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Acoustics of Portuguese Romanesque churches

António P. O. CARVALHO[1]; Francisco M. C. L. M. PEREIRA[2];

[1,2] Laboratory of Acoustics, Faculty of Engineering-FEUP, University of Porto, Portugal

ABSTRACT

This paper summarizes the results of recent measurements in ten very typical Romanesque churches in the North of Portugal to acoustically characterize this type of building. In situ measurements were done regarding Reverberation Time (*RT*) and Rapid Speech Transmission Index (*RASTI*) in empty churches. The results are presented and compared with seven architectural characteristics of the churches (area, volume, ceiling height, length, width, etc.). Statistical correlations and prediction equations are presented among those seven architectural parameters and the two acoustic parameters measured (*RT* and *RASTI*). Values up to 0.91 were found for the related R^2 coefficients.

Keywords: Reverberation Time, *RASTI*, churches

1. INTRODUCTION

The word *church* can have multiple meanings. It can be regarded as an institution, a group of people that take the word of God as a reference and guidance, or it may be considered as a building, where the physical and aesthetical aspects are used to form an adequate location of prayer.

Nowadays, the design of a church considers its Acoustic as one of the strongest, if not the main, priority since this concept must acknowledge all its activities and routines (meditation, speech and music). As a building, a church requires moments of silence as well as moments in which the congregation will need to understand effectively what the orator communicates.

Romanesque architecture was born in the 10th century. After a kind of political stabilization, Western Europe emerges as a consequence of a new society, with demographic expansion, increased mobility, economic growth and significant social and cultural changes. The term *Romanesque* was first written in 1817 by historian C. Gerville, influenced by the culture of the Roman Empire (1).

The building system that defines the Romanesque architecture begins to be defined shortly after the middle of the 11th century. It is in the regions of Burgundy, Languedoc, Auvergne and the Southwest of France plus the kingdoms of Navarre and Castile, which resides the true original artistic creation of this period. (2)

The Portuguese Romanesque style has rural characteristics and is linked to the construction of smaller churches. Depending on the region, these churches would vary in terms of technical quality as well as formal and decorative wealth. The raw materials that were used to construct such churches were the ones more available to each region. In the North of Portugal, it was the general use of granite, in the Center limestone and to the South, brick and *taipa* (a kind of earth structure) (3).

2. METHOD

2.1 Sample

For the execution of this project, certain church features and conditions were chosen among a significant sample, in order to evaluate the acoustic aspects of Romanesque churches. Ten specific churches (show in Table 1 with their respective geometric parameters, and Figures 1 to 6), belonging to the *Rota do Românico do Vale do Sousa*, a cultural and touristic route whose main purpose is to promote, preserve and enhance the architectural heritage (6), in the North of Portugal, were chosen to

[1] carvalho@fe.up.pt [2] miec1208717@fe.up.pt

represent this type of building. In order to select the sample, the churches should gather some specific characteristics:

- Be clearly identified as *Romanesque*, with an important historic background;
- Contain the architectonic and decorative aspects that deeply describe this style;
- Are in full working order, in other words, are not abandoned or in ruins;
- Use granite as the main construction material (walls and facades);
- Be stripped of most interior ornaments and furniture, from earlier periods, as much as possible.

Table 1 – Analyzed churches, GPS locations, and their geometric parameters

Church GPS	V Volume (m^3)	S Surface area (m^2)	H Maximum Height (m)	W Width (m)	L Length (m)	Vn Volume nave (m^3)	Ln Length nave (m)
AIRÃES 41.315055,-8.198615	1249	209	9.55	13.60	20.40	1111	13.49
CETE 41.180636,-8.366329	1515	155	11.80	5.40	28.70	1201	20.20
ESCAMARÃO 41.065948,-8.257106	724	103	7.73	6.20	18.90	596	12.30
FERREIRA 41.264871,-8.343731	2957	230	14.40	8.77	29.40	2400	19.40
GONDAR 41.263531,-8.031465	786	119	7.05	6.60	20.35	626	13.54
ISIDORO 41.207773,-8.143906	574	87	7.56	5.73	17.32	444	10.25
P. SOUSA 41.166071,-8.344658	6028	546	16.80	15.90	43.00	4564	25.10
TELÕES 41.310148,-8.108097	1390	159	9.46	7.60	23.40	1186	17.00
TRAVANCA 41.277676,-8.192871	2801	330	12.80	14.60	28.00	2547	20.30
V. VERDE 41.304861,-8.182076	399	61	7.08	5.37	13.35	293	7.80


Figure 1 - Airães church


Figure 2 - Ferreira church


Figure 3 - Cete church

Figure 4 - Escamarão church

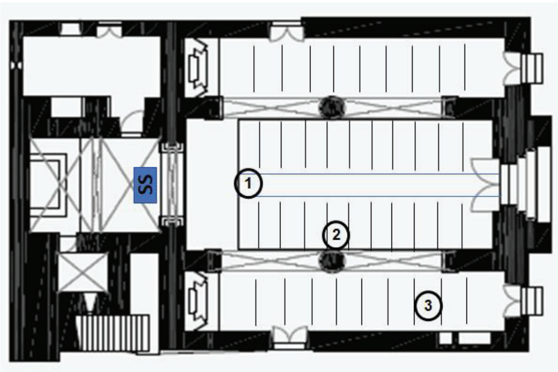
Figure 5 - Gondar church

Figure 6 - Paço de Sousa church

2.2 Investigation

Two types of *in situ* measurements were done during April 2019: Reverberation Time (*RT*) and Rapid Speech Transmission Index (*RASTI*). *RT* values were measured in 1/3 octave bands in each of three set points within each church (Figure 7). *RASTI* values were studied in each of nine different set points within each church (Figure 8), that were divided into three specific zones (*front*, *middle* and *back*) as a function of church length, in order to understand the depth of decay and mean *RASTI* for each of these zones. The equipment used was a sound level meter B&K 2260 B&K, a sound source B&K 4224 and *RASTI* B&K 4419 and 4225.

The ideal *RT* average value in Catholic churches should be approximately 1.0 s (for speech), while for music this value should increase to around 2.0 s or a little more (for example, for organ music). *RASTI* values should be as high as possible in order to achieve suitable speech perception, although values above 0.50 would be acceptable in these cases (4).



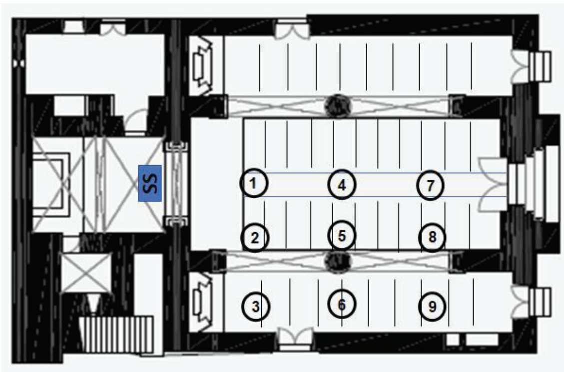


Figure 7 (left) – The three typical *RT* measurement positions in each church, *SS* (sound source)

Figure 8 (right) – The nine *RASTI* measurement positions in each church, *SS* (sound source), (points 1, 2 and 3 are in zone named *front*; 4, 5 and 6 in zone *middle*; 7, 8 and 9 in zone *back*)

3. RESULTS

3.1 Reverberation Time

Figure 9 displays the mean *RT* results obtained from the three measurement points in each church (in total six measurements were used in each point) and Table 2 shows the mean *RT* results. Through the analysis of the mean *RT* values (Figure 9), a decrease from low to high frequencies is observed. This phenomenon occurs in every church, but it is particularly revealed in ones with larger volumetric dimensions, such as the Ferreira, Paço de Sousa, Cete, and Travanca churches, as they present a higher sound absorption. The slight decrease in *RT* values observed in some low frequencies, namely between the 100 and 250 Hz 1/3 octave bands, could be caused by the sound absorption of the existing materials (such as wooden ceilings, paving and ornaments).

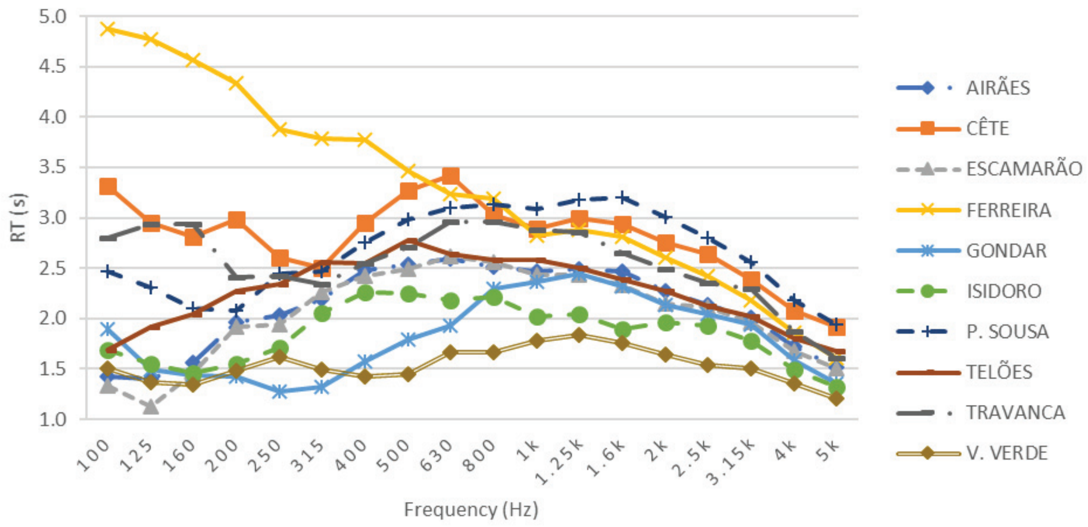


Figure 9 - *RT* values for each 1/3 octave bands in all ten churches of the sample.

Table 2 - Mean *RT* values for each octave band (arithmetic mean of the three bands of the corresponding 1/3 octave band) and mean *RT* values between 400 and 1250 Hz (average of six 1/3 octave bands)

Church	Frequency (Hz)						
	125	250	500	1k	2k	4k	RT_{avg}*(400-1.25k Hz)*
AIRÃES	1.46	2.06	2.54	2.49	2.29	1.75	2.51
CETE	3.03	2.70	3.21	2.97	2.78	2.13	3.09
ESCAMARÃO	1.30	2.04	2.51	2.48	2.20	1.71	2.49
FERREIRA	4.74	4.00	3.49	2.97	2.61	1.88	3.23
GONDAR	1.61	1.34	1.76	2.37	2.16	1.63	2.07
ISIDORO	1.56	1.77	2.23	2.09	1.93	1.53	2.16
P. SOUSA	2.29	2.33	2.95	3.13	3.00	2.23	3.04
TELÕES	1.89	2.39	2.65	2.56	2.26	1.83	2.60
TRAVANCA	3.07	2.39	2.74	2.90	2.50	1.92	2.82
V. VERDE	1.40	1.53	1.51	1.76	1.65	1.36	1.64

3.2 RASTI

Table 3 and figure 10 show the mean *RASTI* results obtained in each of the ten churches. *RASTI* results were compared according to the usual classification conversion table relating to speech intelligibility, as stated in CEI 268-16 that categorizes *RASTI* results on a subjective scale. For values 0 to 0.3 the predicted speech intelligibility is *poor*; 0.30 to 0.45 is *mediocre*; 0.45 to 0.60 is *fair*; 0.65 to 0.75 is *good* and for 0.7 to 1.0 is *excellent* (8).

Once the *RT* values are analyzed it can be verified that the churches with larger dimensions present a *mediocre* mean *RASTI*, particularly Paço de Sousa and Ferreira, with a *RASTIavg* of about 0.38. The remaining churches are also on a *mediocre* intelligibility scale, with the exception of V. Verde and Isidoro that classify as *fair* since they present values of about 0.47, which is probably explained by their smaller volume that enhances speech intelligibility (6).

It is expected for the *RASTI* value to be higher in the *front* zone of the church, however the average value for this zone never exceeds 0.60, which classifies these churches as *fair*, even at their presumed higher speech intelligibility zone.

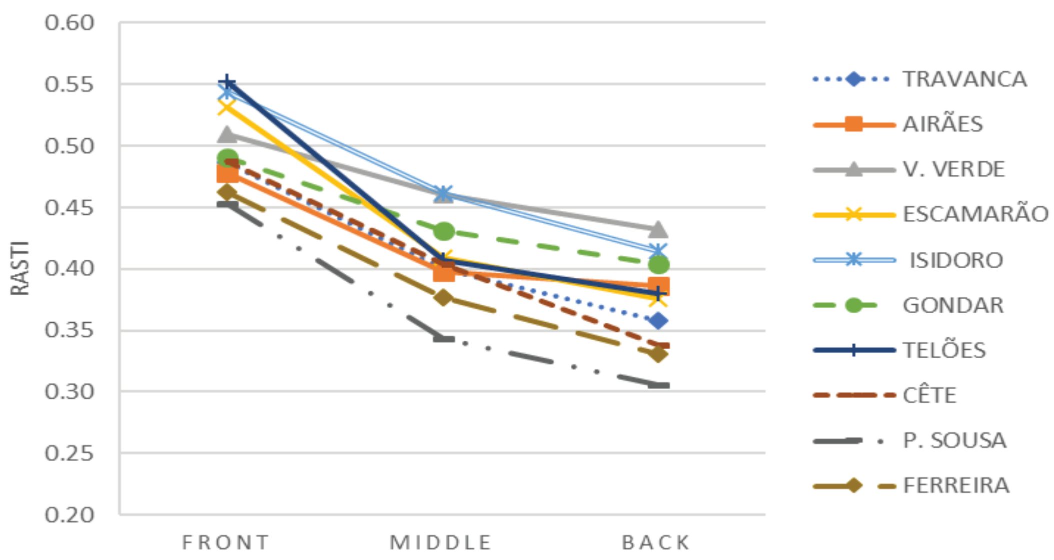


Figure 10 – Mean *RASTI* values measured in each of the three zones (as in figure 8) of each sampled church.

Table 3 – *RASTI* average results in each of the three zones (defined in figure 8)

Church	*Front*	*Middle*	*Back*	$RASTI_{avg}$
AIRÃES	0.48	0.40	0.39	0.42
CETE	0.49	0.40	0.34	0.41
ESCAMARÃO	0.53	0.41	0.38	0.44
FERREIRA	0.46	0.38	0.33	0.39
GONDAR	0.49	0.43	0.40	0.44
ISIDORO	0.54	0.46	0.41	0.47
P. SOUSA	0.45	0.34	0.31	0.37
TELÕES	0.55	0.41	0.38	0.45
TRAVANCA	0.49	0.40	0.36	0.41
V. VERDE	0.51	0.46	0.43	0.47

3.3 Regression Models

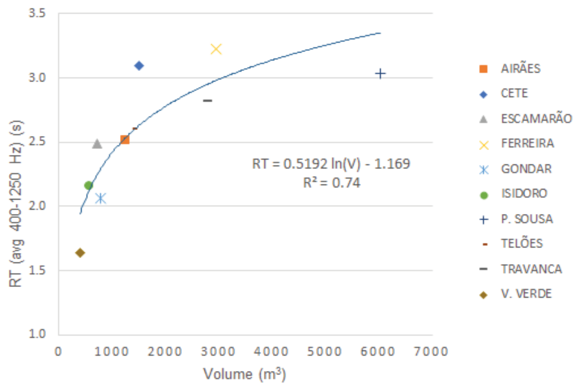
3.3.1 Reverberation Time

The calculated regression models according to the geometric parameters are presented in Table 4. After attempting to raise the correlation coefficient, a sub-set sample containing only the churches with a volume below 2000 m^3 was chosen, as this is the usual size for most the Romanesque churches in this area.

Figure 11 shows that the church with the largest volume (Paço de Sousa), with almost a three times larger volume than Ferreira and Cête churches, presents an inferior $RT_{avg}(400\text{-}1.25k\ Hz)$. This may well be due to the abundance of wooden ornaments and surfaces, and probably because it has been recently renovated as a result of a fire accident. Cête church has a high $RT_{avg}(400\text{-}1.25k\ Hz)$ once compared to its counterparts with similar volumetric characteristics, which could be due to its arched features (coupled spaces) yet mainly because of its large height.

Table 4 – Regression models among *RTavg(400-1.25k Hz)* and geometric parameters of each church.

Geometric parameters	Regression models	*R²*
V -Total Volume (m³)	RTavg = 0.5192 ln(V) - 1.169	0.74
V - Total Volume (sub-set < 2000 m³)	RTavg = 0.1955 $V^{0.367}$	0.80
S - Surface Area (m²)	RTavg = 0.6915 $S^{0.253}$	0.61
H - Maximum Height (m)	RTavg = 1.4346 ln(H) - 0.733	0.79
W - Maximum Width (m)	RTavg = 1.5071 $W^{0,243}$	0.24
L - Length (m)	RTavg = 1.3497ln(L) -1.672	0.78
Vnave - Volume Nave (m³)	RTavg = 0.5102 ln(Vnave) - 0.998	0.75
Lnave - Length Nave (m)	RTavg = 0.5865 $Lnave^{0.537}$	0.83



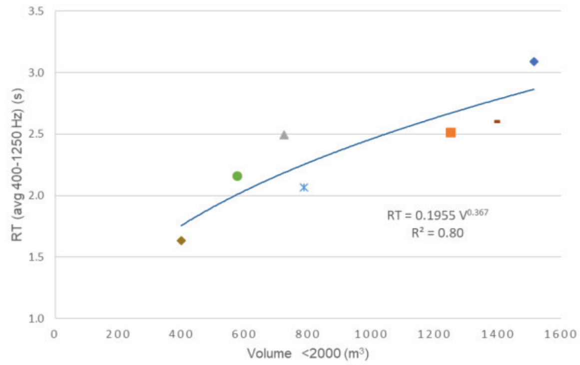


Figure 11 (left) - Relationship between RT_{avg}*(400-1.25k Hz)* and *Volume* for each church

Figure 12 (right) - Relationship between RT_{avg}*(400-1.25k Hz)* and *Volume* (subset V < 2000 m³).

3.3.2 *RASTI*

The *RASTI* regression values as a function of each geometric parameter are presented in Table 5. Unlike the data observed in the *RT*, these equations show the decrease in *RASTIavg* values as *Volume* increases. This illustrates that the acoustic quality of a church is strongly dependent on its *Volume*, which means that, the larger the volume, the more surface areas are available to produce destructive reflections, thus this will originate a lower speech intelligibility.

Table 5 – Regression between *RASTIavg* and the geometric parameters of each church

Geometric parameters	Regression models	*R²*
V - Total Volume (m³)	*RASTIavg* = 0.7988 $V^{-0.087}$	0.87
V - Total Volume (sub-set < 2000 m³)	*RASTIavg* = -0.037 ln(V) + 0.693	0.64
S - Surface Area (m²)	*RASTIavg* = 0.7399 $S^{-0.108}$	0.81
H - Maximum Height (m)	*RASTIavg* = 0.5333 $e^{-0.022H}$	0.88
W - Maximum Width (m)	*RASTIavg* = 0.5571 $W^{-0.127}$	0.48
L - Length (m)	*RASTIavg* = 0.8453 $L^{-0.218}$	0.85
Vnave - Volume Nave (m³)	*RASTIavg* = 0.7678 $Vnave^{-0.084}$	0.85
Lnave - Length Nave (m)	*RASTIavg* = -0.0055 Lnave + 0.515	0.81

3.4 *RASTI* vs *RT*

Figure 13 demonstrates the relationship between $RT_{avg}(400\text{-}1.25k\ Hz)$ and the *RASTIavg* in this sample. The combination of these two parameters is important in order to understand and validate the veracity of the tests carried out, since they create a negative linear relationship in which high *RASTI* values are linked to low *RT* values.

Table 6 illustrates the best regressions between *RASTI* and isolated 1/3 octave frequency bands of the *RT*. The best regressions belong to the higher frequency bands (especially 1.25 and 2 kHz) which is probably partially due to the lower standard deviation value observed between these bands, demonstrating their homogeneity, and the importance of the *RASTI* values in this frequency domain.

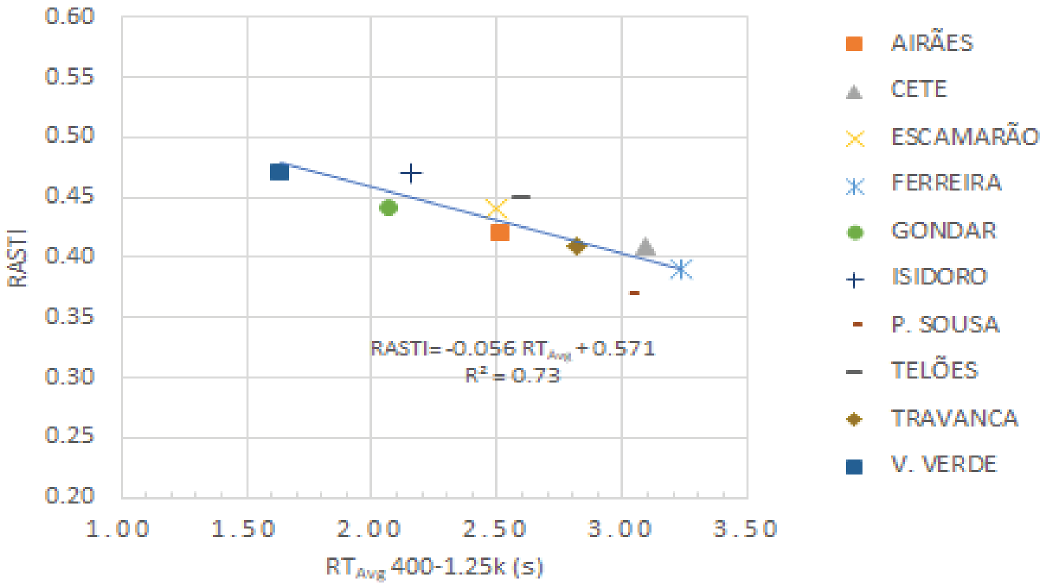


Figure 13 – Relationship between mean $RASTI_{avg}$ and $RT_{avg}(400\text{-}1.25k\ Hz)$ values

Table 6 – Best regressions between $RASTI_{avg}$ and isolated *RT* 1/3 octave frequency bands

1/3 octave frequency band (Hz)	Regression models	R^2
800	$RASTI_{avg}$ = -0.0611 RT_{800} + 0.587	0.79
1000	$RASTI_{avg}$ = -0.0733 RT_{1k} + 0.613	0.83
1250	$RASTI_{avg}$ = -0.0736 $RT_{1.25k}$ + 0.616	0.88
1600	$RASTI_{avg}$ = -0.0704 $RT_{1.6k}$ + 0.601	0.91
2000	$RASTI_{avg}$ = -0.0771 RT_{2k} + 0.607	0.86
2500	$RASTI_{avg}$ = -0.0821 $RT_{2.5k}$ + 0.609	0.82
3150	$RASTI_{avg}$ = -0.0976 $RT_{3.15k}$ + 0.629	0.82
4000	$RASTI_{avg}$ = -0.1142 RT_{4k} + 0.628	0.77
$RT_{avg}(400\text{-}1.25k\ Hz)$	$RASTI_{avg}$ = -0.056 RT_{avg} + 0.571	0.73

3.5 *RASTI* vs *RT* and geometric parameters

The combination between $RASTI_{avg}$ and RT_{avg} values resulted in a high R^2 value, which represents that the mean *RASTI* values are strongly explained by the variations in RT_{avg}.

A multiple linear regression was elaborated with *RASTI* average values as a function of RT_{avg} and all geometric parameters (Table 7). The high values of R^2 (about 0.9) clearly show that there is a strong correlation among these parameters.

Table 7 – Multiple regressions of *RASTI* average values as a function of $RT_{avg}(400\text{-}1.25k\ Hz)$ and geometric parameters

Geometric parameters	Regression models	R^2
V - Total Volume (m^3)	$RASTI_{avg} = -0.0324\ RT_{avg} - 1.026x10^{-5}.V + 0.529$	0.89
S - Surface Area (m^2)	$RASTI_{avg} = -0.0351\ RT_{avg} - 1.158x10^{-4}\ S + 0.540$	0.89
H - Maximum Height (m)	$RASTI_{avg} = -0.0156\ RT_{avg} - 0.00706\ H + 0.540$	0.88
W - Maximum Width (m)	$RASTI_{avg} = -0.0446\ RT_{avg} - 0.003085\ W + 0.569$	0.85
L - Length (m)	$RASTI_{avg} = -0.0225\ RT_{avg} - 0.002479\ L + 0.545$	0.87
Vnave - Volume nave (m^3)	$RASTI_{avg} = -0.0309\ RT_{avg} - 1.363x10^{-5}\ Vnave + 0.527$	0.89
Lnave - Length nave (m)	$RASTI_{avg} = -0.0186\ RT_{avg} - 0.00399\ Lnave + 0.538$	0.82

4. CONCLUSIONS

Regarding *RT*, none of the examined churches demonstrated the ideal acoustical values for speech (between 0.8 and 1.0 s), solely the ones of smaller volume attained a better performance (but we may need to remember that in Romanesque times, religious services were held in Latin…). This is also the result of the Romanesque constructive system that is a quite simple style, with small amounts of ornaments, and in this area, predominantly uses the granite, which causes strong reflections. The best RT_{avg} results belong to the churches with volume below 2000 m^3, obtaining values between 1.6 and 2.5 s, which prove to be suitable for most musical purposes.

The values of speech intelligibility (*RASTI*) are in general *fair* and the worst results registered (about 0.38 in P. Sousa and Ferreira) can be justified by the fact that these were the churches with the largest *volume*.

The calculated regressions that were analyzed for *RT* and *RASTI* resulted in R^2 values that were all close to 0.9, which represents a positive correlation and reliable use of these models for prediction. The geometric parameter that most influenced Romanesque church acoustics was *Length of nave* (*Ln*) for the RT_{avg}, and *Height* for the $RASTI_{avg}$.

Maximum Width obtained very low individual R^2 values for both acoustic parameters (*RT* and *RASTI*); however, by crosschecking this feature with a multiple regression model, it reached figures close to the maximum.

The best regression in this paper, with an outstanding R^2 value of 0.91 was observed for the $RASTI_{avg}$ values as a function of the 1600 Hz 1/3 octave frequency band values.

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