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THE ASSESSMENT OF ACOUSTICAL PERFORMANCE OF MOSQUES IN SHAH ALAM

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ABSTRACT

A mosque is a place where Muslims conduct activities such as praying and listening to talks. Therefore, it is important for a mosque to have great acoustics quality as it influences the worshipper's experience when praying or listening to Imam's preaches. The acoustical evaluation in the mosque is rarely conducted and, in most cases, the development of good acoustic quality in the mosque is never considered at an early stage of design. In the present investigation, two large-volume mosques in Shah Alam were investigated: Section 7 Mosque (MS7) and Sultan Salahuddin Abdul Aziz Mosque (MSA). The objective of this study is to evaluate the acoustical characteristics of the mosque and its quality level. In addition, the speech intelligibility performance of each mosque was also determined using Speech Transmission Index (STI) and Rapid Transmission Index (RASTI). The experimental work found that the reverberation time of MSA has attained recommended values of reverberation time for that given size and volume while MS7 has slightly higher. The speech level attainment of both mosques is sufficient for worshippers to hear comfortably, but the background noise is high. Nevertheless, the signal-to-noise ratio (S/N ratio) indicates that both mosques have been able to obtain more than 15 dB(A) for improved speech intelligibility. The STI and RASTI prediction shows that MS7 has attained 'fair' and 'bad' ratings. In contrast, 'poor' and 'bad' ratings are achieved in the MSA.

Keywords: *Acoustics, Mosque, Reverberation time, Speech intelligibility*

INTRODUCTION

A mosque is associated with all elements of faithful Muslims' lives and serves as the mechanism through which Muslims engage in global events, both as individuals and as communities. Mosques are designed where Muslims could gather themselves to perform 5 times prayers a day or listen to preaching such as 'Khutbah' and 'Kuliah'; led by an Imam. Worshippers may sit on the floor or even stand during the event while the Imam delivers his speech from 'Mihrab'. According to Ibrahim (1991), from his perspective in the architecture world, the design of a 'big hall' such as a mosque only looked forward to the appearance and space function and often, the need for a high level of acoustic quality and its speech intelligibility is neglected by the architects and engineers (Kassim, Putra, & M. Nor, 2015; Orfali, 2007). High-quality sound is essential, particularly for clean tones that must be both broad and effective (Othman, Harith, Ibrahim, & Ahmad, 2016).

The acoustical quality needs of spaces such as mosques, studios, concert halls, auditoriums, lecture halls, and churches are substantially different. In comparison to churches, where the harmony of music is required, activities in mosques are focused on those relating to speech intelligibility. The negative effect can be manifested by the worshipers where they are unable to hear clearly and the message cannot reach them effectively (Othman et al., 2016). Satisfaction of the worshippers during the worship experience is of utmost essential. Nevertheless, there are no precise guidelines for mosques have been developed yet, and there are no suggestions or rules regarding mosque acoustics (Orfali, 2007).

The assessment of the quantity of acoustical quality in a space system can be measured in many aspects: speech level (SL), background noise (BN signal-to-noise ratio (S/N ratio) reverberation time (RT60), noise criteria (NC), early decay time (EDT) for which attributed to the volume, size, shape, loudness, absorbing materials and many more. In terms of speech intelligibility, a rating assessment is used to calculate the strength of the intelligibility; Speed Transmission Index (STI), clarity (C50), Definition (D50) and Rapid Transmission Index (RASTI) (Abdullah & Zulkifli, 2014;

Kassim, Putra, Nor, & Muhammad, 2014; Putra et al., 2013).

Several research studies analysed the acoustic quality of mosques. Abdou (2003) implemented computer simulation studies on the influence of mosque geometry; rectangular, trapezoidal, square, hexagon, and octagon. He found that there were insignificant differences between the geometries. Kassim et al. (2014) reported that different angles of the pyramidal dome could affect the sound clarity in the mosque. Abdullah et al. (2014) showed the increasing occupancy of worshippers could provide better reverberation time (RT60) by employing a mathematical model approach.

Several experimental efforts were done to determine the acoustic performance of mosque interiors in Malaysia. In 2007, Dimon and Rosman (2007) measured the acoustic performance of the historical Kampung Laut Mosque, Kota Bharu, Kelantan which was built around 1676. Abdullah and colleagues (Abdullah & Zulkifli, 2014) performed an acoustic evaluation at the UPM Mosque and Jamek Mosque in Serdang, Selangor. Meanwhile, an extensive study was done at the Sayyidinia Abu Bakar Mosque in Malacca due to its unique ceiling pyramidical shape (Putra et al., 2013). Recently, Azizah Adnan et al. (2018) experimented with 3 mosques in Batu Pahat. In essence, these authors agreed that large mosque volume and size could give a negative effect on the reverberation time and speech transmission index and ultimately, lead to poor acoustic quality and speech intelligibility.

The present investigation aims to evaluate the acoustical performance of mosques in Shah Alam, Selangor. The selection of these mosques referred closely to the modern regionalism approach towards the mosque in Malaysia such as Masjid Bandar Tangkak and Masjid Saidina Abu Bakar Assiddiq (Ismail & Siraj, 2021) Sultan Salahuddin Abdul Aziz Mosque (MSA) was chosen for the case study because MSA has the largest dome volume on the roof and able to accommodate highest numbers of worshippers in Malaysia. Another newly built mosque in Shah Alam; Section 7 Mosque (MS7) was chosen for a fair comparison. There were minor complaints received due to poor acoustic quality by the worshippers in these mosques.

METHODOLOGY

Computer-Aided Design (CAD) Modelling

A computer-aided design (CAD) model was used to present roughly how the main prayer hall inside each mosque. Their physical dimension especially the interior design of each main prayer hall was measured manually using a portable laser distance measure (LOMVUM E40). The physical dimensions are tabulated in Table 1. The exact loudspeaker's location was also identified and accounted for in these studies.

For measuring the acoustic parameters such as speech level, background noise and reverberation time, several extended measuring points (9 points) inside the mosque were determined for the experiment. Each point that was selected to produce modes in the area during the measurement was also referred to as a reference to show the difference between the sound level meter's result based on the distance of the points determined and the sound of the loudspeaker used in both mosques. Figure 1(a) and Figure 1 (b) display the CAD model of the main prayer hall of MSA and MS7. All associated dimensions and the point location of acoustic measurement are also shown in Figure 1.

Table 1. Main Prayer Hall Dimensions in Mosques

Mosque	On-site Floor Plan Measurement			Main prayer hall parameters	
	Length (m)	Width (m)	Height (m)	Area (m^2)	Volume (m^3)
MS7	21.5	24.3	9.5	522.45	4,963.3
MSA	64.5	102.5	36.5	6,611.25	241,310.6

Source: Author

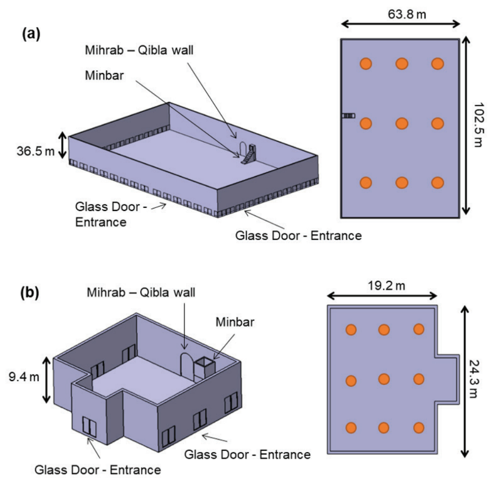

Figure 1. CAD Model of Mosques. The Orange Circles Point out the Locations of Speech Level, Background Noise and Reverberation Time Measurements.

Source: Author

Speech Level (SL) and Background Noise (BN) Measurement

The testing procedure was conducted by using a digital sound level meter to collect sound pressure level (SPL) data. The SLM II application program which enables the user to view the real-time data measurement curve diagram was used to monitor and evaluate the data.

A typical loudness was set up by operating the loudspeakers inside the main prayer hall which resembles during imam's speech. In the case of background noise measurement, the typical operating conditions were applied; mechanical fans and air-conditioning were allowed to operate during the measurement and all the entrance glass doors were closed. Both measurements were referred closely to Azizah Adnan et al. (2018) and Laina Hilma, Izziah, Meutia, & Zulfian's (2020) studies who cited BS ISO 3382:1997, a standard procedure when measuring reverberation time concerning other acoustical parameters. For example, the sound level meter was being monitored 1.5 meters from the floor to assume a person is in a standing position, especially when measuring for speech level, background noise and reverberation time.

Signal to Noise Ratio (S/N Ratio) Calculation

The ratio between speech and noise and the measurement relates to the difference between the long-term average speech level and the long-term average level of background noise (Dimon & Rosman, 2009). The S/N ratio was calculated by the following equations: -

$$S/N\ Ratio = L_{(SL)} - L_{(BN)} \quad (1)$$

$Where,$
$L_{(SL)} = Speech\ pressure\ level\ at\ dB(A)$
$L_{(BN)} = Background\ noise\ pressure\ level\ at\ dB(A)$

Reverberation Time (RT60) Measurement

The RT60 was measured by employing loudspeakers inside the main prayer hall to generate a static sound of 120dB(A). Initially, the digital sound level meter was activated, and the sound from the loudspeakers was silenced after a ten-second interval, allowing the sound level to decay freely. A predetermined amount of time (1 minute) was restricted. The time required to achieve 60dB(A) was recorded and the process was repeated at other points of locations.

Speech Transmission Index (STI) and Rapid Transmission Index (RASTI) Predictions

The RT60 and S/N ratio are lead calculation STI. STI is calculated using the modulation reduction factor given by (Gade, 2007):-

$$m(f_{\mathrm{m}}) = \frac{1}{\left[1 + \left(\frac{2\pi f_{\mathrm{m}}\,\mathrm{RT60}}{13.8}\right)^2\right]^{1/2}} \frac{1}{1 + 10^{\frac{-(\mathrm{S/N})}{10}}} \quad (2)$$

The modulation frequencies fm are 0.63. 0.80, 1.00, 1.00, 1.25, 1.60, 2.00, 2.50, 3.15, 4.00, 5.00, 6.30, 8.00, 10.00 and 12.50. The modulation reduction factor is calculated at each octave bands 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. The ¯m values are converted into an apparent signal-to-noise ratio.

$$(\mathrm{S/N})_k = 10\log_{10}\frac{\overline{m}}{1-\overline{m}} \quad (3)$$

The values above +15 dB are replaced by +15 dB and similarly below -15 dB by -15 dB. After that, an arithmetic average of (S/N)k is calculated at each octave band. The weighted average of the octave band, (S/N) k values is determined by: -

$$(\overline{\mathrm{S/N}})_{app} = \sum_{k=1}^{7} W_k * (\mathrm{S/N})_k \quad (4)$$

Finally, STI is determined by the equation: -

$$\mathrm{STI} = \frac{(\overline{\mathrm{S/N}})_{app} + 15}{30} \quad (5)$$

RASTI is a simplified version of the STI method that uses only two carriers octave band of noises and four plus five modulation frequencies.

$$\mathrm{RASTI} = \frac{(\mathrm{S/N})_k + 15}{30} \quad (6)$$

RESULTS AND DISCUSSIONS

Speech Level

The measured speech level of the random activities that are taken into consideration for measuring such as daily congregational prayer and religious talks inside MSA and MS7 are presented in Figure 2 whereas the speech level contour graph is displayed in Figure 3(a) and Figure 3(b). The bar chart in Figure 2 depicts that MSA has a higher speech level value as compared to MS7. The speech level at MSA scored at an average of 80.1 ± 6.02 dB(A) while MS7 obtained an average of 70.9 ± 6.8 dB(A). Considering the MSA size and volume which is extremely higher with a high ceiling and every loudspeaker attached to every mosque's pillar, the speech level range between 55 dB(A) to 90 dB(A) is considered suitable for religious activities. Louder speech level will cause harm to human hearing.

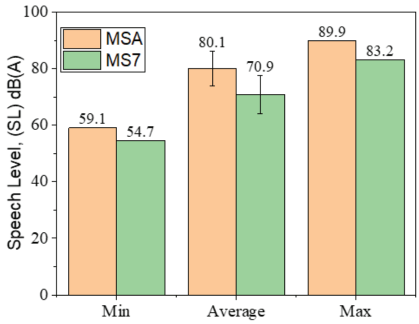

Figure 2. Measured speech level at MSA and MS7

Source: Author

Figure 3(a) depicts that the speech level of MSA has a higher value near the Qibla wall with a more yellow-coloured scale as compared to the MS7 which has a lower near the qibla wall in Figure 3(b). However, MS7 has a lesser loudspeaker for the middle row position which contributed to slightly lower speech level values. It can be distinguished that the contour graph of MSA is well-distributed as compared to MS7, suggesting appropriate placement of loudspeakers in the mosque whereas, for MS7, there is lesser loudspeaker at the pillar of the mosque.

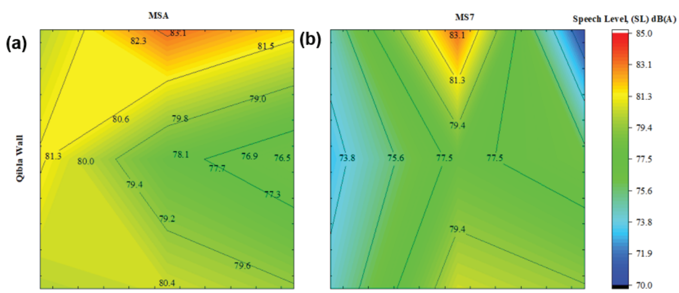

Figure 3. Speech level contour graph of (a) MSA and (b) MS7

Source: Author

Background Noise

The measured speech level of the are depicted in Figure 4. The average of the background noise as seen in Figure 4 shows that both achieved almost the same values with MS7 obtaining 55.8 ± 1.44 dB(A) compared to MSA with 51.5 ± 1 dB(A). According to Moore (1978), both mosques do not meet the standard for background noise level which should be at a maximum of 35 dB(A) for suitable or sufficient background noise in a mosque. These results reflect those of Azizah Adnan et al. (2018) and who also found higher background noise in the Masjid Sultan Ismail, Masjid Dato Bentara Luar and Masjid Sultan Ibrahim in Batu Pahat, Johor.

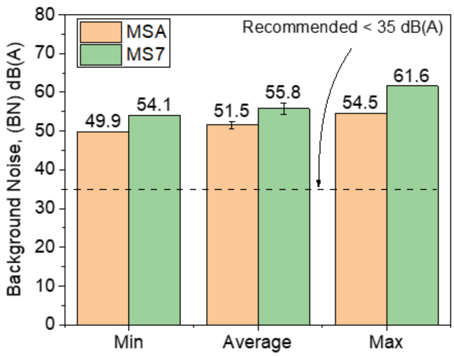

Figure 4. Measured background noise (BN) at MSA and MS7

Source: Author

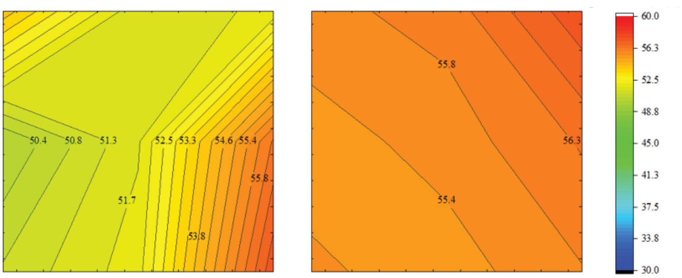

Figure 5: Background noise contour graph of (a) MSA and (b) MS7.

Source: Author

Figure 5(a) and Figure 5(b) show the contour graph of the background noise of MSA and MS7. It is noticeable that the background noise varies around the mosque floor. In Figure 5(a), the Qibla wall region for MSA has a background noise level of around 50.4 dB(A) which is the lowest, whereas the side and rear of the prayer hall have much louder background noise. At the left back of MSA, the mosque seems to experience higher background noise compared to other positions. In contrast, MS7 in Figure 5(b) has a higher value of background noise with intensified orange colour which is well distributed on the floor area as compared to MSA.

Closer observations indicate that the elevated background noise is a result of the sound generated by the air-conditioner and fans which tends to sound louder inside MS7. Another possible reason that can be pointed out is the neighbouring traffic conditions on the major road. MS7 location is nearer to the major road compared to MSA which is located slightly far from the road traffic. Noise is easily permeable, especially for MS7, which its contour graph shows almost all sides of the mosque achieved higher background noise levels during the measurement taken.

Reverberation Time (RT60)

Any religious building should obtain RT60 values between 0.9 to 1.2 seconds and it can be said that the value should be ideal for a mosque (Handryant, 2021). The RT60 obtained from the experimental work of MSA and MS7 is illustrated in Figure 6. Obviously, due to the higher volume and size of MSA compared to MS7 as shown in Table 1, the average RT60 of the former is predicted to be greater than the latter. The experimental result in Figure 6 shows that the average RT60 of MSA is 5.49 ± 1.1 seconds whereas the RT60 of the MS7 is 2.51 ± 0.5 seconds.

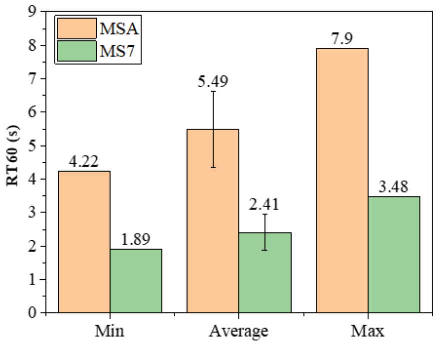

Figure 6. The Min, Max and the Average of RT60 of MSA and MS7

Source: Author

Orfali (2007) proposed the recommendation RT60 which implies the proportional relationship between reverberation time and the size and volume of a mosque. The relationship between RT60 against volume is developed by the following equation: -

$$= \left(\frac{0.163\gamma_L}{16\pi r_R^2}\right) x\ V \qquad (7)$$

Where

γ_L = The effective front-to-random factor of the sound source

r_R = Critical distance

V= Volume

To create a fair comparison between MS7 and MSA, the plotted reverberation time against volume is established and shown in Figure 7. The reverberation time of MSA seems to have good agreement with the Orfali (2007) prediction model. Unfortunately, it can be seen there is an upward deviation for the RT60 of MS7 from the prediction model in Figure 7. Hence, based on Orfali's (2007) consideration, the RT60 of MSA which is 5.49 ± 1.1 seconds can be considered reasonable for the volume of 241,310.6 m3 whereas, for MS7, a lower 1 second of reverberation should be achieved.

We included additional external data from other applicable studies in the plot (Figure 7). Lebuh Acheh Mosque in Penang and Tengkera Mosque in Malacca achieved different reverberation time with 1.84 seconds and 0.85 seconds although their volumes were almost the same; 1,001.5 m3 and 786 m3 respectively (Din, Abd Jalil, Ahmad, Othman, & Otsuru, 2013). A similar result is reported for mosques in Saudi Arabia (Eldien & Al Qahtani, 2012) and Çarşı Mosque, Turkey (Sert & Karaman, 2021). Their interior volume is measured at about ~1,601.8 m3. However, the reverberation time differs substantially; around 2.25 seconds and 1.25 seconds. Sayyidina Abu Bakar Mosque in Malacca with a large volume of 19,500 m3 is also plotted in Figure 7 (Putra et al., 2013). The reported RT60 is 3.5 seconds.

Except for Tengkera Mosque and MSA, all the reference data shift away significantly from the recommended reverberation time against volume as proposed by Orfali (2007). Many reasons may influence the mosque's reverberation time such as absorbing materials, geometry, dome sizing, loudspeaker location and interior style of the mosques. Further work should be carried out to validate this model.

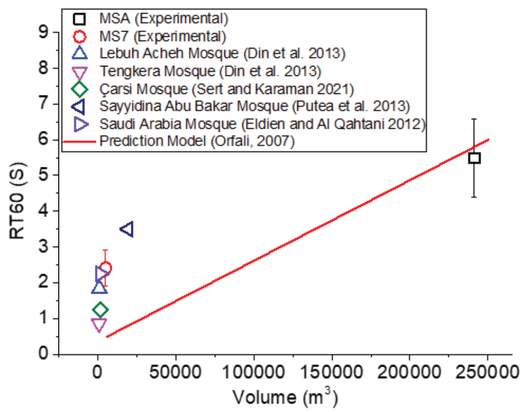

Figure 7. RT60 against the Volume of the Mosques

Source: Author

The RT60 contour plot of MSA and MS7 is shown in Figure 8(a) and Figure 8(b). MSA contour graph shows a well-distributed from the right and left sides towards the rear zone of the mosque as shown in Figure 8(a) since the placement of the loudspeaker at each pillar inside the mosque, especially at the right and left sides. The front-mid for MSA showed an increasing change of RT60 value towards the back-mid as the sound from the loudspeaker was coming mainly from the front-mid only. The sound will travel longer until it stops when it hits the wall at the rear of the mosque. It is also due to MSA's large volume and size.

Furthermore, it also depicted the contour graph of MS7 which achieved a slightly higher value from the recommended reverberation time as shown in Figure 8(b). Although MS7 has lesser speakers in the middle row inside the mosque, the RT60 value shows a well-distributed graph for most of the mosque. However, the rear zone of MS7 achieved a higher value of RT60 compared to other positions.

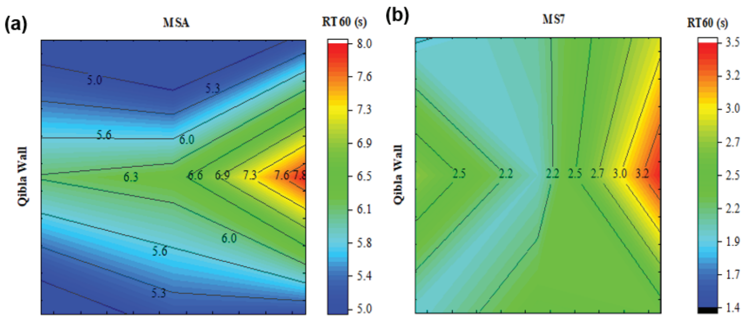

Figure 8. RT60 contour Graph of (a) MSA and (b) MS7

Source: Author

Signal to Noise Ratio (S/N Ratio)

The calculated S/N ratio is illustrated in Figure 9. It shows that MSA attained above the recommended value of the S/N ratio with an average of 27.3 ± 2.6 dB(A) while MS7 obtained a slightly lower value with an average of 15 ± 3.5 dB(A). both mosques met the minimal criteria of 6 dB(A) and exceeded 15 dB(A) for improved speech intelligibility.

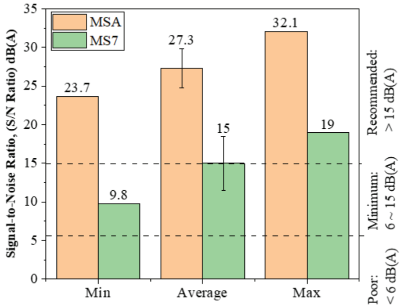

Figure 9. The Min, Max and the Average of S/N Ratio of MSA and MS7.

The S/N ratio contour plot of MSA and MS7 is shown in Figure 10(a) and Figure 10(b). Most of the region inside MSA in Figure 10(a) has achieved above the recommended value of the signal-to-noise ratio. In contrast to MS7 in Figure 10(b), the front side of MS7 has achieved above the recommended range value but it appears a weak S/N ratio can be detected at the rear side of the mosque. If the signal-to-noise ratio increases, it also increases speech intelligibility performance (Dimon & Rosman, 2009).

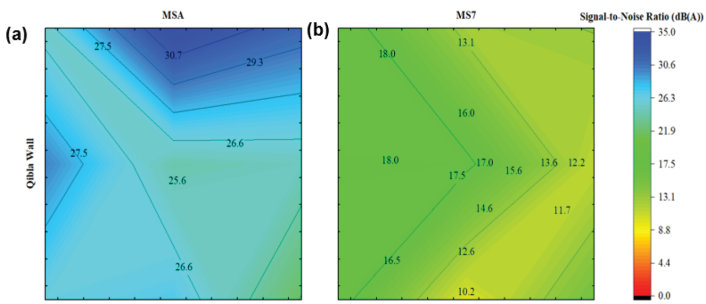

Figure 10: S/N Ratio Contour Graph of (a) MSA and (b) MS7

Source: Author

STI AND RASTI

Generally, STI and RASTI are calculated between 0 and 1. The STI and RASTI result for MSA and MS7 is shown in Figure 11(a) and Figure 11(b). The average value of STI obtained by MSA is 0.32 ± 0.02 which indicates a ‘Poor’ rating while MS7 obtained 0.4 ± 0.04 which indicates a 'Fair' rating. Therefore, MS7 has achieved a better value of STI which implies it has good speech intelligibility as compared to MSA. For the RASTI as illustrated in Figure 11 (b), MSA has been rated as 'Bad' with an average of 0.28 ± 0.03 value whereas MS7 has scored 0.43. However, the RASTI rating indicates 'poor' conditions for both mosques.

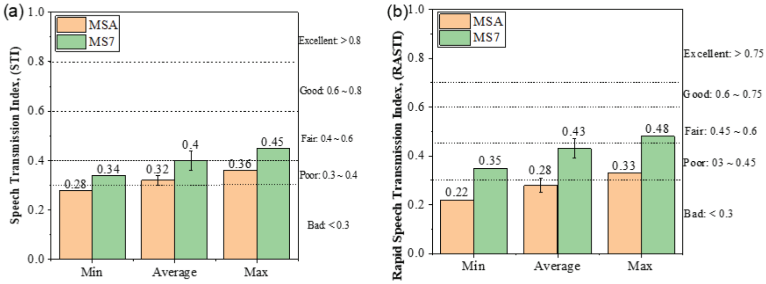

Figure 11. The Min, Max and the Average of STI and RASTI Values of (a) MSA and (b) MS7.

Source: Author

Figure 12(a) and Figure 12(b) demonstrate the comparison of STI values of MSA and MS7 with their respective distribution contours. Overall, STI is not consistent throughout the main prayer hall, especially in MS7. It can be observed that STI is the lowest in the middle area, starting from the Qibla wall towards the rear of the prayer hall. There is a slight improvement of STI towards the end side for MSA as shown in Figure 12(a). Nevertheless, the STI rating is still within 'poor' regardless of the location inside the prayer hall of MSA.

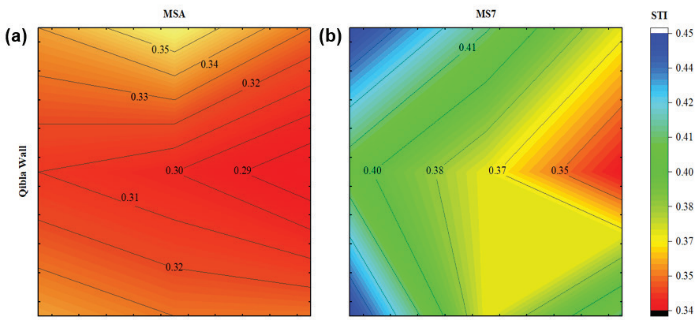

Figure 12: STI Contour Graph of (a) MSA and (b) MS7

Source: Author

In the case of MS7 as shown in Figure 12(b), the blue and green colors which is the highest STI values can be located on the right and left side of the Qibla wall. This is the area where a 'fair' rating is attained and most likely, the worshippers could appreciate the quality of speech intelligibility. Unfortunately, color changes from green to red have been spotted over the middle row towards the rear end of the prayer hall of MS7 where the STI values drop significantly from 0.40 to 0.35, signifying poor speech intelligibility quality in this area. A possible explanation is the location of loudspeakers at the front and middle areas of the MS7. This means the sound must have traveled further in distance to the rear end and ultimately, reverberation is getting worst. The claim is supported by the increasing RT60 as shown in Figure 8(a). In comparison to MSA, the results from STI and RASTI have shown that MS7 possessed better speech intelligibility (Carvalho, 1999; Dimon & Rosman, 2009; Gade, 2007)

CONCLUSION

The acoustical characteristics of the Sultan Salahuddin Abdul Aziz Mosque (MSA) and Seksyen 7 Mosque (MS7) were studied in detail including their speech intelligibility performance. Related acoustical parameters such as speech level (SL), reverberation time (RT60), background noise (BN), and signal-to-noise ratio (S/N ratio) to estimate the speech transmission index (STI) and rapid transmission index (RASTI). The results demonstrated the background noise in mosques was exceeding the acceptable standard, but the speech level was sufficient for listeners inside the mosque to hear and pray comfortably. The RT60 value for MSA is extremely high but still appropriate due to the high-volume type of mosque. The lower value of STI and RASTI has shown that MSA does not possess satisfactory speech intelligibility as compared to MS7.

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CONFLICT OF INTEREST

The authors declared there is no conflict of interest from the inception of the study until the conclusion.

AUTHOR CONTRIBUTIONS

Abdul Hakim Abdullah is responsible for the conceptualization, reviewing and final draft of the manuscript. Muhammad Amir Jazli Mohd Razali is responsible for the methodology, experimental works, analysis, visualization, and initial draft preparations.

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