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Sound absorption characterisation of woven materials. Case study: auditorium restoration

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ABSTRACT

Nowadays building conservation and refurbishment draw the attention of the world we live in. In particular, in the public sector, the change of occupancy is commonly used in order to maintain the existing functional layout of spaces and the original structure of the building. Further improvements need to be also considered in order to save the indoor environmental quality. A case study is provided below by the analysis of acoustical performances of an auditorium in Italy, the historical S. Giorgio Palace in Genoa. The palace was built in 1260 and it was the most important public palace in the town; afterwards it became the headquarters of the Port Authority in 1903. Although the high reflective materials covering the interior surfaces provide high values of reverberation time, the hall is mainly used as a conference hall. The acoustical project of restoration, approved by the Ministry of Italian Cultural Heritage, allows only the application of woven materials for floor and curtains, which can be easily removed in case of a change of destination to respect the historical and architectural value of the hall. Acoustical measurements, by means of the impedance tube, have been performed up to now in order to define the best woven materials to improve the overall acoustic performances of the hall. The normal incidence sound absorption coefficient of different samples of carpet have been tested. A procedure for the samples location in impedance tube measurements has been outlined. Carpet is a textile material with a good sound absorption, mainly at high frequencies. In order to improve its acoustic properties at low frequencies a multilayer system composed of carpet and felt having different characteristics have been experimentally investigated and the optimal configuration has been defined.

1. INTRODUCTION

The Headquarters of the Port Authority of Genoa, are hosted in S. Giorgio Palace, located in the centre of the medieval port area of the city. In San Giorgio Palace, there is the Hall "Sala delle Compere". The palace was built in 1260, and it was the most important public palace of Genoa and afterwards it became the headquarters of the Port Authority in 1903. Even though the hall has an average value of reverberation time of 6 s. [1], it is used as a conference hall.

Under the supervision of the Ministry of Italian Cultural Heritage, in accordance with [2, 3] an experimental measurement campaign on the spot was carried out in order to determine the hall acoustic behaviour and to define the acoustical properties of the existing components of the interior envelope. Furthermore, an analysis of suitable materials and some numerical simulations [1] was performed with the aim of enhancing the interior acoustic performance in the hall with the application of different sound-absorbing materials. Due to the high level of reversibility offered by their application, woven materials are being considered as covering material for floor surfaces and curtains.

Even though some analysis [4, 5, 6, 7] have been undertaken of these particular types of materials, a deeper knowledge of sound propagation through textile materials is of prime importance for evaluating the noise absorption capacities of woven fabrics which can serve as absorbent materials and noise control elements in a wide range of applications.

2. THE PRELIMINARY ACOUSTIC PROJECT OF RESTORATION

The hall (figure 1, 2) is located on the first floor of S. Giorgio palace and has a rectangular plan with a volume of 6000 m^3 and a floor area of 500 m^2.

Figure 1. Interior view of Sala delle Compere

Figure 2. Ceiling of Sala delle Compere

2.1. Experimental campaign of Sala delle Compere

Through experimental measurements, carried out in accordance with ISO 3382 [2], the acoustic behavior of the hall has been determined. In order to understand the spatial distribution of the acoustical parameters, 9 receiver positions have been investigated (figure 3). The experimental results of T20, D50 and C50 as a function of frequency for all the 9 positions are reported respectively in figure 4, 5 and 6.

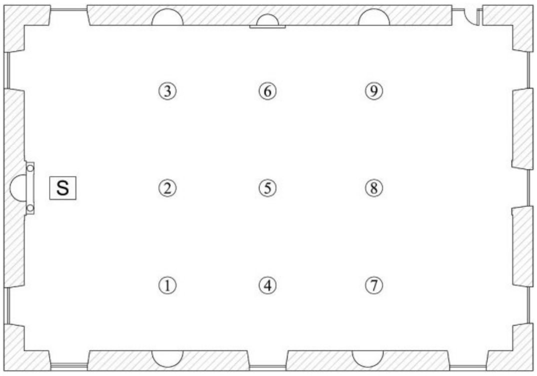

Figure 3. Receivers position

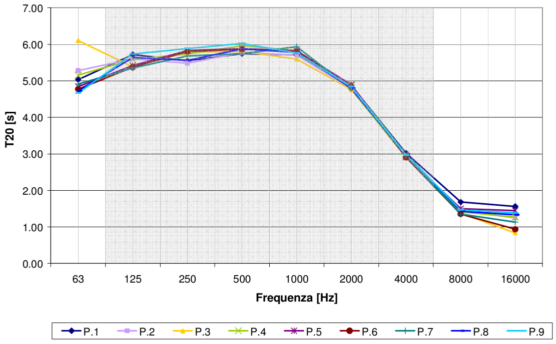

Figure 4. T20 versus frequency in the 9 positions

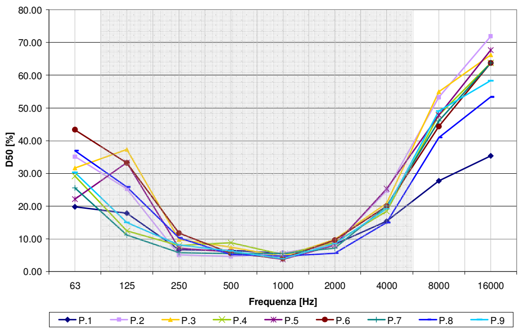

Figure 5. D50 versus frequency in the 9 positions

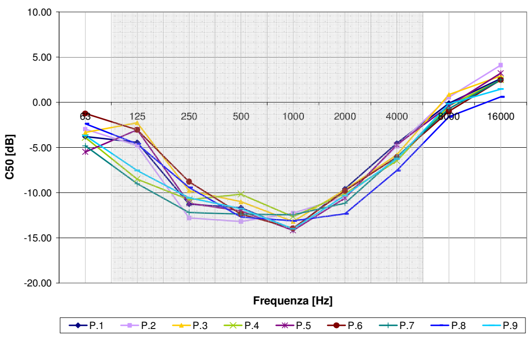

Figure 6. C50 versus frequency in the 9 positions

There is not a significant variation of the acoustical parameters, T20, C50 and D50 among the 9 receiver position, while there is a great difference in the frequency domain. For example Reverberation Time T20 reaches a minimum value of 1 s at 16000 Hz and a maximum value of 6 s at 63 Hz. In the frequency domain more interesting for speaking, between 125 to 4000 Hz, the medium reverberation time is above 5 seconds, while in environments for listening comprehension, the optimal reverberation time should be around 1 s [7]. Also C50 and D 50 do not have a significant spatial variance, especially at medium frequencies. But their values are not suitable for a conference hall: D50 at medium frequencies is around 10% while optimal values should be above 50%; .C50 varies from -14 dB up to + 4 dB, only at 16000 Hz, while optimal values should be above 3 dB.

2.2. Numerical simulations

The acoustic project of the hall restoration, approved by the Ministry of Italian Cultural Heritage, has allowed the following modifications:

- Acoustic plaster in the lateral walls (extension of 890 m^2);
- Curtains to cover the existing windows (extension of 84 m^2);
- Carpet on the existing marble floor reproducing the same design in black and white (extension of 484 m^2);

In order to investigate the efficacy of the identified project numerical simulations with RAMSETE pyramid tracing software have been carried out. The tridimensional model used for the simulation is presented in figure 7.

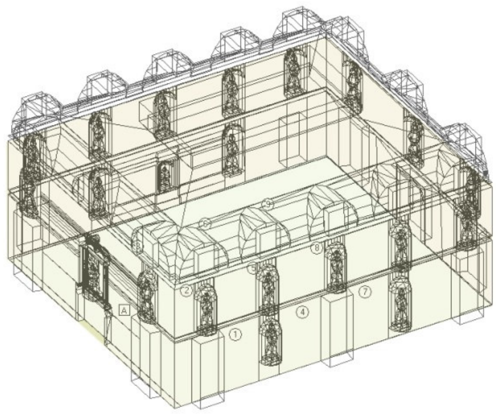

Figure 7. Tridimensional model used for numerical simulation

The absorption coefficient used for numerical simulations are reported in table one. Data were collected by literature [7]. The materials with the star (*) are the ones used to simulate the acoustic behaviour of the hall after restoration.

Table 1. Absorption coefficient as function of frequency used in the numerical simulations. (*material used in the acoustic project of restoration)

Materials	*S [m^2]*	*Absorption coefficient as function of frequency [Hz]*				
		250	*500*	*1000*	*2000*	*4000*
Plaster (2 m)	205.31	0.05	0.06	0.08	0.04	0.06
Marble	50.78	0.05	0.05	0.05	0.05	0.05
Wood	36.24	0.20	0.15	0.10	0.15	0.10
Gypsum	593.11	0.15	0.10	0.05	0.05	0.05
Glass	80.17	0.06	0.04	0.03	0.02	0.02
Carpet*	484.15	0.10	0.30	0.50	0.65	0.70
Curtains*	83.65	0.15	0.35	0.40	0.50	0.50
Acoustic Plaster *	889.81	0.08	0.15	0.29	0.29	0.33

Results of the simulation model of the hall in the existing state have been compared with experimental ones and a good accordance was found. In figure 8 and 9, respectively, spatial values of T20 of numerical simulations before and after restoration are reported. T20 before restoration varies from 5.72 to 5.82 s, while after restoration T20 is considerely reduced up to 1 s. Therefore the optimum values of reverberation time [7] for conference hall are reached with the outlined project.

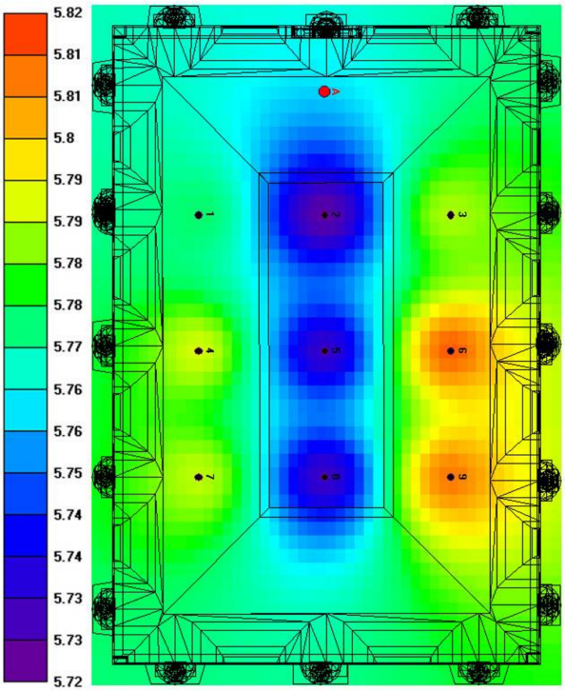

Figure 8. Spatial values of T20 obtained by the numerical simulation "ante operam" of the hall

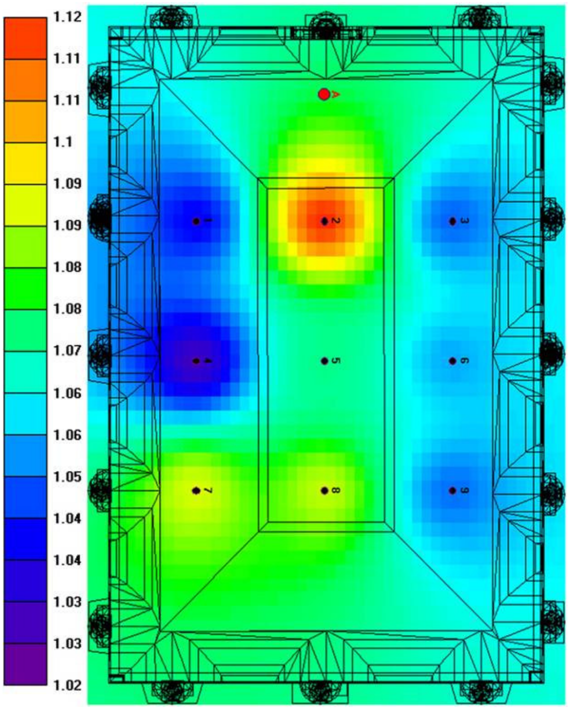

Figure 9. Spatial values of T20 obtained by the numerical simulation "post operam" of the hall

Values of D50 before and after the project of restoration are shown in figures 10 and 11. Also post operam simulated

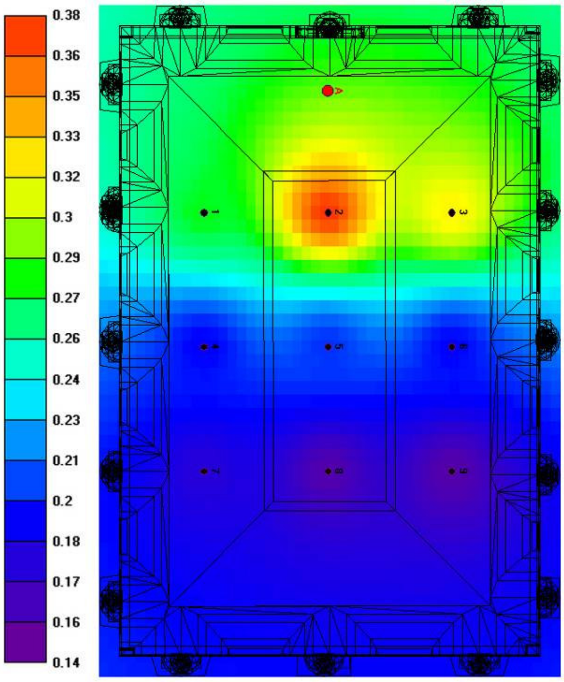

Figure 10. Spatial values of D50 obtained by the numerical simulation "ante operam" of the hall

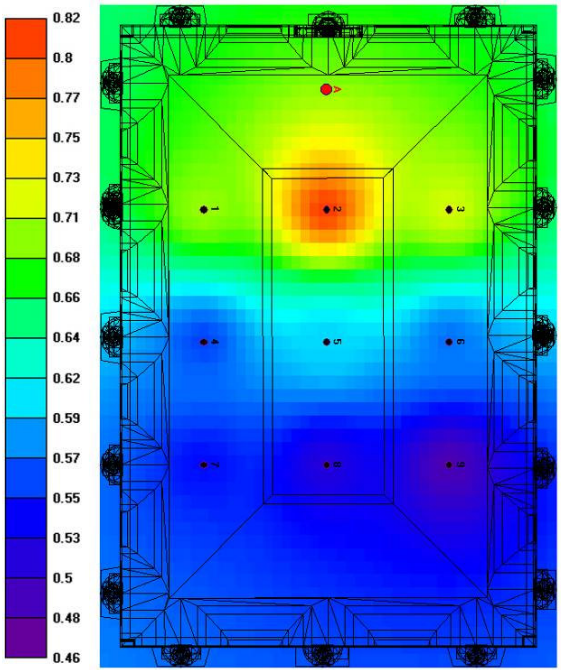

Figure 11. Spatial values of D50 obtained by the numerical simulation "post operam" of the hall

values of D50 are confirming the effectiveness of the defined solution, since future values of D50 are improving the hall definition. From values of 0.14 – 0.30 %, in the actual state, D50 is incresing up to 82% after restoration.

Clarity values of C50 in the existing and future layout have been simulated and results are reported in figures 12 and 13. Also clarity index is ammeliorating after restoration: from minimum values of -8 dB and maximum values of -2 dB in "ante operam" state, C50 achieves values of + 6.5 dB in the "post operam" configuration.

In conclusion, simulated values of T20, D50 and C50 are all demonstrating the acoustic efficiency of the outlined project of restoration.

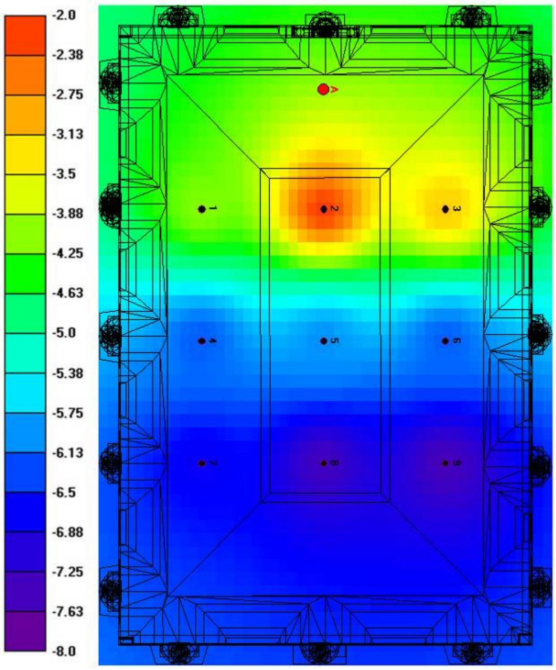

Figure 12. Spatial values of C50 obtained by the numerical simulation "ante operam" of the hall

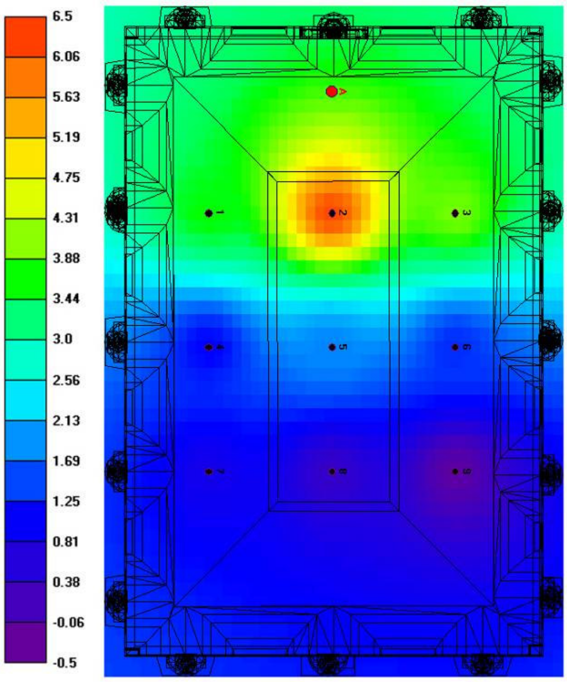

Figure 13. Spatial values of C50 obtained by the numerical simulation "post operam" of the hall

3. ANALYSED SAMPLES OF WOVEN MATERIALS

With the aim to better define the best woven materials to be used in the restoration, experimental measurements have been carried out in order to provide a better understanding of the acoustical properties of woven materials in their application as covering for floors. In order to improve absorption at low frequencies a multilayer system has been experimentally investigated, coupling two different types of materials: carpets and felts. In addition, in this particular case study of "Sala delle Compere", the existing marble floor had to be protected and the felts will also fulfill this necessity.

3.1. Carpet

In order to comply with requirements set by the Ministry of Italian Cultural Heritage were selected carpet manufacturers able to reproduce the design of the floor in black and white of the existing marble floor (figure 1). Two manufacturers were found and 6 different carpet samples were tested, diverse for composition, thickness and mass per unit area. In table 2 the characteristics of each carpet sample are described.

Table 2. Description of the analysed samples of carpet

Test Sample	*Composition*	*Total Thickness [mm]*	*Mass per unit area [g/m^2] of Fibre + Support*	*Colour*
A	100% Wool	12	3934	Brown (Spotted) Cow
B	100% Wool	8	2925	Dark Blue Plain
C	80% Wool 20% Polyamide	14	2752	Brown & Green
D	80% Wool 20% Polyamide	12	3809	Purple Veined
E	80% Wool 20% Polyamide	10	3296	Ochre Plain
F	100% Polyamide	12	2548	Electric Blue with Yellow Pictures

As an example, in figure 14 the sample B is represented, in diameters 100 mm and 30 mm.

Figure 14. Sample B

3.2 Felt

Two different types of felt, have been tested. The characteristics of each felt are reported in table 3.

Table 3. Description of the analysed samples of felt

Test Sample	*Composition*	*Total Thickness [mm]*	*Mass per unit area [g/m^2] of Fibre + Support*	*Colour*
NW3	100% Polyester Needle-punched	3	800	Raw Marlin
NW4		4	950	

As an example, in figure 15 the felt sample of 4 mm thickness (NW4) is represented, in diameters 100 mm and 30 mm.

Figure 15. Felt sample NW4 (4 mm thickness)

4. ABSORPTION COEFFICIENT MEASUREMENT METHOD

The normal incidence absorption coefficient, α_n, has been experimentally determined according to EN ISO 10534-2: 2001 [8], using an impedance tube with two microphones. The spectral range of interest is achieved by two different measurement setup of Kundt tube, summarized in table 4. The analyzed frequencies range is from 400 Hz to 4200 Hz. The lower working frequency is due to the accuracy of the signal processing equipment. The upper working frequency has been chosen to avoid the occurrence of non-plane wave mode propagation.

Table 4. Range of reliability of impedance tube

Diameter [mm]	*Spacing [mm]*	*Frequency f_{min} [Hz]*	*Frequency f_{max} [Hz]*
100	50	400	2000
	100	172	2000
30	20	858	4200

During the experimental measurements the following procedures have been followed, relating to the positioning of the sample material inside the impedance tube:

- samples thickness has been measured with the aid of a gauge and the same distance has been kept between the back plate of the sample holder and the specimen front surface in order to avoid excessive pressure on the samples while mounting them,
- the homogeneity of the carpet hair on the entire sample surface has been checked.

5. ABSORPTION COEFFICIENT RESULTS OF THE SINGLE LAYER SYSTEM

5.1. Experimental characterization of carpet

Each single sample of carpet described in table 2 has been tested and the values of the normal incidence absorption coefficient are shown in figure 16. All the samples provide good performance at high frequencies, but they are not very efficient below 1000 Hz.

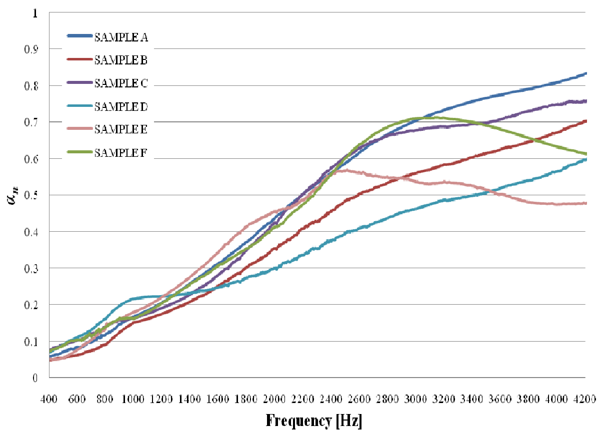

Figure 16. Normal incidence absorption coefficient for the various samples of carpet

The most performing type of carpet is the one represented by sample A, which is the thickest of the 100 % wool samples. The influence on the variation of thickness and composition have been investigated.

5.1.1. Thickness effects on α_n

In figure 17 a comparison between samples, made of the same material (80% wool, 20% polyamide) but characterised by different thickness (10 - 12 - 14 mm), is shown.

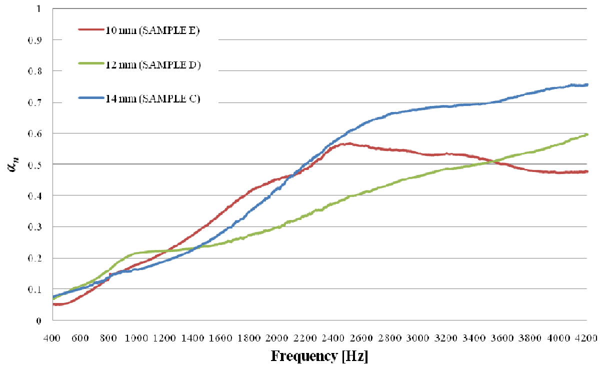

Figure 17. Comparison between α_n of samples with same composition (80% Wool, 20% Polyamide), but different thickness (10 - 12 - 14 mm).

Figure 18 shows the differences between two 100% wool carpets having thickness of 8 and 12 mm.

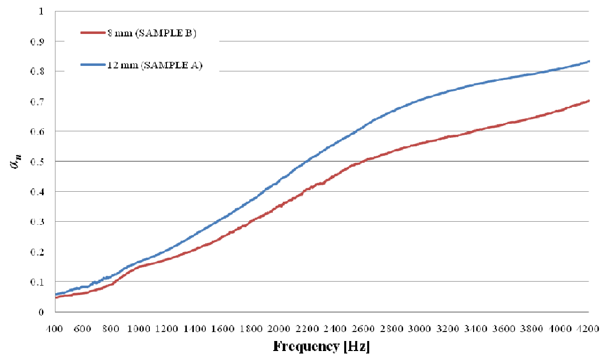

Figure 18. Comparison of α_n of samples with same composition (100% Wool) but different thickness (8 - 12 mm).

It can be noticed that the effect of the increasing thickness is more regular when the carpet is entirely made of the same material (100% wool), rather than two (80% Wool, 20% Polyamide).

5.1.2. Fibre composition effects on α_n

Figure 19 shows that, for high frequencies, 100% wool fibre (sample A) returns an α_n higher than 100% polyamide fibre (sample F), though having the same thickness.

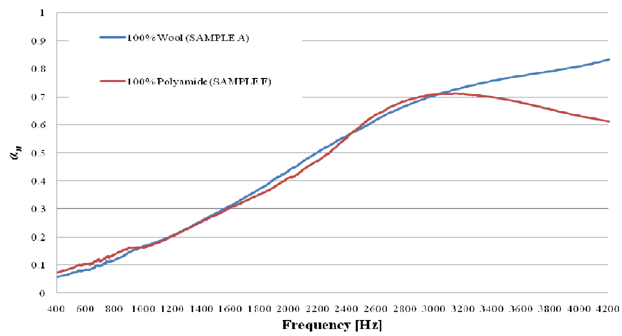

Figure 19. Comparison of α_n of samples with same thickness (12 mm), but different composition (100% Wool and 100% Polyamide).

The absorption behaviour is coincident up to 3000 Hz, after this frequency the sample F, made of 100% polyamide, decreases its acoustic performances while sample A, made of 100% wool, are augmenting.

5.1.3. Consideration on sample F

Test carpet F (Fig. 20) is a particular kind of sample, because the carpet is coupled with a resilient felt. Comparing its absorbing behavior with the other samples of carpet (Fig. 16), it can be affirmed that the absorption coefficient of the sample F is the lowest, although the felt was already applied to the support.

Figure 20. Sample F

In addition, for this sample the α_n curves measured with high frequency tube and low frequency tube do not match. The gap between α_{low} and α_{high} can be noticed in Figure 21.

This is probably due to the fact that this sample is made of three different layers: the carpet, the support and the felt. Therefore, between the rigid back of the sample holder and the rigid carpet support there's a resilient layer. The measured α_n is probably affected by some resonance frequency of the free vibrating rigid carpet support.

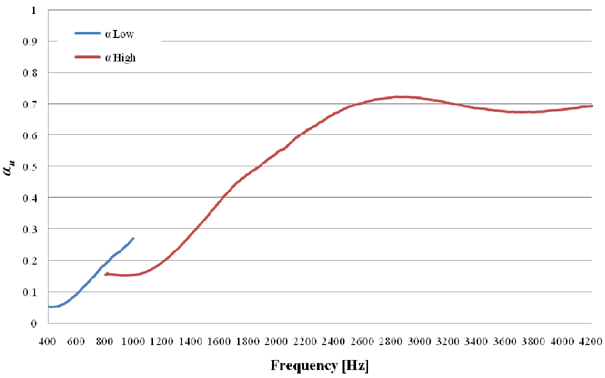

Figure 21. Sample F: gap between α_{low} and α_{high} curves around 1000 Hz frequency.

5.2. Experimental characterization of felt

Figure 22 shows the α_n coefficient obtained from sound absorption tests performed on the felt samples described in Table 3. As foreseeable for porous materials [9], the increasing thickness of the felt corresponds to an increasing absorption coefficient effect.

6. ABSORPTION COEFFICIENT OF A DOUBLE LAYER SYSTEM

Particularly interesting are the results arising by coupling the original carpet with felts made of polyester fibres. As a first step, all the samples with the two types of felt are analyzed together, then, as a second step, considerations on every single sample, by itself and in the double layer system, are carried out.

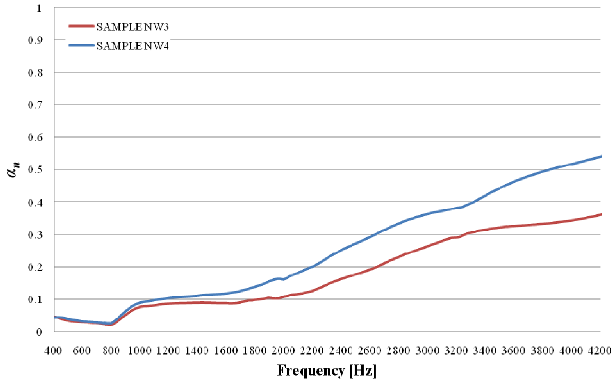

Figure 22. Comparative spectra of α_n for felt samples in the frequency range 400 - 4200 Hz.

Figure 23 shows the results obtained from sound absorption tests performed on each sample of carpet, coupled with a felt polyester fiber thickness of 3 mm.

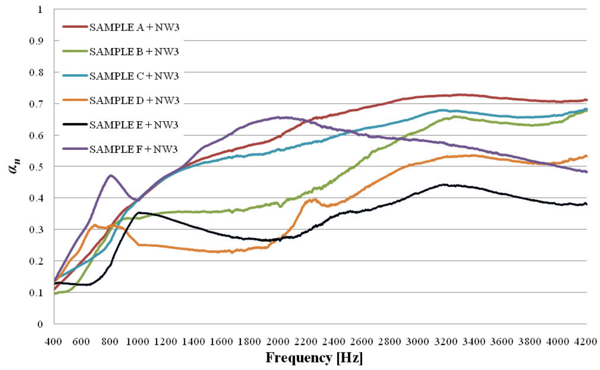

Figure 23. Absorption coefficient spectrum for all the 6 coupled system carpet + 3 mm thick felt in the frequency range 400 - 4200 Hz.

Figure 24 shows, in the 3rd octave frequency bands, the results obtained by sound absorption tests performed on each sample of carpet, coupled with a felt polyester fiber thickness of 4 mm.

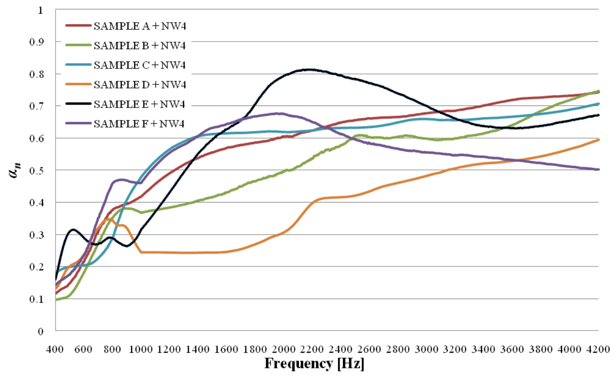

Figure 24. Absorption coefficient spectrum for all the 6 coupled system carpet + 4mm thick felt, in the frequency range 400 - 4200 Hz.

The choice of the most appropriate coupled-system to be used for the acoustic correction of the specific case study depends heavily by the objective to be achieved. In order to select the optimal configuration in tables 5 and 6 report the percentage of increase [%] of the absorption coefficient α_n, obtained by the double layer system compared to the one layer system.

$$\%\Delta\alpha_n = \frac{\left(\alpha_{carpet+felt} - \alpha_{carpet}\right)}{\alpha_{carpet}} \quad (1)$$

Where:

$\alpha_{carpet+felt}$ is the measured absorption coefficient of the coupled system carpet and felt (double layer system)

α_{carpet} is the measured absorption coefficient of the carpet by itself (single layer system).

Table 5. Percentage increase of sound absorption measured on the coupling carpet / felt (3mm)

Test Sample	A	B	C	D	E	F
% $\Delta\alpha_n$	49	57	84	40	11	53

Table 6. Percentage increase of sound absorption measured on the coupling carpet / felt (4mm)

Test Sample	A	B	C	D	E	F
% $\Delta\alpha_n$	58	68	102	81	96	50

As it can be remarked in tables 5 and 6, sample C guarantees the highest percentage increase of absorption in both configurations, with the felt of 3 and 4 mm. Figure 25 shows the comparison of the absorption coefficient of sample C by itself and by adding the two different types of felt.

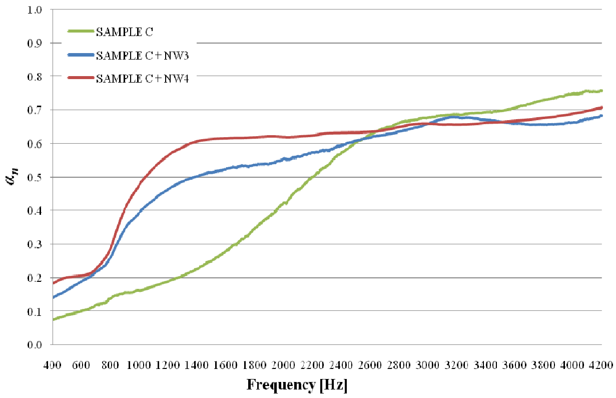

Figure 25. Absorption coefficient spectrum for sample C at different configurations in the frequency range 400 - 4200 Hz

Therefore, if the aim is to accomplish good performance at frequencies in the range of speech, then the optimal solution is the one represented in figure 25, referring to the coupled-system carpet (sample C) plus 4mm thick felt (NW4). This configuration ensures a high value and a proper distribution of the absorption coefficient.

Aiming to analyze the effect of the two layers system in comparison with the one layer system, all the different sample in the three configurations are presented from figure 26 to figure 30.

As a tendency, the double layers systems present always an increase of absorption in lower frequency domain, ameliorating the acoustic performance of the single layer carpet. A singular behavior is reached by the sample F (Figure 26), which is the only one already coupled with a resilient material: the addition of another layer does not improve its performances.

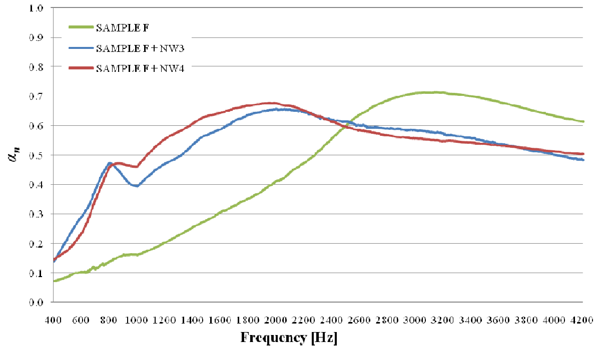

Figure 26. Absorption coefficient spectrum for sample F at different configurations in the frequency range 400 - 4200 Hz

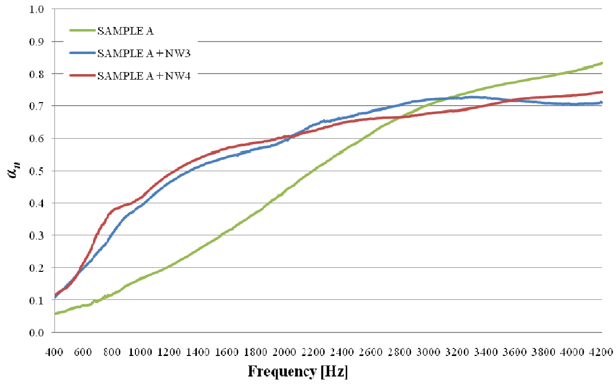

Figure 27. Absorption coefficient spectrum for sample A in different configurations in the frequency range 400 - 4200 Hz

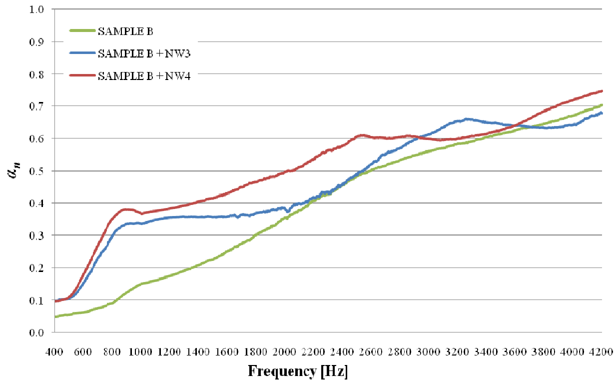

Figure 28. Absorption coefficient spectrum for sample B in different configurations in the frequency range400 - 4200 Hz

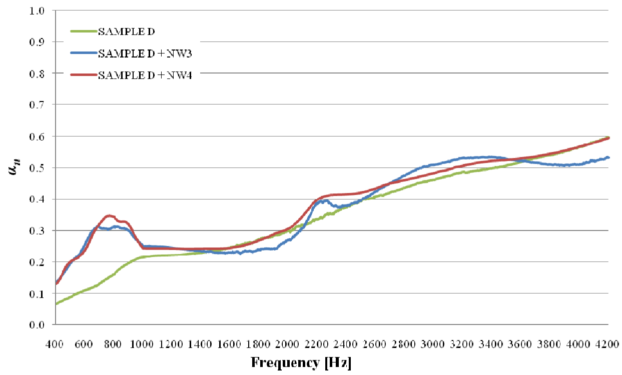

Figure 29 Absorption coefficient spectrum for sample D at different configurations in the frequency range 400 - 4200 Hz

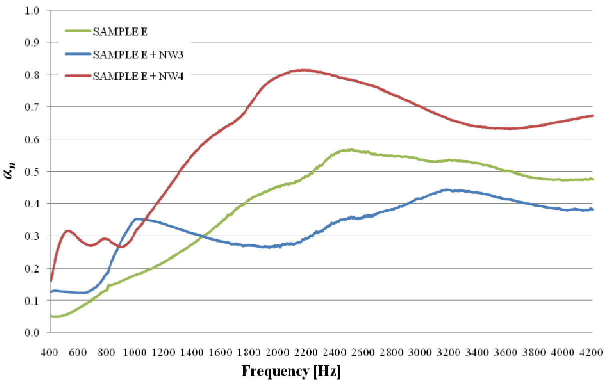

Figure 30. Absorption coefficient spectrum for sample E in the frequency range 400 - 4200 Hz.

8. CONCLUSIONS

A case study of an acoustic restoration of an historic hall by means of application of woven materials has been presented. Experimental campaign results demonstrated the inadequate acoustic response of the hall in its existing state. A restoration project has been outlined in accordance with the Ministry of Italian Cultural Heritage, mainly allowing only temporary solutions with woven materials. Numerical simulation with a pyramid tracing software has been carried out in order to define the effectiveness of the defined solutions. In the restoration configuration reverberation times is considerably reduced from 6 to 1 s, as medium value in the hall. Also C50 and D50 are ameliorating. In order to better define the acoustic characteristic of the woven materials to put in practice, experimental measurements of normal incident absorption coefficient have been carried out. The scope of the research is also to provide a better understanding of the acoustical properties of woven materials in their application as covering for floors.

Six samples of carpet were selected, different for composition, thickness and mass per unit area. All the analyzed samples were characterized by the manufacturer possibility to reproduce the existing design of the floor, as requested by the by the Ministry of Italian Cultural Heritage.

The normal incident absorption coefficient has been determined by means of the impedance tube method with two microphones, in the frequencies range from 400 Hz to 4200 Hz.. A procedure for the samples location in impedance tube measurements has been outlined for this particular type of woven materials.

By analysing the sample experimental results it can be noticed that carpets, as all the porous materials, present an absorption coefficient increasing with frequency, around 0.1 at 400 Hz up to 0.5 or 0.8 at 4200 Hz. The most performing carpet is the sample A, made of 100% wall and having the highest thickness of 12 mm. The influence on the variation of thickness and composition have been investigated. Normally, an increase of thickness corresponds to an augmentation of the absorption coefficient. While this tendency is evident in the carpet sample entirely made of the same material (100 % wool), this behaviour is not linear in the samples made of two material (80% wool and 20%polyammide). The thinner sample (10 mm) of 80% wool and 20% polyammide presents the highest values of absorption in the medium frequency range (1400 – 2000 Hz) with a decrease in the higher frequency (2400 – 4200 Hz). The fibre composition has also been investigated: by analysing the same thickness sample but with different composition it can be affirmed that the absorption behaviour is coincident up to 3000 Hz, after this frequency the sample made of 100% polyamide, decreases its acoustic performances while sample made of 100% wool, are augmenting. A deeper study on the fibre orientation should be necessary. The worse behaviour is obtained by the carpet sample F, even though it is already coupled with a support and a resilient layer. This is probably due to the fact that the measured absorption coefficient is probably affected by some resonance frequency of the free vibrating rigid carpet support.

In order to improve the acoustic performances of carpets at the low frequency range, a two layers system, coupling the selected carpet with two different thickness of felt, has been experimentally investigated. Except for sample F, which is a particular sample already a three layers system, all the coupling system present higher values with the thicker felt (4 mm). In terms of increasing percentage of absorption coefficient between the two layers and the one layer system, sample C, which is the thickest among all (14 mm) and made by 80% Wool and by 20% Polyamide coupled with the 4 mm felt, reaches the highest values. Therefore this configuration can be defined as the optimal one, presenting a minimum of 0.2 at 400 Hz and a maximum of 0.7 at 4200 Hz.

Normal incidence method for measurement of the absorption coefficient (α_n) has proved to be a powerful tool to acquire part of the data for a preliminary qualitative and quantitative selection of carpet samples. The optimal configuration should be tested in a reverberant room aiming to confirm its efficacy also in a wide frequency range and for random incident waves.

9. ACKNOWLEDGMENT

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10. REFERENCES

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