Proceedings of the International Symposium on Room Acoustics, ISRA 2010

29-31 August 2010, Melbourne, Australia

Good speech intelligibility through novel acoustics material of geometric perforated panel in mosques

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PACS: D3.55.DT, 43.55.EV, 43.55.GX, 43.55.HY

ABSTRACT

Achieving good speech intelligibility is a central issue in a mosque. This is considering mosque is a place for prayers and particular Friday's sermon and regularly held lecture inside. Due to budgetary constrain for government project built mosques, architect normally reluctant to include typical porous material as an acoustics treatment inside. This requires new paradigm in quest of achieving optimum acoustics quality in particular its RT60. In Malaysia, considering almost warm weather all years round, it was envisage it is possible to achieve good speech intelligibility through the use of novel acoustics material such as geometric perforated panel. The almost optimize and very minimal use of geometric perforated panel in relation to its RT60 and hence its STI are discussed in details in this paper. The STI for mosque with almost optimize geometric perforated panel indicates good speech intelligibility is achieved. However, for mosque with minimal geometric perforated panel indicates rather challenging STI. This finding suggest, this novel acoustics material in the form of geometric perforated panel can contribute to good RT60 and hence STI without any additional cost to government. This is considering this material act as part of mosque wall panel. This shall open exciting and new possibilities allowing geometric perforated panel act also as sound absorber material.

INTRODUCTION

In Malaysia, many mosques have been built to accommodate the number of congregations according to population density in a place. This to ensure congregation comfortness during prayer. Mosques are used constantly and almost every time for Muslim to perform congregational prayer through five compulsory daily prayers and weekly Friday prayer.

Speech intelligibility in the mosques is a crucial aspect in order for the congregation to perform congregational prayer and to hear Friday's sermon, tazkirah (*short reminder*) and lecture given. When performing daily prayer in congregation, the congregations must hear clearly recitation done by the *Imam* (leader) before following the actions, and movements. Regularly, tazkirah or lecture will be held after the congregational prayer. During Friday prayer, the Imam stands up to deliver Friday's sermon before lead the prayer. Hence, acoustic quality and speech intelligibility is a vital aspect in the construction of mosques.

Due to budgetary constrain, mosques are build without porous material as an acoustic treatment inside as compare to hall or auditorium. Back to the past, most of the old mosque is without acoustical treatment with plain concrete wall or glasses panel used as part of the wall. It has affected the speech intelligibility inside because these materials acted as reflector. Hence, the RT60 value became too high to result in good speech intelligibility.

THE MOSQUES

Among the key features of a mosque construction are minarets, domes and prayer hall. However, its architectures and style are subjected to the influence and culture of a society. One of the current trends in the construction of a mosque is the use of perforated panel as part of the wall. The usage can contribute to the optimum acoustics quality without any additional cost. Hence, two mosques have been selected for the analysis of RT60 and STI with almost optimize use of geometric perforated panel at Al Faizin Mosque, Pontian, Johor and very minimal use at Taman Putri Kulai Mosque, Kulai, Johor

Al Faizin mosque

Al Faizin mosque situated in small and pleasant Parit Semerah village, about 1.5 km from Pontian town and 25 km from Johor Bahru city. This mosque has two levels and can contain full capacity of 670 congregations during Friday prayer. The mosque basically is a typical modern square plan mosque in Malaysia with the use of almost optimize perforated panel on its first floor wall. Perforated panel with geometric pattern which is made from Galvanized Reinforced Concrete (GRC) at the back, left and right side of the mosque as seen in Figure 1, Figure 2, and Figure 3 below.

The details of Al Faizin Mosque perforated panel is as in Figure 1. Its pattern is dominated by 8 edges star type surrounded by diamond and square-triangular patterns. The thickness is 67 mm of Galvanized Reinforced Concrete

(GRC) with 46% perforation ratio. The geometric perforated panel mainly positioned as part of the right, left and back wall. The total area of the perforated panel for this mosque is 81 m^2. The other part of the wall mainly of plain glass and plain concrete wall panel and wood door panel

Figure 2 shows the right side wall mosque where the use of perforated panel as part of wall is optimised.

Figure 3 shows the left side wall mosque where the use of perforated panel is on the lower part of the wall.

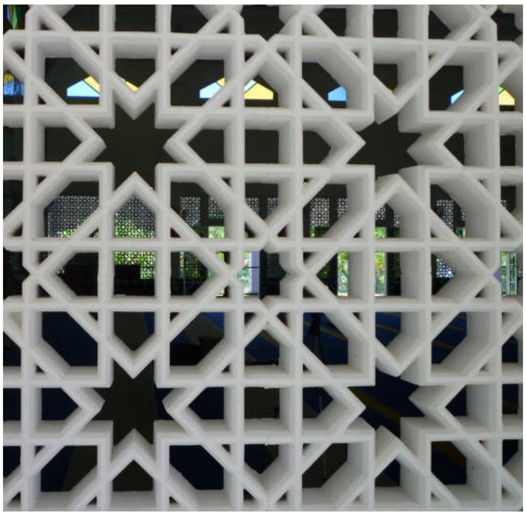

Figure 1. Details of Al Faizin mosque perforated panel

Figure 2. Right side wall mosque with almost optimize use of perforated panel

Figure 3. Left side wall with perforated panel on part of wall

Taman Putri Kulai mosque

The Taman Putri Kulai Mosque is a newly completed mosque that serves the congregations of this surrounding area. The mosque is located in Kulai, about 60km from Johor Bahru and it is a single floor mosque. The volume of this mosque is 3425 m^3. The main prayer area able to accommodate around 600 congregations. The material surface inside the mosque is of mainly plain concrete wall with glass panel. There are 340 m^2 and 100 m^2 surface area respectively. The floor is carpeted and ceiling is of plaster board material. The area of perforated wall is only about 22 m^2 divided into six panel of perforated wall, where two panels each located on its left, right and back part of the wall.

The details of Taman Putri Kulai Mosque perforated panel is as in Figure 4. Its pattern is dominated by 8 edges star type surrounded by diamond and triangular patterns. The thickness is 70 mm of Galvanized Reinforced Concrete (GRC) with 40% perforation ratio. The geometric perforated panel mainly positioned as part of the right, left and back wall. The total area of the perforated panel for this mosque is 22 m^2. The other part of the wall mainly of plain glass and plain concrete wall panel and wood door panel.

Figure 5 shows the perforated panel as part of the back wall while Figure 6 shows the perforated panel as part of the right side wall. These two figures indicate, the use of perforated panel in this mosque is rather minimal. As can be seen from Figure 5 and Figure 6, the rest of the wall is mainly of glass panel. Only small part of the wall is made from full concrete pillar to support the mosque load structure.

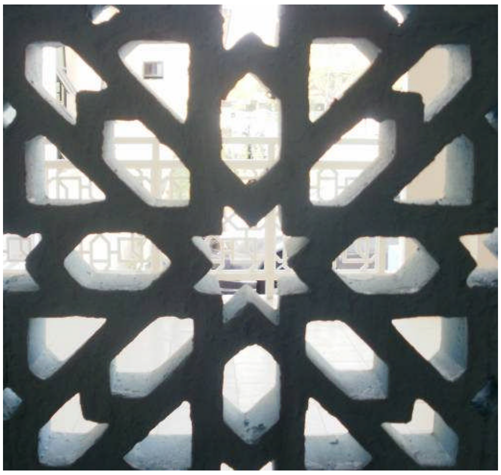

Figure 4. Details of Taman Putri Kulai mosque perforated panel

Figure 5. Parts of perforated panel on back wall

Figure 6. Mosque right side wall consist of perforated panel, glass wall and closed door.

The surface areas and volume of these two mosques were analyzed and calculated based on the architectural drawing provided by Public Work Department (PWD), Johor Bahru, Johor. In addition, site visit were also done to confirm and appreciate the insitu surfaces details in particular its perforated panel surfaces.

SOUND ABSORPTION COEFFICIENT

W.C Sabine defined sound absorption coefficient as the ratio between the non reflected sound intensity and the incident sound intensity. Sabine sound absorption coefficient (α) consist of two components. They are dissipation coefficient (δ) and transmission coefficient (τ) [1]. Therefore, the definition of sound absorption coefficient adopted in this research work is

$$\alpha = \delta + \tau \tag{1}$$

It is worthy to highlight here that the concept adopted by Sabine sound absorption is not only confined to the transformation of sound energy into heat energy (dissipation). It is also adopted in this work that, the sound absorption goes beyond the traditionally believed concept which is only dissipation process. From the equation (1) above, the transmitted sound energy to other side of material also became part of sound absorption. From the equation (1) above, clearly there are two extreme cases of sound absorption that could occur, either due to dissipation process only, $\alpha = \delta$ as in thick porous material placed on the wall or due sound transmission process only, $\alpha = \tau$ as in open window [1]. Another way of looking into sound absorption coefficient is from the sound energy perspective interacting with the standalone acoustics material. This is as in Figure 7.

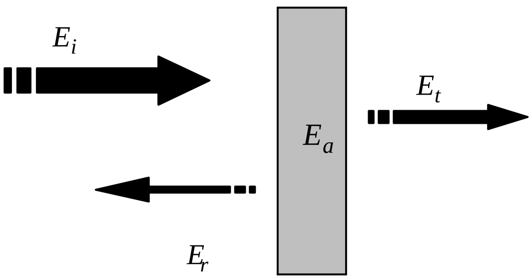

Figure 7. Reflection, absorption and transmission of sound energy

When a sound energy interacting with standalone acoustics material as in Figure7, its energy is divided into three parts. When a sound energy incident on the acoustics material, (E_i), part of the sound energy is reflected back, (E_r) while some part of the sound energy is absorbed, (E_a). From Figure 7, the rest of the sound energy is transmitted, (E_t) to the other side of acoustics material. This phenomenon known as conservation of sound energy and can be written as [6].

$$E_i = E_r + E_a + E_t \tag{2}$$

The sound absorption coefficient is defined as follow

$$\alpha = \frac{E_i - E_r}{E_i} = \frac{E_a + E_t}{E_i} \tag{3}$$

Equation (2) shows that all portion of the sound energy which is not reflected is considered to be absorbed. Equation (1) and equation (3) are the basis of classifying perforated panel as sound absorber material. This is mainly due to the transmitted sound energy to the other parts of the perforated panel. Also in this work, it is assumed that the sound energy being absorbed by the perforated panel is minimal and therefore it is ignored. Therefore, from equation (3), the sound absorption coefficient of perforated wall panel is mainly due to the transmitted sound energy (E_t) to the other side. This sound energy behaviour, qualify perforated wall panel as a unique and novel sound absorber material.

REVERBERATION TIME (RT60)

If the sound level when the sound source is abruptly switch off is 90dB and takes 1.6 seconds for the sound level to decrease to 30 dB, then the reverberation time of the room is 1.6 seconds [5]. Sabine was credited with modeling the reverberation time with simple relationship which is called Sabine metric formula [2].

$$RT_{60} = 0.16 \frac{V}{\Sigma A_e} \tag{4}$$

where

V = The volume of the enclosure

A_e = Effective amount of absorber

$$\Sigma A_e = \alpha_1 S_1 + \alpha_2 S_2 + \ldots\ldots + \alpha_n S_n \tag{5}$$

α_n is the sound absorption coefficient associated with given area, S_n . This formula is essential and will be used in RT60 analysis.

The RT60 is the established acoustic criteria in determining the suitability of an enclosed room or building interiors such as mosque to have good speech intelligibility [3][8]. Eventhough the established RT60 is basically based on Westerner acceptance, it is foresee, is still valid to the used for Malaysian population acceptance. However, it is an interesting and worthy to also conduct in-depth research confirming Malaysian RT60 population acceptance.

THE SPEECH TRANSMISSION INDEX (STI)

The speech intelligibility analysis of Al Faizin Mosque and Taman Putri Kulai mosque use Speech Transmission Index (STI) for the speech intelligibility prediction. STI technique was developed in Holland during the 1970s and 1980s by two Dutch [4][9] researchers, Tammo Houtgast and Herman Steeneken.

Calculation of the Speech Transmission Index (STI)

In order to calculate STI, modulation transfer functions (MTFs) of seven octave bands between 125 and 8000 Hz are used. This is because of the human speech is normally in the range of 125 to 8000 Hz.

For each octave band, ($m_{k,f}$), the octave band (k) and the modulation frequency (f) is obtained for the modulation frequencies corresponding to the envelope of the speech signal.

$$m_{kf} = \frac{1}{\left[1+\left(\frac{2\pi f_m RT_{60}}{13.8}\right)^2\right]^{1/2}} \cdot \frac{1}{1+10^{\frac{-(S/N)}{10}}} \tag{6}$$

Those are 14 frequencies between 0.63 and 12.5 Hz divided in a one third octave manner. First, $m_{k,f}$ is transformed to the signal to noise ratio *(SNR_k)* as follows.

$$SNR_k = 10 \ \mathbf{log}_{10} \ \frac{m_{kf}}{1-m_{kf}} \tag{7}$$

Next, the average of SNR is calculated by the average of summation all 7 octave band center frequencies weighting factors *(w_k)* as in Table 1 multiplied by *$(SNR)_k$*:

$$\overline{SNR} = \sum_{k=1}^{7} wk \ \ x \ \ \mathbf{(}SNR\mathbf{)}_k \tag{8}$$

Table 1. STI weighting factor for each octave band center frequency

Octave band center frequency (Hz)	***STI Weighting Factors***
125	0.13
250	0.14
500	0.11
1000	0.12
2000	0.19
4000	0.17
8000	0.14

Then, SNR_k is normalized to Speech Transmission Index (STI). In this transformation, *SNR* between -15 dB and +15 dB is normalized between -1 and +1 as equation (9). *SNR* below -15 become -1, and *SNR* above +15 become +1.

$$STI = \frac{\overline{(SNR)}+15}{30} \tag{9}$$

Due to unavailability of STI measuring system at our laboratory, it was decided to capitalize equations (6), (7), (8) and (9). This mainly to be able to predict the speech intelligibility of these mosques based on RT60 measured results and predicted RT60 with congregations. This is considering, in the predicted STI analysis, the S/N was set to 30 dB as in actual sermon delivery and hence is not a factor degrading STI. The only factor remain affecting the predicted STI is the RT60 as in Equation (6). These predicted STI were correlated with established STI rating as in Table 2.

Table 2. STI ratings

Ratings	*STI*
Poor	< 0.4
Fair	0.4 ~ 0.6
Good	0.6 ~ 0.8
Excellent	> 0.8

However, this rating shall only be a guideline for the monosyllables whereas Malay language uses dual syllables rather than monosyllables.

DISCUSSION ON REVERBERATION TIME, RT60

RT60 empty was measured for both mosques and RT60 with 50, 100 and 588 congregations were based on calculation. The calculated RT60 were taking into account α for mosque surfaces including perforated panel and α for designated number of congregations. The sound absorption coefficient for a single congregation is as in Table 3.

Table 3. Sound absorption coefficient of a single congregation

Freq (Hz)	*250*	*500*	*1k*	*2k*	*4k*
α	0.25	0.3	0.35	0.4	0.45

This α was adapted from Peter Mapp (1991). This is the most realistic α for our local congregations as our congregations sitting arrangement is very close to the reported α by Peter Mapp which is based on audience (m^2 per item / person) The mosque congregation sitting arrangement during the sermon is also basically occupying $1m^2$ for each congregations. Knowing α for one congregation, the additional amount of sound absorption can be estimated based on the designated number of congregations. The additional amount of sound absorption is as in Table 4. These RT60 are as in Table 5 and Table 6.

Table 4. Additional amount of sound absorption coefficient for various congregations

Freq (Hz)	*250*	*500*	*1k*	*2k*	*4k*
50 congr.	12.5	15	17.5	20	22.5
100 congr.	25	30	35	40	45
588 congr.	147	176.4	205.8	235.2	264.6

Table 5. Measured and calculated RT60 values of Al Faizin Mosque

	Closed Door (Hz)				
	250	*500*	*1k*	*2k*	*4k*
empty	1.98	1.81	1.28	1.13	1.02
50	1.88	1.71	1.22	1.08	0.97
100	1.8	1.63	1.17	1.03	0.93
588	1.24	1.09	0.83	0.73	0.66

Table 6. Measured and calculated RT60 values of Kulai Mosque

	Closed Door (Hz)				
	250	*500*	*1k*	*2k*	*4k*
empty	3.57	2.74	1.94	1.53	1.39
50	3.3	2.55	1.83	1.45	1.31
100	3.07	2.38	1.73	1.38	1.25
588	1.82	1.46	1.12	0.92	0.83

Considering these two applications of perforated panel, it is worthy to note that the area of perforated panel in Al Faizin Mosque is four times than the area of perforated panel in Taman Putri Kulai mosque.

Based on the earlier research work, it is estimated that the sound absorption coefficient (α) for geometric perforated panel surfaces for Masjid Taman Putri Kulai and Masjid Al Faizin are as in Table 7 and Table 8 [11]. These α have been used to calculate the Reverberation Time (RT60) for various conditions for these two mosques. These various RT60 were then used to predict the Speech Transmission Index (STI) of these two mosques.

Table 7. Sound absorption coefficient of Al Faizin mosque perforated panel

Freq (Hz)	*250*	*500*	*1k*	*2k*	*4k*
α	0.9	0.8	0.7	0.5	0.4

Table 8. Sound absorption coefficient of Taman Putri Kulai perforated panel

Freq (Hz)	*250*	*500*	*1k*	*2k*	*4k*
α	0.9	0.70	0.65	0.5	0.4

At 1kHz, RT60 empty measured for Al Faizin mosque is 1.28 second and Taman Putri Kulai Mosque is 1.94 second. Generally, the RT60 measured for Taman Putri Kulai mosque is higher than Al Faizin mosque for all centre octave frequency. The RT60 for Al Faizin mosque seems more favourable to result in good speech intelligibility, whereas RT60 for Taman Putri Kulai mosque seem very challenging to result in good or acceptable speech intelligibility [8][10].

The predicted RT60 for small congregations with 100 congregations is 1.17 second and 1.73 second respectively. This translates into STI of 0.53 and 0.47 respectively. However, with full congregation, the predicted RT60 is 0.83 second and 1.12 second respectively. This translates into predicted STI of 0.58 and 0.54 respectively. The predicted STI suggest reasonably good speech intelligibility performance for Al Faizin mosque and rather challenging speech intelligibility for Taman Putri Kulai mosque.

What really significant by using the perforated panel as part of wall is its contribution toward RT60 as in Masjid Al Faizin. As even with small congregations i.e 100 congregations, the RT60 is 1.17 second and 1.73 second, which translate into STI of 0.53 and 0.47 respectively. This suggest, the use of perforated panel contribute significantly to the speech intelligibility quality of the respected mosque. This is achieved without additional cost as perforated panel is part of the wall.

DISCUSSION ON SPEECH TRANSMISSION INDEX (STI).

STI analysis are as in Table 9 and Table 10. It is worthy to highlight that the STI subjective rating is based on monosyllable word. Whereas, in Malaysia the Malay Language spoken word in mosque is basically bisyllable. At this stage, there is yet exhaustive research work undertaken to ascertain the applicability of the subjective rating to the spoken Malay language.

Table 9. STI analysis for Al Faizin Mosque

Condition	***Congregation***	***STI***	***SI***
Door Closed	empty	0.51	Fair
	50	0.52	Fair
	100	0.53	Fair
	588	0.58	Fair

Table 10. STI analysis for Kulai Mosque

Condition	*Congregation*	*STI*	*SI*
Door Closed	empty	0.45	Fair
	50	0.46	Fair
	100	0.47	Fair
	588	0.54	Fair

The STI for empty, 50, 100 and 588 congregations for Al Faizin mosque are 0.51, 0.52, 0.53 and 0.58 respectively. Whereas STI for Taman Putri Kulai mosque are 0.45, 0.46, 0.47 and 0.54 respectively. These STI indices suggest fair intelligibility for all situations for both mosques [7][8]. However, it is very interesting and worthy to highlight that, discussion with Al Faizin mosque officials indicate this mosque experience no speech intelligibility challenges at all occasions. These indeed very interesting phenomena eventhough subjective STI rating is only fair. These situations foresee further extensive works require to correlate STI objective and subjective rating for spoken Malay Language.

CONCLUSIONS

Considering these two cases of the use of perforated panel in small size mosques, it is very apparent, the use of perforated panel even at only 82 m^2 contribute significantly to the good reverberation time (RT60) inside. This good RT60 translate into acceptable speech intelligibility. As in the case of Masjid Taman Putri Kulai, the use of perforated panel of only 21 m^2 which is considerably minimal, does not contribute significantly to the good RT60. This eventually predicted results in very challenging speech intelligibility inside.

Based on these findings, it is very promising in future mosque construction to use perforated panel optimally as part of the wall. There is no additional cost involve and yet the good RT60 can be realized. It translate in to good speech intelligibility requires for effective functionality of mosques.

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