 https://doi.org/10.1051/e3sconf/202567405008

Acoustic Performance Comparison Between the Historic Traditional and Contemporary Forms of Tropical Mosques

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Abstract. Mosques serve not only as places for worship but also reflect unique acoustic properties influenced by their architectural design and materials. This study aims to compare the acoustic features of traditional mosque architecture with those of contemporary designs, examining how spatial shape and materials influence the sound environment. The research was conducted in the Sunan Ampel Great Mosque in Surabaya, Indonesia, as a case study. As the oldest mosque in Indonesia, built in 1421, it showcases traditional Javanese architecture. This mosque has undergone multiple expansions, resulting in four distinct architectural styles, making it an ideal subject for this study. The methodology involved field measurements using the impulse response technique, employing Room EQ Wizard software, an omnidirectional microphone, and a sound level meter. Findings indicate that the area with a contemporary design and flat roof has the most uniform sound pressure level (SPL) distribution compared to other sections. Additionally, the contemporary dome-roofed area has the longest reverberation time (RT). Overall, the contemporary design featuring a smaller pyramidal roof has the best acoustic quality. Meanwhile, the old building area with a pyramidal roof performs moderately overall, better than the dome-roof zone but not as balanced as the smaller pyramidal-roof area. These findings highlight the role of traditional design in shaping the acoustic character of sacred spaces of historical mosques, as well as guide the design of contemporary religious architecture.

1 Introduction

Mosques, as places of worship, rely heavily on sound, where clear speech, Qur'anic recitation, and group prayers play a crucial role in the spiritual experience of the attendees. Unlike traditional speech rooms, mosques have unique acoustic needs because of their large size and special architectural characteristics. The acoustic environment in mosques serves not only a practical purpose in transmitting speech but also plays a significant emotional and spiritual role in linking worshippers to their rituals [1].

Studies of traditional mosques reveal that architectural features, such as domes, vaults, and mihrabs, significantly impact the perception of time, sound Clarity, and the spatial

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distribution of voices. For example, investigations into Indonesian traditional mosque, the Yogyakarta Grand Mosque, which, with a pyramidal roof and wood as the primary building material, can achieve a good quality of room acoustics [2]. Moreover, the wooden material can also enhance speech intelligibility, as seen in the Sultanahmet Mosque in Turkey [3].

In contrast, contemporary mosques, often designed with minimalist aesthetics and contemporary materials, frequently encounter challenges in achieving ideal acoustic conditions, especially regarding excessive reverberation and diminished speech intelligibility. It also happens in an Indonesian mosque. The use of materials in a mosque may cause a high reverberation time, exceeding the recommended value for a mosque. For example, the Pusdai Mosque in West Java [4], the Makasar Great Mosque [5], and the Baiturrahman Great Mosque in Aceh [6].

Case studies from Southeast Asia indicate that newly built mosques in Indonesia and Malaysia often need acoustic adjustments to resolve problems like extended reverberation and poor clarity indices [7]. These results highlight a growing disparity between the sound-sensitive design principles of historic mosques and the acoustic limitations prevalent in many modern examples. Some previous researches on mosque acoustics study the effects of different ceiling structures and plan typologies on acoustical conditions of historical mosques, none of them directly compares the traditional and contemporary forms of a mosque.

Compared to previous studies on mosque acoustics, this research is more comprehensive as it examines a building that integrates both traditional and contemporary design elements. Few studies have directly compared these two design approaches. Therefore, this paper contributes to the growing body of research on mosque acoustics by providing a direct comparison of the acoustic performance between traditional and contemporary mosque designs. Using established acoustic metrics such as sound pressure level, reverberation time, and clarity [8], the study aims to identify the acoustic characteristics of each type. Through this comparison, the research aims to draw lessons from traditional mosque architecture that can guide future design standards, ensuring that contemporary forms of mosques meet both the functional and spiritual needs of worshippers.

2 Methodology

This study compares the room-acoustic performance of a traditional and a contemporary mosque form using in-situ measurements to determine sound pressure level (SPL), background noise, reverberation time (RT), Clarity (C50, C80), and definition (D50). The case study of this research is the Sunan Ampel Great Mosque in Surabaya, Indonesia. The reason for choosing this mosque as the case study was that it is the oldest mosque in Indonesia, built in 1421, which incorporates traditional Javanese architecture and has undergone some extension and renovation. The renovation has never touched the original traditional mosque. The new building parts were constructed adjacent to the original ones, incorporating contemporary design elements: a flat roof, a combination of flat and smaller pyramidal roofs, a dome roof, and concrete materials (Figure 1). Therefore, this mosque now features four distinct architectural design forms, making it an ideal case study.

2.1 The Case Study (Sunan Ampel Great Mosque)

The Sunan Ampel Great Mosque is in Surabaya, East Java, Indonesia. The initial construction of the Sunan Ampel Mosque was completed in 1421, featuring a square floor plan and a two-tiered roof supported by 16 wooden pillars (*saka*). This architectural form reflects traditional Javanese building design. During its development, the main mosque building underwent the addition of a space in the form of a porch on the west, east, south, and north sides (1954).

This addition of space was influenced by colonialism and modernity. The building's form is simple, without ornamentation, featuring a flat roof with a combination of several small pyramidal forms and monochrome colors. In 1972, the mosque was expanded to the southwest. This new building adapted the design of the old building, yet utilized modern construction technology, incorporating concrete materials and a steel roof frame. The shape of the dome roof conceals the pyramidal-type roof visible from the outside [9].

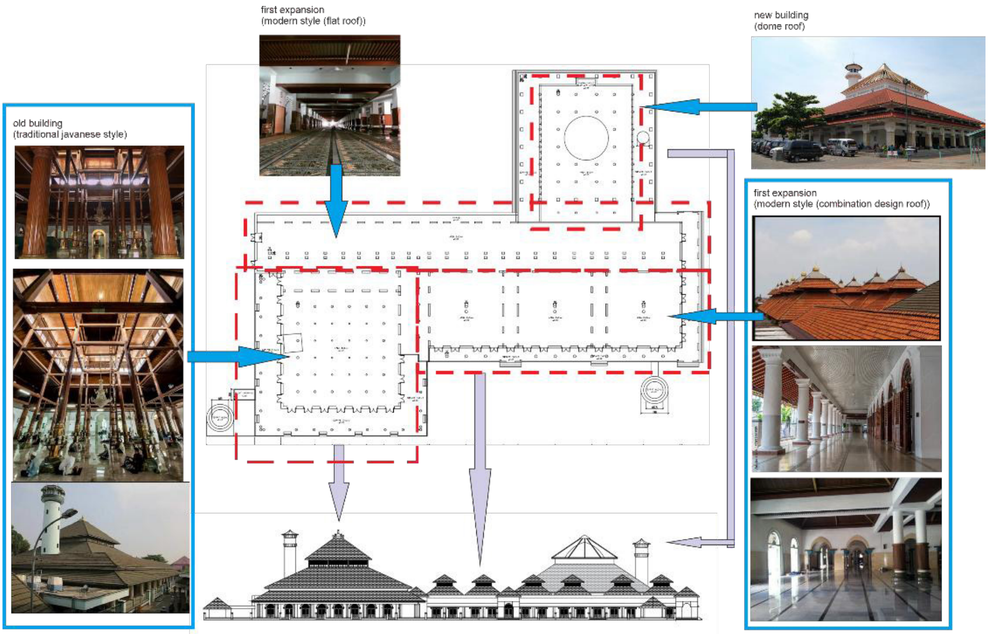


Fig. 1. Sunan Ampel Great Mosque Architectural Design.

Table 1. Material Absorption Coefficient of Sunan Ampel Great Mosque Surabaya [3], [4].

Zone	Building element	Material	Frequency (Hz)					
			125	250	500	1000	2000	4000
Old building area (pyramidal roof) 12.523 m³	Floor	Granite	0.01	0.01	0.01	0.01	0.02	0.02
	Wall	Brick plastered	0.07	0.03	0.02	0.02	0.02	0.03
	Door	Wood	0,14	0,10	0,06	0,08	0,10	0,10
	Coloumn	Wood	0,14	0,10	0,06	0,08	0,10	0,10
	Roof/ceiling	Wood	0,14	0,10	0,06	0,08	0,10	0,10
First expansion building area (Flat roof area: 8580 m^3, small pyramidal roof area: 10.479 m^3)	Floor	Granite	0.01	0.01	0.01	0.01	0.02	0.02
		Carpet	0.11	0.14	0.37	0.43	0.62	0.75
	Wall	Brick plastered	0.07	0.03	0.02	0.02	0.02	0.03
	Door	Wood	0,14	0,10	0,06	0,08	0,10	0,10
	Coloumn	Concrete	0.09	0.07	0.01	0.01	0.01	0.02
	Roof/ceiling	Concrete	0.09	0.07	0.01	0.01	0.01	0.02
		Wood	0,14	0,10	0,06	0,08	0,10	0,10
New building area (dome) 14.743 m3	Floor	Granite	0.01	0.01	0.01	0.01	0.02	0.02
	Wall	Brick plastered	0.07	0.03	0.02	0.02	0.02	0.03
	Door	Wood	0,14	0,10	0,06	0,08	0,10	0,10
	Coloumn	Concrete	0.09	0.07	0.01	0.01	0.01	0.02
	Roof/ceiling	Steel	0,05	0,05	0,05	0,06	0,04	0,02
		Concrete	0.09	0.07	0.01	0.01	0.01	0.02

2.2 Acoustic Measurement Method

The in-situ measurements in this study to find the SPL and noise used a sound level meter (SLM) tool. Meanwhile, the impulse-response analysis was conducted using Room EQ Wizard (REW, v5.x). Metrics reported are T20/T30, EDT, C50, C80, and D50. The speech-related assessment emphasizes the importance of C50 and D50, while the Clarity of C80 in Qur'an recitals is presented as a benchmark for evaluating recitation support. Measurements adhere to the core principles of ISO 3382 for source directivity, microphone placement, and averaging, while also accommodating the operational constraints of active worship facilities.

The response impulse measurement condition was empty-hall measurements outside prayer times to ensure access and control, while doors/windows were in a typical operational state. The sound source used was an omnidirectional loudspeaker positioned in front of the *mihrab* at a height of 1.2 m. The receiver was placed in the middle of each zone and utilized an omnidirectional microphone. Meanwhile, the SPL and background noise measurements had been taken at 23 points, uniformly covering near, mid, and far prayer rows, including under the dome, beneath galleries, and corner zones. The measurement point is shown in Figure 2.

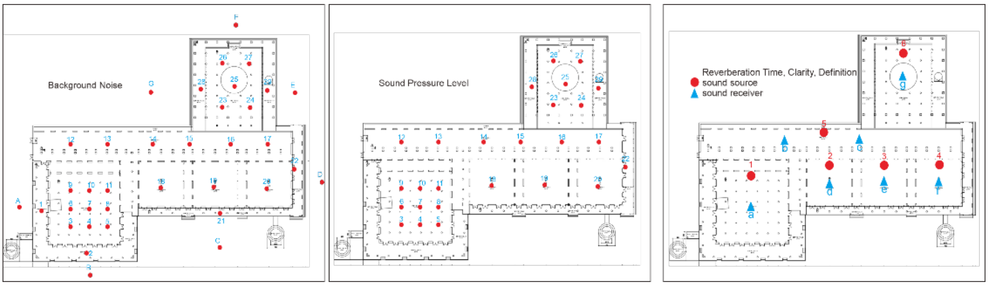


Fig. 2. The measurement point.

3 Result and Discussion

3.1 Background noise

Background noise measurements were conducted at 9 a.m., when the mosque was not in use. The results at the Sunan Ampel Grand Mosque indicated that none of the measurement points achieved the recommended background noise levels. The recommended background noise for worship buildings is 35 dB. Meanwhile, the lowest recorded noise level was 46 dB in the flat-roofed section of the mosque, while the highest was 61.25 dB in the pyramid-roofed section. These values were recorded when the average noise source in the mosque reached 68.56 dB. The highest noise levels were found in the old building area, which is directly close to the surrounding commercial zone. The detailed measurement results are shown in Figure 3, and a comparison between the architectural types is presented in Table 2 and Figure 4.

Fig. 3. The Background Noise of Sunan Ampel Great Mosque shows the highest level is in the pyramidal roof area, and the lowest level is in the flat roof area.

Table 2. Background Noise Comparison

Zone	Background noise min	Background noise max	Average background noise	Outdoor noise	Indoor and outdoor noise deviation
Old building (pyramidal roof)	52.25 dB	61.25 dB	56.67 dB	58.3 dB	1.63 dB
First expansion area (flat roof)	45 dB	53.3 dB	48.8 dB	57.15 dB	8.36 dB
First expansion area (smaller pyramidal roof)	50.3 dB	60 dB	53.9 dB	56.17 dB	2.27 dB
New building (dome)	53.3 dB	58.4 dB	55.54 dB	57.9 dB	2.36 dB

Table 2 and Figure 4 demonstrate that the lowest average background noise was recorded in the flat-roof zone. This can be attributed to the relatively quiet surroundings of the area and the smaller size of its ventilation openings compared to those of other zones. The greater deviation observed in the background noise of this zone suggests that its architectural configuration provides more effective attenuation of external noise, underscoring the influence of enclosure and façade permeability on acoustic performance. In contrast, the old building zone, which is located adjacent to a commercial area, exhibited the highest average background noise. The wider and more open ventilation design in this zone facilitates greater noise transmission, allowing external sounds to penetrate more easily into the interior. These findings reflect a broader characteristic of tropical mosque architecture, where large openings are intentionally incorporated to enhance natural ventilation and thermal comfort. However, this design strategy often compromises acoustic quality by reducing the building's capacity to shield against external noise.

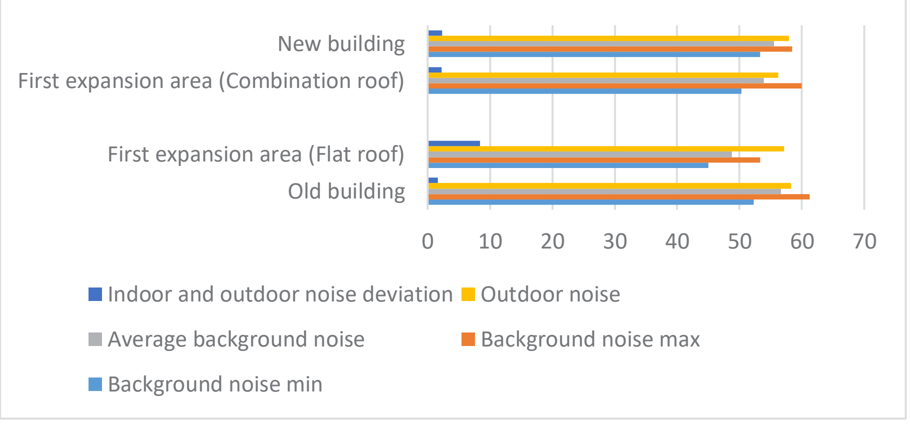


Fig. 4. The Background Noise of Sunan Ampel Great Mosque shows that the old building (the pyramidal roof area) has the least deviation of indoor and outdoor noise, means that the area cannot reduce much noise from the outside.

When compared with previous studies of mosques in Indonesia, the findings are relatively consistent. For instance, the Makassar Grand Mosque reported a noise level of 57 dB [5], the Yogyakarta Grand Mosque 68.6 dB [2], and the Al-Furqan Mosque 54 dB [10]. In contrast, mosques located outside tropical regions exhibit noise levels closer to the recommended standards. Examples include the Menemen Mosque in Turkey (30 dB)[11], the Gocbeyli

Mosque in Turkey (28 dB)[11], and the Fatih Pasha Mosque in Turkey (31.5 dB)[12]. This discrepancy can be attributed to architectural differences. In Indonesia, as in other tropical regions, mosques typically feature numerous ventilation openings designed to enhance thermal comfort. However, these openings also allow external noise to penetrate the interior, negatively affecting the acoustic environment easily. By comparison, mosques in Mediterranean climates tend to be more enclosed, thereby providing better noise control.

3.2 Sound Pressure Level (SPL)

Excessively high SPL (> 80 dB(A)) can cause discomfort and mask clarity, while too low (<45 dB(A)) may not provide sufficient audibility in larger spaces. A balanced SPL of 55–65 dB(A) for speech in medium-to-large mosques is typically considered optimal. The SPL distribution of Sunan Ampel Great Mosque can be seen in Figure 5.

Figure 5 illustrates that the overall SPL values in the Sunan Ampel Grand Mosque range from 58 to 80 dB. In the old building area with a pyramidal roof, the SPL is relatively stable, ranging from 64 to 73 dB. The first expansion area, with a smaller pyramidal roof, exhibits a slightly lower distribution, ranging from 58 to 67 dB. By contrast, the first expansion area with a flat roof demonstrates the most uniform distribution, ranging from 60 to 65 dB. In the new building area, however, the SPL is unevenly distributed, with values spanning from 64 to 80 dB.

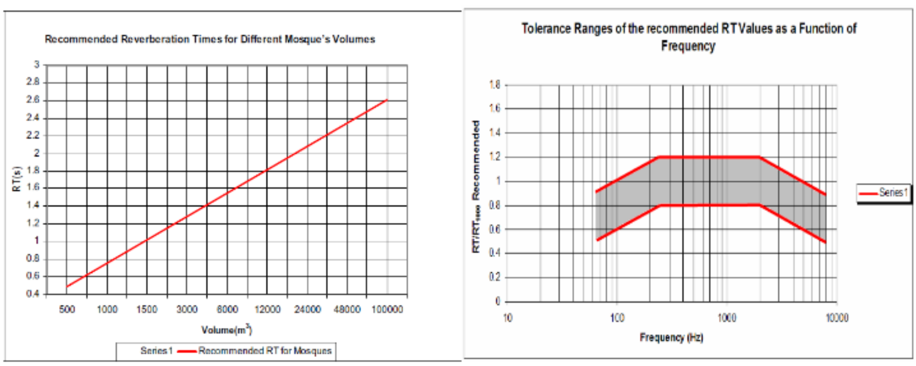
Fig. 5. The SPL distribution of Sunan Ampel Great Mosque that range from 58 to 80 dB.

These results suggest that roof geometry plays a critical role in shaping the acoustic field of the mosque. Flat-roof structures promote a more uniform sound distribution by reflecting sound waves at angles equal to their incidence, thereby minimizing acoustic focusing and supporting diffuse sound fields. In contrast, dome structures exhibit the poorest distribution, as their concave geometry causes sound reflections to converge and accumulate beneath the dome, creating zones of excessive loudness alongside areas of reduced audibility. This phenomenon aligns with the principle of acoustic focusing commonly associated with curved surfaces. The findings are consistent with previous research on the Baiturrahman Mosque in

Aceh, where a domed roof also produced uneven SPL distribution, ranging from 50 to 75 dB [6]. These observations highlight the importance of roof form in mosque acoustics, where flat or planar geometries are more effective in achieving balanced sound fields compared to curved or domed structures [13].

3.3 Reverberation Time (RT)

Researchers primarily use reverberation time (RT) as the key acoustic parameter because it is crucial for assessing a room's acoustic quality. The RT value should closely match the standard for the room, which varies based on the room's volume and intended activities. RT measures the duration it takes for sound to diminish in an enclosed space after the sound source has ceased. The recommended RT value for a mosque is shown in Figure 6.

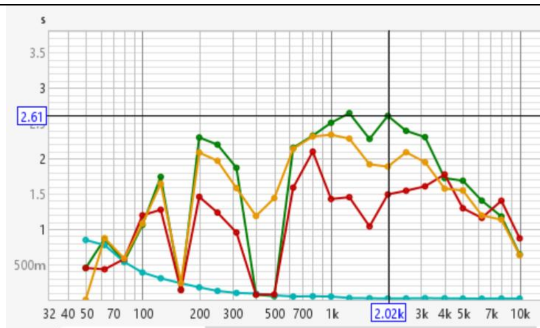
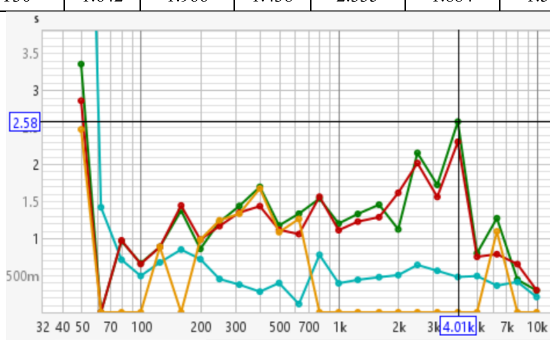
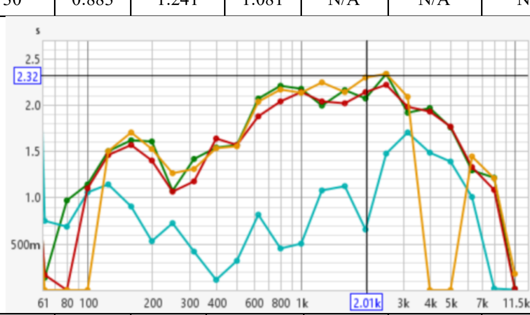


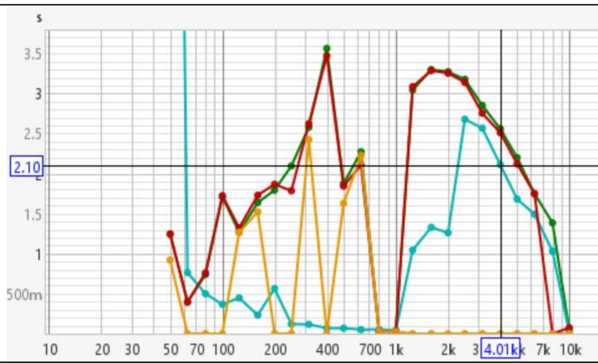
(a) (b)

Fig. 6. (a) Recommended RT values for various mosque volumes (b) RT value tolerance range based on frequency [8].

Based on Figure 6, the optimum reverberation time (RT) for each section of the mosque can be calculated based on its volume. The old building area, with a pyramidal roof, has a volume of 12,523 m³. The first expansion, featuring a flat roof, has a volume of 8,580 m³. The second expansion, with a smaller pyramidal roof, has a volume of 10,479 m³. The new building area, with a dome roof, has a volume of 14,743 m³. Accordingly, the recommended RT values are 1.8 s for the old building area, 1.65 s and 1.75 s for the flat and small pyramidal roof areas, respectively, and 1.9 s for the new building area. The measured RT values for the Sunan Ampel Grand Mosque are presented in Table 3.

Table 3. Reverberation Time (RT) of Sunan Ampel Great Mosque

<table>
<tr><th>Zone</th><th colspan="7">RT and EDT</th><th>Recommended RT</th></tr>
<tr><td rowspan="5">Old building (pyramidal roof)</td><td colspan="7">
</td><td rowspan="5">1.8 s</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>Topt</td><td>1.739</td><td>2.195</td><td>0.051</td><td>2.504</td><td>2.602</td><td>1.722</td></tr>
<tr><td>T 20</td><td>1.274</td><td>1.233</td><td>0.075</td><td>1.425</td><td>1.491</td><td>1.773</td></tr>
<tr><td>T30</td><td>1.642</td><td>1.966</td><td>1.438</td><td>2.335</td><td>1.884</td><td>1.573</td></tr>
<tr><td rowspan="5">First expansion area (flat roof)</td><td colspan="7">
</td><td rowspan="5">1.65 s</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>Topt</td><td>0.883</td><td>1.219</td><td>1.172</td><td>1.198</td><td>1.120</td><td>2.573</td></tr>
<tr><td>T 20</td><td>0.882</td><td>1.163</td><td>1.113</td><td>1.108</td><td>1.613</td><td>2.301</td></tr>
<tr><td>T30</td><td>0.883</td><td>1.241</td><td>1.081</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="5">First expansion area (smaller pyramidal roof)</td><td colspan="7">
</td><td rowspan="5">1.75 s</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>Topt</td><td>1.499</td><td>1.072</td><td>1.564</td><td>2.171</td><td>2.067</td><td>1.963</td></tr>
<tr><td>T 20</td><td>1.457</td><td>1.062</td><td>1.565</td><td>2.136</td><td>2.135</td><td>1.926</td></tr>
<tr><td>T30</td><td>1.499</td><td>1.261</td><td>1.551</td><td>2.129</td><td>2.293</td><td>N/A</td></tr>
</table>

Zone	RT and EDT	Recommended RT
New building (dome)		1.9 s

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Topt	1.268	2.096	1.874	3.044	3.273	2.560
T 20	1.321	1.784	1.844	3.085	3.254	2.510
T30	1.266	N/A	1.629	N/A	N/A	N/A

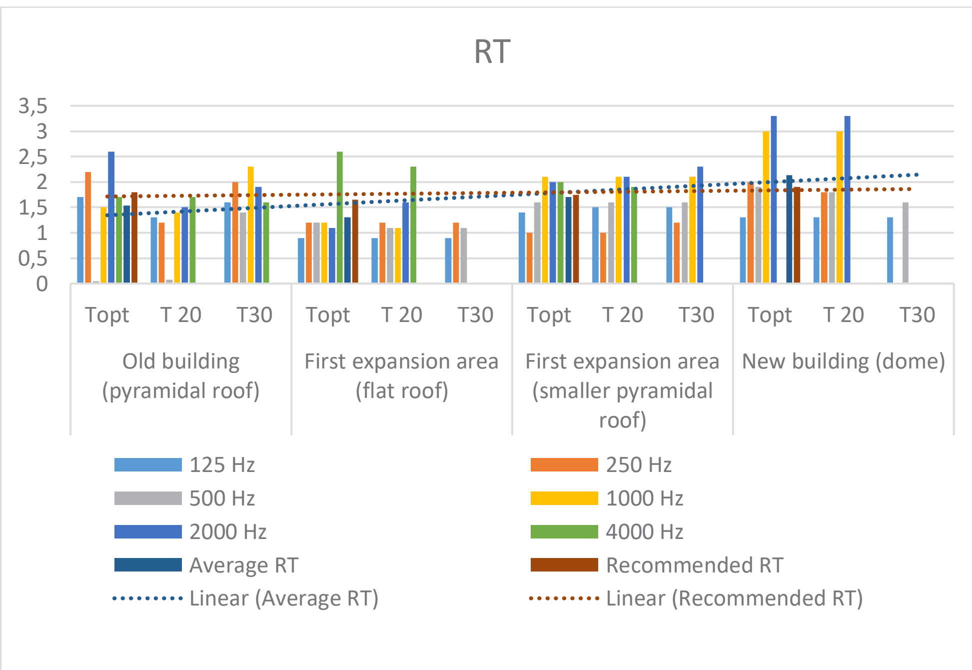


Fig. 7. Reverberation Time of Sunan Ampel Great Mosque shows the highest Reverberation time is in the new building (dome area), while the nearest RT to the recommended value is in the first expansion area (smaller pyramidal roof).

Details of the reverberation time are shown in Table 3 and Figure 7. The average RT of the old building area is 1.54 s, the flat-roof area 1.3 s, the smaller pyramidal roof area 1.7 s, and the new building area 2.1 s. The results indicate that none of these areas fully align with the recommended RT values. At specific frequencies, the RT is lower than recommended, while at others it is higher. Overall, the highest RT was measured in the new building area with the dome roof, which can be attributed to its larger volume and the use of more reflective materials. Conversely, the lowest RT was observed in the flat-roof area, likely due to its smaller volume and the presence of carpet flooring, which has a relatively high absorption coefficient.

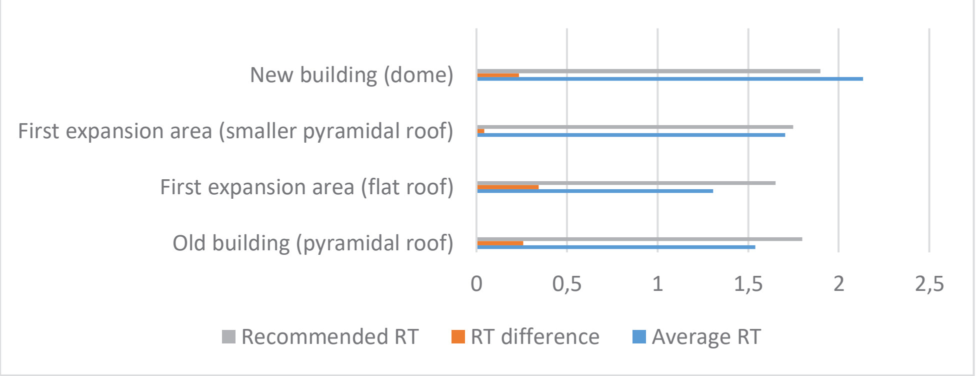


Fig. 8. Reverberation Time Comparison Between Zones of Sunan Ampel Great Mosque shows the best RT is in the smaller pyramidal roof area that has the least difference value with the recommended RT for a mosque.

When comparing average RT values with the recommended RTs (Figure 8), the first expansion area with the smaller pyramidal roof shows the smallest deviation, indicating that this zone most closely approximates the optimal acoustic condition. By contrast, the flat-roof area exhibits the largest deviation from the recommended value, making it acoustically the least favorable. Its measured RT is approximately 0.3 s lower than recommended, most likely because it is the only area with carpeted flooring, resulting in excessive absorption.

According to ISO 3382-1:2009 and guidelines for worship spaces, an RT between 1.5 and 2.0 s is generally considered optimal for large-volume spaces used for speech and recitation, as it provides both speech clarity and sufficient reverberant support for religious chanting. In this context, the results of the Sunan Ampel Grand Mosque indicate that while some zones (such as the smaller pyramidal roof expansion) fall close to this optimal range, others, particularly the flat-roof and dome-roof areas, diverge significantly, thereby affecting overall acoustic quality. These findings highlight the significant impact of architectural form, material selection, and spatial volume on achieving RT values that meet international standards for worship environments.

These findings are consistent with previous studies on mosques. For example, the Baiturrahman Mosque in Aceh (with a domed roof) recorded RT values ranging from 1.9 to 2.4 s, exceeding the recommended range and resulting in reduced speech intelligibility [6]. Similarly, in Yenisehir and Menemen Mosques in Turkey, RT values around 1.6–1.8 s were reported, aligning more closely with ISO recommendations due to their more enclosed designs and careful material selection [11]. However, this RT value can be decrease along with the adding of the people's praying. Comparisons such as these underscore how differences in architectural form, climate-driven design choices, and material use directly impact whether RT values align with international standards for worship environments.

3.4 Clarity

Clarity is defined as the logarithmic ratio in dB of the energy of the sound arriving in a closed volume within the first 80 ms to the energy of the sound arriving at the receiver after this period. For clarity of speech and music, it is generally accepted that the optimum range for C80 is 0 to -4 dB in musical activities and -2 to +2 dB in speech activities. However, it is stated that the feeling of spaciousness and sacred feeling surrounds the listeners in the volumes with the optimum C80 values between -2 and 0 dB for musical activities [3].

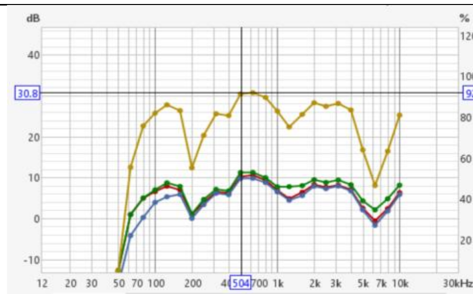
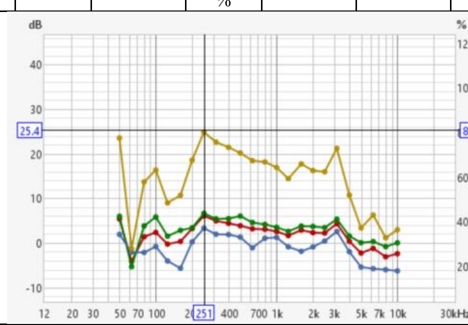
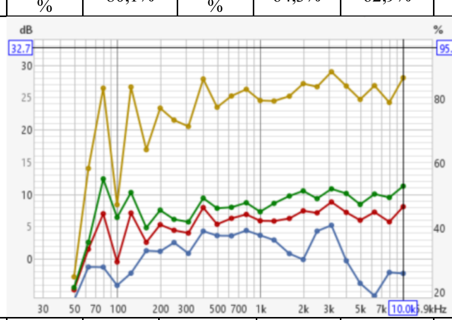
The concept of "Definition" (D50) holds a significant role, similar to its counterpart, Clarity (C80). While clarity focuses on the energy ratio within a specific time frame, D50 focuses on another crucial auditory characteristic, the early-to-late energy ratio. As with Clarity, D50 is a valuable metric for assessing the acoustic quality of spaces designed for speech or public lectures. The study introduces a classification system comprising three distinct categories: "good," "fair," and "bad." Notably, these classifications correspond closely with specific ranges of D50 values. Specifically, zones classified as "good" encompass D50 values ranging from 60% to 100%, indicating areas characterized by a favorable balance of early and late energy. Similarly, the "fair" category encompasses D50 values between 30% and 60%, while the "bad" category encompasses D50 values ranging from 0% to 30%. This categorization, anchored in D50 values, introduces a useful approach to assess and enhance the acoustic quality of mosque spaces. D50 is related to speech intelligibility and needs to be greater than 50%. However, D50 values that are higher than 20% are considered sufficient for speech intelligibility in some studies [14].

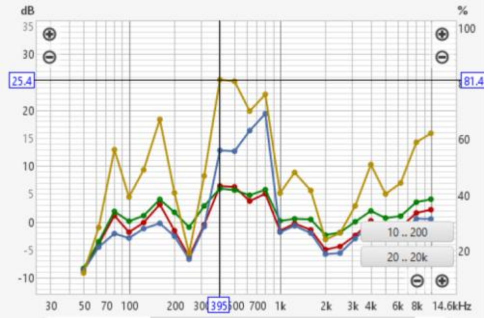
Table 4 presents the Clarity (C_{80}) measurement results for the Sunan Ampel Grand Mosque in Surabaya. According to ISO 3382-1:2009, the optimum clarity for music (and, by extension, Qur'anic recitation, which also benefits from a balance of reverberation and intelligibility) lies between –4 and 4 dB, while the optimum range for speech is narrower, between –2 and 2 dB. The clarity values closest to these ranges were observed in the flat-roof area and in the dome area at frequencies above 1000 Hz. This suggests that the mosque provides more favorable acoustic conditions for Qur'anic recitation than for spoken communication, consistent with observations from other studies of large-volume worship spaces [15].

Concerning definition (D_{50}), ISO 3382 considers values above 50% acceptable, with 60–100% generally regarded as suitable for speech intelligibility. In the Sunan Ampel Mosque, most areas exhibited D_{50} values between 60% and 100%, indicating satisfactory performance. However, the new building with a dome roof showed substantially lower D_{50} values, ranging from 30% to 60% at 1000 Hz and 2000 Hz, which corresponds to only a fair level of intelligibility. This reduction is closely related to the longer reverberation times (RT) recorded in the dome-roof area, where excessive late reflections reduce the ratio of early-arriving to late-arriving sound energy. In contrast, the flat-roof area, which demonstrated shorter RT values due to its smaller volume and the presence of highly absorptive carpeting, achieved both higher clarity and stronger definition values.

These findings are consistent with previous studies on mosques. For example, research at the Baiturrahman Mosque in Aceh reported similarly reduced clarity and definition in domed sections due to excessive reverberation [6], while studies of Ottoman mosques in Istanbul found that domed geometries often enhanced Qur'anic recitation but diminished speech intelligibility [15]. These comparisons highlight that roof geometry, volume, and material choices significantly impact the acoustic balance between speech and recitation in mosques.

Table 4. The Clarity of Sunan Ampel Great Mosque

<table>
<tr><th>Zone</th><th colspan="7">Clarity</th></tr>
<tr><td rowspan="5">Old building (pyramidal roof)</td><td colspan="7">
</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>C50</td><td>7,87</td><td>3,89</td><td>10,18</td><td>6,85</td><td>8,25</td><td>7,02</td></tr>
<tr><td>C80</td><td>8,69</td><td>4,62</td><td>11,19</td><td>7,70</td><td>9,44</td><td>8,21</td></tr>
<tr><td>D50</td><td>86%</td><td>71%</td><td>91,2 %</td><td>82,9%</td><td>87%</td><td>83,4%</td></tr>
<tr><td rowspan="5">First expansion area (flat roof)</td><td colspan="7">
</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>C50</td><td>-0,29</td><td>6,04</td><td>3,84</td><td>2,55</td><td>2,29</td><td>0,33</td></tr>
<tr><td>C80</td><td>1,49</td><td>6,62</td><td>6</td><td>3,49</td><td>3,67</td><td>1,53</td></tr>
<tr><td>D50</td><td>48,3 %</td><td>80,1%</td><td>70,8 %</td><td>64,3%</td><td>62,9%</td><td>51,9%</td></tr>
<tr><td rowspan="5">First expansion area (smaller pyramidal roof)</td><td colspan="7">
</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>C50</td><td>7,07</td><td>4,39</td><td>5,33</td><td>5,86</td><td>7,41</td><td>7,17</td></tr>
<tr><td>C80</td><td>10,24</td><td>6,08</td><td>7,81</td><td>7,27</td><td>10,49</td><td>10,09</td></tr>
<tr><td>D50</td><td>83,6 %</td><td>73,3 %</td><td>77,3%</td><td>79,4%</td><td>84,6%</td><td>83,9%</td></tr>
</table>

<table>
<tr><th>Zone</th><th colspan="7">Clarity</th></tr>
<tr><td rowspan="5">New building (dome)</td><td colspan="7">
</td></tr>
<tr><td></td><td>125 Hz</td><td>250 Hz</td><td>500 Hz</td><td>1000 Hz</td><td>2000 Hz</td><td>4000 Hz</td></tr>
<tr><td>C50</td><td>-0,17</td><td>-6,25</td><td>6,23</td><td>-1,64</td><td>-4,99</td><td>0,16</td></tr>
<tr><td>C80</td><td>1,07</td><td>-0,99</td><td>5,66</td><td>0,14</td><td>-2,4</td><td>1,93</td></tr>
<tr><td>D50</td><td>49%</td><td>19,2 %</td><td>80,8%</td><td>40,7</td><td>24,1%</td><td>50,9%</td></tr>
</table>

4 Conclusion

The acoustic evaluation of the Sunan Ampel Grand Mosque reveals that the architectural form, spatial volume, and material selection have a significant influence on the overall sound environment. Background noise levels across the mosque exceeded the recommended limits for worship spaces, mainly due to the open ventilation designs characteristic of tropical architecture and the mosque's proximity to commercial areas. Sound pressure level (SPL) measurements further revealed uneven sound distribution, with the flat-roof area performing most effectively. In contrast, the dome-roof area exhibited acoustic focusing effects, resulting in localized intensity variations.

Reverberation time (RT) analysis revealed that the dome-roof area had the highest RT, attributed to its large volume and reflective materials. In contrast, the flat-roof area had the lowest RT due to its smaller volume and the presence of highly absorptive carpeting. Among the zones, the smaller pyramidal-roof expansion most closely approximated the recommended RT, indicating a balance between volume and material absorption.

Clarity (C_{50}) and definition (D_{50}) measurements further supported these findings. While overall clarity values suggested that the mosque provides more favorable conditions for Qur'anic recitation than for speech, only certain zones approached the optimal ranges. Definition values were generally good, except in the dome-roof area, where excessive reverberation reduced intelligibility. These results align with previous studies of domed mosques in Indonesia and Turkey, which similarly reported trade-offs between the enhancement of recitation and the loss of speech intelligibility.

Overall, the first expansion area, featuring a smaller pyramidal roof, has the best acoustic quality. Although the flat-roof area provided more balanced SPL and higher clarity, its RT was too low compared to international standards, making it less suitable for Qur'anic recitation. In contrast, the smaller pyramidal-roof expansion achieved the closest match to the recommended RT while maintaining acceptable clarity and definition values, making it the most acoustically balanced zone of the mosque. In contrast, the new dome-roof building performs the worst acoustically, as its large volume, highly reflective materials, and concave roof geometry result in excessive reverberation and poor speech intelligibility. While domes may symbolically enhance grandeur and provide reverberant support for recitation, in this case, they compromise overall acoustic quality compared to other roof forms in the mosque. Meanwhile, the old building area (with a pyramidal roof) performs moderately overall, better than the dome-roof zone but not as balanced as the smaller pyramidal-roof expansion. Overall, compared to traditional mosque architecture, the contemporary one may have better acoustic quality, except for the dome roof/ceiling design.

Taken together, the findings underscore that the acoustic performance of the Sunan Ampel Grand Mosque is shaped by the inherent compromises of tropical mosque design: large openings and dome structures promote ventilation and symbolic expression but simultaneously introduce challenges for acoustic control. Future design and renovation efforts for mosques in similar contexts should consider strategies such as selective use of absorptive materials, optimized roof geometry, and controlled ventilation openings to balance thermal comfort, architectural expression, and acoustic quality in accordance with international standards.

This research is funded by Beasiswa Indonesia Bangkit, LPDP Kementerian Agama Republik Indonesia.

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