs a long reverberation time and good speech intelligibility to create a sacred space [9]. To create a mosque design with the proper qualities, acoustic optimization using simulation must be performed.

Research on mosque acoustics is commonly conducted, assuming the mosque is full and vacant. Both occupancy conditions indicate a change in reverberation time and speech intelligibility [8 – 10]. In fact, mosque occupancy varies. As a result, there must be a change in reverberation time and speech intelligibility. Therefore, it is necessary to assess how variations in occupancy affect the changes in reverberation time and speech intelligibility.

Mosques typically have a square or rectangular form with a dome-shaped or concave ceiling. Although there is a possibility of sound focusing, mosques with domes often have good acoustics [10]. Many mosques in Indonesia have pyramidal ceilings in addition to domes. According to one of the studies conducted on the mosque with the pyramidal ceiling, the mosque's construction has good acoustic qualities [11]. This study uses a rectangular mosque with a pyramidal ceiling as an object since its shape is the characteristic of Indonesian mosques. Yet, there haven't been many studies about it.

This study aims to evaluate and optimize the acoustic conditions of the pyramidal ceiling mosque through a simulation. Evaluation is conducted based on occupancy variations and absorbent materials' use. The optimal conditions, a long reverberation time and good speech intelligibility (dB > -2), in the mosque were identified through optimization.

METHODS

This research is generally divided into two processes: simulation with modifications of the roof material and the occupancy level and analysis of reverberation time and speech intelligibility under each condition. Both processes were carried out after modelling the geometry of the mosque. Figure 1 depicts the steps of the study.

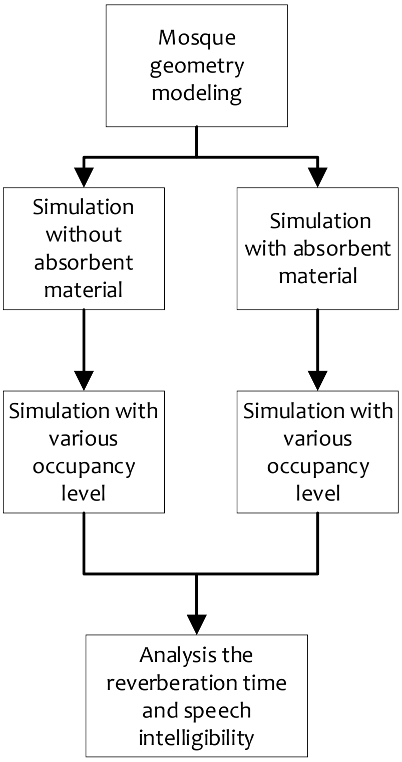


Figure 1. Steps of the experiment

SketchUp was used to create the geometry of the mosque with a pyramidal ceiling, and the dimensions are 15 m x 15 m x 5 m and a 5 m roof height [12]. Figure 2 illustrates how the basic geometry, devoid of windows and doors, is used in this simulation. This is due to the simulation's assumption that the material for the windows and doors is a hard material deemed the same as the wall. Furthermore, the geometry is used for room acoustic simulation with I-Simpa [13]. The materials utilized in the simulation are displayed in Table 1.

Variations of gypsum roof material and acoustic tile were simulated. The floor area is divided into 15 rows for each material and simulated from unoccupied to occupied. As a result, indicated in Table 2, there are 16 possibilities investigated for each type of material. The unoccupied condition indicates that the simulation's floor material is tile, whereas the occupied condition indicates that the floor material is the audience sitting down.

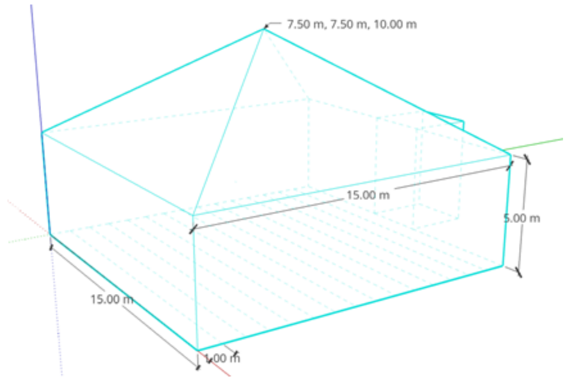


Figure 2. Geometry used in the simulation

Table 1. The absorption coefficient of Materials used in the simulation

Plane	Material	Absorption coefficient (α)					
		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Floor [14]	Tile	0.01	0.01	0.01	0.01	0.02	0.02
Floor [15]	Audience sitting down	0.19	0.52	0.76	0.89	0.85	0.96
Wall [14]	Concrete block painted	0.10	0.05	0.06	0.07	0.09	0.08
Roof [14]	Gypsum panel, ½ inch	0.29	0.10	0.05	0.04	0.07	0.09
Roof [14]	Acoustic tile, therma-tex ther-mofon, 1.5 cm	0.55	0.75	0.75	0.80	0.95	1.00

Table 2. Scenarios used in simulation

Scenario	Occupancy level in gypsum panel ceiling	Scenario	Occupancy level in the acoustic ceiling tile
1	Unoccupied	17	Unoccupied
2	1 row occupied	18	1 row occupied
3	2 rows occupied	19	2 rows occupied
4	3 rows occupied	20	3 rows occupied
5	4 rows occupied	21	4 rows occupied
6	5 rows occupied	22	5 rows occupied
7	6 rows occupied	23	6 rows occupied
8	7 rows occupied	24	7 rows occupied
9	8 rows occupied	25	8 rows occupied
10	9 rows occupied	26	9 rows occupied
11	10 rows occupied	27	10 rows occupied
12	11 rows occupied	28	11 rows occupied
13	12 rows occupied	29	12 rows occupied
14	13 rows occupied	30	13 rows occupied
15	14 rows occupied	31	14 rows occupied
16	15 rows occupied	32	15 rows occupied

The frequency range used in this simulation is the range of the speech spectrum produced by the human voice [16]. Therefore, it is crucial to create ideal conditions, such as long reverberation time and good speech intelligibility (dB > -2) [17]. Thus, the sound produced can be heard clearly, the message conveyed can be well received, and the sacred conditions in the mosque are also realized.

RESULT & DISCUSSION

Based on the simulation results, we will analyze the effect of using absorbent materials on roofs and modifications in the number of occupied rows on sound intelligibility and reverberation time in this section.

The simulation results generally display a consistent pattern for speech intelligibility at each frequency. Up to line 4, the clarity of the sound greatly improves without absorbing material. Following that, speech intelligibility improves slightly but not significantly. It takes 13 rows to fill in order to get good speech intelligibility. Meanwhile, even in empty conditions, the speech intelligibility is decent with absorbent material and continues to improve as the occupancy increases, although this is not considerable. It demonstrates that absorbent material improves speech intelligibility and is unaffected by the number of filled rows, as shown in Figure 3.

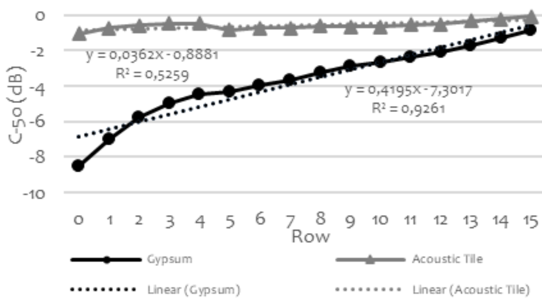


Figure 3. The effect of occupancy level on each ceiling material on the speech intelligibility at the frequency of 1 kHz

The reverberation time simulation findings also indicate a consistent pattern. Up to lines 4 and 6, the absence of absorbent material causes a significant reduction in reverberation time. Following that, the reverberation time value fluctuates. The reverberation time fluctuates when absorbent material is used, and its value is greater than when it is not used. As shown in Figure 4, using sound-absorbing materials and row occupancy does not significantly affect the reverberation time.

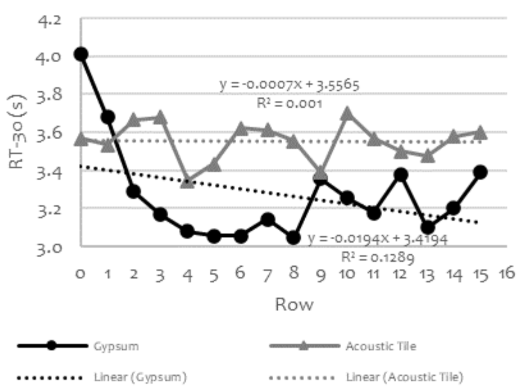
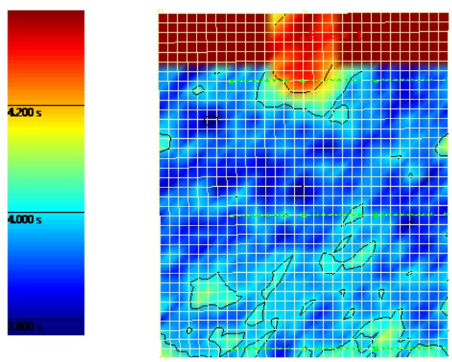


Figure 4. The effect of occupancy level on each ceiling material on the reverberation time at the frequency of 1 kHz

The simulation results show that absorbent materials improve speech intelligibility and reverberation time. These findings contrast those of earlier studies, which found that sound-absorbing materials decreased reverberation time and improved speech intelligibility in a mosque with a flat ceiling [8].

Without absorbent material, the reverberation time is non identical throughout the mosque, with values ranging from 3.8 s to 4.2 s in empty conditions. The reverberation time value in the occupied condition, without absorbent material, is more inhomogeneous than in the unoccupied condition, which ranges from 1 s to 4 s. In some spots, the reverberation time is substantially longer than in others. As in the previous conditions, the reverberation time values obtained in the empty condition with absorbent material range from 1 s to 4 s. The values are more uniform although there are certain points where they are greater. In the occupied condition with absorbent material, the reverberation time obtained is uniform in practically all points, ranging from less than 2 s to 4 s. Because of this uniform value, the average reverberation time obtained is longer for both empty and filled conditions as compared to the condition without absorbent material. Figures 5 and 6 show a more detailed depiction.

According to the total sound reflection, which includes direct sound and reflection from the roof, the presence of worshipers only reduces the amount of direct sound. The magnitude of reflected sound from the roof is constant whether the mosque is full or empty. In empty and full conditions, the direct sound value obtained with absorbent material is similar to the one obtained without it. However, the value of the reflected sound from the roof is lower than the one without the absorbent material. This demonstrates that the purpose of placing absorbent materials on the roof is to control the sound intensity caused by roof reflection. Figures 7 and 8 display the visualization of total sound reflection



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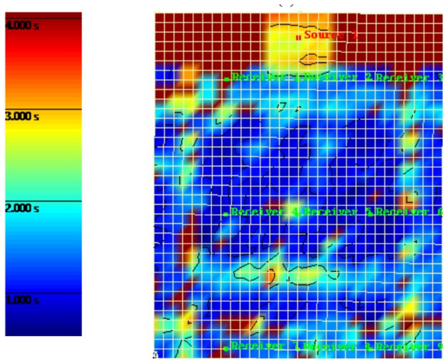
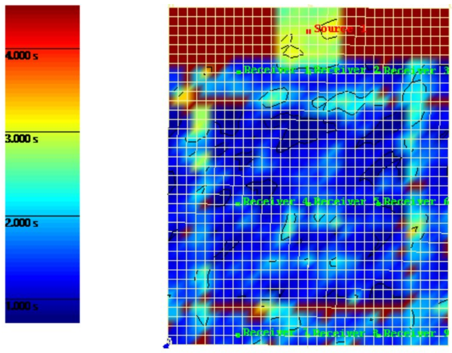


(b)

Figure 5. The reverberation time of a mosque without absorbent material: (a) Unoccupied and (b) Occupied



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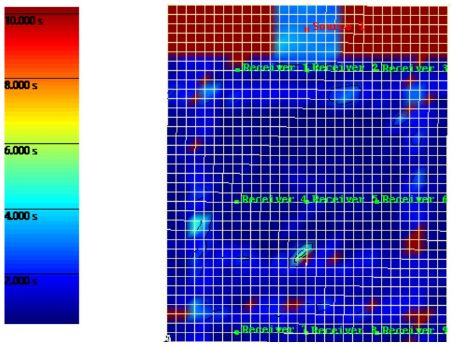
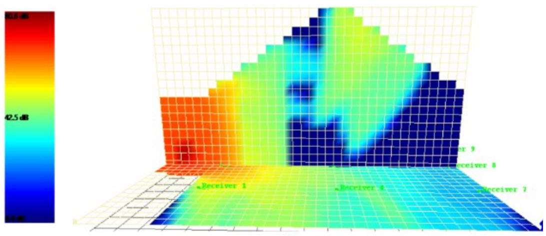


(b)

Figure 6. Reverberation time of mosque with absorbent material: (a) Unoccupied and (b) Occupied



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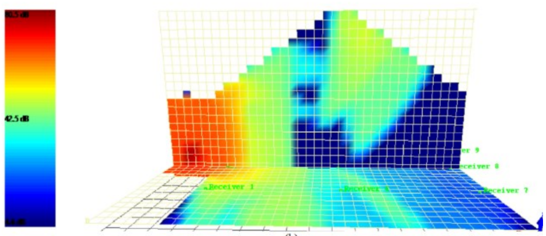
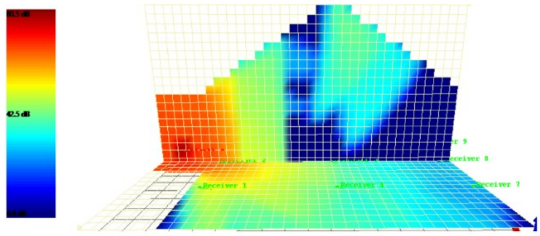


(b)

Figure 7. Total sound reflection without absorbent material at 0.05 s: (a) Unoccupied and (b) Occupied

The ideal situation for a mosque is long reverberation time with good speech intelligibility (dB > -2), especially at a frequency of 500 Hz to 4 kHz. Without absorbent material, ideal conditions are obtained when the mosque is occupied, as shown in the grey shade in Table 3.



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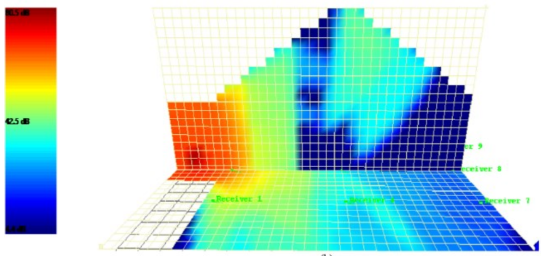

(b)

Figure 8. Total sound reflection with absorbent material at 0.05 s: (a) Unoccupied and (b) Occupied

Regarding speech intelligibility, the mosque's design with sound-absorbing material in this simulation may be stated to give good quality and reach ideal conditions at all frequencies. Previous investigations of an occupied mosque with a flat ceiling using sound-absorbing materials, for example, found that the speech intelligibility from 125 Hz to 4 kHz ranges from -3.6 to 1.9 [8]. While, in this study, speech intelligibility was attained in the range of -1.0 to 1.9 for the identical settings. The reverberation time obtained using sound -absorbing material is between 2.0 s and 4.4 s. The reverberation time is longer than it would be without sound-absorbing material.

Additionally, compared to other research conducted under the same ceiling material conditions [8], the obtained reverberation time is shorter. However, the reverberation time is more uniformly measured for each investigated condition. Table 4 provides more specific information about the simulation's findings.

The commonly used standard to determine the acoustic quality of a room is the reverberation time. The recommendations are typically at 1 kHz and are based on the volume of the room. The mosque in this study has a volume of 1545 m^3. As seen in Table 5, a comparison is then conducted based on the volume.

The reverberation times predicted by the simulation at various levels of mosque occupancy are longer than those predicted by earlier research and recommendations. Note that in the previous research, the mosque has a flat ceiling. The mosque in this simulation can convey the sense of being in a holy place because of its long reverberation time and good speech intelligibility. As a result, the mosque has good acoustics.

Table 3. Reverberation Time and C50 Values from various occupancy levels without absorbent material

Frequency [Hz]	Occupied row															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	C50 [dB]															
125	-3.6	-3.5	-3.4	-3.3	-3.3	-3.2	-3.2	-3.1	-3.1	-3.0	-2.9	-2.9	-2.9	-2.8	-2.7	-2.6
250	-8.0	-7.2	-6.5	-6.2	-5.8	-5.7	-5.4	-5.1	-4.9	-4.6	-4.4	-4.3	-4.0	-3.8	-3.5	-3.2
500	-8.8	-7.5	-6.4	-5.7	-5.3	-5.0	-4.6	-4.4	-4.1	-3.6	-3.4	-3.2	-2.9	-2.6	-2.3	-1.8
1000	-8.5	-7.0	-5.7	-5.0	-4.5	-4.3	-3.9	-3.7	-3.3	-2.9	-2.7	-2.4	-2.1	-1.7	-1.3	-0.9
2000	-6.3	-5.3	-4.4	-3.8	-3.5	-3.4	-3.1	-2.8	-2.5	-2.2	-1.9	-1.7	-1.3	-1.0	-0.8	-0.3
4000	-4.6	-3.7	-2.8	-2.4	-2.1	-2.2	-1.9	-1.6	-1.4	-1.0	-0.7	-0.6	-0.2	0.1	0.4	0.9
Frequency [Hz]	Reverberation time [s]															
125	2.5	2.5	2.5	2.7	2.8	2.5	2.6	2.8	2.5	2.5	2.6	2.6	2.6	2.9	2.6	2.6
250	3.9	3.7	3.6	3.5	3.5	3.5	3.5	3.5	3.6	3.6	3.7	3.8	3.7	3.8	3.9	4.1
500	4.1	3.8	3.5	3.4	3.3	3.4	3.3	3.3	3.6	3.5	3.4	3.6	3.7	3.6	3.7	3.7
1000	4.0	3.7	3.3	3.2	3.1	3.1	3.1	3.1	3.0	3.4	3.3	3.2	3.4	3.1	3.2	3.4
2000	3.3	3.0	2.7	2.6	2.3	2.5	2.3	2.4	2.4	2.4	2.3	2.5	2.5	2.2	2.3	2.4
4000	2.5	2.2	2.0	1.8	1.7	1.7	1.6	1.7	1.9	1.8	2.1	2.1	1.9	2.0	1.9	1.9

Table 4. Reverberation Time and C50 Values from various occupancy levels with absorbent material

Frequency [Hz]	Occupied row															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	C50 [dB]															
125	-1.4	-1.4	-1.3	-1.3	-1.2	-1.3	-1.3	-1.3	-1.2	-1.2	-1.2	-1.2	-1.1	-1.1	-1.0	-1.0
250	-1.9	-1.8	-1.6	-1.6	-1.6	-1.8	-1.7	-1.6	-1.7	-1.6	-1.6	-1.6	-1.5	-1.5	-1.4	-1.3
500	-1.6	-1.4	-1.2	-1.1	-1.2	-1.4	-1.3	-1.3	-1.2	-1.1	-1.2	-1.2	-1.1	-0.9	-0.9	-0.6
1000	-1.1	-0.7	-0.6	-0.5	-0.5	-0.8	-0.7	-0.7	-0.6	-0.7	-0.7	-0.6	-0.5	-0.3	-0.2	-0.1
2000	0.5	0.6	0.7	0.8	0.8	0.4	0.5	0.5	0.6	0.5	0.4	0.4	0.5	0.7	0.8	1.0
4000	1.4	1.5	1.6	1.6	1.7	1.4	1.4	1.3	1.4	1.2	1.1	1.2	1.3	1.4	1.6	1.9
Frequency [Hz]	Reverberation time [s]															
125	2.9	2.7	3.0	2.9	2.3	3.1	2.9	2.7	3.0	3.2	3.0	2.9	2.9	3.0	2.9	3.0
250	4.3	4.2	4.2	4.4	4.4	4.4	4.3	4.3	4.2	4.3	4.3	4.3	4.3	4.3	4.3	4.4
500	3.9	3.9	4.0	3.9	4.0	3.9	3.9	3.8	3.8	3.8	4.0	4.0	3.9	4.0	3.9	3.9
1000	3.6	3.5	3.7	3.7	3.3	3.4	3.6	3.6	3.6	3.4	3.7	3.6	3.5	3.5	3.6	3.6
2000	2.7	3.0	2.8	2.8	2.8	3.0	3.0	3.0	2.9	3.0	2.9	2.9	2.7	3.0	2.5	2.8
4000	2.1	2.5	2.2	2.2	2.2	2.3	2.3	2.1	2.1	2.2	2.0	2.3	2.2	2.0	2.2	2.2

Table 5. The comparison of the various occupancy levels' Reverberation Time and other recommendations and study

	Reverberation Time at 1 kHz [s]
Various occupancy level	3.3 – 3.7
Optimum condition unoccupied, from the previous study [8]	3.2
Optimum condition occupied, from the previous study [8]	1.8
Recommendation for worship hall [18]	1.6
Recommendation for mosque [19]	1.7

CONCLUSION

The assessment process of the cultural From this study, it can be concluded that the speech intelligibility value increases with an increase in the number of filled rows, both with and without sound-absorbing material. With absorbent material, speech intelligibility is significantly better than the one without it. On the other hand, the reverberation time is unaffected by the number of filled rows and is extended by using sound-absorbing materials.

Hence, in a mosque with pyramidal and no sound-absorbing ceiling material, optimal acoustic conditions are attained when the mosque is fully occupied. Meanwhile, using sound-absorbing materials on the mosque's ceiling establishes optimal acoustic conditions for all occupancy levels. This demonstrates that using sound-absorbing materials improves the acoustic quality of the mosque with pyramidal ceiling.

The mosque's primary acoustic feature is good speech intelligibility. On the other side, a long reverberation time is an essential aspect of establishing a sacred atmosphere. This study shows that good speech intelligibility can be attained with a competent acoustic design approach, even at a long reverberation time (exceeding the recommended time). Even with absorbent material on the ceiling, a significant reverberation time still exists. If a shorter reverberation time is needed, an absorbent material can be attached to the mosque's walls.

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