ICSV19
Vilnius, Lithuania
July 08-12, 2012

# ACOUSTIC REHABILITATION OF MIDDLE TWENTIETH CENTURY PORTUGUESE CHURCHES

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This paper analyzes two Catholic churches in Portugal (*Our Lady of Conception* in Porto, and *Our Lady of Assumption* in Santo Tirso) with acoustic problems related with a very long Reverberation Time and poor speech intelligibility. Both were built in the middle 20th century with a large reverberant interior (volumes of 10,000 and 12,500 $m^3$). The results of in situ acoustic measurements are presented and also compared to those of other Portuguese churches with similar volumetric dimensions. Proposals for the acoustic rehabilitation for each church with a short cost analysis are presented.

## 1. Introduction

A church is a public area of prayer which makes vitally important that everyone should be able to clearly hear and understand the spoken words. It is also important that no background noise may become a disturbing nuisance, especially at times when the church is used for personal prayer.

This paper analyzes the impact of middle 20th century architecture in the acoustics of churches taking as example the church of the Sanctuary of Our Lady of Assumption, in Santo Tirso and the church of Our Lady of Conception in Porto (Portugal), which are characterized as being modern churches with acoustics problems regarding highly reverberant interiors and poor speech intelligibility. The latter church is one of the most remarkable examples of Portuguese twentieth century religious architecture.

The main goals of this paper are to characterize the interior acoustics, to identify the acoustic problems, to compare with churches with similar volumetric dimensions, and to present some corrective intervention measures.

## 2. The sample

The sample is composed by the church of the Sanctuary of Our Lady of Assumption (Fig. 1, 2 and 9), in Monte Córdova, Santo Tirso, Portugal (initial project made in 1928 by Ernesto Korrodi, 1870-1944, but only totally finished in the 1970´s) and by the church of Our Lady of Conception (Fig. 3, 4 and 10), in downtown Porto (project made in 1938 by the French architect Paul Bellot, 1876-1944, and inaugurated in 1947). Their main geometric features are shown in Table 1.

**Table 1.** Geometric data of both churches studied.[1,2]

| Church | Volume ($m^3$) | Area ($m^2$) | Height max. (m) | Length max. (m) | Width max. (m) |
|---|---|---|---|---|---|
| Our Lady of Assumption (Santo Tirso) | 9855 | 715 | 16.0 | 38.1 | 27.2 |
| Our Lady of Conception (Porto) | 12532 | 1011 | 17.0 | 49.0 | 22.0 |


**Figures 1 and 2.** Church of Our Lady of Assumption, Santo Tirso (left: East view), (right: interior). [1]



**Figure 3, 4 and 5.** Church of Our Lady of Conception, Porto (left: East view), (center: interior), (right: ceiling). [2]

## 3. Measurements and results

*In situ* measurements were done regarding the following parameters: Reverberation Time (RT) from 125 to 4k Hz, level of background noise and RASTI (Rapid Speech Transmission Index). These parameters were obtained at several points in the unoccupied churches (four points for the RT measurements, two points for the background noise level measurements and six for the RASTI measurements in each church). The background noise was examined without any HVAC (Heating, Ventilation and Air Conditioning) equipment as the churches are not equipped with this kind of system.

The equipment used was a B&K 2260 sound level meter with a 4189 B&K microphone, a B&K 4224 sound source, and the B&K 3361 RASTI kit (4225 + 4419).

Tables 2, 3 and 4 (as well as Figure 6) display the averaged results achieved.

**Table 2.** Averaged Reverberation Time data of both churches studied. [1,2]

| RT by frequency band (Hz) / Church | 125 | 250 | 500 | 1k | 2k | 4k |
|---|---|---|---|---|---|---|
| Our Lady of Assumption (Santo Tirso) | 16.3 | 12.7 | 11.9 | 10.1 | 7.0 | 4.9 |
| Our Lady of Conception (Porto) | 5.8 | 5.6 | 6.5 | 6.6 | 5.7 | 4.1 |

**Table 3.** Averaged RASTI data of both churches studied (SRS - sound reinforcement system). [1,2]

| RASTI<br>Church | without SRS | with SRS | ΔRASTI (=with-without SRS) |
|---|---|---|---|
| Our Lady of Assumption (Santo Tirso) | 0.28 | 0.30 | 0.02 |
| Our Lady of Conception (Porto) | 0.31 | 0.39 | 0.08 |

**Table 4.** Average background noise levels in both churches studied (outside noise only - No HVAC present). [1,2]

| Background noise level<br>Church | Leq (dB) | LAeq (dB) |
|---|---|---|
| Our Lady of Assumption (Santo Tirso) | 45 | 26 |
| Our Lady of Conception (Porto) | 48 | 27 |

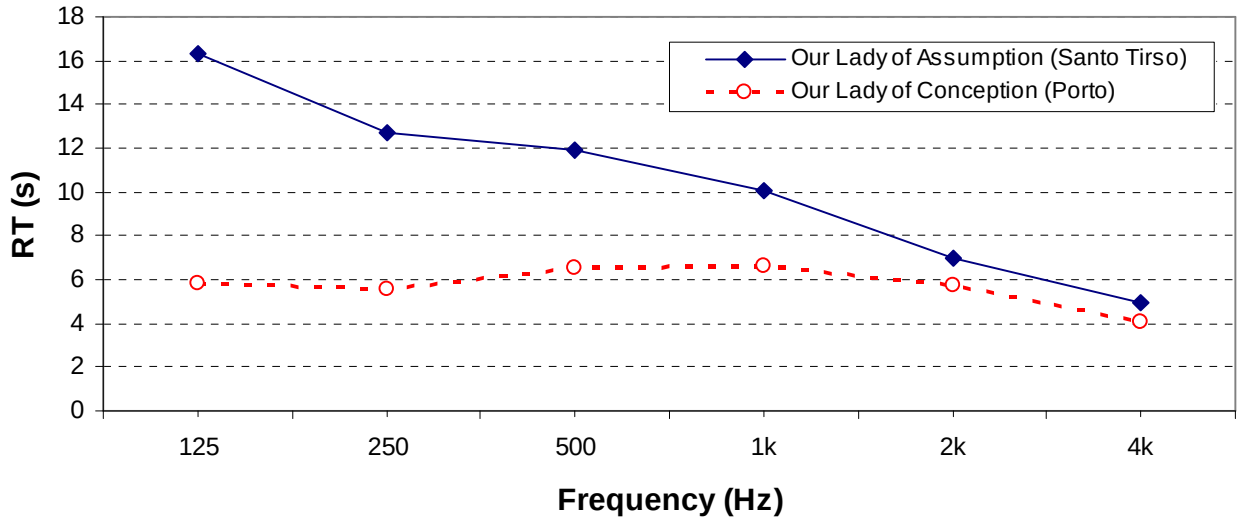



**Figure 6.** Measured Reverberation Time values in both churches. [1,2]

Average RT (500, 1k Hz) of about 7 s and 11 s were obtained (Table 2). These values (and Fig. 5 spectra) clearly state the high reverberant interior characteristics of those spaces that make then unsuitable for clear speech intelligibility (in Catholic churches, average RT values above 3 s are usually considered inappropriate).

The RASTI data also confirm those findings with averaged values of 0.28/0.31 (sound system turned off) and 0.30/0.39 (sound system turned on) (Table 3). RASTI values below 0.45 clearly indicate poor speech intelligibility. That Table 3 also shows the minimum increase of RASTI average values by the use of their Sound Reinforcement System (about 0.02/0.08). This means that not even their sound reinforcement systems can really improve the speech intelligibility within those two churches.

Regarding the background noise in these churches due to outside noise (no HVAC systems are present), average sound pressure level (Leq) of 45/48 dB and average sound level (LAeq) of 26/27 dB were found (Table 4). These values indicate that background noise is not a problem in any of these churches.

As seen by the measured results the main acoustic requirements regarding reverberation and speech intelligibility are not met and the interior environment is unsuited for today's Catholic church services.

But are those RT and RASTI values unusual in Catholic churches of those dimensions?

## 4. Comparative analysis

The RT and RASTI measured values were compared to other nine Portuguese churches with similar volume (from the 14th to the 20th centuries). It was concluded that these two modern churches have higher RT values and lower RASTI values, to what could be expected for churches with that volume (Table 5 and Figures 7 and 8).

These two churches really stand out as worse than could be expected. Can we fix them?

**Table 5.** RT (500-1k Hz) and RASTI (without SRS), averaged values for both tested churches in comparison with other nine Portuguese churches with similar volume. [1,2,3,4]

| Church (town) | Volume ($m^3$) | RT 500-1k Hz (s) | RASTI (no SRS) |
|---|---|---|---|
| Our Lady of Conception (Porto) | 12532 | 6.6 | 0.31 |
| Our Lady of Assumption (Santo Tirso) | 9855 | 11.0 | 0.28 |
| New church of Cedofeita (Porto) | 8470 | 3.1 | 0.41 |
| Monastery of Tibães (Braga) | 8608 | 2.7 | 0.45 |
| Monastery of Leça do Bailio (Matosinhos) | 9795 | 4.4 | 0.39 |
| Sé (Silves) | 10057 | 3.9 | 0.34 |
| Lapa (Porto) | 11423 | 5.7 | 0.40 |
| Serra do Pilar (V. N. Gaia) | 11566 | 7.8 | 0.34 |
| S. Francisco (Porto) | 12045 | 1.8 | 0.55 |
| Cathedral (Lamego) | 13424 | 4.6 | 0.38 |
| S. Roque (Lisbon) | 14207 | 3.8 | 0.40 |

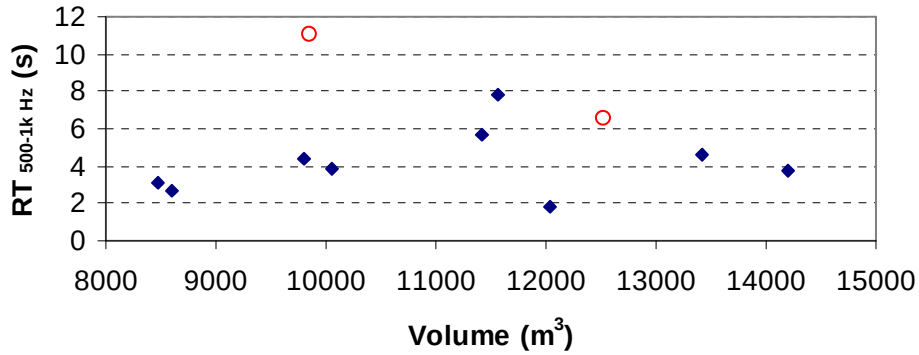



**Figure 7.** RT (500-1k Hz) values for both tested churches (open red circles) in comparison with other nine Portuguese churches with similar volume (blue closed lozenges). [1,2,3,4]

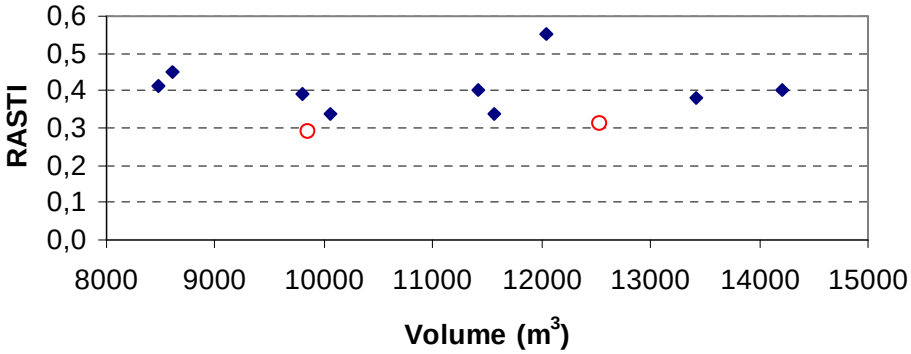



**Figure 8.** RASTI averaged values for both tested churches (open red circles) in comparison with other nine Portuguese churches with similar volume (blue closed lozenges). [1,2,3,4]

## 5. Acoustic rehabilitation

Acoustic corrections were proposed for these two churches in order to decrease their RT values (and to increase RASTI). They include the use of projected absorptive material (*K13* type cellulose fibers) or the use of *BASWAphon* type systems, on the ceiling of the nave. Analyses were done to predict the reverberation time values after the application of these materials.

In the church of Our Lady of Assumption (Santo Tirso) eighteen options of absorptive materials/systems were tested (Fig. 11) to be put on the 540 $m^2$ of the ceiling area (Fig. 9).

In the medium/high frequency bands there are no significant differences among the predicted RT values (about 2.8 ± 0.4 s). In the low frequencies, differences up to 8 s in the 125 Hz can be expected (Fig. 11).

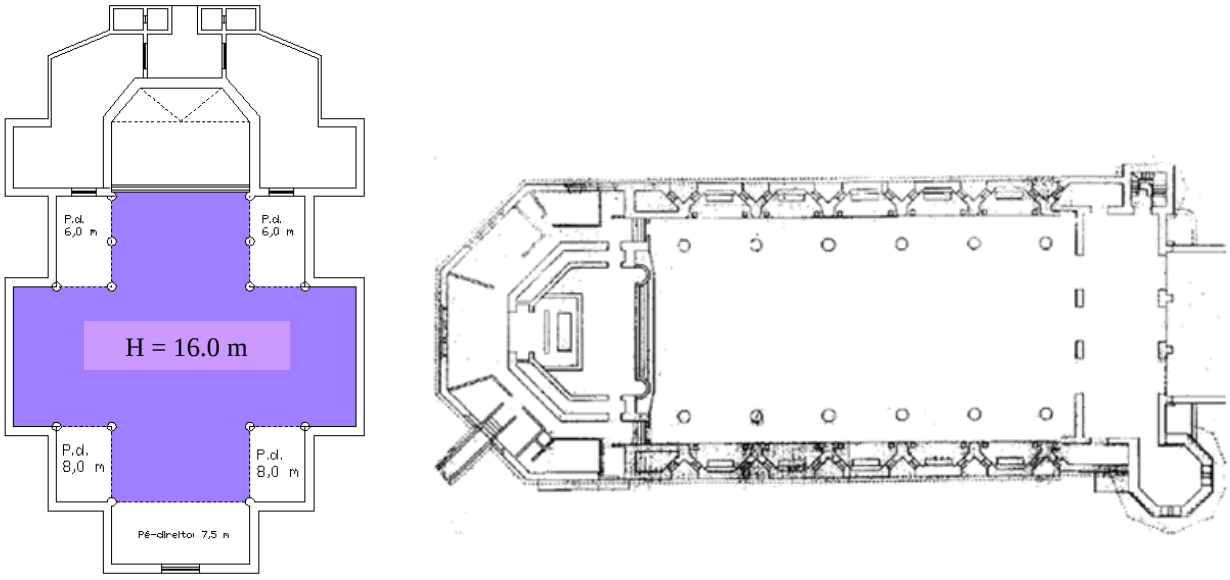



**Figure 9.** (left) Church of Our Lady of Assumption (Santo Tirso). Area (≈ 540 $m^2$) on the ceiling (height = 16.0 m) to be covered with absorptive material. [1]

**Figure 10.** (right) Church of Our Lady of Conception (Porto). Floor plan. [2]

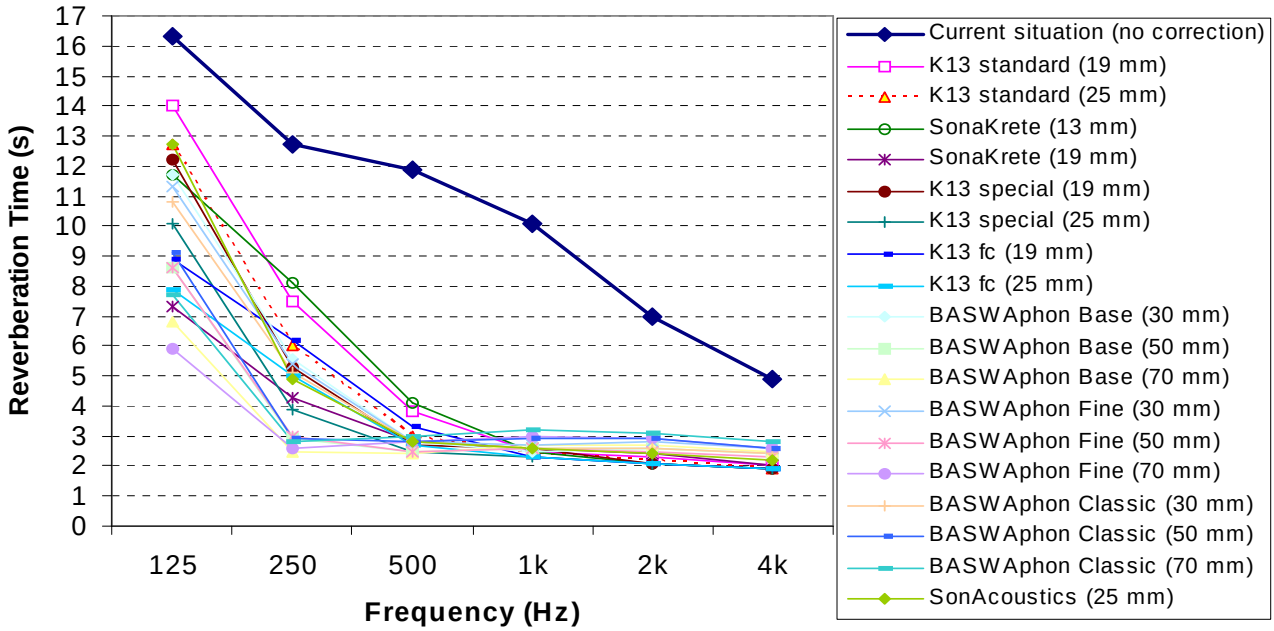



**Figure 11.** Predicted RT spectra regarding each of the eighteen tested options of materials to be used on the ceiling of the church of the Our Lady of Assumption (Santo Tirso) compared with the current situation (no correction). [1]

From those eighteen options, seven were selected to check costs (Table 6). From those, the most adequate and economical solution would be the *K13 special* (19 mm) with about 13,500 € of total cost. A better solution would be the *SonaKrete* (19 mm) but with a triple total cost (about 37,800 €).

In general, the averaged RT can be lowered about 8 s (from 11 s to 3 s) in the 500-1k Hz and at least 4 s in the 125 Hz, at a reasonable cost.

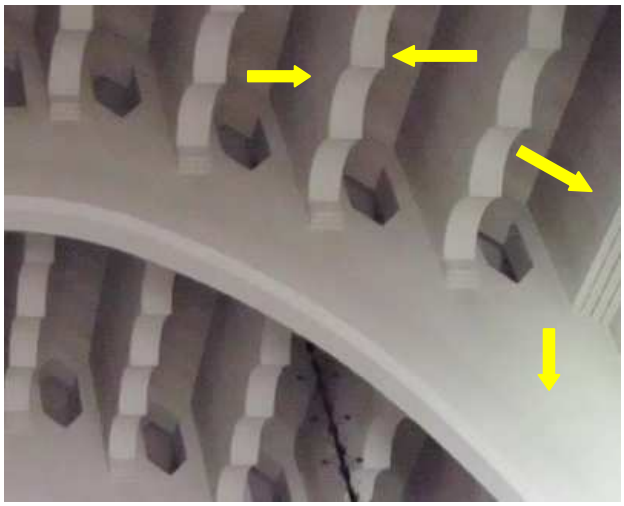
**Table 6.** Church of Our Lady of Assumption (Santo Tirso). Predicted RT average values and projected total costs regarding the seven best options for absorptive materials to be put on the ceiling area shown in Figure 9 (≈ 540 m$^2$). [1]

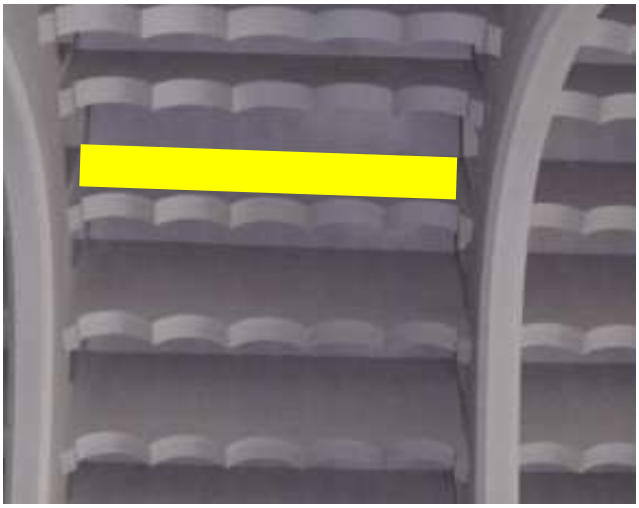
| System | Thickness [mm] | RT predicted [s] | | ΔRT * [s] | Cost by sec. improved in RT ** [€/s] | Total cost [€] |
|---|---|---|---|---|---|---|
| | | 125 Hz | 500-1k Hz | | | |
| *K13 standard* | 19 | 14.0 | 3.2 | -7.8 | 1,600 | 12,400 € |
| | 25 | 12.7 | 2.7 | -8.3 | 1,700 | 14,000 € |
| *K13 special* | 19 | 12.2 | 2.6 | -8.4 | 1,610 | 13,500 € |
| | 25 | 10.1 | 2.4 | -8.6 | 1,800 | 15,100 € |
| *BASWAphon Base* | 30 | 11.7 | 2.7 | -8.3 | 6,800 | 56,700 € |
| | 50 | 8.6 | 2.5 | -8.5 | 7,300 | 62,100 € |
| *SonaKrete* | 19 | 7.3 | 2.7 | -8.3 | 4,600 | 37,800 € |
| Current situation (no corrections) | | 16.3 | 11.0 | - | | |

* = RT with corrections - RT without corrections (for the 500-1k Hz) ** = Total cost / ΔRT

In the church of Our Lady of Conception, Porto (Figure 3) twenty-six options of absorptive materials/systems to be put on the ceiling total area were tested (Figure 10).[2] These options were similar to the ones tested for the church of Our Lady of Assumption (Figure 11).

However in this church the ceiling has a peculiar shape (Figures 4 and 5). It has several "hanging" pieces of concrete (arches and beams) that allow for a creation of deep recesses (Figures 12 and 13). In this church absorptive material was studied to be put on all the deep recesses (like the example in Figure 13) and in both sides of the vertical longitudinal and transversal "hanging" pieces and beams (like the examples in Figure 12). As the sound waves can be "trapped" in these recesses a reducing factor was used in the absorptive coefficient (α) to allow to compensate for the decrease of effectiveness of the material to be put in those areas.





**Figures 12 and 13.** Church of Our Lady of Conception (Porto) - Examples of the proposed areas on the ceiling to put absorptive material (left: both sides on the vertical areas; right: curved "horizontal" areas in the deep recesses between beams). [2]

In the medium/high frequency bands there are no major differences among the predicted RT values (about 1.8 ± 0.3 s).[2] In the low frequencies, differences up to 4 s in the 125 Hz frequency band can be expected.[2]

From those twenty-six options, four were selected concerning total cost and performance (Figure 14 and Table 7). From those, the most adequate and economical solution would be the *K13 special* (32 mm) with a total cost of about 55,000 €. A slightly better solution would be the *SonaSpray fc* (25 mm) but with a total cost of about 82,000 €.

In general, the averaged RT (500-1k Hz) in this church can be lowered about 5 s (from 7 s to 2 s) and circa 2 s in the low frequency (125 Hz).

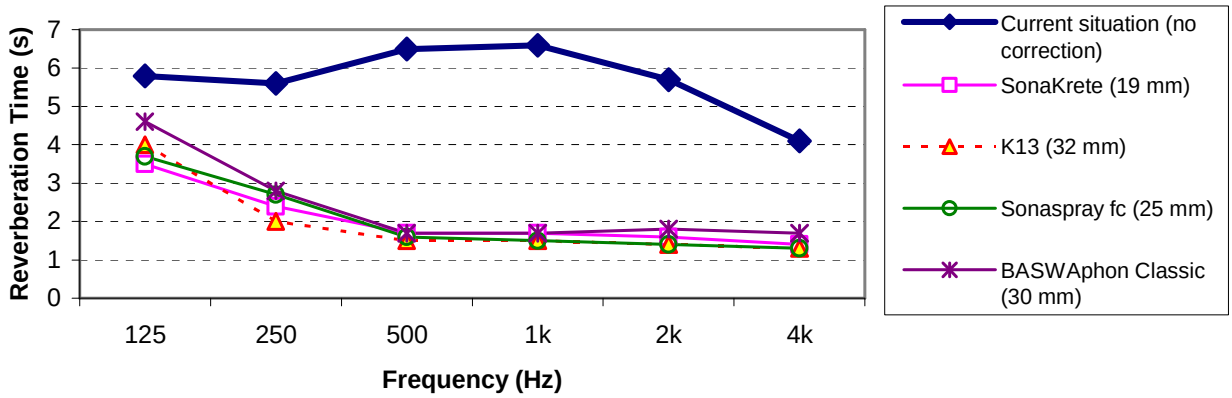



**Figure 14.** Predicted RT spectra regarding each of the four best options of materials to be used on the ceiling of the church of the Our Lady of Conception (Porto) compared with the current situation (no correction). [2]

**Table 7.** Church of Our Lady of Conception (Porto). Predicted RT values and total costs for the four best corrective options. [2]

| System | Thickness [mm] | RT predicted [s] | | ΔRT * [s] | Cost by sec. improved in RT ** [€/s] | Total cost [€] |
|---|---|---|---|---|---|---|
| | | 125 Hz | 500-1k Hz | | | |
| *SonaKrete* | 19 | 3.5 | 1.7 | -4.9 | 19.000 | 93.000 |
| *K13 special* | 32 | 4.0 | 1.5 | -5.1 | 10.800 | 55.000 |
| *SonaSpray fc* | 25 | 3.7 | 1.5 | -5.1 | 16.000 | 82.000 |
| *BASWAphon Classic* | 30 | 4.6 | 1.7 | -4.9 | 46.300 | 227.000 |
| Current situation (no corrections) | | 5.8 | 6.6 | | | |

* = RT with corrections - RT without corrections (for the 500-1k Hz) ** = Total cost / ΔRT

## 6. Conclusions

Two modern churches of the diocese of Porto, Portugal have been facing acoustic problems regarding highly reverberant interior and poor speech intelligibility.

Average RT values of about 7 s and 11 s were measured (with a RASTI of circa 0.30). These values confirm the common subjective impression of the bad acoustic environment because they are well off the reasonable maximum limit of roughly 3 s for the RT and the minimum limit of around 0.45 for the RASTI, usually found desirable in most Catholic churches.

The large interior volume (10,000 and 12,500 $m^3$) with very reflective surfaces is typical of middle twentieth century religious architecture and is the major cause of those detected acoustic problems, not uncommon in many other churches of this period.

Several proposals for the improvement of the acoustic conditions of these two churches were studied, which can considerably decrease the RT values.

It was shown that covering a very large part of the ceiling with an adequate acoustic material, can substantially lower the average RT values (5 s to 8 s in the medium/high frequencies and 2 s to 4 s in the low frequencies bands) with total costs from 14,000 € to 55,000 € (about $18,000 to $72,000 USD).

## ACKNOWLEDGEMENTS

The authors acknowledge and thank to the *CEC – Centro de Estudos da Construção* (FEUP) and the *Institute of Construction* (IC) for their financial and technical support to this work.

## REFERENCES

1 Pereira, G. C. G., *Igrejas Modernas com Problemas Acústicos. O Caso da Igreja do Santuário da N.ª Sr.ª da Assunção (Santo Tirso)*, Master of Science Thesis, Civil Engineering, FEUP - Faculty of Engineering University of Porto, Portugal, (2011).

2 Cruz, M. T., *Igrejas Modernas com Problemas Acústicos. O Caso da Igreja da Nossa Senhora da Conceição (Porto)*, Master of Science Thesis, Civil Engineering, FEUP - Faculty of Engineering University of Porto, Portugal, (2011).

3 Silva, T. E. L., *Guião da Acústica de Igrejas em Portugal*, Master of Science Thesis, Civil Engineering, FEUP - Faculty of Engineering University of Porto, Portugal, (2008).

4 Carvalho, A. P. O., *Influence of architectural features and styles on various acoustical measures in churches*, Ph.D. dissertation, University of Florida, USA, (1994).