

Investigating the Impact of Environmental Noise, Humidity and Surface Treatment on Mosque Acoustic Performance in Makassar, Indonesia

Asniawaty Kusno¹, Nazli Bin Che Din^{2*}, Abdul Wafi Razali³, Baharuddin Hamzah¹, Nurul Jamala¹, Rosady Mulyadi¹, Edward Syarif¹ and Kusno Kamil⁴

¹Department of Architecture, Faculty of Engineering, Hasanuddin University, Gowa 92171, Indonesia.

²Department of Architecture, Faculty of Built Environment, Universiti Malaya Malaysia, 50603 Kuala Lumpur, Wilayah Persekutuan Kuala Lumpur.

³Department of Quantity Surveying, Faculty of Built Environment, Universiti Malaysia Sarawak, 94300, Kota Samarahan, Sarawak.

⁴Mechanical Engineering Department, Engineering Faculty, Universitas Muslim Indonesia, Makassar 90231, Indonesia.

*Corresponding author: nazlichedin@um.edu.my

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Abstract

Mosques serve as significant social venues where acoustic quality is paramount for enhancing speech intelligibility during prayers, sermons, and recitations. In contrast to performing venues, mosque acoustics necessitate a precise balance between reverberation for spiritual ambience and clarity for effective speech. However, in mosque architecture, acoustic considerations tend to be overlooked in the initial phases of architectural development. This study seeks to examine the impact of environmental noise, relative humidity, and surface treatments on the acoustic performance of two mosques in Makassar, Indonesia, namely the Mosque A and the Mosque B. The measurement of background noise levels (BN), reverberation time (RT), speech transmission index (STI), and sound pressure level (SPL) distribution was conducted through field measurement. The influence of different relative humidity levels and several surface treatment designs on essential parameters was conducted through acoustic simulation using ODEON room acoustic software. The findings indicated that both mosques displayed elevated background noise levels, primarily resulting from mechanical ventilation systems and traffic on nearby main roads. In both instances, RT measures are beyond recognised acoustic standards, suggesting acoustic conditions that could jeopardise speech intelligibility and comfort. Simulation analyses indicated that relative humidity profoundly affected RT, especially in the higher frequency ranges, while showing little effect on the STI and SPL distribution. The simultaneous use of wall and ceiling absorptive materials yielded the most substantial enhancements in acoustic performance, highlighting the significance of an integrated materials approach in mosque design.

1.0 INTRODUCTION

Historically, places of worship have served as significant social structures that embody a community's religious and spiritual beliefs. A mosque is a significant structure that exemplifies the practice of Islam and its principles (Sert & Karaman, 2021). The mosque reflects the essence or the fundamental core of Islamic architecture. It functions as a principal material emblem of faith.

The historical development of mosques in various regions has significantly influenced the fundamental aspects that characterise their architectural style and functional identity. These elements can be generically classified into essential and supplemental components. The fundamental components include the prayer hall, courtyard, prayer niche, and pulpit, which together form the primary spatial and liturgical structure of the mosque. Supplementary elements that augment both the aesthetic and functional dimensions of the mosque comprise the minaret, dome, ablution facilities, arcaded porch, enclosed area for the leader of congregational prayer or dignitaries, reading desk, assorted furniture, and the entrance gate (A. Q. Ahmed & Fethi, 2024). Diverse mosque types have developed in various regions, each shaped by local architectural characteristics and environmental conditions (Hoteit, 2015). Although fundamental components like arches, domes, minarets, and prayer niche are prevalent across the Muslim world, regional differences have resulted in unique forms (S. Ahmed, 2016).

Contemporary mosque design typically adheres to two primary trajectories: classical and modern. The classical approach conforms to the architectural lexicon of the "Classical Ottoman Mosque Era," distinguished by the replication and reworking of its established formal and spatial components. Conversely, the modern approach embodies a continuous quest for innovative and varied architectural forms within the mosque typology. Kalayci and Çeldk (2014) delineate four distinct stylistic tendencies in contemporary mosque design, particularly in the post-World War II context: (i) vernacular interpretations, (ii) revivalist or replicated styles, (iii) modern regionalist approaches, and (iv) modernist expressions.

Acoustic design is a crucial aspect of mosque architecture, considering the multifunctional role of mosques as public spaces that accommodate diverse worship related activities, each with specific acoustic needs (Khabiri et al., 2013). Sü and Caliskan (2013) emphasise that attaining superior sound quality in the primary prayer hall is a crucial criterion for mosques and other places of worship. The paramount significance of acoustic performance arises from the dependence on unambiguous aural transmission for religious activities, including recitation, prayer, and sermon presentation. Moreover, Ismail (2013) underscores that in modern mosque architecture, the clarity of voice has become increasingly important due to the broader range of activities often conducted within prayer halls, including Qur'anic recitation, religious lectures, and public addresses. Thus, guaranteeing superior acoustic conditions is essential for promoting the clarity and efficacy of both spoken discourse and recited liturgy, thereby enriching the whole spiritual experience.

Although acoustics play a vital part in mosque architecture, it is sometimes neglected during the preliminary phases of architectural planning in numerous modern instances. The attainment of ideal acoustic conditions is inherently connected to the spatial and material arrangement of the mosque's interior. Optimal acoustic performance is significantly influenced by elements like room geometry, surface treatments, and spatial interaction between the worshipper and the sound source. Reducing the distance between the audience and the sound source improves voice clarity and diminishes dependence on the ambient noise of the environment. Many modern mosques demonstrate inadequate acoustic conditions, mainly due to prolonged reverberation time and high background noise levels, which considerably hinder voice intelligibility and the overall hearing experience (Karabiber, 1999; Hammad, 1990).

Modern mosque design increasingly emphasises a comprehensive and interdisciplinary approach, focussing on sustainability, creative architectural forms, and comparative evaluations of current mosque typologies. Moreover, there is an increased emphasis on improving acoustics by strategically altering material characteristics, spatial configurations, and refurbishment methods. Alongside these initiatives, the

creation of extensive acoustic frameworks and design guidelines relevant to both physical and virtual mosque settings have become essential for ensuring that auditory performance meets the functional and spiritual requirements of worship spaces (Hossam Eldien et al., 2023)

Recent research highlights the need of integrating acoustic design into the architectural process, showing that this method leads to markedly enhanced results. Moreover, collaboration between architects and acousticians in the initial design phases can provide significant cost reductions by reducing the necessity for subsequent alterations, such as repositioning architectural components or modifying material requirements (Sü & Caliskan, 2013). The evaluation of speech audibility and intelligibility in mosques depends on various acoustic metrics often used in the assessment of speech-oriented auditoria. The characteristics encompass background noise level (BN), reverberation time (T60, T30), early decay time (EDT), clarity (C80), A-weighted sound pressure level (SPL-A), speech transmission index (STI), and articulation index (AI) (Hossam Eldien & Al Qahtani, 2012). Attaining superior acoustic quality is essential for both ensuring clarity in spoken communication and creating a serene and reflective atmosphere suitable for worship. Speech intelligibility is significantly affected by the extent of signal deterioration resulting from reverberation and ambient noise, which might obstruct the clarity and efficacy of verbal communication in sacred places (Azizah Adnan et al., 2018).

Background noise (BN) is a primary element that diminishes speech intelligibility in mosque surroundings. Effective oral communication necessitates that background noise levels adhere to particular limits appropriate for the building's use. Beranek (1989) indicates that the advisable noise criterion (NC) for religious environments is within the NC25–30 range, ensuring optimal conditions for speech intelligibility. Similarly, Knudsen and Harris (1950) emphasise the essential requirement for acoustic insulation in places of worship, asserting that interior background noise must not surpass 30 dB to maintain the holiness and clarity of religious practices.

Background noise in mosques generally results from two sources: ambient noise and mechanical ventilation systems. In mosques featuring open courtyards, the exposure to external noise disturbances is markedly elevated. Special attention must be given to the design of such structures to alleviate the delayed transmission of sound from loudspeakers set on minarets, as this can produce echoes and diminish speech intelligibility. Orfali (2009) underscores the necessity of meticulously positioning and directing the minaret sound systems to reduce sound reflections from adjacent structures and elevated terrains that could transmit undesirable sounds into the courtyard. In addition, Abdullah and Mohd Razali (2023) recognise traffic noise from nearby main highways as a primary source of environmental noise pollution in mosque environments, highlighting the imperative for strategic site selection and sound insulation.

Most modern mosque designs exhibit inadequate acoustic performance, primarily due to prolonged reverberation time and increased ambient noise. This shortcoming is sometimes ascribed to the widespread utilisation of hard and reflective materials, such as marble, tiles, and glass, which, despite their visual attractiveness and minimal upkeep, considerably enhance persistent reverberation (Karaman & Güzel, 2017). An increase in the overall volume of the prayer hall inevitably results in longer reverberation time, hence reducing both verbal intelligibility and acoustic clarity. Conversely, an excessively low reverberation time may create acoustic "dead" areas that detract from the immersive experience of spiritual rituals and impair the focus of worshippers (Orfali, 2009). To remedy these issues, passive acoustic parameters specifically reverberation time, sound clarity, and speech intelligibility should be prioritised in the first phases of mosque design. Furthermore, internal noise sources, including mechanical ventilation systems, must be meticulously assessed and acoustically attenuated to avert additional deterioration of the acoustic environment (Kaygısız et al., 2024). Recent research has disclosed preferences for reverberation time among worshippers, regardless of age or gender. A reverberation time of around 1.58 s is preferable for Qur'anic recitation, whereas 0.91 s is favoured for speech related activities. A compromise RT of 1.51 s is deemed acoustically balanced for facilitating both forms of use (Elkhateeb & Eldakdoky, 2022).

Acoustic parameters are affected by numerous aspects, including thermo-hygrometric factors, which correspond to the impact of temperature and relative humidity on sound propagation (Winkler-Skalna & Nowoświat, 2021). Studies indicate that an increase in temperature and humidity correlates with an extended reverberation time, however the degree of this variation differs among various frequency bands (Nowoświat, 2022). Specifically, reverberation time demonstrates a negative linear link with temperature in the higher frequency ranges (Granzotto et al., 2023). Gomez-Agustina et al. (2014) demonstrated that elevated high-frequency reverberation time correlate favourably with fluctuations in temperature and humidity, concurrently exerting a detrimental influence on speech-related acoustic metrics, including the speech transmission index (STI). This suggests that the climatic factors within a mosque specifically temperature and humidity can substantially affect acoustic performance, influencing speech intelligibility and overall sound quality.

This study aims to assess the acoustic performance of two mosques via field measurements, concentrating on key parameters including background noise (BN), reverberation time (RT), and speech transmission index (STI). A thorough analysis will be performed to evaluate the effects of elevated noise levels, relative humidity, and surface treatments on these acoustic parameters. Furthermore, simulation approaches will be utilised to model and examine the impact of these environmental and material elements on the overall acoustic performance of the mosques.

2.0 METHOD

2.1 Case Study

The acoustic performance evaluation measurements were carried out at two separate mosques in Makassar, Republic of Indonesia: Mosque A, located on the main campus of Hasanuddin University, and Mosque B, located in the city center and bordered by major roads on the eastern, southern and western sides of the building. Both mosques are constructed to facilitate congregational prayers and additional religious activities, including public lectures and Quran recitations. Mosque A, situated on elevated ground and encircled by verdant surroundings, benefits from a degree of isolation from traffic noise owing to its distance from primary roadways. Conversely, Mosque B is situated next to a major road, rendering it more susceptible to noise from vehicles. The precise geographical coordinates of the two case study sites are illustrated in Figure 1.



Figure 1. Satellite-mapped location of (a) Mosque A and (b) Mosque B.
(Source: google earth, 2025)

The Mosque B, designed by architect Muhammad Soebardjo, was originally constructed between 1948 and 1949, drawing inspiration from the fuselage of a B-29 bomber aircraft. A significant refurbishment commenced in 1999 and concluded in 2005, yielding a two-story edifice capable of housing up to 10,000 congregants. The design integrated Mediterranean and Middle Eastern architectural inspirations with an emphasis on natural ventilation, and an open layout that replaces traditional walls with steel columns encased in natural stone. This architectural strategy is congruent with Makassar's tropical environment, promoting thermal comfort and enriching the worship experience.

Table 1. Surface materials of selected mosques.

Surface material	Mosque A	Mosque B
Floor	Carpet & Marble	Marble
Ceiling	Plasterboard	Suspended perforated gypsum
Wall	Plastered brick wall	NA
Window	Casement glass	NA
Door	Sliding glass	NA

2.2 Field Measurement

An on-site evaluation of the acoustic performance was performed in Mosque A on the morning of August 16, 2024, and at Mosque B on August 17, 2024. During the examination at Mosque A, all doors and windows were securely closed and public access to the main prayer hall was temporarily prohibited to reduce external disturbances. The evaluation of Mosque B was conducted in accordance with its standard open-courtyard architectural plan. While outside activities did not disrupt the measurements, ambient noise from adjacent vehicles was evident during the assessment.

Background noise (BN)

Background noise levels were evaluated by measuring the continuous equivalent sound levels (LAeq) in two scenarios: (a) with the HVAC system operational and (b) with the HVAC system inoperative. Before measurement, all windows and doors in Mosque A were firmly closed to establish a controlled acoustic environment. Measurements were performed at 33 receiver positions within Mosque A and 30 receiver points in the comparable area, as depicted in Figure 2. The data were recorded at each designated position for a duration of two minutes, with recordings taken at one-second intervals. The Cirrus CR:171B sound level (SLM) meter was positioned 1.2 meters above floor level. The average A-weighted sound pressure level was calculated over the frequency range of 63 Hz to 8000 Hz.

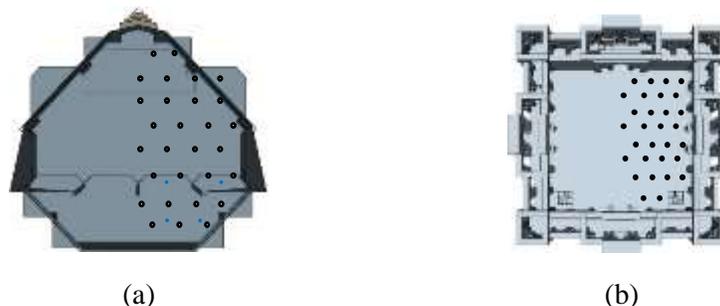


Figure 2. Receiver' points of BN measurement for (a) Mosque A and (b) Mosque B.

Reverberation Time (RT) and Speech Transmission Index (STI)

Reverberation time (RT) measurements were performed with an omnidirectional dodecahedron loudspeaker. The excitation signal was transmitted using a Crown XLS1000 amplifier. A GRAS 46AE ½" measuring microphone was placed 1.2 metres from floor level to record the acoustic response. The GRAS 46AE ½" microphone was linked to an audio interface (Focusrite Scarlett 2i4) for signal capture. The calculation of RT was conducted with ODEON Room Acoustics Software, version 17. Both RT and STI were measured at the identical position as the BN assessment. Figure 3 illustrates a schematic illustration of the measuring setup.

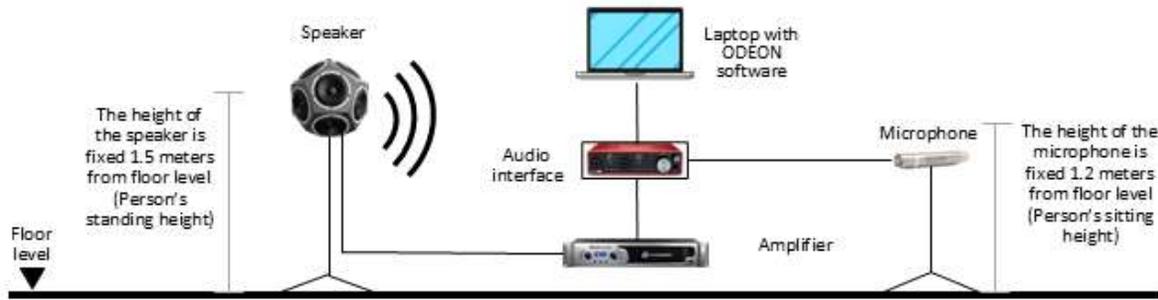


Figure 3. Schematic drawing of RT and STI measurement arrangements.

Sound Pressure Level (SPL)

In the prayer leader's designated area, a BOSE speaker was positioned 1.6 metres above the floor. The Minirator MR2 signal generator was connected to the Crown XLS1000 audio amplifier, which produced a pink noise output. All receiver locations enabled the recording and examination of the sound signal using the Cirrus SLM. Figure 4 illustrates the arrangement of the equipment dedicated to the SPL measurement.

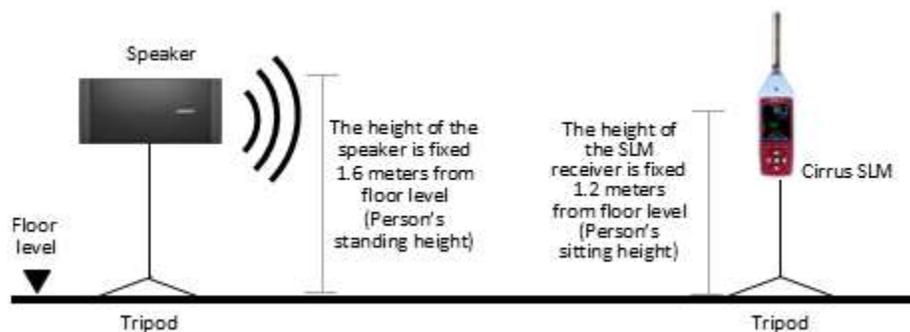


Figure 4. Schematic drawing of SPL measurement arrangements.

2.3 Acoustic Simulation

Using Sketchup Pro® software for acoustic modelling, the 3D model of Mosque A was developed, as shown in Figure 5. The measurements utilised in the model creation were precisely acquired at the physical site. Precisely calculating the surface area is essential to reduce errors in the model throughout the process of validation. Jalil et al. (2019) states that a maximum reduction for surface materials up to 80% is allowable during the 3D model verification process. Factors include model configurations and modelling techniques, as well as material absorption and scattering coefficients, which may fluctuate the extent of reduction.



Figure 5. Mosque A 3D model perspectives (a) ISO and (b) section view.

Validating the acoustic parameters of the 3D model using ODEON Room Acoustic Software version 18 to ensure they correspond with the existing room environment is crucial before commencing the simulation work. It is important to ensure the suitability as well as effectiveness of every material used on each surface to obtain the required results. The selection of sound source types and positions, as well as the placement of microphone receivers, should be arranged in accordance with the field measurement configuration. A preliminary RT estimation must be conducted to identify the ideal impulse response length for calculation of RT during the model verification. The evaluation of STI must include the addition of background noise acquired during field measurements. Before initiating the simulation, the minimum recommendation of just noticeable difference (JND) for relative difference, which includes RT, SPL, and STI, must be achieved. Due to the equipment limitation for field measurement, the verification process excludes the speech clarity (C50) parameter.

The simulation explores the influence of relative humidity on acoustic parameters, in particular RT. Three various relative humidities were assessed: 65%, 75%, and 85%. The relative humidity values were calculated by approximating the mean of the minimum, average, and maximum measurements taken throughout the city of Makassar, Republic of Indonesia (Bikos, n.d.).

The simulation also encompasses the assessment of the impact of surface design treatment in the absence of floor carpeting. This seeks to assess the feasibility of omitting carpets to minimise maintenance efforts and maintain hygienic standards. Four (4) surface treatment strategies, namely Alt-1, Alt-2, Alt-3 and Alt-4, were proposed. Table 2 shows the details of surface treatment for each proposed strategy. The detailed sound absorption coefficient for each proposed material is presented in Table 3.

Table 2. Detailed surface area treatment for each design strategy.

Design Strategies	Surface area treatment	Surface area (m ²)	Proposed material	Absorption coefficient (α)
Alt-1	Wall	193	Low frequency fabric with perforated hard surface panel	0.2
Alt-2	Floor	1072	10mm soft carpet on concrete	0.25
Alt-3	Ceiling	539	Perforated gypsum board with white non-woven fabric backside + 25mm glass wool	0.5
Alt-4	Wall and Ceiling	732	Low frequency fabric with perforated hard surface panel & Perforated gypsum board with white non-woven fabric backside + 25mm glass wool	0.2 & 0.5

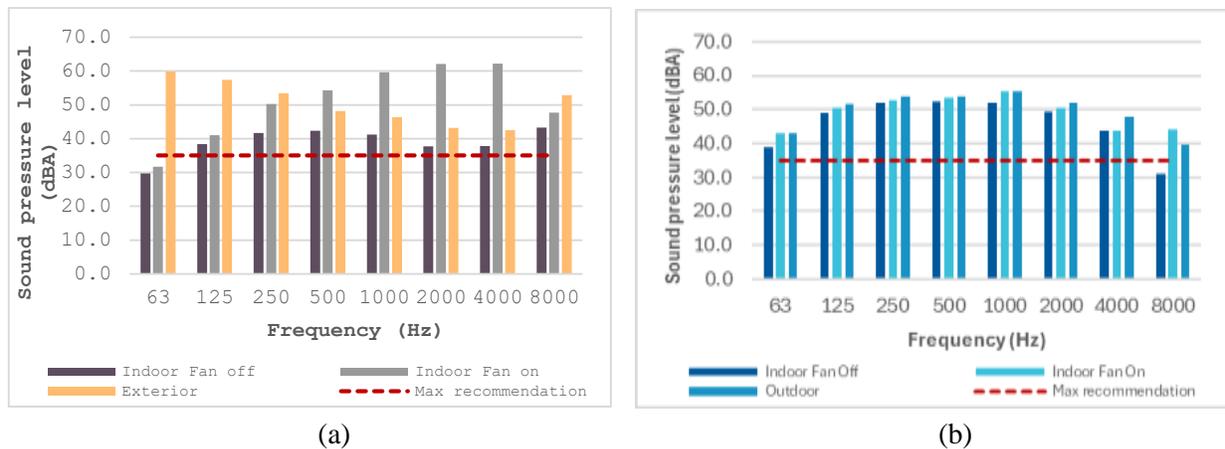
Table 3. Sound absorption coefficient detail of proposed materials.

Surface material	Frequency (Hz)					
	125	250	500	1000	2000	4000
Low frequency fabric with perforated hard surface panel	0.98	0.88	0.52	0.21	0.16	0.14
10mm soft carpet on concrete	0.09	0.08	0.21	0.27	0.37	0.37
Perforated gypsum board with white non-woven fabric backside + 25mm glass wool	0.45	0.50	0.55	0.50	0.40	0.45

3.0 RESULTS AND DISCUSSIONS

3.1 Field Measurement

Background Noise (BN)

**Figure 6.** Background noise recorded at (a) Mosque A and (b) Mosque B.

Background noise levels were assessed at two mosques in Makassar, Indonesia, Mosque A and Mosque B under three operational conditions: fan activated, fan deactivated, and external ambient noise. The results indicate significant differences due to mechanical systems and architectural-environmental context as depicted in Figures 6a and 6b.

The Mosque A, located away from the primary road and enveloped by planted natural features, recorded a background noise level of 48.9 dBA with the fan turned off, signifying a comparatively pleasant baseline acoustic setting. When the fan was operational, the background noise level rose substantially to 66.2 dBA, indicating that the fan system contributes around 17.3 dBA to the noise within. This notable increase indicates either an acoustically inefficient mechanical ventilation system or inadequate isolation of mechanical noise. According to the findings, the measured exterior noise level was 64.6 dBA, which may be attributed to design elements such as open ventilation systems or the noise from traffic on the adjacent road.

In contrast, Mosque B, characterised by an open-concept architecture lacking confining walls and situated next to a congested major road, demonstrated consistently elevated ambient noise levels under all situations. When the fan was switched off, the background noise recorded at 58.0 dBA, however the fan's operation resulted in a slight elevation to 59.8 dBA. Exterior noise levels were recorded at 60.9 dBA, indicating the influence of persistent road activity and exposure resulting from the open architectural design.

The small variance of 1.8 dBA between fan-on and fan-off settings indicates that mechanical noise is acoustically masked by surrounding external noise sources.

The evaluation highlights the substantial impact of environmental setting and architectural design on the acoustic environment of places of worship. The Mosque A advantages from its position and enclosed space regarding baseline quietness, although it suffers from internal mechanical noise. The open design of Mosque B and its proximity to traffic lead to consistently high and stable noise levels, irrespective of the utilisation of mechanical ventilation systems.

Reverberation Time (RT)

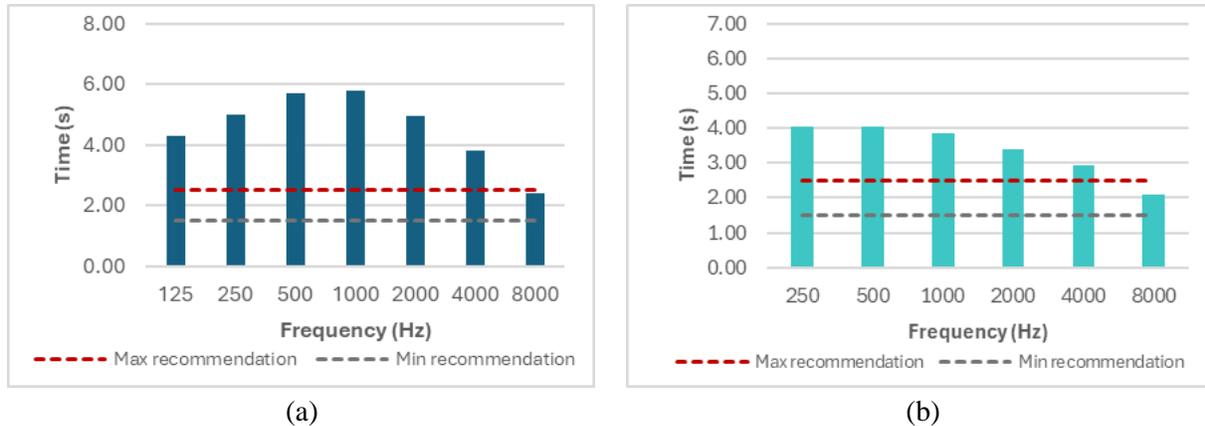


Figure 7. Reverberation time results of (a) Mosque A and (b) Mosque B.

The Mosque A demonstrated an average RT of 4.56 s, reflecting a highly reverberant environment which presented in Figure 7a. This extended reverberation results from the architectural design and the prevalence of hard, reflective surfaces in the interior. Materials including ceramic tile flooring, plastered brick walls, plasterboard ceilings, and large glass features (slide doors and windows) exhibit minimal sound absorption, hence facilitating continuous sound reflections. The prolonged RT in this instance is likely to impair voice intelligibility, a crucial element during prayers and sermons where clarity of verbal communication is vital.

Figure 7b shows the RT results for Mosque B. Conversely, the Mosque B exhibited a reduced average RT of 3.39 s, which, although still beyond the optimal range for communication (often 1.5 - 2.5 s for places of worship), signifies a marked enhancement compared to Mosque A. The diminished reverberation is due to the use of perforated gypsum ceiling panels, which offer better sound absorption relative to plasterboard. The mosque's open-air architectural design, without enclosing walls, facilitates natural sound dispersion and minimises internal sound reflections. The ceramic tile flooring, meanwhile, maintains a reflecting surface, constraining additional reduction of reverberation.

These findings underline the major influence of interior surface treatments and spatial containment on RT. The longer reverberation observed at Mosque A indicates a necessity for acoustic treatment measures, such as the incorporation of absorbing surfaces on walls or ceilings, to improve speech intelligibility. Mosque B, while physically open and acoustically absorbent, could still improve through selective material optimisation to meet the specified acoustical criteria for worship areas.

Speech Transmission Index (STI)

The average STI measured at Mosque A across 33 locations were 0.36, defining it as "poor" intelligibility according to ISO 9921 and IEC 60268-16 standards. According to Figure 8a, out of the 33

measurement points, 29 were designated poor, while only 4 were assessed as fair. The poor performance corresponds with the previously noted longer RT (4.56 s) and excessive background noise during fan operation (66.2 dBA). The extensive adoption of reflecting materials and inadequate absorption surfaces worsen a decline of speech intelligibility. Under these circumstances, spoken prayers, sermons, and call-to-prayer recitations are likely to have diminished comprehensibility, especially in regions distant from the loudspeaker position.

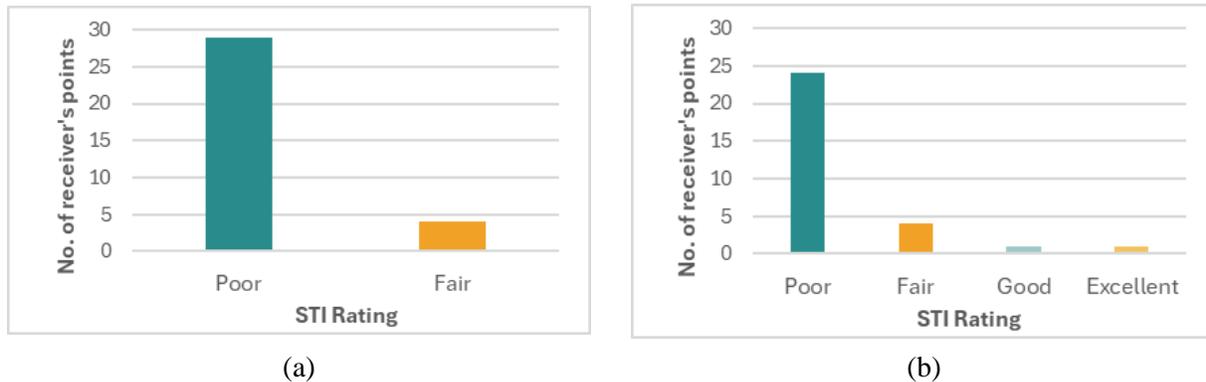


Figure 8. Speech transmission index rating of (a) Mosque A and (b) Mosque B.

The Mosque B had a moderately better STI pattern, with an average STI of roughly 0.41 across 30 assessed locations as illustrated in Figure 8b. This average, while still below optimal recommendation, is slightly higher than that of Mosque A. 24 points were assessed as poor, four as fair, one as good, and one as excellent. The fluctuation in ratings can be associated with the open architectural design, which mitigates RT of 3.39s, especially in areas subjected to open air and direct sound pathways. The utilisation of perforated gypsum ceiling panels seems to moderately improve speech clarity. Nevertheless, elevated ambient noise from nearby road activity with average external noise of 60.9dBA remains a significant obstacle to attaining consistent intelligibility.

Both mosques primarily belong to the "poor" STI category, implying a necessity for targeted acoustic improvements. In Mosque A, the emphasis must be on diminishing reverberation by absorptive finishes and mitigating mechanical noise. To improve intelligibility at Mosque B, minimising traffic noise with landscaping, partial barriers, or selective wall improvements may be effective, especially in the surrounding areas.

Sound Pressure Level (SPL)

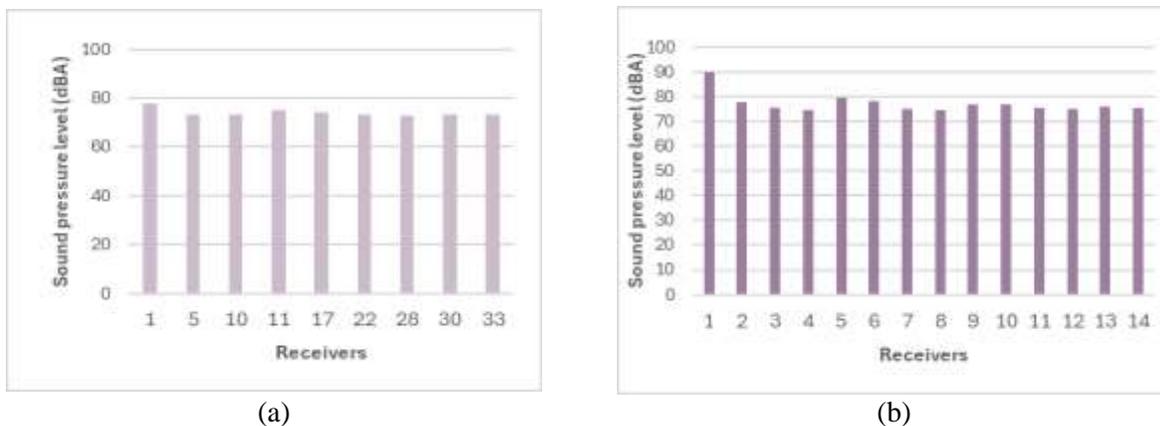


Figure 9. Sound pressure level distribution of (a) Mosque A and (b) Mosque B.

Figures 9a and 9b show the SPL distribution results for both Mosque. SPL measurements at Mosque A were conducted at 9 separate locations, resulting in values between 72.9 dBA and 78.0 dBA, with a mean SPL of 74.1 dBA. The relatively modest range of 5.1 dBA implies a relatively uniform sound field, implying that the mosque's enclosed architecture and internal geometry facilitate a more consistent sound distribution throughout the prayer space. Nevertheless, the comparatively longer RT of 4.56 s may obscure part of this consistency by mixing direct sound energy with excessive reflections. Although the SPL coverage seems adequate in amplitude, it does not guarantee intelligibility, as seen by the mosque's low average STI of 0.36. This indicates that while loudness is uniform, clarity is diminished due to excessive reverberation and interference from background noise.

The Mosque B demonstrated a wider SPL range, with recorded values spanning from 74.6 dBA to 89.9 dBA across 14 locations, yielding a higher overall average SPL. The 15.3 dBA fluctuation throughout the area indicates a notable variance in sound level distribution. This is probably attributable to the mosque's open architectural design, which lacks sound-reflective walls essential for uniform acoustic distribution. The peak value of 89.9 dBA may indicate localised amplification around the sound source. This gap may lead to excessive amplification in nearby zones and suboptimal functioning in distant location, correlating with the varied STI outcomes, ranging from poor to excellent ratings.

3.2 Acoustic Simulation

a) 3D Model Verification

The 3D model verification process involved an assessment of STI, RT, and SPL based on simulation and field measurement results. A maximum of 5% and 0.03 relative difference is the practical recommendation of subjective limen for RT and STI parameters (Christensen & Koutsouris, 2013). Bistafa and Bradley (2000) stated that the 10% of maximum relative difference for RT is more suitable in the engineering approach. For SPL spatial decay, a maximum of 3 dB(A) for relative difference is recommended by Wang and Bradley (2002). The comparison of field measurements and simulation results for average RT was conducted within the frequency range of 125 Hz to 8000 Hz. Additionally, SPL and STI results were examined at various positions. As illustrated in Table 4, all parameters manage to achieve the recommended JND criteria during the verification process.

Table 4. Just noticeable difference (JND) of RT, STI and SPL.

Parameter	Measured (On-site)	Simulation	Just noticeable difference (JND)	Recommended JND
Reverberation time	4.56s	4.55s	0.1%	> 10%
Speech transmission index	0.36	0.34	0.02	> 0.03
Sound pressure level	74.1dBA	76.1dBA	2dBA	> 3dBA

b) Relative Humidity

The impact of relative humidity on the acoustic properties of Mosque A demonstrates a varied yet acoustically essential trend in reverberation time (RT), especially within the higher frequency range. Measurements conducted at three specific relative humidity (RH) levels 65%, 75%, and 85% exhibit a gradual increase in average RT from 4.54 s at 65% RH to 4.57 s at 75% RH, and subsequently to 4.60 s at 85% RH. Figure 10a depicts the maximum differences of RT simulated in three (3) different RH. The results indicate that the highest maximum differences observed were in frequency 4000 Hz and 8000 Hz with a value of 0.19 and 0.3 s respectively. Although the overall alteration in average RT seems minimal with an increase of 0.06 s, the effect becomes more significant when the result is examined by frequency bands.

The most significant variances occur around 4000 Hz and 8000 Hz. At 4000 Hz, RT values increase by approximately 3% and 4% as RH escalates from 65% to 75% and 85%, respectively. Moreover, RT at 8000 Hz rises by 8% and 14% with equivalent increments in humidity.

These findings were similar to the previous research conducted by (Gomez-Agustina et al., 2014). The study revealed that the RT on the platform is affected by changes in humidity for octave frequency ranges exceeding 1 kHz. Beyond this threshold, RT consistently increases with greater humidity levels, with the most significant effects observed in the higher frequency bands of 4 kHz and 8 kHz. Furthermore, variability in RT measurements, attributed to fluctuations in temperature and relative humidity, can be substantial for acoustics in spaces with moderate to low acoustic absorption (Winkler-Skalna, 2025). The standard ISO 9613-1 (1993), addresses the influence of air absorption on sound wave propagation and facilitates a direct relationship with temperature, relative humidity, and static pressure. In addition, (ISO 354, 2003) standard indicates that variations in temperature and relative humidity during measurement can significantly impact the recorded RT, particularly at higher frequencies and low relative humidity levels.

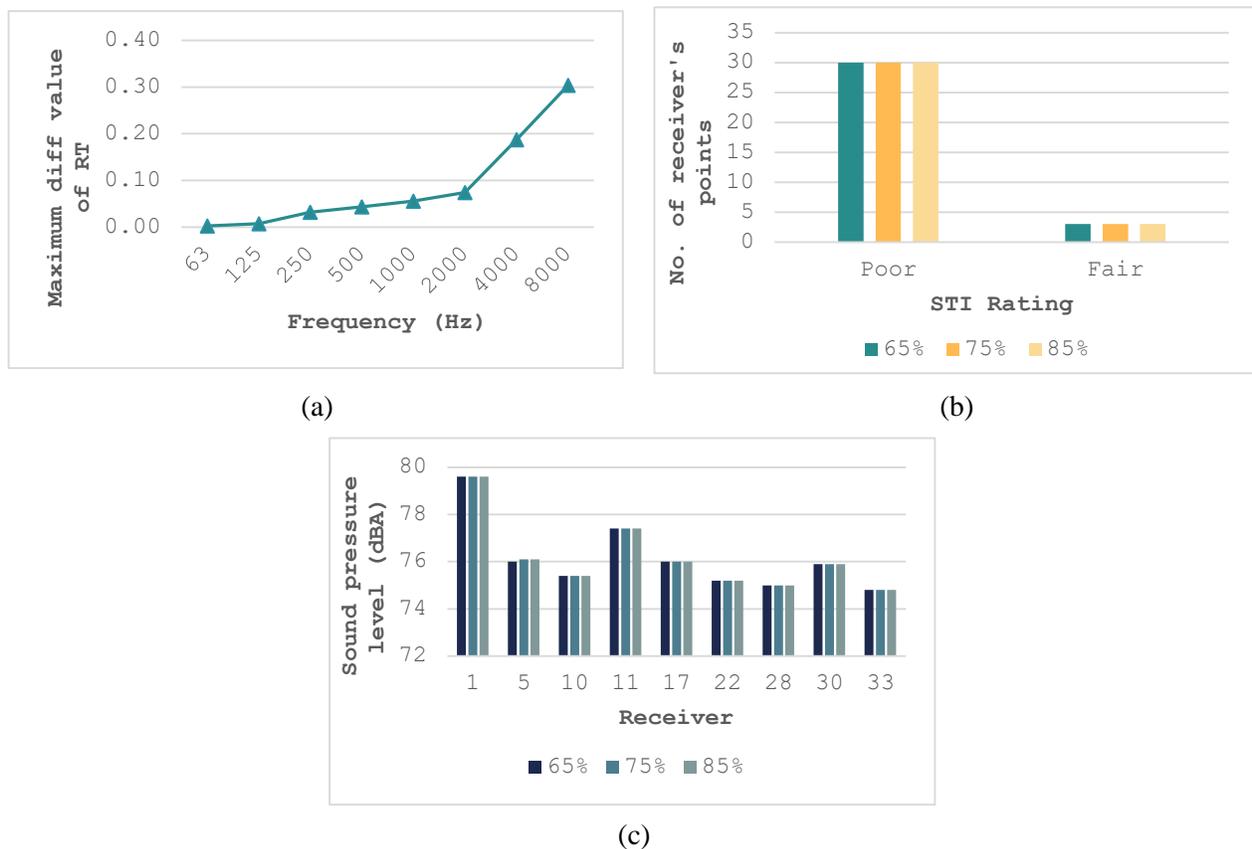


Figure 10. The impact of relative humidity on a) RT, b) STI and c) SPL for Mosque A.

The variability in RT at varying relative humidity levels contrasted with the measurements of STI and SPL distribution in Mosque A, which showed no significant change as humidity increased from 65% to 85% as depicted in Figures 10b and 10c. This stability, nevertheless, seemingly insignificant, provides important insights into the distinctive ways through which environmental elements interact with various acoustic parameters and explains the relative receptivity of each parameter to atmospheric conditions. STI integrates elements of modulation transfer, ambient noise, and reverberation within a comprehensive framework. A comprehensive investigation indicates that the STI is profoundly influenced by RT and the speech-to-noise ratio (SNR), as evidenced by Kang et al. (2023). However, Leccese et al. (2018) suggest that a minimal

reduction of 0.1 s in RT does not lead to a significant improvement in STI. While high frequency reverberation exhibited a slight increase with humidity, particularly at frequencies of 4000 Hz and 8000 Hz, the 0.06s increase in RT was insufficient to significantly impact the speech signals in a manner that would decrease the STI rating.

c) Surface Treatment

The untreated condition of Mosque A exhibited an average RT of 4.56 s, significantly exceeding the acceptable standards for speech-oriented environments. Significant decreases in RT were seen following the use of surface treatments as presented in Figure 11a. The wall treatment alone (Alt-1) achieved a moderate reduction in RT to 3.72 s, indicating some absorption of mid-to-high frequency energy along the vertical surfaces. Alt-2, which involved the installation of carpets on the floor, resulted in a further decrease to 2.89 s. The substantial impact is likely attributable to the carpet's elevated absorption coefficients, especially in mid-frequency ranges essential for speech intelligibility.

The ceiling treatment (Alt-3) revealed the most notable individual effect, decreasing the RT to 2.37 s. This outcome highlights the ceiling's function as a primary reflective surface in extensive areas, especially in typical of mosque architecture, where ceiling reflections significantly enhance late sound signal. The optimal configuration, Alt-4, integrated wall and ceiling treatments, resulting in a RT of 2.06 s, below the permissible acoustic standards for clarity in speech-centric environments. As stated by Abdullah and Mohd Razali (2023), numerous factors may affect the mosque's RT, including absorptive materials, geometry, dome dimensions, speaker placement, and the architectural style of the mosques. The usage of better absorptive materials as a replacement to reflective materials is encouraged. According to Kavraz (2016) wood cladding would lead to a decrease in RT values at low frequencies when substituting the plaster covering on wall surfaces.

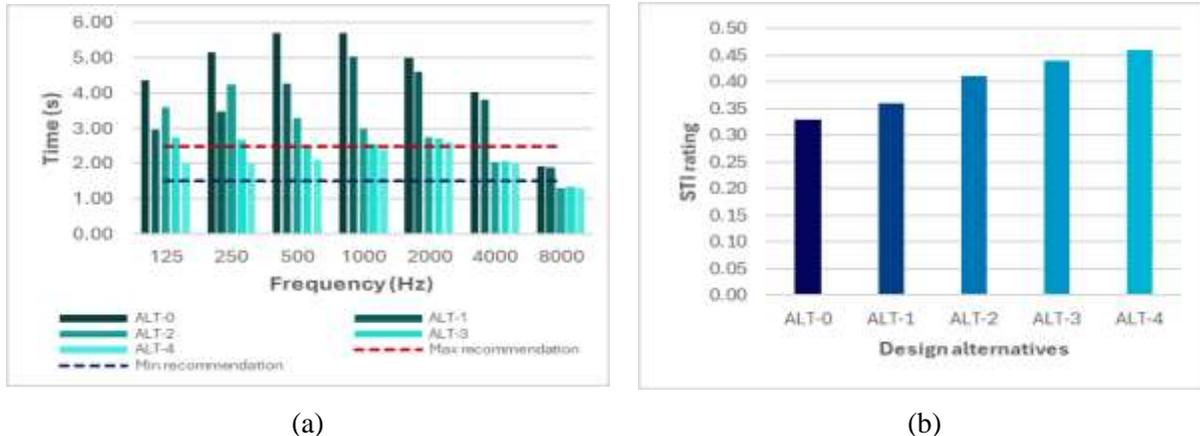


Figure 11. Surface area treatment impact on (a) RT, and (b) STI of Mosque A.

Speech intelligibility, measured by STI, steadily enhanced throughout the four treatment configurations as shown in Figure 11b. The baseline STI of 0.33, categorised as "poor," verifies the significant reverberation in the untreated area. Post-treatment, STI enhanced to 0.36 (Alt-1), 0.41 (Alt-2), 0.44 (Alt-3), and 0.46 in Alt-4. This pattern reflects the associated decreases in RT and signifies a direct correlation between reverberation reduction and speech intelligibility. The highest STI scores were attained with combination ceiling-wall (Alt-4) treatments, underscoring the need of addressing prominent reflective surfaces to improve speech intelligibility. Despite the STI values remaining beneath the optimal threshold of 0.6, often indicative of "good" intelligibility, the transition from "poor" to "fair" ratings in Alt-4 signifies

a significant acoustic enhancement. Finding by Karaman and Güzel (2017) revealed that to enhance speech intelligibility, the reverberant sound can be minimised in relation to the useful direct sound, particularly through the installation of sound-absorptive materials in the last prayer portion of the mosque. As RT increases, high reverberation may impair speech intelligibility by overlapping consecutive syllables and diminishing temporal resolution. This is due to the substantial impact of reverberation on the STI, when reverberation levels increase, the STI declines correspondingly (Leccese et al., 2018). Consequently, regulating RT is crucial for enhancing speech intelligibility in these environments.

Figure 12a and 12b depict the SPL distribution between the untreated and surface treatment Alt-4 in Mosque A. The untreated mosque had an average sound pressure level of 76.1 dBA at the measured locations. Following treatment, SPL values marginally declined to 74.3 dBA (Alt-2), 74.1 dBA (Alt-3), and 73.8 dBA (Alt-4), while Alt-1 persisted at 76.1 dBA. The little decreases in SPL align with the acoustic control provided by absorbent materials, which diminish the formation of reflected energy in the environment. Floor and ceiling treatments, specifically, mitigated overall loudness levels and possibly facilitated a more uniform distribution of sound energy throughout the mosque. The slight reductions in SPL indicate a beneficial decrease in perceived loudness and a potential enhancement in acoustic comfort for congregants.

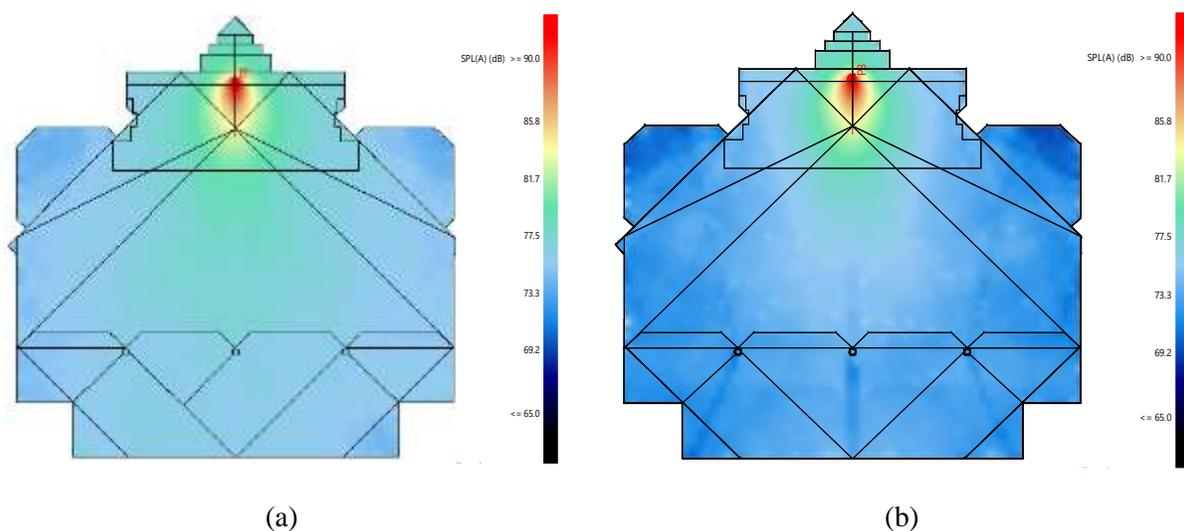


Figure 12. SPL grid mapping of (a) untreated and (b) treatment ALT-4 for Mosque A.

4.0 CONCLUSIONS

The results indicated that architectural design and environmental impact significantly affected the acoustic properties of both mosques. Mosque A, situated within a natural landscape and distanced from primary main roads, demonstrated markedly reduced background noise levels when mechanical systems were inactive (48.9 dBA). In contrast, Mosque B, characterised by its open-plan architecture and proximity to a major roadway, exhibited persistently higher noise levels under all circumstances.

The RT in both mosques surpassed the recommended limits for speech-oriented environments, with Mosque A measuring 4.56 s and Mosque B 3.39 s. The extended RT in Mosque A is attributed to the prevalence of solid, reflective materials including ceramic tiles, plaster, and glass. The STI values in both mosques predominantly fell into the "poor" category with regard to all measured points, signifying impaired speech intelligibility. Mosque B demonstrated modestly higher STI ratings probably because to its open

design and utilisation of perforated ceiling panels, yet both environments did not satisfy the recommended acoustic requirements.

Mosque A had an average sound pressure level of 74.1 dBA, while Mosque B demonstrated greater variability, with peaks reaching 89.9 dBA, likely attributable to external noise interference and the lack of sound-dampening barriers. At Mosque A, the impact of relative humidity on RT was minimal overall but more significant at higher frequencies, with RT increasing by up to 14% at 8000 Hz as humidity increased from 65% to 85%. These modifications, however, did not substantially influence STI or SPL, indicating that humidity predominantly affects RT at high-frequency spectrum without modifying overall intelligibility or amplitude.

The implementation of surface treatments in Mosque A resulted in significant acoustic improvements. The systematic application of wall, floor, and ceiling treatments reduced RT from 4.56 to 2.06 s and improved STI from 0.36 to 0.46, elevating intelligibility ratings from "poor" to "fair." The SPL levels exhibited a minor reduction, indicating enhanced sound absorption and a more stabilised sound field. Single ceiling treatment and combination of ceiling and wall treatments proved notably efficient, highlighting the significance of addressing predominant reflective surfaces in large worship environments. The findings underline the essential influence of design, materiality, and environmental setting on mosque acoustics. The importance of integrating certain acoustic treatments and contextual factors to improve the acoustic experience in worship environments are also emphasised. Future design and retrofitting initiatives must prioritise absorptive ceiling and wall finishes, particularly in enclosed high-traffic areas, to ensure clarity, comfort, and inclusion for all.

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