Article

Journal of Industrial Textiles

2021, Vol. 50(8) 1262–1280

DOI: 10.1177/1528083719858771
journals.sagepub.com/home/jit
SAGE

The effect of the combination of multiple woven fabric and nonwoven on acoustic absorption

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Abstract

Textile materials can be used as acoustic materials. In this study, the acoustic absorption coefficient of multilayer fabrics with 60 ends/cm and 15, 30, 45, and 60 picks/cm is measured when the fabric is added as a resistive layer on top of a polyester nonwoven, in order to study the influence of the fabric spatial structure in the acoustic absorption of the assembly. Five different fabric structures are used. Design of experiments and data analysis tools are used to describe the influence of two manufacturing factors on the sound absorption coefficient of the ensemble. These factors are the fabric weft count (picks/cm) and the thickness of the nonwoven (mm). The experimental conditions under which the maximum sound absorption coefficient is achieved are found. The influence of each factor and a mathematical model are obtained. Results of statistical and optimization analysis show that for the same fabric density, sound absorption coefficient increases as the number of layers decreases.

Keywords

Textile, acoustic, absorption, woven, fabric, nonwoven, multilayer, multiple cloth, experiment

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Introduction

Many human activities are developed indoor, like working, attending classes, visiting shopping centers, restaurants, etc., and these environments are often noisy. The continuous exposure to high levels of noise can cause different health problems, and many efforts are done to reduce these problems [1,2]. Acoustic absorption reduces the sound pressure, helping to achieve acoustic comfort. There are many types of acoustic absorbers, like resonators, porous, or combined absorbers [3]. Textile materials are included in the group of porous fibrous materials.

Sound absorbing properties of porous fibrous materials have been widely studied [4,5]. The resistive layer of this material is a multiple cloth fabric, characterized by a microstructure in which there are two main phases: one solid phase, or frame formed by the yarns with their fibers, and one gas phase formed by the air in the pores. One characteristic of porous absorbers is that they show some resistance against air flow through their pores. This produces a difference of pressure at both sides of the pore. This pressure drop is mainly caused by the friction of air particles in the pore with the frame but is only noticeable when these pores are very narrow. When a sound wave impinges on the fabric, its flow resistivity depends on the shape and size of the fabric pores. A highly resistive fabric with small pores and lower porosity produces a high flow distortion, while a fabric with a higher open porosity produces a low flow distortion. In this case, the thermo-viscous effects responsible of an important part of the sound absorption of porous materials, like the one being studied, are less important, causing a decrease in the absorption. The Johnson Champoux Allard model explains this matter, and other authors apply it to textiles [6–10].

Nonwovens can be obtained through various processes and from different natural fibers like kenaf, wood, hemp, coconut, cork, cane, cardboard, and sheep wool [11–13] kapok and milkweed [14], jute [15], etc. Synthetic mineral fibrous materials like glass or rock wool [16] have also been studied. Synthetic polymeric materials, like polyester [17], a combination of polypropylene and polyester [18], Kevlar [19] as a flame retardant, and recycled materials like polypropylene and polyester from bottles [20,21] are suitable for sound absorption.

The acoustic characteristics of textile fabrics have been studied in the form of tufted carpets [22], curtains [23–27], warp and weft knitting [28–33], and also using honeycomb 3D weave [34]. Some works study fabrics based on fiberglass [35], or micrometric mesh based on polyester and polyamide monofilament yarns [36]. In these cases, the surface of the threads is smooth and regular.

Multilayered materials are widely used to improve the efficiency of fibrous absorbers [37–39]. When in combination of a woven fabric layer and a nonwoven, the fabric acts as a resistive layer that modifies the absorption of the obtained composite material [40–42]. Besides, it has been observed that in double porosity absorbent materials, the hole profile has a strong influence so a progressive decrease of the meso-porosity as the wave penetrates inside the material increases the absorption coefficient in a wide frequency band [43].

Numerical methods like multiple regression analysis have been conducted on woven fabrics [44] and design of experiments, on thermo-compressed recycled end of life tyres (ELT) [45]. In this work, design of experiments and data analysis tools are used to describe the influence of two manufacturing factors on the sound absorption coefficient of the composite material formed by a multiple cloth fabric with different configurations and a polyester nonwoven. The fabric is used as a perforated facing, and the nonwoven is used as a porous material. The result is a lightweight, easy to handle, flexible, and easy maintenance material.

Experimental

Materials

The studied material is formed by a multilayer fabric placed on top of a polyester nonwoven, without glue.

The fabrics tested in our work have the structure of multiple cloths, based on plain weave. The choice of the plain weave was previously justified [46] due to the short length of its floats, which reflect the sound more randomly than other weaves. In addition, it is the weave that provides more stitching points, and therefore possible openings in the fabric. By varying the warp and weft densities, the number of layers and the warp and weft ratios in each layer, it is possible to vary the size of the inter-yarn pores. The advantage of using shed fabrics lies in the possibility of obtaining porous sheets in which the size and arrangement of the pores can be modified by varying the number of ends and picks per centimeter and, where appropriate, the type of yarns. In this study, textured yarns are used as they increase their volume and coating capacity. Besides, this type of yarns has the advantage of producing intra-yarn pores, formed by the gaps between their multiple filaments. The general characteristics of the fabrics studied are shown in Table 1.

Samples are produced with a Smit GS 900 weaving machine 190 cm wide, with a Stäubli DX-100 electronic Jacquard machine. The filling density is electronically controlled. Fabrics are used as they are produced at the loom without any further treatment.

Table 1. Fabric general characteristics.

Warp yarn	Warp density (ends/cm)	Filling yarn	Filling density (picks/cm)
Polyester 167 dtex 40 filaments Continuous Textured	60	Polyester 167 dtex 40 filaments Continuous Textured	15, 30, 45, 60

Plain weave–based multiple cloths, with evenly spaced stitching points, are designed and woven with different warp and weft ratios and filling densities. They are named according to Table 1.

In Table 2, a schematic view of the different structures studied is represented. In the images, the warp yarns are represented in red, and weft yarns are represented in white. The balanced and unbalanced structures can be distinguished, as in the first ones, the warp yarns are equally divided in all layers. The unbalanced structures, with uneven distribution of the warp yarns, result in a larger pores size in the fabric of the top face than those in the bottom face, causing therefore a decrease of the pores size in the direction in which the sound wave goes through the fabric.

The polyester nonwoven web is obtained through dry-laid method with thermal bonding, using fibers in the mix with a lower melting point. Its characteristics are summarized in Table 3. The nonwoven approximated thickness is 15 mm. Thicknesses of 30 and 45 mm are obtained by simple overlaying two or and three layers of nonwoven, without glue. The aim of this work is to use the minimum thickness of nonwoven, so 45 mm is considered the maximum acceptable thickness.

Methods

Fabric surface density and thickness: The fabric surface density is determined following the procedure described in the standard UNE-EN_12127 = 1998_ Determination of the Mass per Unit of Surface of Small Samples, except that only three specimens are taken with respect to five that indicates the standard. This is done by checking that the standard deviation is very low (less than 4), and not being the factor of decisive importance.

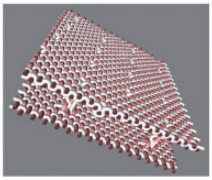
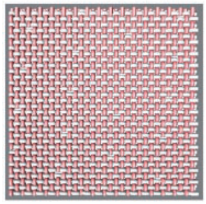
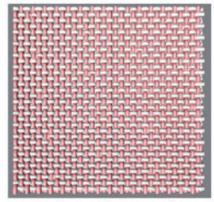
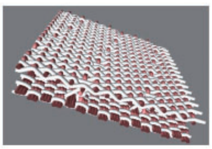
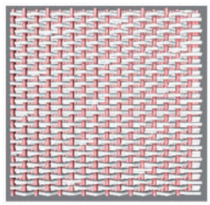
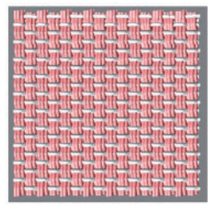
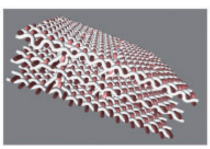
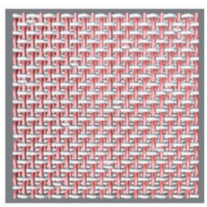
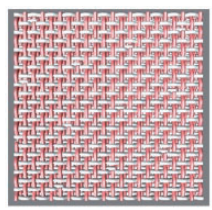
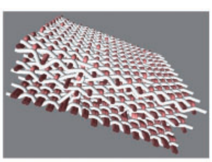
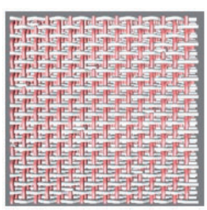
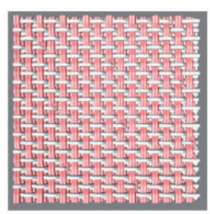
Thickness is measured using a material thickness gauge.

Normal incidence sound absorption coefficient: In order to perform the measurements of the absorption coefficient of the different samples, the method described in ISO 10534-2 is followed: Determination of Acoustic Absorption Coefficient and Acoustic Impedance in Impedance Tubes, Part 2: Transfer Function Method. By means of this method the acoustic absorption coefficient for the normal incidence is obtained using a tube of standing waves, two microphones and a digital system of signal analysis. A source of noise generates flat waves in the tube. By measuring the acoustic pressure in two positions with microphones mounted on the wall, the decomposition of the interferential field is performed. Next, using a Matlab function designed for this purpose, the complex acoustic transfer function of the signals in the two microphones is determined, from which the absorption coefficient at normal incidence is deduced.

The impedance tube is a narrow, rigid, and airtight duct that must meet the characteristics described in the mentioned standard.

To perform the test, the sample is placed at one end of the impedance tube (Figure 1), without air cavity. The fabric is placed on the face closest to the

Table 2. Classification and schematic view of fabrics.

Name	Structure		
2Warp 2Weft			
		Front	Back
	Balanced double cloth	Warp ratio: 1, 1	Weft ratio: 1, 1
4Warp 2Weft			
		Front	Back
	Unbalanced double cloth	Warp ratio: 1,3	Weft ratio: 1, 1
3Warp 3Weft			
		Front	Back
	Balanced triple cloth	Warp ratio: 1, 1, 1	Weft ratio: 1, 1, 1
4Warp 3Weft			
		Front	Back
	Unbalanced triple cloth	Warp ratio: 1, 1, 2	Weft ratio: 1, 1, 1

(continued)

Table 2. Continued.

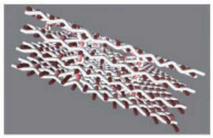
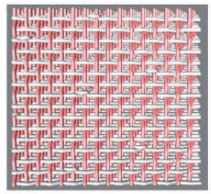
Name	Structure		
4Warp 4Weft			
		Front	Back
	Balanced quadruple cloth	Warp ratio: 1, 1, 1, 1	Weft ratio: 1, 1, 1, 1

Table 3. Characteristics of nonwoven.

Material	Density (g/m^2)	Fibers length (mm)	Fibers count (dtex)	Fibers section	Thicknesses tested (mm)
Polyester	160	63	112.33	Solid circular	15, 30, 45

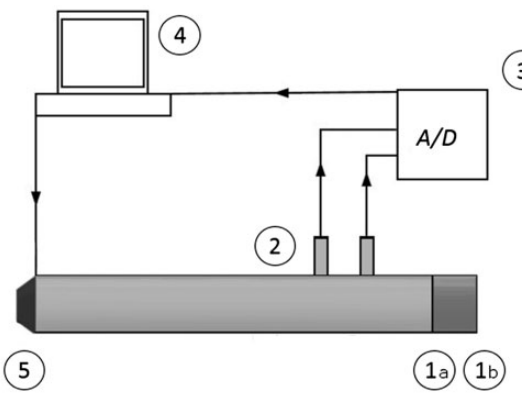


Figure 1. Scheme of the apparatus used to measure the sound absorption coefficient, where: (1a) sample: fabric side; (1b) sample: nonwoven side; (2) the two microphones (microphones G.R.A.S. model 40AO); (3) the data acquisition system (NI-9233); (4) the PC, and (5) the sound source.

sound source. In the case of unbalanced fabrics, the face of less density is the one that is placed on the side of the sound source. The specimen must fit well to the sample holder without being unduly compressed or adjusted so firmly that it is bulged.

Table 4. Experimental and response factors.

	Number	Names	Levels of factors	Continuous
Experimental factors	2	Picks/cm,	15, 30, 45, 60	Yes
		Nonwoven thickness (mm)	15, 30, 45	Yes
Responses	4	SAC_500 Hz		
		SAC_1000 Hz		
		SAC_2000 Hz		
		SAC_4000 Hz		

SAC: sound absorption coefficient.

The reflection coefficient is determined by the following equation

$$r = \frac{H_{12} - H_i}{H_R - H_{12}} \cdot e^{2 \cdot j \cdot k_0 \cdot x_1} \tag{1}$$

where H_{12} is the complex transfer function; H_i is the imaginary part of H_{12}; H_R is the transfer function of the reflected wave; k_0 is the complex wave number; and x_1 is the distance from the sample to the last position of the microphone.

And the acoustic absorption coefficient for normal incidence is determined by the equation

$$\alpha = 1 - |r|^2 \tag{2}$$

Design of experiment: A response surface design is used for each one of the five fabric structures. The base design is summarized in Table 4. The aim of the experiment is to determine the optimal values of the experimental factors by maximizing the sound absorption coefficient in four octave bands. The measured sound absorption coefficient values are reduced to four values according to four intervals, named by their central frequencies: 500, 1000, 2000, and 4000 Hz. An analysis of the experiment is run using Statgraphics Centurion software.

Results and discussion

Fabric surface density

Values of the surface density and thickness of the different fabrics obtained by varying the weft density are shown in Tables 5 and 6. As expected, it is observed that fabrics with the same thread densities, although different structures, have very similar surface densities, with variation coefficients (VC) smaller than 0.05.

Table 5. Surface density of the obtained fabrics (60 ends/cm).

Weft density (picks/cm)	Mass per surface unit (g/m^2) 2Warp 2Weft	3Warp 3Weft	4Warp 2Weft	4Warp 3Weft	4Warp 4Weft	Mean	VC
15	132.57	132.1	133.77	135.1	136.8	134.07	0.0128
30	159.95	160.87	163.57	161.7	161.6	161.54	0.0074
60	216.03	212.93	217.23	214.67	214.53	215.08	0.0068

VC: variation coefficients.

Table 6. Thickness of the obtained fabrics.

Weft density (picks/cm)	Thickness (mm) 2Warp 2Weft	3Warp 3Weft	4Warp 2Weft	4Warp 3Weft	4Warp 4Weft
15	0.5	0.6	0.55	0.65	0.7
30	0.45	0.65	0.5	0.7	0.75
60	0.4	0.6	0.6	0.67	0.8

Thickness of nonwoven

By increasing the thickness of the nonwoven, the resistive layer is separated from the rigid wall, which causes a decrease in the frequency of maximum absorption. It is observed that there is an increase in the sound absorption coefficient, produced by adding a fabric layer to the nonwoven. Otherwise, as the thickness of the nonwoven layer increases this effect is less important.

Figure 2 shows the sound absorption curve of a 15 mm nonwoven and the effect of overlaying different fabrics on it, with a low weft density of 15 picks/cm, as an example. Figures 3 and 4 show sound absorption curves of the same configurations, with nonwoven thickness of 30 mm in Figure 3, and 45 mm in Figure 4.

Table 7 shows the maximum values of the absorption coefficient of the fabric-nonwoven assembly. The VC is different depending on the fabric structure. For example, structures like 2Warp2Weft and 2Warp4Weft, which are double cloths, have a smaller VC than triple and quadruple cloths.

For all studied thicknesses of nonwoven, fabrics that produce the highest absorption values are those formed by two layers, then those formed by three layers and finally those formed by four layers. Within the two-layer fabrics, those formed by balanced double cloths produce a slightly higher absorption than those formed by unbalanced double cloths. This difference varies in a nonlinear way, according to the thickness of the nonwoven layer, being greater in the case of using 30 mm of

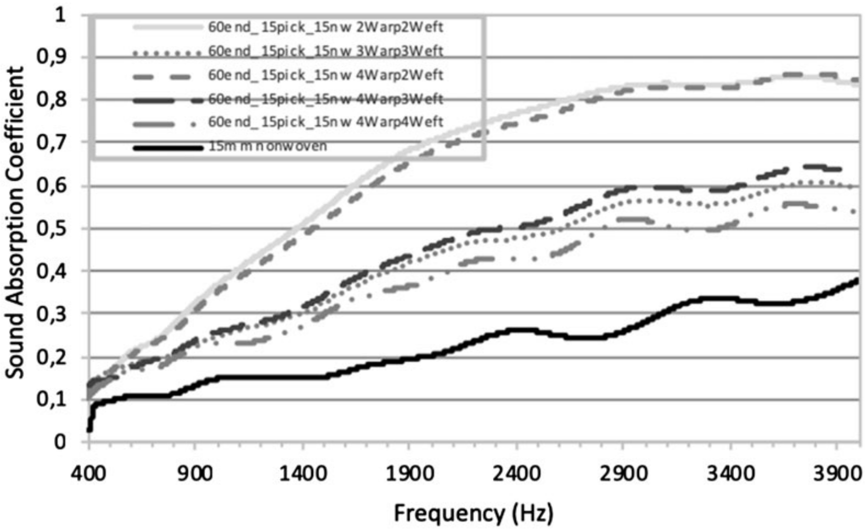


Figure 2. Sound absorption coefficient of multilayer fabrics with 15 picks/cm facing plus 15 mm nonwoven backing.

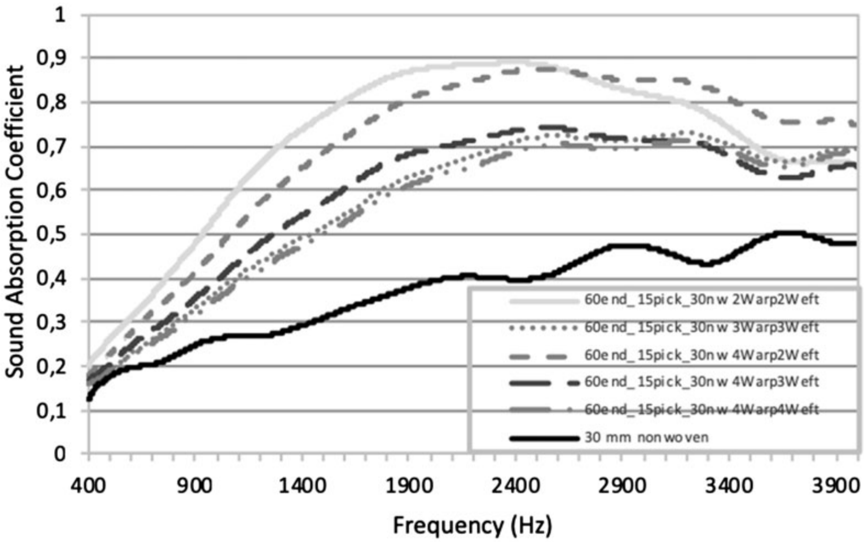


Figure 3. Sound absorption coefficient of multilayer fabrics with 15 picks/cm facing plus 30 mm nonwoven backing.

nonwoven than in cases where 15 and 45 mm of nonwoven are used. Within the three-layer fabrics, the opposite occurs: absorption is generally better when the warp ratio is 1–1–2. This effect is lower in the case of adding 45 mm of nonwoven and is inverted in the case of 30 mm of nonwoven at frequencies above 2938 Hz.

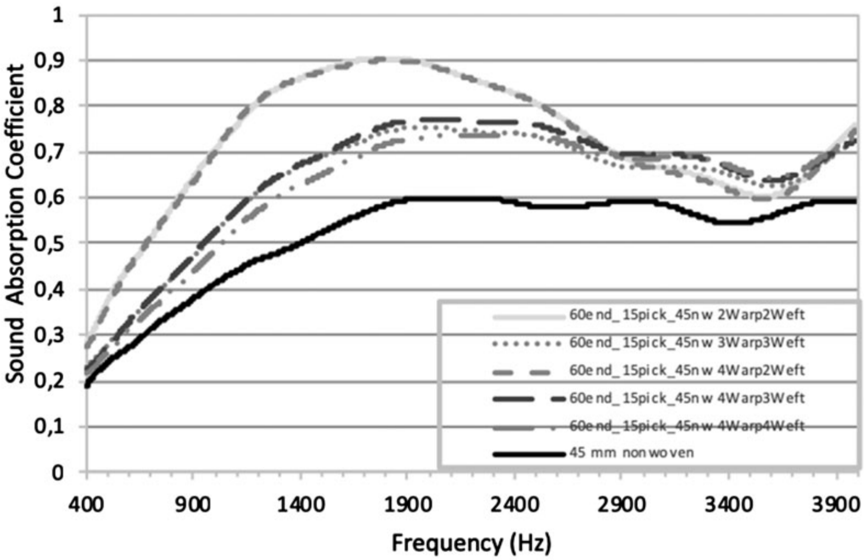


Figure 4. Sound absorption coefficient of multilayer fabrics facing with 15 picks/cm plus 45 mm nonwoven backing.

Table 7. Maximum absorption coefficients of the combination of a 60 ends/cm and 15 picks/cm fabric with 15, 30, and 45 mm nonwoven.

Specimen 60 ends/cm 15 picks/cm	Maximum sound absorption coefficient 15 mm nonwoven	Maximum sound absorption coefficient 30 mm nonwoven	Maximum sound absorption coefficient 45 mm nonwoven	Variation coefficient (%)
2Warp2Weft	0.86	0.89	0.90	2.85
3Warp3Weft	0.61	0.73	0.76	11.21
4Warp2Weft	0.86	0.88	0.90	2.27
4Warp3Weft	0.64	0.74	0.77	9.37
4Warp4Weft	0.56	0.71	0.74	14.79

Fabric density

The sound absorption coefficient increases with the increment of fabric density for all fabric structures, except for the 2Warp2Weft samples. In these fabrics, which reach a maximum absorption coefficient of 0.97 at 1204.83 Hz with 45 picks/cm, if the weft density is increased to 60 picks/cm, there is an alteration of the curve, with two maxima: from 0.87 to 814.21 Hz and from 0.88 to 1851.80 Hz. In addition, a lower coefficient of absorption is obtained than the one presented by nonwoven without facing, between 2907 and 3741 Hz.

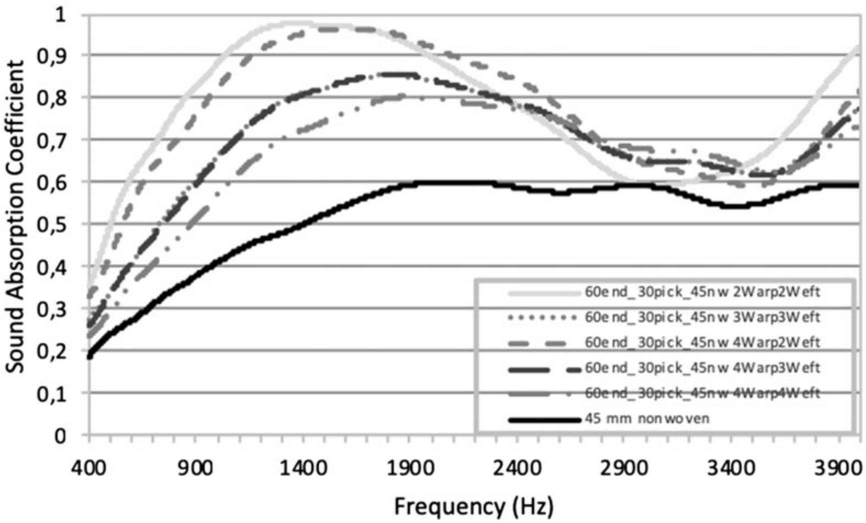


Figure 5. Sound absorption coefficient of multilayer fabrics with 30 picks/cm plus 45 mm nonwoven backing.

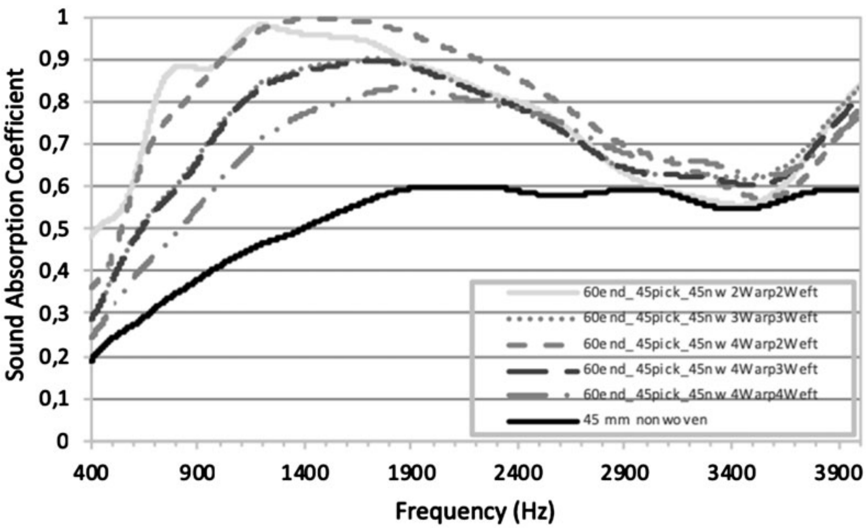


Figure 6. Sound absorption coefficient of multilayer fabrics with 45 picks/cm plus 45 mm nonwoven backing.

Figure 5 shows the sound absorption curve of a 45 mm nonwoven and the effect of overlaying a 30 picks/cm fabric on it, as an example. Figures 6 and 7 show sound absorption curves of the same configurations, but with a weft density of 45 picks/cm in Figure 6, and 60 picks/cm in Figure 7.

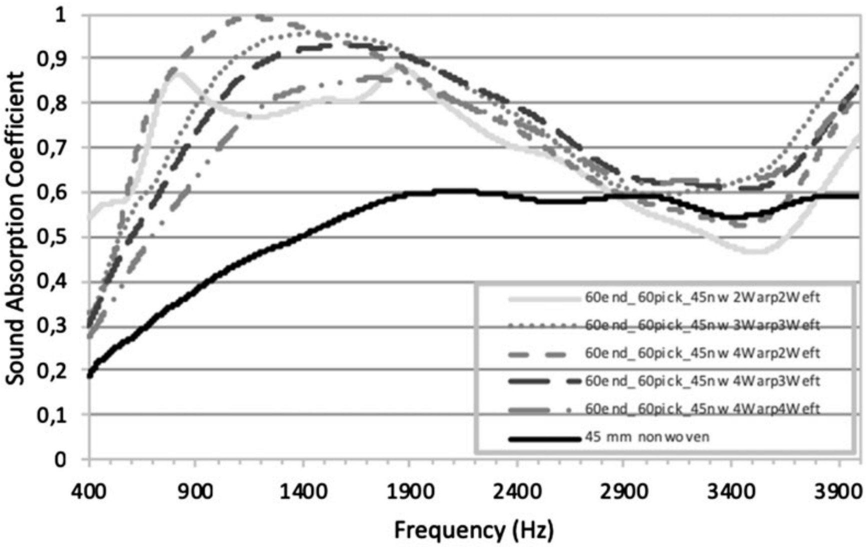


Figure 7. Sound absorption coefficient of multilayer fabrics with 60 picks/cm plus 45 mm nonwoven backing.

By increasing the weft density of the fabric, and therefore its mass, the size of the generated inter-yarn pores decreases. This also produces some narrowing of sound absorption curves which indicate an increase in the selectivity of the absorbed sound.

Fabric balancing

Comparing balanced cloths, with equalled sized pores in their layers, with unbalanced cloths, with smaller sized pores in the top layer, curves of sound absorption coefficient are very similar. There is an exception in the case of double fabrics with 60 picks/cm. In this case, it is observed that while the unbalanced fabric follows the expected curve, the balanced fabric exhibits a different behavior. It seems that there is a limit value between 30 and 60 picks/cm from which the balanced double cloth structure begins to decrease its beneficial effect on absorption at some frequencies. This may be because the size of the pores is reduced so that the fabric begins to work as a nonporous membrane. This confirms that the application of a resistive layer on a nonwoven does not always improve the sound absorption of the ensemble.

Design of experiment

Terms that contribute most to the variability in the response: The influence of each experimental factor and the interaction of the influences exerted by both factors on the response are obtained. By means of the Pareto chart of the effects, the relative

Table 8. Relative magnitude and statistical significance of the main effects and of their interaction.

Frequency (Hz)	Factors		2Warp 2Weft	3Warp 3Weft	4Warp 2Weft	4Warp 3Weft	4Warp 4Weft
			Standardized effect				
500	Picks/cm	A	13.07	21.70	16.74	12.18	11.91
	Nw. mm	B	19.28	45.98	36.06	26.73	22.23
	Interaction	AB	*0.47*	13.94	3.22	5.26	3.38
		AA	*0.14*	*0.43*	3.43	*0.11*	*0.91*
		BB	*0.68*	6.47	*0.93*	3.86	*1.50*
1000	Picks/cm	A	10.38	29.55	24.20	17.89	24.79
	Nw. mm	B	9.03	48.46	28.17	30.48	59.57
	Interaction	AB	5.71	8.26	4.13	2.86	4.08
		AA	*0.11*	*0.98*	*0.59*	*0.14*	1.18
		BB	2.13	2.66	*0.21*	*1.36*	*2.47*
2000	Picks/cm	A	9.26	9.53	1.93	11.41	11.54
	Nw. mm	B	14.68	6.59	23.31	19.46	*0.30*
	Interaction	AB	*1.13*	10.11	4.25	17.49	13.25
		AA	9.51	*0.21*	3.30	4.51	*1.13*
		BB	*0.27*	3.22	*0.56*	3.97	7.05
4000	Picks/cm	A	1.97	23.10	16.80	23.10	23.90
	Nw. mm	B	0.33	21.72	1.48	23.27	29.50
	Interaction	AB	7.94	8.11	17.84	9.57	10.66
		AA	7.63	*1.85*	11.72	*1.50*	5.22
		BB	6.16	13.87	8.18	12.36	13.17

Non significant values are shown in italics.

magnitude and the statistical significance of both the main effects (picks/cm and nonwoven thickness) and their interactions are compared. The absolute values of the standardized effects (t-statistics which test the null hypothesis that the effect is 0, so the term coefficient in the model is equal to 0) are summarized in Table 8. The effects that are not statistically significant at a significance level of 5% (risk of concluding that the effect exists when there is no effect) will be removed for further analysis. In case that a main effect is not significative, if it is involved in a significant interaction, it is retained.

Terms with statistically significant effects on the response: To determine if the experimental factors have a significant effect on the dependent variable, an analysis of variance is performed for sound absorption coefficients at 500, 1000, 2000, and 4000 Hz. As an example, the results are shown in Tables 9 to 12. They correspond to the composite material when the fabric structure 2Warp2Weft is used. In these

Table 9. Analysis of variance for SAC500.

Source	Sum of squares	Df	Mean square	F-ratio	*P*-value
A: Picks/cm	0.17435	1	0.17435	206.52	0.0000
B: Nw. mm	0.362211	1	0.362211	429.04	0.0000
Residual	0.0227945	27	0.000844242		
Total (corr.)	0.582137	29			

R-squared = 96.0843%. *R*-squared (adjusted for d.f.) = 95.7943%. Standard error of Est. = 0.0290558. Mean absolute error = 0.0234244. Durbin–Watson statistic = 1.65047 (*P* = 0.1371). Lag 1 residual autocorrelation = 0.13601.

Table 10. Analysis of variance for SAC1000.

Source	Sum of squares	Df	Mean square	F-ratio	*P*-value
A: Picks/cm	0.372855	1	0.372855	119.36	0.0000
B: Nw. mm	0.27445	1	0.27445	87.85	0.0000
AB	0.106919	1	0.106919	34.23	0.0000
BB	0.0155754	1	0.0155754	4.99	0.0347
Residual	0.0780975	25	0.0031239		
Total (corr.)	0.866187	29			

R-squared = 90.9838%. *R*-squared (adjusted for d. f.) = 89.5412%. Standard error of est. = 0.0558919. Mean absolute error = 0.0412814. Durbin–Watson statistic = 2.12449 (*P* = 0.6411). Lag 1 residual autocorrelation = −0.0885422.

Table 11. Analysis of variance for SAC2000.

Source	Sum of squares	Df	Mean square	F-ratio	*P*-value
A: Picks/cm	0.0876723	1	0.0876723	95.44	0.0000
B: Nw. mm	0.206494	1	0.206494	224.79	0.0000
AA	0.093184	1	0.093184	101.44	0.0000
Residual	0.0238836	26	0.0009186		
Total (corr.)	0.43592	29			

R-squared = 94.5211%. *R*-squared (adjusted for d.f.) = 93.8889%. Standard error of est. = 0.0303084. Mean absolute error = 0.0224874. Durbin–Watson statistic = 1.88751 (*P* = 0.2967). Lag 1 residual autocorrelation = 0.0167054.

tables, the R-squared or coefficient of determination shows the percentage of the observed variation that can be explained by the studied experimental factors. It is used when there is one variable that explains differences in another variable. In our case, as there are more than one experimental factors in the model, R-squared

Table 12. Analysis of variance for SAC4000.

Source	Sum of squares	Df	Mean square	F-ratio	*P*-value
A: Picks/cm	0.00300387	1	0.00300387	3.88	0.0604
B: Nw.mm	0.0000847387	1	0.0000847387	0.11	0.7435
AA	0.0450535	1	0.0450535	58.24	0.0000
AB	0.0487619	1	0.0487619	63.03	0.0000
BB	0.0293884	1	0.0293884	37.99	0.0000
Error total	0.0185668	24	0.000773615		
Total (corr.)	0.173587	29			

R-squared = 89.304%. *R*-squared (adjusted for d.f.) = 87.0757%. Standard error of est. = 0.0278139. Mean absolute error = 0.0181709. Durbin–Watson statistic = 1.97491 ($P = 0.4583$). Lag 1 residual autocorrelation = −0.00646337.

adjusted for degrees of freedom is more adequate to explain the effect of adding variables which can produce points that do not fit the model, reducing the percentage of variation in the sound absorption coefficient explained by a variation of the experimental factors. The Durbin–Watson statistic tests for the presence of correlation in the errors of adjacent observations used for the regression model. Finally, Lag 1 residual autocorrelation shows the estimated correlation between consecutive residuals.

Equations of the regression model adjusted to the data: The underlying model takes the form of a multiple linear regression model. The response variable is expressed as a linear function of the two main effects, the two-factor interaction represented by a cross product of weft density and nonwoven thickness, the quadratic terms, and the error term. The quadratic effect causes the estimation of the response surface to show a curvature.

The regression equations for each octave are obtained by design of experiment analyse procedure. As an example, regression equations of the composite material obtained with the 2Warp2Weft fabric structure and a layer of nonwoven are shown in Table 13.

Optimization

Having built statistical models for the four responses, optimal settings of the factors are determined. After applying the multiple response optimization procedure to the four analyses of experiments (SAC500, SAC1000, SAC2000, SAC4000), the combination of levels of the experimental factors that maximize sound absorption coefficient is obtained by the multiple response optimization procedure. Table 14 shows the combination of levels of each factor at which the optimum is reached for the five different fabric structures. It also shows the maximum acoustic absorption coefficient accomplished at each frequency at those levels. The 2Warp2Weft and

Table 13. Regression equations corresponding to the sound absorption coefficient of the composite material when the fabric structure 2Warp2Weft is used.

Frequency (Hz)	Equations
500 Hz	$SAC500 = -0.041694 + 0.00456831 \times PICKS/CM + 0.00882696 \times NW\ THI$
1000 Hz	$SAC1000 = -0.258057 + 0.0149842 \times PICKS/CM + 0.0315743 \times NW\ THI - 0.000269998 \times PICKS/CM \times NW\ THI - 0.000228556 \times NW\ THI^2$
2000 Hz	$SAC2000 = 0.778572 + 0.01575 \times PICKS/CM - 0.00672214 \times NW\ THI - 0.000253964 \times PICKS/CM^2$
4000 Hz	$SAC4000 = 0.176778 + 0.0200035 \times PICKS/CM + 0.0266922 \times NW\ THI - 0.00018501 \times PICKS/CM^2 - 0.000182936 \times PICKS/CM \times NW\ THI - 0.000328237 \times NW\ THI^2$

Table 14. Multiple response optimization.

		Optimum factors		Optimum responses			
		Picks/cm	Nw. mm	SAC500	SAC1000	SAC2000	SAC4000
2u2t	Balanced	41.59	34.28	**0.45**	**0.79**	0.76	**0.96**
3u3t	Balanced	60	37.36	0.40	0.76	0.73	0.91
4u2t	Unbalanced	53.10	28.94	0.39	0.77	**0.77**	**0.96**
4u3t	Unbalanced	60	32.08	0.34	0.67	0.73	0.91
4u4t	Balanced	60	45	0.39	0.70	0.67	0.80

Maximum sound absorption coefficients are shown in boldface.

4Warp2Weft structures are the ones that lead to higher sound absorption coefficients.

Optimization of experiments has helped to find the values of weft density and nonwoven thickness that lead to the highest sound absorption coefficient in a wide range of frequencies, for each fabric structure. It is found that it is not necessary to use a large nonwoven thickness, neither high values of weft density to achieve a high absorption. The optimum nonwoven thickness is 34.28 mm for the material with 2Warp2Weft fabric and 28.94 mm for the material with 4Warp2Weft fabric.

Conclusions

The influence of the fabric spatial structure in the acoustic absorption of a layered material made up of a multiple cloth fabric in combination with a nonwoven has been studied. High levels of sound absorption in some frequencies have been achieved.

A mathematical model is obtained based on regression equations. The main factors that cause variation in the sound absorption coefficient are obtained.

These factors have different influence at each frequency, and for each fabric structure.

Optimization of experiments has permitted to compare the five different fabric structures and their influence on the sound absorption coefficient of the layered material. Double cloth structures result to be the ones that achieve higher sound absorption coefficient, with lower weft density and smaller nonwoven thickness. Results of statistical analysis coincide with previous observations of sound-absorbing curves, whereas the number of layers decreases, for the same fabric density, absorption increases. This may be due to the decrease in inter-yarn pores size, and the consequent increase in viscous friction.

For future studies, design of experiments is considered as a helpful tool in order to improve textile composite sound-absorbing materials design.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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