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# COMPARISON OF THE ACOUSTICS OF MOSQUES AND CATHOLIC CHURCHES

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Catholic churches and mosques are worship places but with different occupation modes and acoustic requirements, decoration and architectural styles. This work reports on their acoustic performance to describe main similarities and differences. It is analysed the variability between objective acoustical parameters (Reverberation Time, Clarity $C_{50}$ or $C_{80}$ and STI or RASTI) and architectural parameters (volume, area, length, height and width). Regression models were created to find the best relationships among the parameters. A comparison between the acoustics of churches and mosques was established using data analysis to allow for a discussion relating to the comprehension of those parameters' variability.

## 1. Introduction

Mosques and Catholic churches are gathering religious buildings for two of the major religions in the world. They both have common points especially: believe in one true God; follow a Holy book (Coram and Bible); recognize Jesus and Mary (with different levels of holiness); have internal divisions or denominations (Sunnis/Shiites and Roman/Orthodox); and they both use specific spaces for their religious services that have similar features among themselves in each religion (shape and interior decoration) that make their acoustics very specific.

Churches began slowly appearing as a special building after the 4$^{th}$ century but only after the 11th century they began having specific characteristics and individuality and architectural styles (Romanesque, Gothic, Renaissance, Baroque, etc.).

The mosque (the word comes from the Arab “Masjid” meaning place of worship and prostration) serves as the place where Muslims can come together for prayer as well as a centre for information and education. They began being built in the 7$^{th}$ century in the Arabian Peninsula following the model of Mahomet's home in Medina.

In mosques the main acoustic objective is speech intelligibility but in Catholic churches there is also the requirement for adequateness for music (organs, choirs, congregation singing, etc.).

## 2. Method

The purpose of this work was to identify some of the similarities and differences on the acoustics of mosques and Roman Catholic churches. The acoustic data (all for unoccupied spaces) and information about the churches and mosques was based on previous work and available literature[1-4]. The goals of this research are:

- To characterize Catholic churches and mosques regarding their main acoustical and architectural features.
- To compare the acoustical behaviour of Catholic churches and mosques.

The acoustic and architectural parameters used in this work are presented in Table 1. The samples of buildings used are explained and numerically characterized in Tables 2 and 3.

**Table 1 – Acoustic and architectural parameters used.**

| Buildings | Acoustic parameters | Architectural features | |
|---|---|---|---|
| 41 Roman Catholic churches (Portugal) | *RT* (Reverberation Time)*<br>$C_{80}$ (Clarity 80 ms)*<br>*RASTI* (Rapid Speech Transmission Index) | Volume (total)<br>Area (total)<br>Length (maximum)<br>Height (maximum)<br>Width (medium) | V ($m^3$)<br>S ($m^2$)<br>L (m)<br>H (m)<br>W (m) |
| 21 Mosques (Saudi Arabia) | *RT* (Reverberation Time)*<br>$C_{50}$ (Clarity 50 ms)*<br>*STI* (Speech Transmission Index) | | |

* average 500/1k Hz octave bands

**Table 2 – Main statistics for the architectural parameters for churches and mosques.**

| Archit. Param. | 31 churches[2,3] (RASTI) | | | 41 churches[1] (RT / $C_{80}$) | | | 21 mosques[4] (RT / $C_{50}$ / STI) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min. | Mean | Max. | Min. | Mean | Max. | Min. | Mean | Max. |
| V ($m^3$) | 751 | 8046 | 30380 | 299 | 5772 | 18674 | 520 | 3185 | 23390 |
| S ($m^2$) | 108 | 593 | 1300 | 56 | 450 | 1031 | 131 | 569 | 2704 |
| L (m) | 17.9 | 39.3 | 63.3 | 11.5 | 33.2 | 62.2 | 11.6 | 27.4 | 52.0 |
| H (m) | 5.9 | 16.2 | 35.1 | 6.5 | 14.8 | 39.0 | 3.3 | 4.8 | 8.7 |
| W (m) | 5.4 | 14.8 | 28.8 | 5.0 | 13.6 | 36.8 | 9.7 | 17.7 | 52.0 |

**Table 3 – Number of churches and mosques per group.**

| Groups | A | B | C | D | E | F | Total |
|---|---|---|---|---|---|---|---|
| Volume ($m^3$) | < 1000 | 1000-1500 | 1500-2000 | 2000-3000 | 3000-10000 | 10000-30000 | |
| Churches | 5 | 6 | 2 | 4 | 15 | 9 | 41 |
| Mosques | 4 | 5 | 4 | 4 | 3 | 1 | 21 |

## 3. Results

### 3.1 Controlling for groups

Fig. 1 presents the results of the average RT and $C_{50}/C_{80}$ (average 500/1k Hz octave bands) for each of the six groups defined on Table 3 regarding their volume.

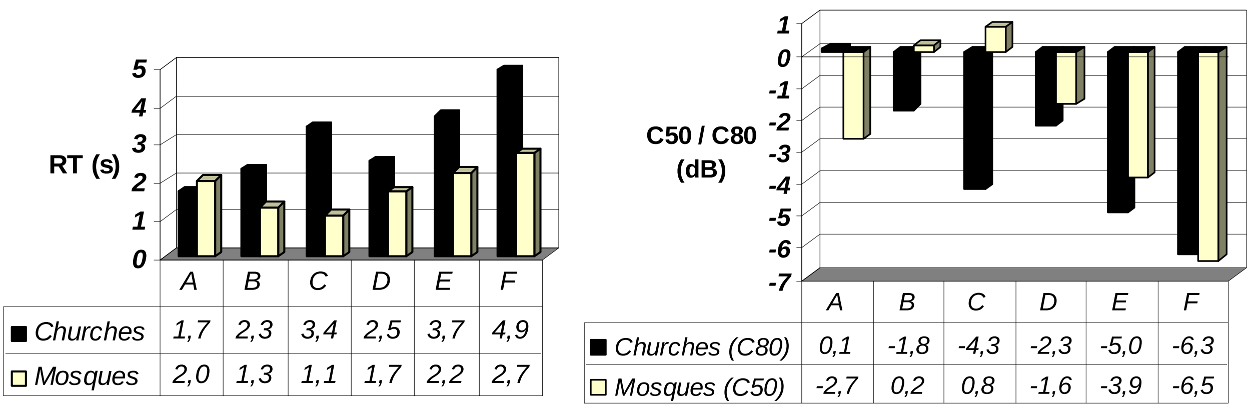


**Figure 1.** Variation of the RT and $C_{80}/C_{50}$ average values (500/1k Hz octave bands) controlling for groups.

## 3.2 Regression models

### 3.2.1 Reverberation time

Tables 4 and 5 show the equations (and $R^2$) for the best regression models for the RT average values in each type of space regarding each of the five architectural parameters tested[5].

**Table 4 – Best regression models between RT and the architectural parameters (churches).**

| Architectural parameter | Equation | $R^2$ |
|---|---|---|
| V – Volume ($m^3$) | $RT = 0.25 \cdot V^{0.3050}$ | 0.51 |
| S – Area ($m^2$) | $RT = 0.3074 \cdot S^{0.3933}$ | 0.47 |
| L – Length (m) | $RT = 0.3158 \cdot L^{0.6626}$ | 0.35 |
| H – Height (m) | $RT = 0.00248 \cdot H^2 + 0.0745 \cdot H + 1.6309$ | 0.56 |
| W – Width (m) | $RT = 0.6781 \cdot W^{0.6034}$ | 0.41 |

**Table 5 – Best regression models between RT and the architectural parameters (mosques).**

| Architectural parameter | Equation | $R^2$ |
|---|---|---|
| V – Volume ($m^3$) | $RT = -3.01 \times 10^{-9} \cdot V^2 + 0.000127 \cdot V + 1.38$ | 0.64 |
| S – Area ($m^2$) | $RT = 3.01 \times 10^{-8} \cdot S^2 + 0.000398 \cdot S + 1.4388$ | 0.63 |
| L – Length (m) | $RT = 0.0269 \cdot L + 0.9879$ | 0.42 |
| H – Height (m) | $RT = 1.8084 \cdot \ln(H) - 1.1271$ | 0.65 |
| W – Width (m) | $RT = 0.00015 \cdot W^2 + 0.0205 \cdot W + 1.2644$ | 0.63 |

### 3.2.2 Clarity ($C_{50}$ and $C_{80}$)

Tables 6 and 7 show the best regression models for the $C_{80}$ and $C_{50}$ average values in each type of space regarding each of the five architectural parameters tested[5].

**Table 6 – Best regression models between $C_{80}$ and the architectural parameters (churches).**

| Architectural parameter | Equation | $R^2$ |
|---|---|---|
| V – Volume ($m^3$) | $C_{80} = -1.9954 \cdot \ln(V) + 12.405$ | 0.59 |
| S – Area ($m^2$) | $C_{80} = -2.5557 \cdot \ln(S) + 10.997$ | 0.53 |
| L – Length (m) | $C_{80} = -4.4625 \cdot \ln(L) + 11.359$ | 0.42 |
| H – Height (m) | $C_{80} = 0.0062 \cdot H^2 - 0.5431 \cdot H + 2.4894$ | 0.49 |
| W – Width (m) | $C_{80} = -3.8216 \cdot \ln(W) + 5.6106$ | 0.44 |

**Table 7 – Best regression models between $C_{50}$ and the architectural parameters (mosques).**

| Architectural parameter | Equation | $R^2$ |
|---|---|---|
| V – Volume ($m^3$) | $C_{50} = 1.41 \times 10^{-8} \cdot V^2 - 0.000605 \cdot V - 0.1076$ | 0.72 |
| S – Area ($m^2$) | $C_{50} = -1.15 \times 10^{-7} \cdot S^2 - 0.00202 \cdot S - 0.3397$ | 0.71 |
| L – Length (m) | $C_{50} = -0.1335 \cdot L + 1.9078$ | 0.49 |
| H – Height (m) | $C_{50} = -8.7027 \cdot \ln(H) + 11.963$ | 0.72 |
| W – Width (m) | $C_{50} = -0.00059 \cdot W^2 - 0.1082 \cdot W + 0.5747$ | 0.70 |

### 3.2.3 Speech transmission index (RASTI / STI)

Mosques' data relate to STI values but in churches only RASTI values were available. On both cases there are values with the Sound Reinforcement System (SRS) *off* and *on*. The average values in each space were related to the five architectural parameters by linear regressions (Tables 8 and 9)[5].

**Table 8 – Linear regressions between RASTI and the architectural parameters (churches).**

| Architectural parameter | SRS off | | SRS on | |
|---|---|---|---|---|
| | Equation | R | Equation | R |
| V ($m^3$) | $RASTI = -1.34\times10^{-6}\cdot V + 0.4264$ | 0.10 | $RASTI = -1.23\times10^{-6}\cdot V + 0.4509$ | 0.09 |
| S ($m^2$) | $RASTI = -1.82\times10^{-5}\cdot S + 0.4264$ | 0.07 | $RASTI = -4.95\times10^{-5}\cdot S + 0.4704$ | 0.20 |
| H (m) | $RASTI = -1.32\times10^{-4}\cdot H + 0.4208$ | 0.38 | $RASTI = -0.00137\cdot H + 0.4631$ | 0.10 |
| L (m) | $RASTI = -0.00529\cdot L + 0.5012$ | 0.02 | $RASTI = -4.54\times10^{-4}\cdot L + 0.4588$ | 0.07 |
| W (m) | $RASTI = -0.00175\cdot W + 0.4414$ | 0.13 | $RASTI = -0.00404\cdot W + 0.5007$ | 0.29 |

**Table 9 – Linear regressions between STI and the architectural parameters (mosques).**

| Architectural parameter | SRS off | | SRS on | |
|---|---|---|---|---|
| | Equation | R | Equation | R |
| V ($m^3$) | $STI = -9.86\times10^{-7}\cdot V + 0.4565$ | 0.10 | $STI = -3.06\times10^{-6}\cdot V + 0.4951$ | 0.30 |
| S ($m^2$) | $STI = -1{,}33\times10^{-5}\cdot S + 0{,}4609$ | 0.16 | $STI = -2.44\times10^{-5}\cdot S + 0.4987$ | 0.28 |
| H (m) | $STI = -1.12\times10^{-2}\cdot H + 0.5073$ | 0.25 | $STI = -1.13\times10^{-2}\cdot H + 0.5405$ | 0.25 |
| L (m) | $STI = -6.07\times10^{-4}\cdot L + 0.4700$ | 0.14 | $STI = -8.50\times10^{-4}\cdot L + 0.5085$ | 0.19 |
| W (m) | $STI = -8.65\times10^{-4}\cdot W + 0.4686$ | 0.17 | $STI = -1.22\times10^{-3}\cdot W + 0.5065$ | 0.23 |

# 4. Analysis

## 4.1 Reverberation Time

Fig. 1 also shows that churches have, in general, larger RT average values (about 1 to 2 s) than mosques, except in very small buildings (volume < 1000 $m^3$).

From Tables 4 and 5 and Fig. 2 to 4 (that present the best of the models described on Tables 4 and 5) it can be concluded that RT average values increase with increasing size of these architectural parameters. Such growth is more pronounced in churches than in mosques.

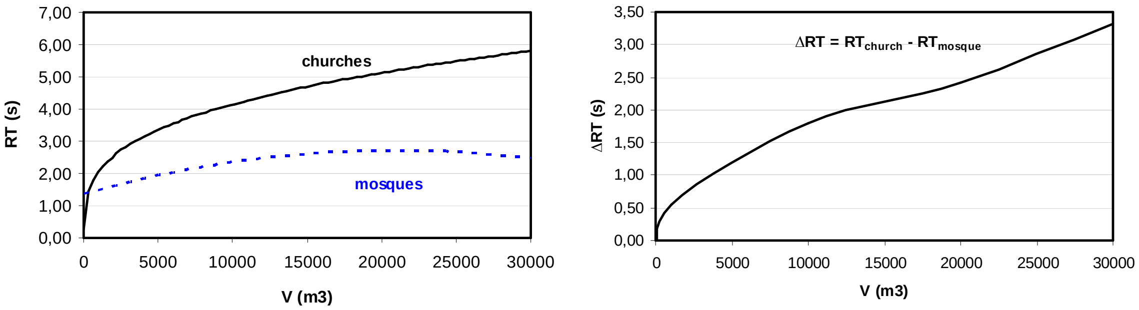


**Figure 2.** Difference between the behaviour for the RT values regarding *Volume* for churches and mosques.

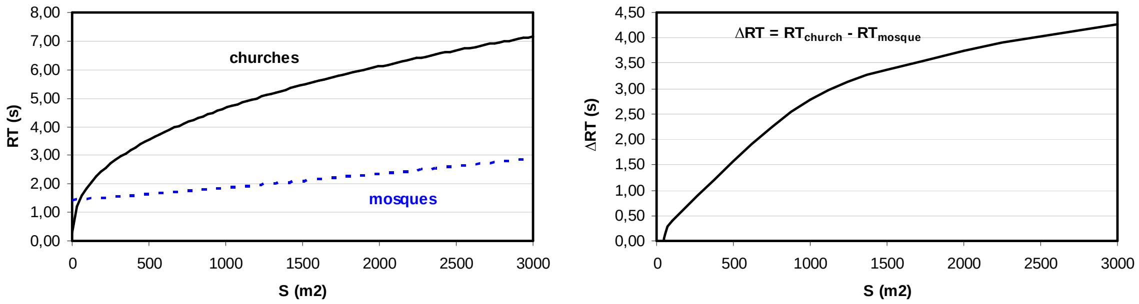


**Figure 3.** Difference between the behaviour for the RT values regarding *Area* for churches and mosques.

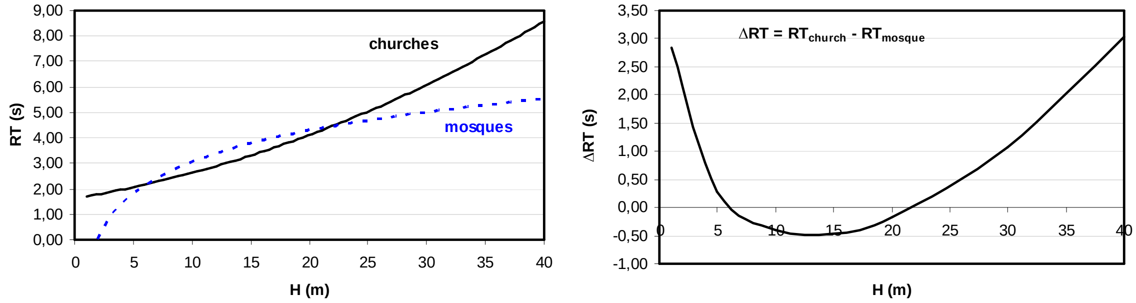


**Figure 4.** Difference between the behaviour for the RT values regarding *Height* for churches and mosques.

Except for the case of *Height*, all other geometrical characteristics show a growing difference between churches and mosques RT average values (ΔRT). In the case of *Height*, RT values are greater in small churches than in mosques of the same size, although this tends to change until intermediate heights, resuming in buildings with very large heights.

## 4.2 Clarity ($C_{50}$ and $C_{80}$)

The acoustic parameter Clarity was evaluated for both places, although the direct comparison between the results cannot be made because churches were measured with $C_{80}$ (usually related to music perception) and mosques with $C_{50}$ (used to evaluate the intelligibility of speech). The most relevant results are shown in Fig. 5 to 8 except that the difference in Clarity (ΔC) is not represented because the parameters $C_{80}$ and $C_{50}$ are not exactly the same.

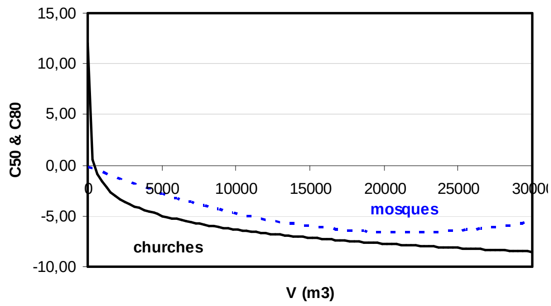


**Figure 5.** Behaviour for the $C_{50}$ / $C_{80}$ values regarding *Volume* for mosques / churches.

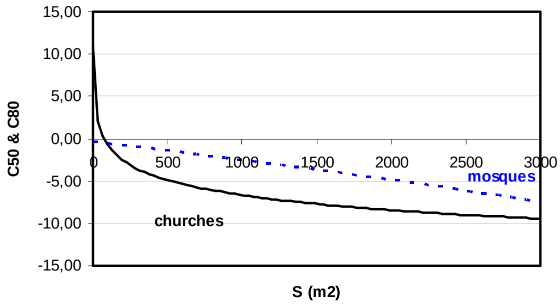


**Figure 6.** Behaviour for the $C_{50}$ / $C_{80}$ values regarding *Area* for mosques / churches.

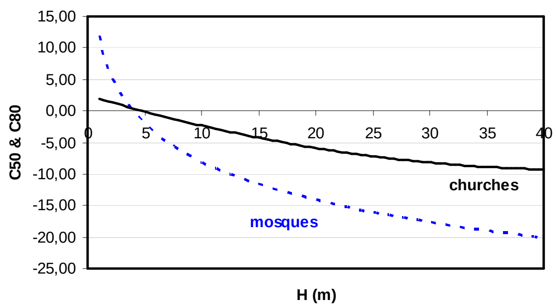


**Figure 7.** Behaviour for the $C_{50}$ / $C_{80}$ values regarding *Height* for mosques / churches.

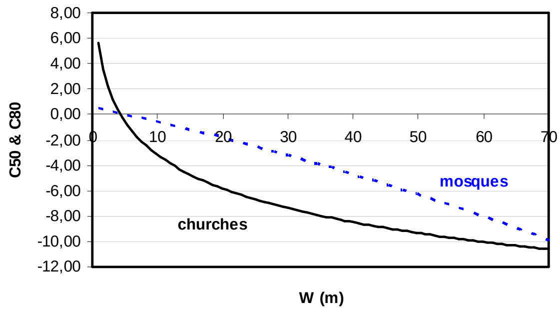


**Figure 8.** Behaviour for the $C_{50}$ / $C_{80}$ values regarding *Width* for mosques / churches.

The comparison that can be drawn is about the evolution of this parameter with the architectural features or to see if in churches, music clarity is lost more quickly with the increase of the geometric dimensions than the clarity of speech in mosques with the same increase in size.

In both churches and mosques, there is a decrease of Clarity mean values with the increase of any of the architectural parameters. Clarity values vary in fairly identical ways in both buildings.

Only for *Height*, the Clarity of speech ($C_{50}$) in mosques decreases faster than the Clarity of music ($C_{80}$) in churches. For all other architectural parameters there is an opposite trend.

Fig. 5 to 8 show that, for very small churches (up to 1000 $m^3$ and with the other architectural parameters of low value), music can be perceived with good clarity (showing positive values for this parameter). However this tends to reverse to a situation where the sound shows little sharpness. From about 1000 $m^3$, $C_{80}$ tends to negative values. For higher values, $C_{80}$ is still strongly negative but almost always tends to a constant value. For mosques, it appears that $C_{50}$ also varies in a similar manner (except for very small volumes and areas).

## 4.3 Speech transmission index (RASTI / STI)

### *4.3.1 Sound reinforcement system off*

According to the results shown in Tables 8 and 9 *Height* is the geometric feature that, for churches and mosques, shows the higher *R* (0.38 and 0.25). However, all the other models presented smaller *R* values.

Fig. 9 to 13 have the graphic representation of some of the linear regression lines of the RASTI (churches) and STI (mosques) relationships. Although the relationships for these acoustic parameters averages are not strong, these analyses can give an approximate idea of the difference between the evolution of these parameters in both places. The nomenclature *ΔRASTI/STI* refers to the difference *STImosques - RASTIchurches*.

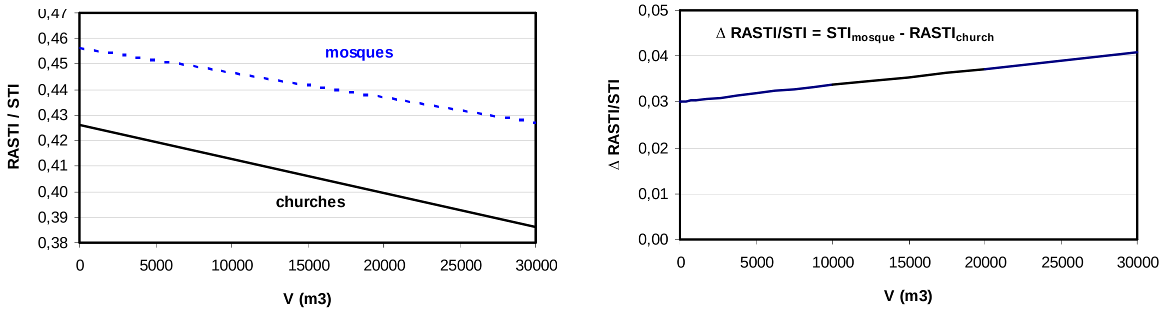


**Figure 9.** Behaviour for the RASTI / STI values regarding *Volume* for churches / mosques (SRS off).

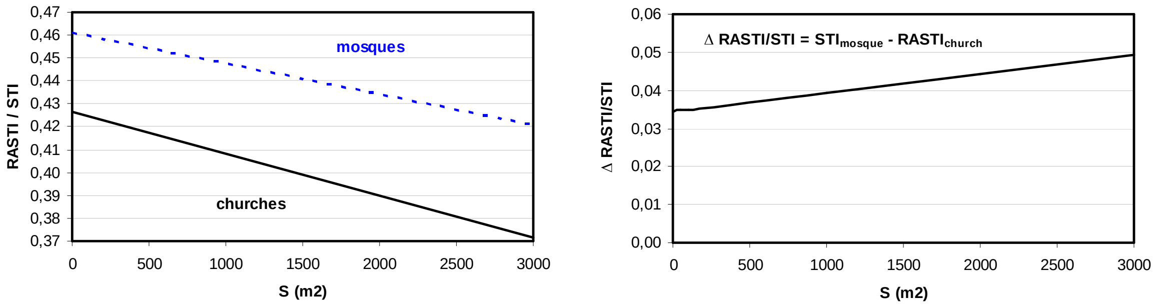


**Figure 10.** Behaviour for the RASTI / STI values regarding *Area* for churches / mosques (SRS off).

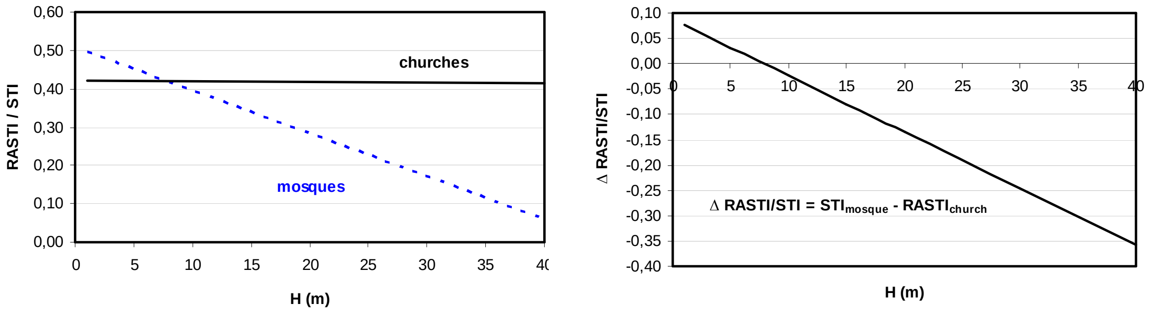


**Figure 11.** Behaviour for the RASTI / STI values regarding *Height* for churches / mosques (SRS off).

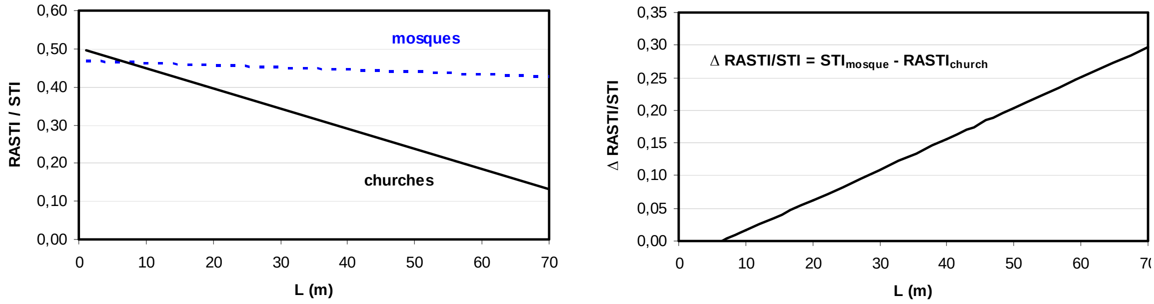


**Figure 12.** Behaviour for the RASTI / STI values regarding *Length* for churches / mosques (SRS off).

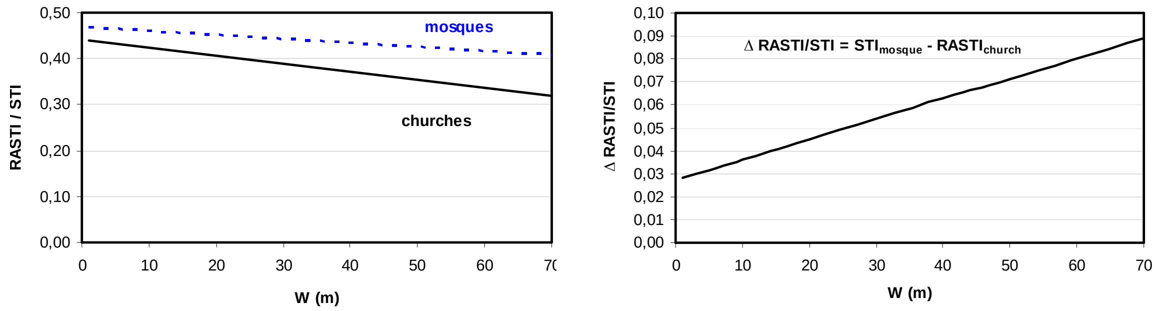


**Figure 13.** Behaviour for the RASTI / STI values regarding *Width* for churches / mosques (SRS off).

### *4.3.2 Sound reinforcement system on*

These objective speech intelligibility parameters allow to make a conversion of their values to a subjective scale of speech intelligibility, which is important to know the difference between the results for the two places of worship[6]. Table 10 presents a summary of these results for Sound Reinforcement System (SRS) *on* and *off*.

**Table 10 – Statistics regarding speech intelligibility (Sound Reinforcement System SRS off/on).**

| STI / RASTI | Classification[6] | SRS off | | SRS on | |
|---|---|---|---|---|---|
| | | 31 churches | 21 mosques | 31 churches | 20 mosques |
| 0.00 – 0.30 | Bad | 3 (10%) | - | 1 (3%) | - |
| 0.30 – 0.45 | Poor | 17 (55%) | 9 (43%) | 15 (48%) | 4 (20%) |
| 0.45 – 0.60 | Fair | 11 (35%) | 12 (57%) | 14 (45%) | 16 (80%) |
| 0.60 – 0.75 | Good | - | - | 1 (3%) | - |
| 0.75 – 1.00 | Excellent | - | - | - | - |

With the SRS *off*, 10% of the churches have a *Bad* average speech intelligibility but none of the twenty-one mosques shows that worst classification. The majority of churches have a *Poor* average rating while the majority of mosques are classified as *Fair*.

With the SRS *on* there is a general improvement in the results of the speech intelligibility. Now, only one church (3%) shows a rating of *Bad*, while previously three (10%) had that classification. In mosques the improvement is more pronounced (from 43% *Poor* to only 20%).

Table 10 indicates that 65% of churches presented an average *Poor* or *Bad* speech intelligibility with the SRS *off*. With the activation of SRS, 52% of churches still have *Poor* or *Bad* speech intelligibility. There is an improvement in the perception of speech, but it can not be considered that the SRS solves the problem. The overall mean RASTI value in churches only increases slightly from 0.42 to 0.44 with the activation of the SRS[2,3].

In mosques, the result is only slightly different. With the SRS *off* an overall mean STI value of 0.45 was found while after the activation of the SRS, a mean STI of 0.49 was obtained. But the impact of this equipment in mosques is more apparent if it is found that with SRS *off*, 43% of the mosques had an average of *Poor* intelligibility and with the SRS *on* that figure fell to 20% (especially because they just surpassed the border limit value of 0.45 of this "class").

## 5. Conclusion

Churches have in general an average RT (500/1k Hz) of 2 to 5 s when mosques have only about 1 to 3 s, what can be a consequence of the different interior decoration (mainly floor type). These larger RT average values found in churches can be also partially justified because churches have different acoustic objectives than mosques. In both spaces speech is present, but in churches also music has to be taken into account. Here, in addition to the choirs and congregation singing, there is the usual presence of the organ and possibly other instruments, which makes sound designing a church a strong challenge to find a balance between the perception of speech and music. Spaces designed just for speech require a shorter reverberation time than others directed to music. In general, longer reverberation times reduce the intelligibility of speech.

It seems that mosques have an overall better acoustic behaviour in this regard. Perhaps due to the sound absorption effect of the floor surface (covered with carpets).

The improvements found by using SRS in worship spaces, may sometimes force a tendency to laxity in the implementation of a previous acoustic project which should be counteracted. However, despite the improvements that the SRS has over sound behaviour in places of worship, these devices are still not a real solution to acoustical problems.

These results show that these equipments have different results in places of worship. In general they can be used for a small improvement in the acoustic outcome, but they are not the final solution in the acoustic performance of buildings. These findings reinforce the idea that good architecture and design of a worship project are the key elements for the acoustic performance of churches and mosques.

These overall results are largely not in disagreement with other studies about this subject[7-11].

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