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ORIGINAL PAPER

Optimization of acoustic performance of EPDM-based foams using Taguchi design of experiments: Appropriate content of additives

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ABSTRACT

Novel EPDM-based polymer foams were prepared using a combination of nanomaterials, namely nano silica, nano clay, and graphene nanoplatelets. In order to achieve optimal acoustic performance, the Taguchi design (TD) technique was applied to reduce the number of experiments and optimize the formulation. By employing an orthogonal array of L9(3^4), four controlled factors, including content of the three nanomaterials and the blowing agent (Unicell D200A), were chosen. In practice, the acoustic properties of the nine suggested experiments with TD were examined with an impedance tube, and the signal-to-noise ratio analysis revealed two more optimal formulations for foam composites. Further experiments for the last two formulations compared to the nine Taguchi tests, showed an improvement of 13.04 and 19.68%, respectively, for noise reduction coefficient (NRC) and average transmission loss (ATL). It seemed that the idea of using multiple nanomaterials simultaneously is to be an effective way. Besides, the SEM images of nine samples proved that the smaller cell size of the foam were achieved using the higher concentration of nanoparticles. These findings are in accordance with the acoustic results, as the sample with larger cell size and more open cells (C_3) showed higher NRC and the sample with larger cell size and closed cells (B_2) showed higher ATL values. To complete the study, some blank samples with zero level or only one type of the nanomaterial were also investigated. Interestingly, the obtained results indicated that the formula should contain more than one type of nanoparticle to achieve a better acoustic performance. Comparing the result obtained in this study for EPDM foam with the same EVA foam in our previous work, it can be seen that EPDM showed an increase of 15.56% in NRC and a slight decrease of 2.5% in ATL. This behavior could be due to the difference in their morphology, in which the EPDM has probably more open cells and thinner cell walls. **Polyolefins J (2023) 10: 211-224**

Keywords: EPDM foam; nanomaterial; acoustic; Taguchi design; foam morphology.

INTRODUCTION

Development of polymeric foams using different types of nanofillers has greatly expanded among the scientific community [1,2]. Along with advances in nanotechnology, new materials have emerged which could fulfill even the complex requirements of products [3-6]. Dispersed nanoparticles in the rigid part of the polymeric matrix can affect the cellular structure and lead to new applications over conventional foams. These applications include weight reduction, damping, thermal and acoustic insulation to more novel ones, such as electromagnetic interference (EMI) shielding and tissue engineering scaffolds [7-10].

Someone skilled in art knows that ethylene-propylene-diene terpolymer (EPDM) has high chemical stability, mechanical performance, and good aging resistance. EPDM has found increasing acceptance in cellular structures, especially nanoparticle-containing materials [11]. In 2020, a single-layer and also a double-layer EPDM foam was designed based on OBSH blowing agent and phenolic resin, in order to improve sound

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absorption properties. With the maximum sound absorption coefficient of 0.75, the curve of the double-layer composite with the same diameter and thickness moved to a lower frequency, reduced by 400 Hz [12]. Moreover, to investigate the influence of various nano-particles on the rheology and mechanical behavior of the EPDM foam, Karrabi et al. employed 1D carbon nano-tube (CNT), 2D nano-clay, and 3D nano-silica particles. It was observed that these nanofillers can change the cell structure and curing behavior of the foam rubber, in a way that the curing rate was facilitated by CNT and nano-clay addition [13]. In general, EPDM foam nanocomposites can be used for potential applications such as sound panels and air sound insulation in the automotive, construction and aerospace industries [14].

On the other hand, for the successful development of acoustic materials, it is necessary to fully understand the relationship between material structures and acoustic science. To achieve this, numerous pieces of research have been dedicated to determining the acoustic performance of polymer-based foams and tailoring this to their morphology [14-16]. The examples include a novel sound absorber EPDM-based foam for low-frequency waves with the aid of infused multi-walled carbon nanotubes [15]. How a material interacts with the air and causes the energy to be attenuated depends strongly on its cellular structure. Several mechanisms are involved in converting energy into heat [17]. As was shown earlier, different nanoparticles have been utilized in the prior arts to provide polymeric foams with better acoustic properties [18]. This approach is based on the fact that nanofillers can act as heterogeneous nucleation sites to decrease cell size and at the same time reinforce the polymeric matrix [1]. The most popular nanoparticles include nano clay, graphene nanoplatelets, and nano-silica, which were proven to be able to control the morphology of the foam, in the literature [19-22]. Actually, nano clay is a cheap-enough nano particle. It consists of a nanometer-thick layered structure that has shown high sound resistance properties in many studies [23-25,14]. In addition, there are many reports of successful use of this material in acoustic walls. On the other hand, the graphene nanoplatelets are very expensive, and this limitation makes the researchers to report excellent acoustic properties with a mixture of this material in various foams [25].

To contribute to this field of study, this project focused on preparing some EPDM foams and studying their acoustic performance in the presence of nano clay, graphene nanoplatelets, and nano-silica. In order to achieve a suitable cellular structure with EPDM as the base polymer in the presence of sulfur/DCP as a curing agent, it would be wise to use azodicarbonamide (ADCA) as a blowing agent. But to avoid plenty of experiments, a DOE technique known as Taguchi design (TD) was employed which helped us to select the optimal levels of each parameter. In this design, four controllable factors were evaluated along with noise parameters, and the aim was to minimize the effects of noise in a group of experiments towards the acoustic performance of sound. In continue, blank samples were implied with zero level of nanoparticles. This approach has already been used for EVA-based foams by our research team [26]. The use of the Taguchi scheme for structural properties was also previously successfully applied to some EPDM composites [27].

EXPERIMENTAL

Materials and formulation

The list of materials used in this study along with their brand names and manufacturing companies is given in Table 1. Here, the materials have been divided into masterbatch materials and additives. The formula of masterbatch materials and curing agents are selected according to Table 2. In this research, masterbatch refers to the entire polymer mixture without curing materials and additives specified in Table 1.

Aimed of the work was focused on finding improved sound absorption efficiency via modification of the cellular structures, which is strongly influenced by the type and the content of the nanomaterials and blowing agent. In order to achieve the results at the minimum number of experiments, a TD method was applied to determine the appropriate level of the nanomaterials and the blowing agent. As shown in Table 3, three levels were chosen for the three nanomaterials, and ADCA was designated as $\lambda_i^{(A)}$, $\lambda_i^{(B)}$, $\lambda_i^{(C)}$ and $\lambda_i^{(D)}$, $i \in \{1, 2, 3\}$. After careful selection of the factors and their levels, the suggested experiments using the L9 Taguchi array appeared as presented in Table 4. The signal-to-noise ratio (S/N) was the output parameter of the experiment. The S/N ratio, η, is defined as [18]:

$$\eta = -10 \times \log\left(\frac{1}{N}\sum_{i=1}^{N}\frac{1}{y_i^2}\right) \tag{1}$$

where N is the number of samples (here 9) and y_i is the value of the sound resistance characteristic parameter under study.

Table 1. List of materials used for the EPDM foam preparation.

	Materials		Trade name	Manufacturing company
	Name	Type		
Masterbatch material	EPDM	rubber	KEP 330	Kumho Polychem
	Zinc oxide (ZnO)	activator	zinc oxide	Pars Chemical
	stearic acid	processing aid	stearic acid rubber grade	Minda Kota Sdn Bhd (MINKO)
	carbon black	filler	N-330	Pars Carbon Black
	Calcium carbonate	filler	OMYACARB® 3-MH	Omya
	calcium oxide	additive	CALOXOL CP2	Omya
	rubber process oils	process oils	HP ELASTO 245	HP Lubricants
Curing agent	Dicumyl peroxide	curing agent	DCP99%	Pergan
	Sulfur		Industrial micronized sulfur powder	Setareh Sulfur Powder Company
	MBTS	accelerator (powder)	Richon	Dalian Richon Chem CO., LTD.
Additive	Unicell D200A	blowing agent	ADCA D200A	Dongjin Semichem
	Nano clay	nano material	Cloisite® 20A	BYK Company
	Graphene nanoplatelets		Research grade	United Nanotech Innovations
	Nano silica		Aerosil 200	Evonik Degussa GmbH

Table 2. Formula of the masterbatch and the curing agent used.

	EPDM	ZnO	Stearic acid	Carbon black	Calcium carbonate	Calcium oxide	Rubber process oils	Dicumyl peroxide	Sulfur	MBTS
phr level	100	4	2	2	4.5	3	5	0.5	1.5	0.74

Compounding and foam preparation

For compound preparation, EPDM and carbon black were mixed together using a laboratory kneader mixer machine (Model: KD-5 of Hamgartoos Company) with Z-type blades at 60 rpm and a temperature of 120°C, until it was completely homogenous. The other materials of the masterbatch were added according to the Table 1, and mixing continued for further 5 minutes. Then, the nano ingredients were added and kneaded for an extra 15 minutes to homogenize the compound. Before adding ingredients such as curing and blowing agent, it should be sure that the temperature of the mixture is less than 80-90°C. Final mixing was carried out in a two-roll mill (Model: W150AP of German Collin Company with a diameter and width of 15 cm and 40 cm respectively) several times until a homogenous compound was formed. During that time, the temperature of the roller and the rotational speed of the milling machine were set to 35°C and 30 rpm, respectively. The compound should rest for at least 24 h before baking. Baking took place under 160°C and 3 bar conditions by using a hot press (Model: Santam SPH-500). The preparation method and conditions were identical in all samples.

Characterization methods

In order to minimize any possible errors, every measurement was repeated three times for any sample

Table 3. Description of the factors and their related levels for TD.

No.	Parameter code	Factor	Level (phr)		
			-1	0	1
1	A	nano silica	$\lambda_1^{(A)}$	$\lambda_2^{(A)}$	$\lambda_3^{(A)}$
2	B	nano clay	$\lambda_1^{(B)}$	$\lambda_2^{(B)}$	$\lambda_3^{(B)}$
3	C	graphene nanoplatelets	$\lambda_1^{(C)}$	$\lambda_2^{(C)}$	$\lambda_3^{(C)}$
4	D	ADCA	$\lambda_1^{(D)}$	$\lambda_2^{(D)}$	$\lambda_3^{(D)}$

Table 4. Orthogonal array L9 of experimental design.

No.	Sample code	Factor			
		Nano silica (A)	Nano clay (B)	Graphene nanoplatelets (C)	ADCA (D)
1	A_1	$\lambda_1^{(A)}$	$\lambda_1^{(B)}$	$\lambda_1^{(C)}$	$\lambda_1^{(D)}$
2	B_1	$\lambda_2^{(A)}$	$\lambda_1^{(B)}$	$\lambda_2^{(C)}$	$\lambda_2^{(D)}$
3	C_1	$\lambda_3^{(A)}$	$\lambda_1^{(B)}$	$\lambda_3^{(C)}$	$\lambda_3^{(D)}$
4	C_2	$\lambda_1^{(A)}$	$\lambda_2^{(B)}$	$\lambda_2^{(C)}$	$\lambda_3^{(D)}$
5	A_2	$\lambda_2^{(A)}$	$\lambda_2^{(B)}$	$\lambda_3^{(C)}$	$\lambda_1^{(D)}$
6	B_2	$\lambda_3^{(A)}$	$\lambda_2^{(B)}$	$\lambda_1^{(C)}$	$\lambda_2^{(D)}$
7	B_3	$\lambda_1^{(A)}$	$\lambda_3^{(B)}$	$\lambda_3^{(C)}$	$\lambda_2^{(D)}$
8	C_3	$\lambda_2^{(A)}$	$\lambda_3^{(B)}$	$\lambda_1^{(C)}$	$\lambda_3^{(D)}$
9	A_3	$\lambda_3^{(A)}$	$\lambda_3^{(B)}$	$\lambda_2^{(C)}$	$\lambda_1^{(D)}$

code and the average results were reported.

Density measurement

Density of the foams was measured according to the ASTM D792 standard [28]. The LA-120S analytical balance of German Sartorius was utilized to measure the volumetric density with the accuracy of 0.0001 gr.

Volume change percentage

The volume change percentage of the foams was also carried out according to the PSA D45 1180 standard.

Stress–strain and elongation

The yield stress, elongation, and Young's modulus of elasticity for all prepared L9 array samples were determined according to the ASTM D412 die C and at a rate of 50 mm/min [29]. The stress–strain curve of the samples was also examined by the universal tensile machine of SANTAM company.

Morphology

Scanning electron microscopy (SEM) is a very important technique to determine the morphology and consequently correlate that with the acoustical properties of the materials. To obtain cross-sectional areas suitable for analysis, foam samples must be floated in liquid nitrogen at a temperature of about -196°C for 30 minutes to harden the foam structure enough to be easily cut. In this study, a VP 1450 SEM model of the German company LEO with 20 kV voltage and a magnification factor of 100 was utilized. Then, to determine cell wall thickness, the SEM images were processed using the software ImageJ 1.52V. These findings would also help to determine whether the structure of the cells is open or closed.

Sound absorption and transmission loss

Both absorption and transmission loss characteristics were measured by an impedance tube, according to the ISO 10534-2 standard [30]. The impedance tubes used in this study were SW420 and SW470 models of the BSWA Tech. Co. LTD, which includes two tubes with different diameters of 30 and 100 mm and designed for high and low-frequency acoustic tests, respectively. The method used is based on the transfer function method, which is able to separate the incident and reflected energy from the measured transfer function, and then estimate the acoustic properties of the tested sample installed in the tube [31]. For sound absorption coefficient, a two-microphone configuration is required. This equipment also supports a four-microphone method for sound transmission loss measurements [32]. Four microphones measure the sound pressure level (SPL) on both tubes and the relevant data is reported to a computer using the data analyzer. Then, by comparing the SPLs, the transmission loss of the sample is computed. Each of the tests was repeated at least three times to obtain consistent and representative results and the average result was reported.

Noise reduction coefficient and average transmission loss

In engineering, the term noise reduction coefficient has been established to characterize sound-absorbing materials and is defined as the mean average value of the absorption coefficient α at frequencies of ω (= 250, 500, 1000, and 2000 Hz), as follows [33]:

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \tag{2}$$

In a similar way, the ATL has also been defined as the mean average value of the transmission loss at the 1/3 octave band between the low frequency of 100 Hz and the intermediate frequency of 4000 Hz (100, 125, 160, …, 250, 3150 and 4000 Hz), as the following equation [33]:

$$ATL = \frac{TL_{100} + TL_{125} + ... + TL_{3150} + TL_{4000}}{17} \tag{3}$$

To compare sound absorbing or sound insulation capabilities of materials over a wide range of frequencies, the NRC or ATL of foams were here considered as the numerical index. The higher NRC and ATL, the better acoustic performance of absorption. After completion of the nine suggested experiments by TD, these parameters should be extracted from the corresponding responses of their acoustical behavior.

RESULTS AND DISCUSSION

As mentioned before, the formulations of the foams were based on the phr values given in Table 2 for the masterbatch and the curing agent, and Table 5 for both the nanomaterials and blowing agent, according to the suggested experiments by the Taguchi L9 array (Table 4). It should be noted that using the higher level of graphene nanoplatelets was very smaller than those of other nano materials due to its less availability and high cost.

Mechanical characterization tests

The volumetric density of the suggested samples is listed in Table 6. In addition, the volume change percentage of these samples is presented in Figure 1.

Table 5. Numerical values of the phr levels for the nano materials and the ADCA used in the Taguchi L9 array.

Factor	Parameter code	*i*		
		1	2	3
Nano silica	$\lambda_i^{(A)}$	2.0	4.0	6.0
Nano clay	$\lambda_i^{(B)}$	2.0	4.0	6.0
Graphene nanoplatelets	$\lambda_i^{(C)}$	0.1	0.2	0.3
ADCA	$\lambda_i^{(D)}$	3.0	6.0	9.0

According to this data, sample A_2 showed the lowest density and so a higher volume change percentage, too. Furthermore, the results for yield stress, elongation, and the elastic module for all samples are shown in Figures 2a, 2b, and 2c, respectively. In addition, the results of the stress-strain curve of the samples are presented in Figure 2d. In general, there was not a meaningful correlation between the results of the volume change percentage and the modulus of elasticity of the samples.

Morphological study

So far, many studies have been devoted to investigating the effect of nanoparticles on cellular morphology, including cellular size and the wall thickness of foams [1]. Herein, the SEM images of nine samples are illustrated in Figure 3. As it is shown, the higher concentration of the nanoparticles used the smaller cell size of the foam resulted, because they would provide more heterogeneous nucleation sites per unit volume, in comparison with other traditional fillers at the same concentration [1, 34]. To measure the thickness of the cell walls, it is possible to use Figure 4 to calculate it. Keeping in mind that the thickness of the walls was not constant across the foam, so an average value should be assessed based on a visual inspection. The results are plotted in Figure 5. As can be seen, samples A_1, A_2, A_3 and C_3 had relatively more open cells and larger cellular sizes, so a larger value of NRCs is expected. On the other hand, samples A_1, B_1, B_2, and C_1 had smaller cell sizes and more closed cells, which could lead to a larger value for ATLs. These predictions should be verified by experimental acoustic results in the next section.

Acoustic properties

As mentioned earlier, two samples with 100 and 30 mm of diameters were required for each impedance

Table 6. Volumetric density of the EPDM foams suggested by the Taguchi L9 array.

No.	Sample code	Density(gr/cm³) (average ± SD)
1	A_1	0.934 ± 0.003
2	A_2	0.928 ± 0.005
3	A_3	0.955 ± 0.003
4	B_1	0.930 ± 0.028
5	B_2	0.929 ± 0.014
6	B_3	0.935 ± 0.006
7	C_1	0.981 ± 0.001
8	C_2	0.976 ± 0.003
9	C_3	0.950 ± 0.010

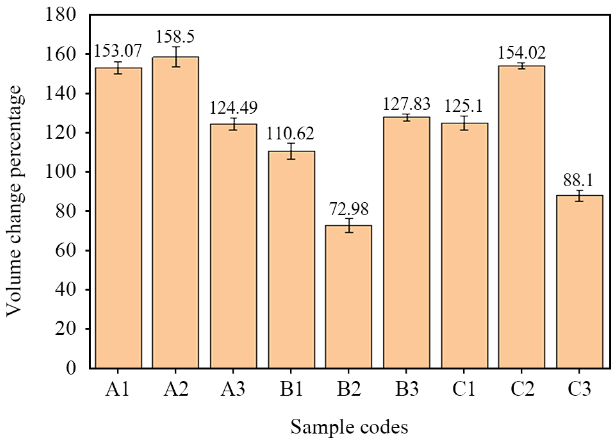


Figure 1. Volume change percentage of the EDPM foams suggested by the Taguchi L9 array.

tube measurement, with a thickness of 10 mm [27]. The results of the average sound absorption coefficient as well as the transmission loss of the samples have been presented in Figures 6a and 6b, respectively. In addition, the values of the NRC and ATL for the samples of the Taguchi L9 array were calculated (Figure 7) and with the analysis of ANOVAs, the responses were obtained and the significance of the factors at some stated level of confidence, say 95%, was discussed.

The plot indicated that samples C_3 and B_2 provide higher NRC and ATL values, respectively. Sound absorption in cellular materials is based on the conversion of sound energy into heat through thermal and viscous loss mechanisms. One of the mechanisms is viscous loss, which is defined as relative motion between two phases due to the air permeability in open cell structures. So, in closed-cell foams, the only energy consumption mechanism includes structural damping and thermal losses [20]. This is how the morphology analysis presented in the last section could be justified with our observations.

Foam formulations with optimal NRC and ATL

An optimized formulation might not necessarily be one of the nine suggested samples in Table 4. To ensure, the signal-to-noise ratios (S/N) were computed for three levels of the four factors considered for the NRC and ATL by using Minitab 17 and the results are

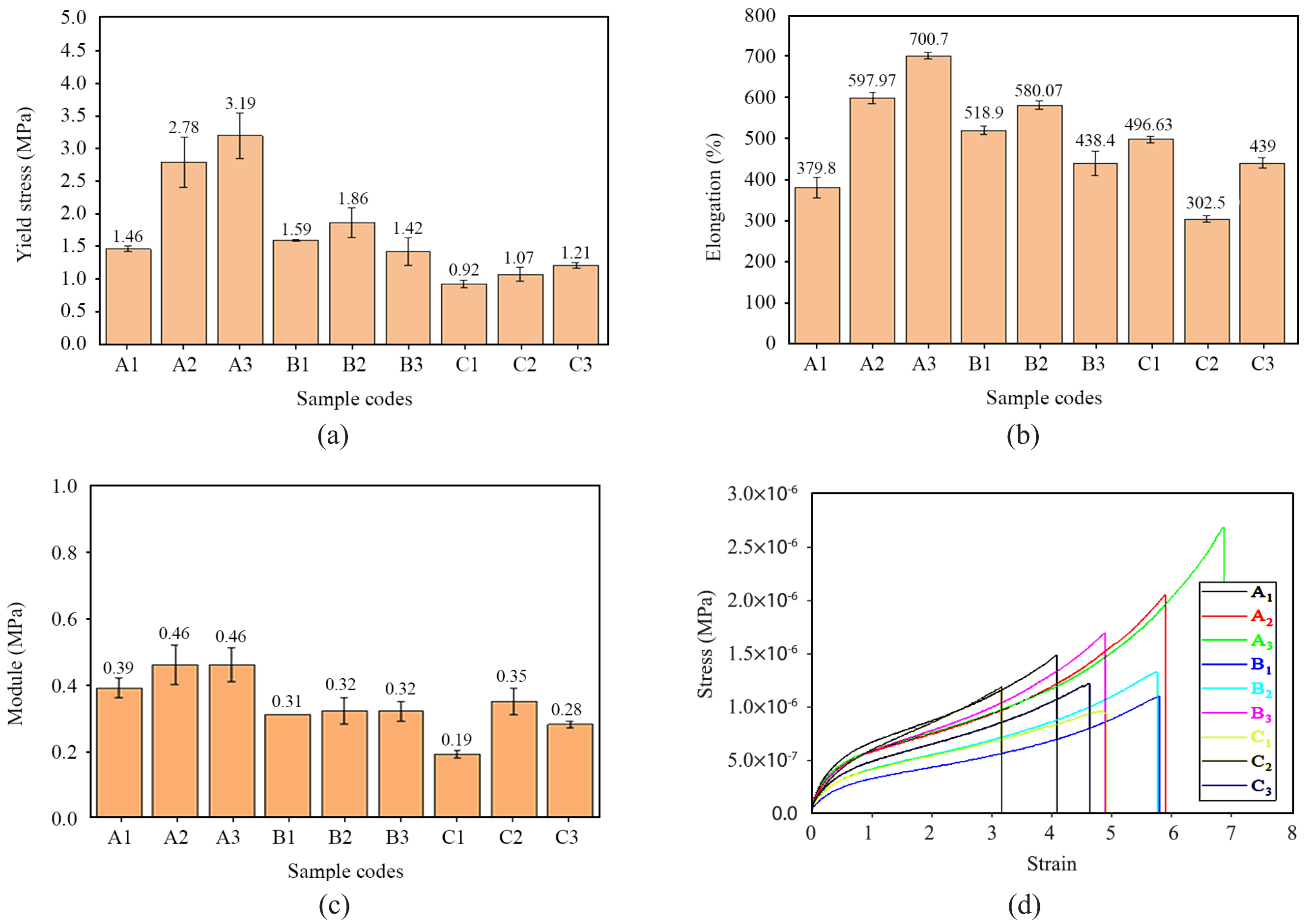


Figure 2. (a) Yield stress (b) elongation (c) Young's modulus and (d) stress–strain curves of the EPDM foams suggested by the Taguchi L9 array.

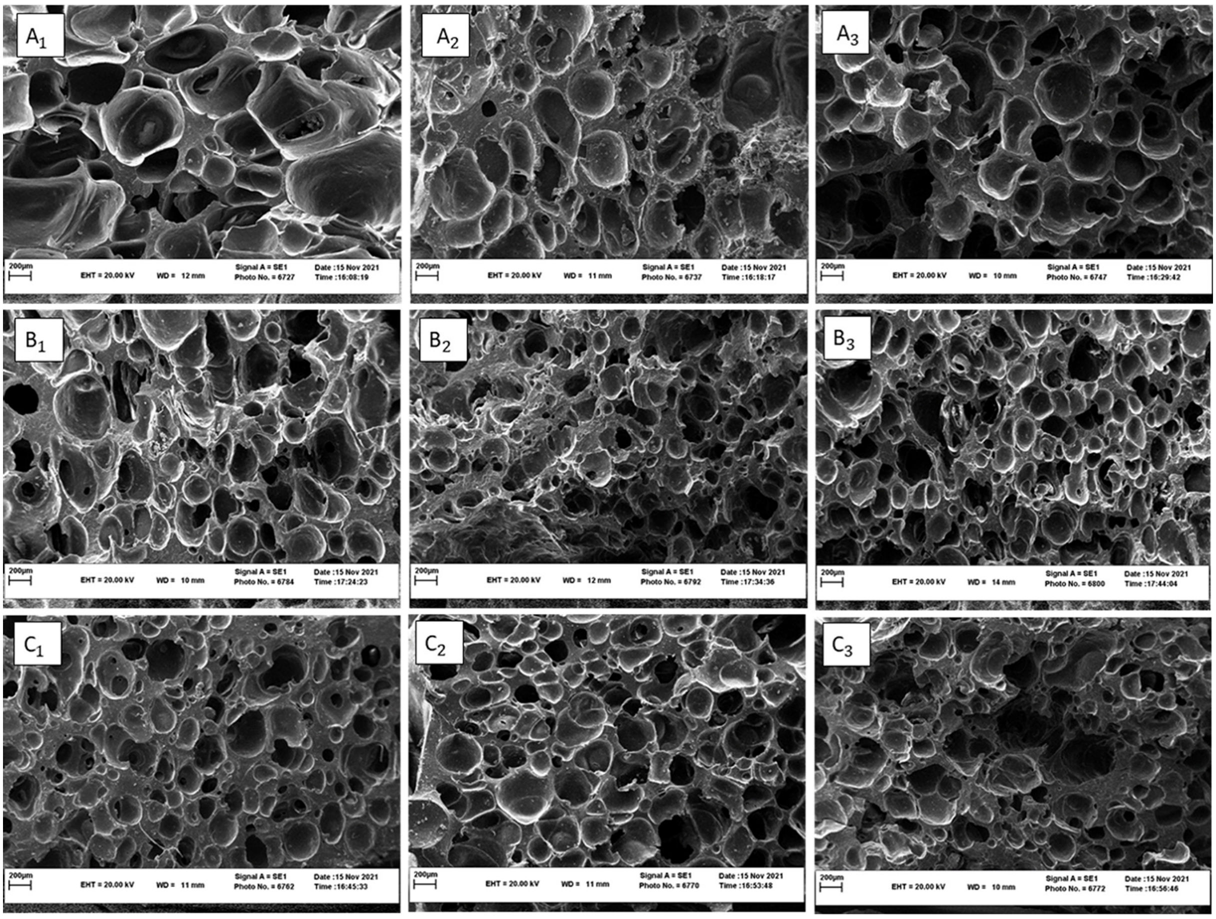


Figure 3. SEM images of the prepared nanocomposite EPDM foams according to the formulation in Table 4.

compiled in Table 7. Remember that the performance characteristic in the analysis is "the higher the better", so a larger value of the S/N ratio corresponds to the both larger NRC and ATL values. As expected, the S/N ratio for samples C_3 and B_2 was optimum for the NRC and ATL, respectively. It is interesting to note that the B_2 levels of nano clay and graphene nanoplatelets samples are at levels 2 and 1, respectively, but sample B_2 has a smaller cell size and more closed cells compared to other samples as shown in Figure 3, which can lead to an increase in ATL value in sample B_2.

The S/N graphs for both of the NRC and ATL values are shown in Figure 8. It was revealed that the best combination of the four factors to obtain the optimal NRC, was as follows: first level of nanosilica (2 phr), third level of nano clay (6 phr), second level

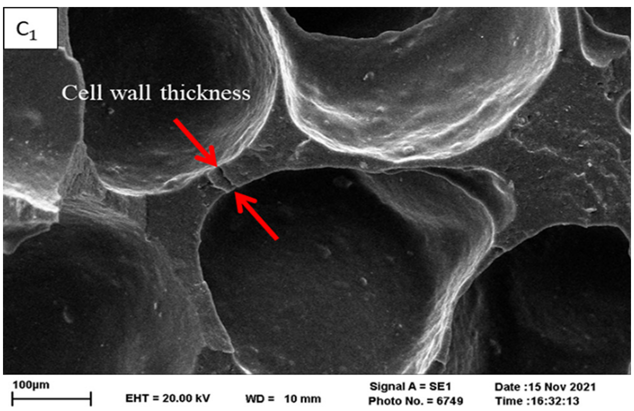


Figure 4. Image of the wall between two cells and its thickness.

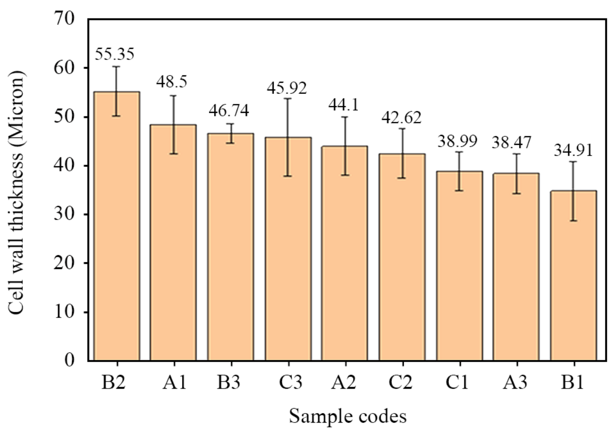


Figure 5. Average cell wall thickness of the prepared EPDM foams.

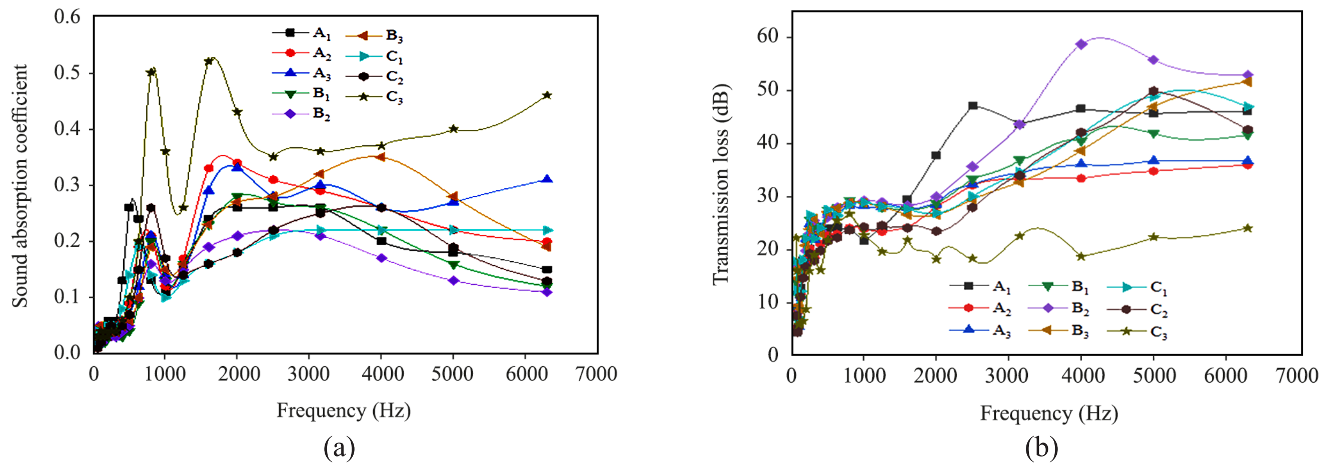


Figure 6. (a) Average sound absorption coefficient and (b) average transmission loss of the nine TD samples with thickness of 10 mm.

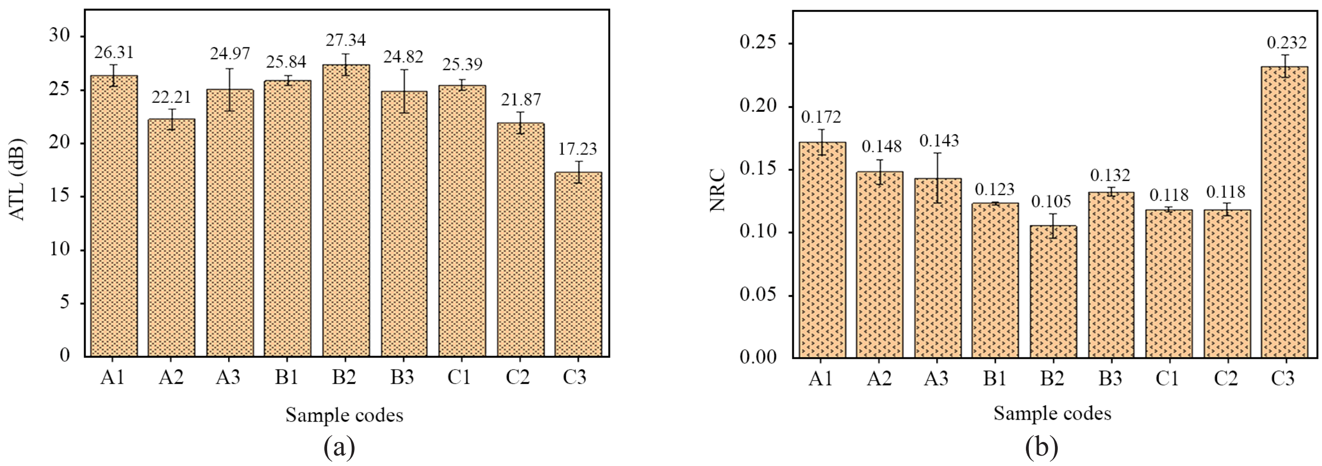


Figure 7. Average values of (a) NRC and (b) ATL for the nine TD samples with thickness of 10 mm.

of graphene nanoplatelets (0.2 phr), and first level of ADCA (3 phr). Similarly, these factors should be at their second (6 phr), first (3 phr), third (0.3 phr), and

Table 7. Experimental results of the ATL and NRC and the corresponding S/N ratios.

No.	Sample code	Average transmission loss		Average sound absorption	
		ATL (dB)	S/N ratio	NRC	S/N ratio
1	A_1	26.30	28.40047	0.17	-15.391
2	B_1	22.21	26.93028	0.15	-16.6242
3	C_1	24.97	27.9498	0.14	-16.9237
4	C_2	25.84	28.24625	0.12	-18.2373
5	B_2	27.34	28.73709	0.11	-19.5762
6	A_2	24.82	27.89542	0.13	-17.7211
7	B_3	25.39	28.09346	0.12	-18.5992
8	A_3	21.87	26.79534	0.12	-18.5992
9	C_3	17.23	24.72808	0.23	-12.6715

third (9 phr) level, respectively to achieve the optimal value of the ATL. It is also worth mentioning that the impact of cellular thickness on the NRC values was also investigated and the relevant results are depicted in Figures 9 and 10. Obviously, there was not a regular correlation between the cell wall thickness and acoustic behavior, because so many factors, such as cell morphology and cell size, were affecting the foam behavior.

For further study, two EPDM foams with the optimal formulations (Table 8), which were extracted from the S/N ratio analysis, were prepared and recognized as δ_1 and δ_2 samples. Then, the relevant acoustic tests were carried out on these samples using the impedance tube. The sound absorption coefficient of the optimal sample δ_1 was compared with sample C_3, which had the best NRC records among the nine TD experiments (Figure 11a). The sound absorption coefficient of the sample δ_1 was better at the most frequencies used, as expected. The NRC of this optimal sample was

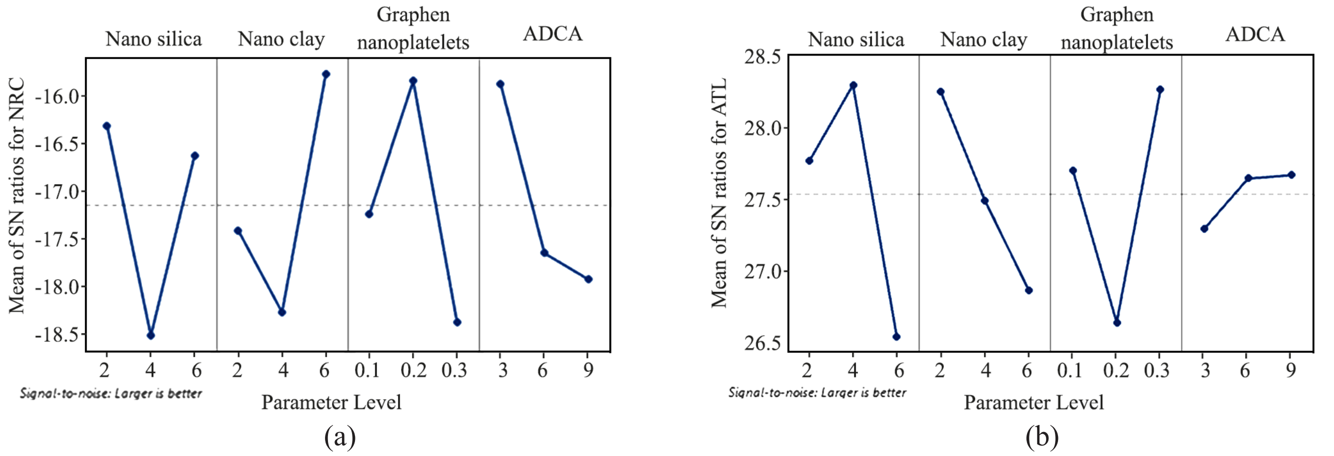


Figure 8. S/N graphs for the (a) NRC and (b) ATL.

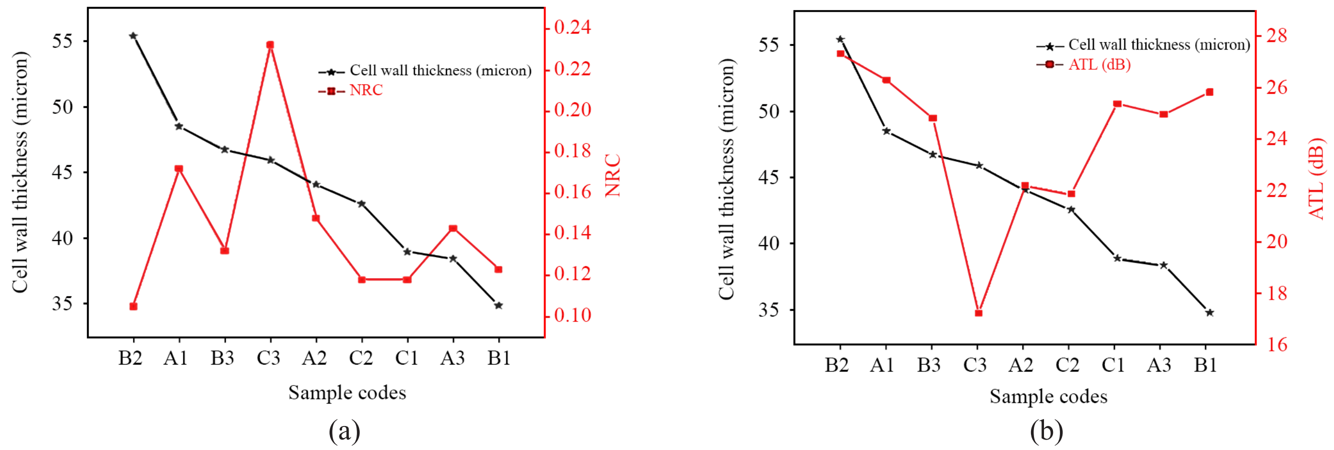


Figure 9. Effect of cell wall thickness on both of the (a) NRC and (b) ATL.

0.26, which was 13% better compared to the NRC of sample C_3. Similarly, in Figure 11b, the transmission loss of the optimal sample δ_2 is compared with that of sample B_2 which had the best ATL among the nine TD experiments. Again, it is observed that the transmission loss of the optimal sample δ_2 was appreciably higher than that of B_2 at almost all frequencies implemented. There was an ATL improvement of 19.68% from 27.34 dB to 32.72 dB. The results have been summarized in Table 8.

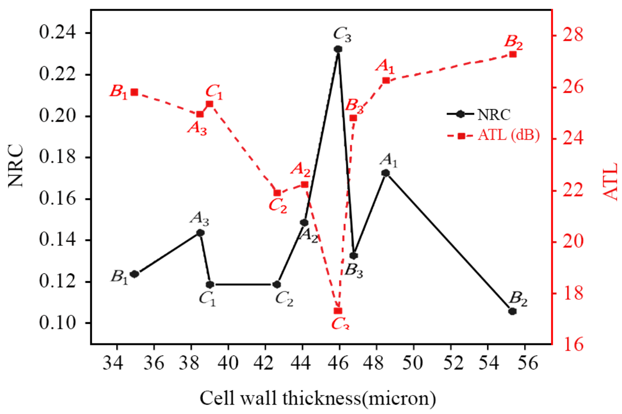
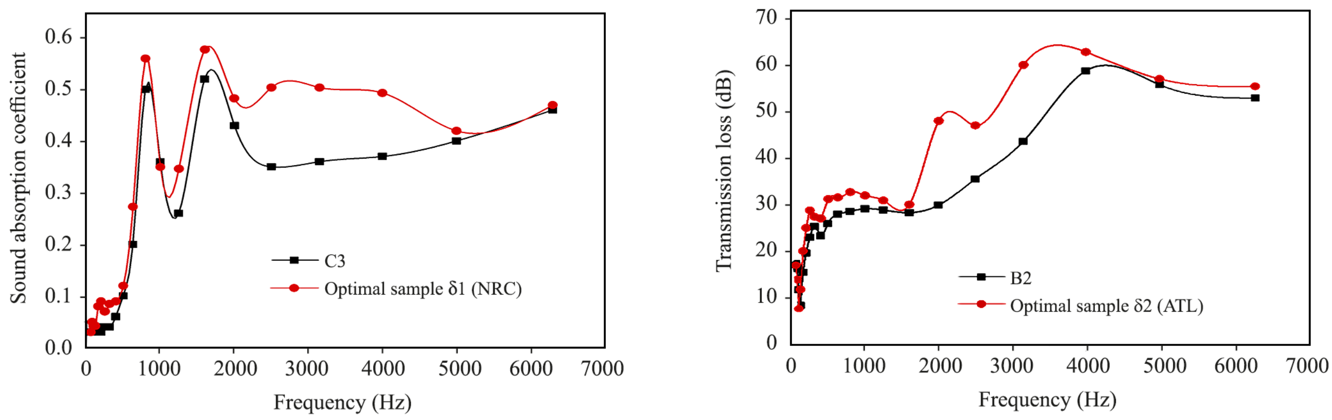


Figure 10. NRC and ATL versus cell wall thickness.

Effects of nanomaterials

So far, nine TD experiments plus two optimal extracted formulas from S/N ratio have been studied. To complete our study, a few more formulations should be considered. For instance, a question still remains: what would happen at zero level of nanomaterials? To answer this question, three blank samples were proposed, namely A_0, B_0, and C_0 with no nanomaterial and with 3, 6 and, 9 phr of the ADCA, respectively. On the other hand, the effect of a single nanomaterial was also restricted in the Taguchi array, since all nanomaterials were present simultaneously in all suggested experiments. To overcome this limitation, the three sets of formulations were proposed for further studies in the presence of only one nanomaterial. The



(a) (b)

Figure 11. Comparison of the (a) average sound absorption coefficient of the sample C_3 with the optimal sample δ_1 (b) average transmission loss of the sample B_2 with that of the optimal sample δ_2.

Table 8. Average optimal formulation for the EPDM foams, extracted from S/N analysis.

Sample name	Formulation				Results	
	Nano silica	Nano clay	Graphene nanoplatelets	ADCA	NRC	ATL
δ_1 (optimal NRC)	2 phr	6 phr	0.2 phr	3 phr	0.26	—
δ_2 (optimal ATL)	4 phr	2 phr	0.3 phr	9 phr	—	32.72

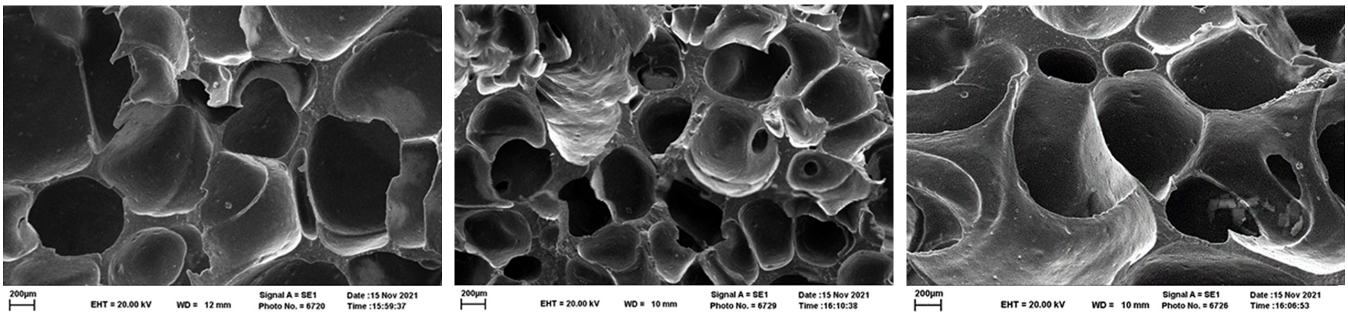
details are given in Table 9. It should be mentioned that all experiments proposed above contained 6 phr of the ADCA. Based on the results obtained in the blank samples, sample B_0 which contain 6 phr ADCA had better acoustic behavior.

As can be deduced from the SEM images (Figure 12), the foams had non-uniform structures with larger cells. This leads to a lower modulus of elasticity, which was confirmed with the obtained results (Table 10). These results were based on the preliminary measurements of E_{A0}= 0.27 MPa, E_{B0}= 0.25 MPa, E_{C0}=0.25 MPa, in which E is Young's modulus of elasticity. The sound absorption coefficient and the transmission loss of all new samples were examined using the impedance tube. The results are presented in Figures 13 and 14 for the blank and B_i (i = 4, 5, …, 12) samples, respectively. Summaries are collected in Table 9. In general, according to Table 10, with the use of nanoparticles, the modulus of elasticity increases compared to samples without nanoparticles. For example, the elastic modulus is improved by at least 44.44, 24 and 7.69% in the samples with 3, 6 and 9 percent foaming agents, respectively.

To summarize, some of the achievements of this research are described below. Totally, the combination of different nanoparticles in the foam provided better

Table 9. Summary of the formulations and the average results of the NRC and ATL for the (a) blanks samples and for (b) samples with only one nano particle.

Sample set	Sample code	phr level				NRC	ATL (dB)
		Nano silica	Nano clay	Graphene nanoplatelets	ADCA		
Blank sample	A_0	---	---	---	3	23.10	0.24
	B_0	---	---	---	6	20.84	0.14
	C_0	---	---	---	9	11.37	0.21
Samples with nano clay	B_4	---	2	---	6	19.48	0.19
	B_5	---	4	---	6	23.98	0.14
	B_6	---	6	---	6	27.26	0.13
Samples with nano silica	B_7	2	---	---	6	17.94	0.13
	B_8	4	---	---	6	27.79	0.08
	B_9	6	---	---	6	18.87	0.21
Samples with graphene nanoplatelets	B_{10}	---	---	0.1	6	20.47	0.18
	B_{11}	---	---	0.2	6	18.65	0.23
	B_{12}	---	---	0.3	6	19.06	0.22

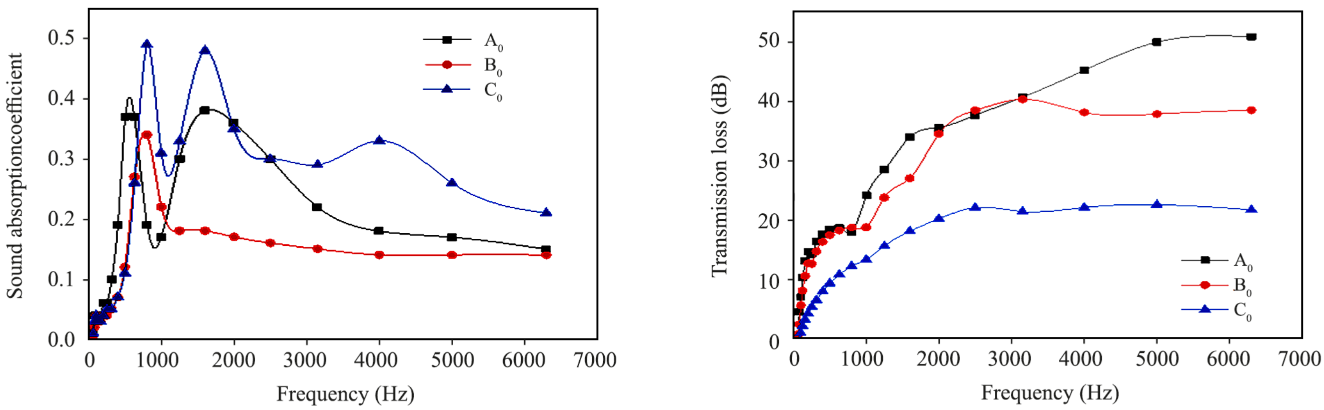


(a) (b) (c)

Figure 12. SEM images of blank EPDM foams without nano particles (a) A_0 (with 3 phr of ADCA) (b) B_0 (with 6 phr of ADCA) and (c) C_0 (with 9 phr of ADCA).

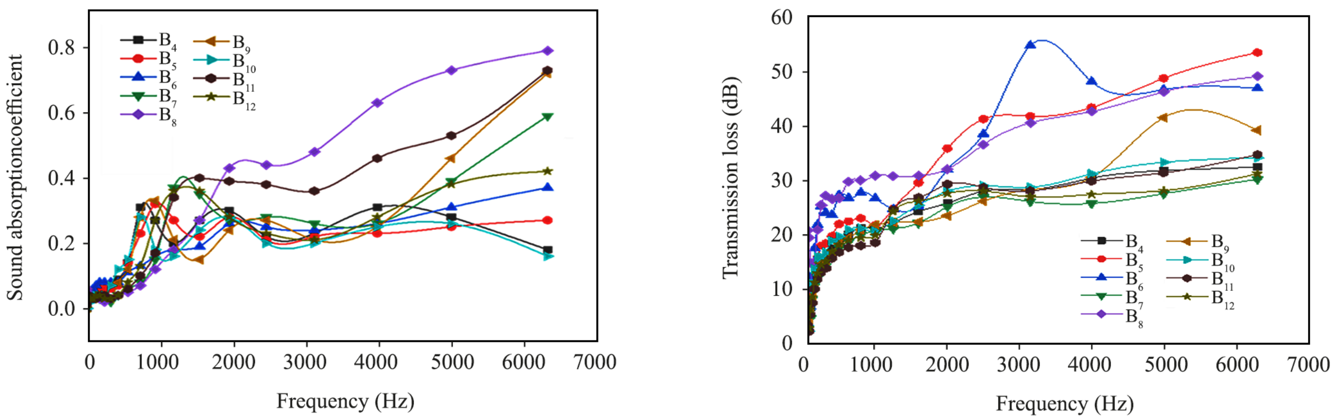
Table 10. Summary of average improvements in elastic modulus of the EPDM foams.

samples A	improvement (%)	samples B	improvement (%)	samples C	improvement (%)
A_0	--	B_0	--	C_0	--
A_1	44.44	B_1	24.00	C_1	11.54
A_2	70.37	B_2	28.00	C_2	34.62
A_3	70.37	B_3	32.00	C_3	7.69



(a) (b)

Figure 13. (a) Average sound absorption coefficient and (b) transmission loss average of blank EPDM samples.



(a) (b)

Figure 14. (a) Average sound absorption coefficient and (b) transmission loss average of samples B_i (i = 4,5, …, 12) corresponded to the cases with a single nano material.

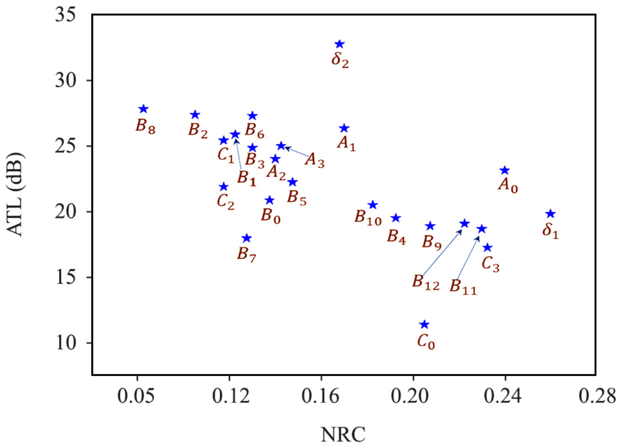


Figure 15. Average representation of integrated NRC and ATL of all samples studied in this present research.

ATL compared to the samples in which at most one nanoparticle was present. Generally, nanomaterials could represent an advantage for the reinforcement of porous structures. But each of them improves the acoustic behavior in its own way. For example, clay and graphene nanoplatelets with layered structures are good candidates so that sound waves do not pass through their structure. This justifies why samples B_4, B_5, and B_6 with higher levels of the nano clay showed better performance than the samples B_{10}, B_{11}, and B_{12} with smaller levels of the graphene nanoplatelets (Figure 14b). On the other hand, since nano-silica is a good nucleating agent, samples B_7, B_8, and B_9 showed a high sound absorption coefficient among the others (Figure 14a). As a rule of thumb, the use of different nanomaterials simultaneously in the foams leads to better sound transmission loss properties. This conclusion could be verified by the experimental data compiled in Tables 7 and 9. As the nanomaterials provide smaller cell sizes and reinforced walls, the morphology of the blank samples shows larger cells with predominantly open cells. This morphology allows the sound wave to easily pass through the foam and be converted into heat and finally dissipated. As to our expectation, the blank samples had relatively higher values of the NRCs. Taking a look at the integrated results in Figure 15, for all of the samples studied here, reveals that the Taguchi method could efficiently be used to derive optimal formulation for the EPDM foam to achieve optimal acoustic performance in the presence or absence of nanomaterials.

AVONA results

The results of the analysis of variance (ANOVA) are presented in Table 11. P-value (the statistical normal error) is an index to check the significance of a parameter on the response variable. A parameter that has a p-value less than 0.05 is an effective statistical parameter. As the results show, all two parameters (NRC & ATL) are significantly far from the statistical point of view with p-value = 0.000.

ANOVA was performed using the linear model (G.L.M) of statistics of SPSS software, version 26. In this section, the comparison and statistical analysis between the averages of 21 samples were obtained from the output of the Taguchi L9 array and control samples with the optimal samples (Optimal ATL: δ2, Optimal NRC: δ1) and it was proved that due to the fact that the p-value is less than 0.05, there is a significant difference between the average of the optimized sample and the other constructed samples. In other words, the average of the obtained data of the ATL and the NRC based on Taguchi is 22.1324 and 0.1614 respectively, which are less than the average of the optimized samples of the ATL and the NRC, which are 32.72 and 0.26, respectively.

CONCLUSION

An effective approach based on the Taguchi method was proposed to find the optimum formulation for the EPDM foams with optimal sound absorption and transmission loss behavior. The goal was to suggest some new materials with the hope that they can be used in certain applications to diminish disturbing noises around us. Acoustic behavior is strongly dependent on cellular structures and the relationship between structure and noise reduction is still uncertain. However, cell morphology, cell size, cell wall thickness, cell openness or closeness and their interconnectivity definitely have an impact on their final performance. The idea of adding multiple nanomaterials seemed to be an

Table 11. ANOVA results.

Source	Mean	Std. deviation	Sig. (2-tailed)	Mean difference	95% Confidence interval of the difference	
					Lower	Upper
NRC	0.1614	0.04683	0.000	-0.09857	-0.1199	-0.0773
ATL	22.1324	4.17112	0.000	-10.58762	-12.4863	-8.6889

effective way. As a result, two compounds extracted from the S/N analysis, shown as δ_1 (nano silica: 2, nano clay: 6, graphene nanoplatelets: 0.2 phr) and δ_2 (nano silica: 4, nano clay: 2, graphene nanoplatelets: 0.3 phr) were found to be the optimal formulations for the sound absorption and transmission loss performance, respectively. They showed an improvement of 13.04% in the sound absorption coefficient and 19.68% in transmission loss, compared to the experiments suggested by the Taguchi method. The significance of the factors was confirmed at a level of confidence, with 95%, by the ANOVA. In general, according to Table 10, with the use of nanoparticles, the modulus of elasticity increased compared to samples without nanoparticles. For example, the elastic modulus in the samples with the percentage of foaming agents 3, 6, and 9 is observed to improve by at least 44.44%, 24%, and 7.69%, respectively. Comparing the result obtained with EPDM foam, in the present study, with its identical EVA foam in our previous work, one can see that the EPDM has shown an increase of 15.56% in the NRC and a subtle decrease of 2.5% in the ATL. The behavior could be due to the difference in their morphology, in which the EPDM has probably more open cells and thinner cell walls. Perhaps, it could be related to the difference in their morphology, in which EPDM has probably more open cells and thinner cell walls. Anyway, it still remains a huge challenge how to produce materials that show good sound absorption and transmission loss at the same time over a wide range of frequencies. That is why studying multilayer composites for modification as a golden solution would be very promising.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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