Acoustic Properties of Recycled Rubber at Normal Incidence

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This paper presents the results of testing acoustic properties of samples formed of recycled rubber granules and a binding agent made of polyurethane resins. The testing was performed in an impedance tube with the diameter of 100mm by using the transfer function method between two microphones defined by the standard SRPS EN ISO 10534-2. The samples with the thickness between 10mm and 50mm were tested. The results show that recycled rubber has excellent absorption properties and that the increase in thickness of the material leads to the increase in the values of the sound absorption coefficient at lower frequencies.

Keywords: recycled rubber, absorption coefficient, passive noise protection

1. INTRODUCTION

The consequence of constant increase in human population and development of engineering is big environmental problems which are particularly pronounced in the increased level of noise in urban environments and the need for storing different types of industrial waste. Storing and recycling of used car tyres have become, in the last decades, one of the biggest problems related to the environment. The solution of the problem is being searched for in the possibility of recycling rubber waste.

Until several years ago, waste tyres in Serbia were deposited in legal and illegal waste dumps. They were used as a fuel in technically inadequate furnaces and uncontrolled burning processes (brick yards/fields, lime pits...) thus being a serious ecological problem. Since 2009, these problems have been coordinated with the EU legal regulations and today, in compliance with the Rulebook on Methods and Procedures for Waste Tyre Disposal Management (The Official Gazette of RS number 104/2009), more and more waste tyres are being recycled into various rubber raw materials and products [1].

Acoustic properties of rubber have been the subject of a lot of research [2÷14] in order to test the possibility of using rubber for passive noise protection. It has been shown that the preliminary results of the absorption coefficient of these tyre samples, under normal incidence conditions, are rather high.

This paper presents the initial results of the research organised for the purpose of finding possibilities for mastering new products on the basis of recycled rubber granules. The research was realised within the project TR 37020 "Development of Methodologies and Means for Noise Protection in Urban Environments" financed by the Ministry of Education, Science and Technological Development of the Republic of Serbia [15].

2. EXAMINATION OF ABSORPTION PROPERTIES OF RECYCLED RUBBER

2.1. Research plan

The research plan foresaw testing of acoustic properties of recycled rubber granules in the frequency range 125Hz-1600Hz as well as the dependence of the sound absorption coefficient on the material thickness. The factors tested and the intervals of their change are presented in Table 1.

Table 1. Factors for response surface study

Factor	Name	Mark	Units	Low Level (-1)	High Level (+1)
A	frequency	*f*	Hz	125	1600
B	thickness	*d*	m	0.01	0.05

2.2. Material and preparation of samples

The testing samples were made of recycled rubber granules (granule dimensions from 3 to 5mm) and a binding agent made of polyurethane resins. They were cast in moulds whose diameter was 100mm and thickness 10mm, 20mm, 30mm, 40mm and 50mm (Figure 1) without pressing in order to provide the porosity of samples. Porosity is necessary because it provides the loss (dispersion) of sound energy in interconnected pores of the material.

Figure 1. Samples made of recycled rubber

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The physical properties of the material made of recycled rubber were taken from the catalogue of the manufacturer "Tigar – Technical Rubber" a.d. – Pirot [16], and they are shown in Table 2.

Table 2. Physical properties of the material made of recycled rubber [16]

Hardness	[ShA]	70±10
Density	[kg/m^3]	750 - 900
Tensile strength	[MPa]	0.4
Abrasion resistance	[mm^3]	200
Elongation	[%]	50
Compression	[%]	4.3

2.3. Method and equipment

The measurement of absorption was done in the impedance tube by using the transfer function method between two microphones, described in the SRPS EN ISO 10534-2 standard [17]. This method is based on the decomposition of the standing wave which is formed in the tube by recording signals from two microphones and calculating their transfer function. The reflection coefficient is calculated from the transfer function, and then the absorption coefficient is calculated. This method results in obtaining the values of the absorption coefficient at normal incidence, in the frequency range defined by the physical dimensions of the tube and the distance between the microphones. By using this method, it is possible to obtain fast measurements for normal incidence, using small samples.

$$\alpha = 1 - |R|^2 \quad (1)$$

where R is the reflection coefficient calculated according to the expression:

$$R = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k(l+s)} \quad (2)$$

Where:

- *H* – the corrected transfer function,
- *s* – the distance between the microphones,
- *I* – the distance between the closer microphone and the sample, and
- *k* – the wave number.

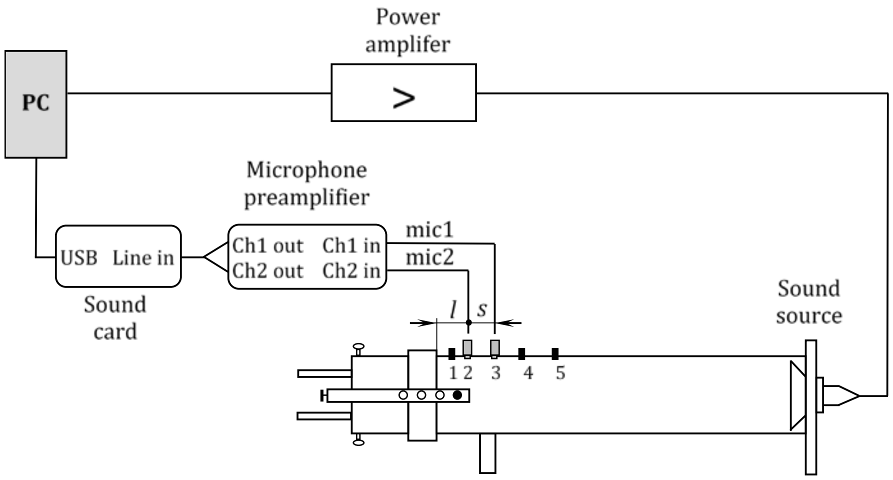

Figure 2. System for measuring absorption according to the standard SRPS EN ISO 10534-2 [17]

The method of impedance of the tube has numerous advantages, which are described in the literature [17], the most important of them being:

- the measuring device is of small dimensions, so that it is very practical for use,
- the samples themselves have small dimensions, which facilitates their preparation for measurement,
- small costs of the experiment.

The disadvantages of this method:

- only normal incidence of waves are measured, although it is possible to apply correction to obtain a value of the absorption coefficient with random incidence,
- different diameters of tubes and samples are necessary in order to cover a wider frequency range.

3. RESULTS AND DISCUSSION

3.1. Experimental results

Experimental values of the absorption coefficient per 1/3 octave bands for different material thicknesses obtained by measuring in the impedance tube are shown in Table 3.

Table 3. Values of the absorption coefficient for recycled rubber

f (Hz)	*d* (cm)				
	1	2	3	4	5
125	0.062079	0.061709	0.074983	0.079582	0.078801
160	0.046224	0.048147	0.061382	0.072933	0.082575
200	0.050688	0.064102	0.071529	0.088792	0.093929
250	0.033774	0.043948	0.060364	0.095229	0.10363
315	0.047438	0.051707	0.078651	0.11827	0.13687
400	0.052127	0.067505	0.08809	0.17284	0.20107
500	0.051058	0.069412	0.11152	0.23979	0.28714
630	0.057375	0.086028	0.14524	0.36262	0.44561
800	0.068572	0.111380	0.20821	0.5924	0.72293
1000	0.077245	0.146640	0.31118	0.85416	0.95535
1250	0.10620	0.245290	0.54574	0.91899	0.87541
1600	0.14311	0.410970	0.85543	0.72432	0.65755

From Table 3 and Figure 3 the following can be noted:

- At low frequencies up to 400Hz, recycled rubber does not have pronounced absorption properties and the absorption coefficient ranges in the interval from 0.03 for the thickness of 10mm to 0.2 for the material thickness of 50mm.

- The absorption coefficient increases with the increase in the material thickness. For the material thicknesses from 10mm to 30mm, the maximum value of the absorption coefficient is at the frequency of 1600Hz, as follows: for d=10mm it is α=0.14, for d=20mm it is α=0.42 and for d=30mm it is α=0,86.
- For the rubber thickness of d=40mm, the maximum value of the absorption coefficient is α=0.92 for the frequency f=1250Hz, while this value decreases at higher and lower frequencies. Rubber accomplishes the highest efficiency regarding absorption in the range from 800Hz to 1600Hz, where the absorption coefficient ranges in the interval from 0.6 to 0.92.
- For the rubber thickness d=50mm, the maximum value of the absorption coefficient is α=0.96 for the frequency f=1000Hz, while this value decreases at higher and lower frequencies. Rubber accomplishes the highest efficiency regarding absorption in the range from 700Hz to 1600Hz, where the absorption coefficient ranges in the interval from 0.6 to 0.96.

It can be concluded that the absorption coefficient of recycled rubber increases with the increase in the material thickness, but at the same time its maximum moves toward relatively lower frequencies up to 1000Hz.

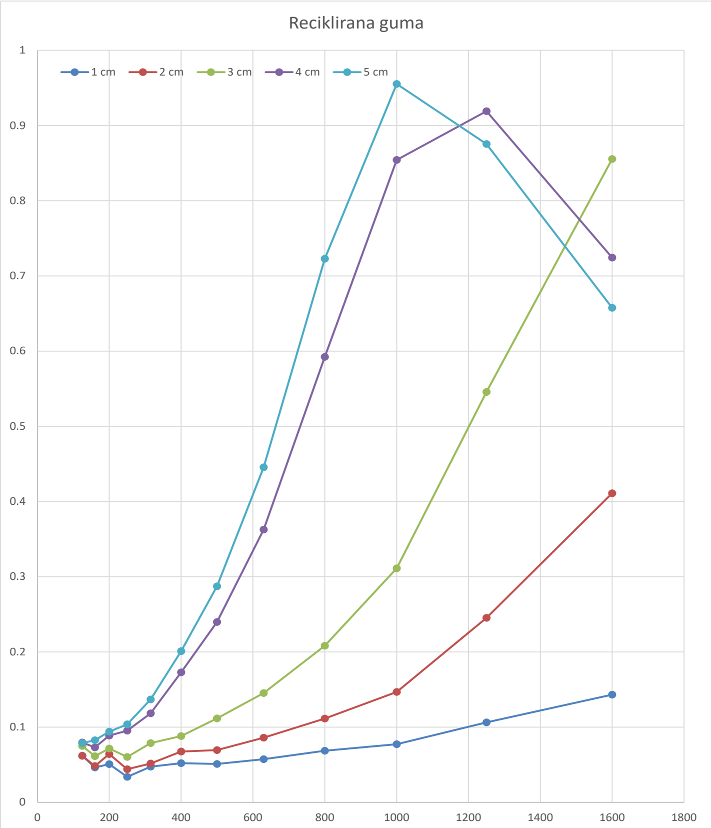

Figure 3. Values of the absorption coefficient for recycled rubber

3.2. Procession and analysis of the experimental results

In order to carry out the procedure of regression analysis and perform the selection of an adequate regression model after the selection of the experimental plan and performed experimental measurements, it is necessary to carry out the following phases [18, 19]:

- Entering experimental data
- Summary statistics of possible mathematical models
- Selection of the stochastic model
- ANOVA analysis – evaluation of the significance of the model
- Evaluation of the model adequacy
- Interval evaluation of the model parameters
- Diagnostics of the model and, if necessary, transformation of the model
- Interval evaluation of the regression function
- Graphical interpretation and interpretation of the model.

The data procession was performed in the software package Design Expert v.9.0.6.2. [20, 21]. Out of the available mathematical models, the models proposed have the form of third and fourth degree polynomials (Table 4).

Table 4. Summary statistics of possible mathematical models

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.37	0.8620	0.8571	0.8418	8.71	
2FI	0.32	0.8933	0.8875	0.8514	8.18	
Quadratic	0.30	0.9140	0.9060	0.8680	7.27	
Cubic	0.14	0.9812	0.9779	0.9681	1.76	Suggested
Quartic	0.12	0.9876	0.9837	0.9473	2.90	Suggested
Fifth	0.10	0.9922	0.9885	0.9369	3.47	Aliased

The cubic model was adopted. In order to improve the results of the analysis, it was necessary to perform the transformation of the response function by means of the natural logarithm (Natural Log, k=0, λ=0). After reduction of nonsignificant members from the proposed model, the analysis of variance (ANOVA) for the transformed cubic model was performed.

Table 5. ANOVA report for recycled rubber

ANOVA for Response Surface Cubic model						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	54.02	9	6.00	290.60	< 0.0001	significant
A-f	5.89	1	5.89	285.21	< 0.0001	
B-d	6.56	1	6.56	317.81	< 0.0001	
AB	0.72	1	0.72	34.69	< 0.0001	
A^2	1.03	1	1.03	49.83	< 0.0001	
B^2	0.69	1	0.69	33.37	< 0.0001	
A^2B	2.51	1	2.51	121.63	< 0.0001	
AB^2	0.65	1	0.65	31.65	< 0.0001	
A^3	0.25	1	0.25	12.26	0.0010	
B^3	0.28	1	0.28	13.68	0.0005	
Residual	1.03	50	0.021			
Cor Total	55.05	59				

The high F value of the model (F=290.60) and the low value of probability (p<0.0001) indicate that the model is significant. The coefficient of determination (R-Squared) and other statistics (Table 6) have good values, which justifies the selection of the adopted mathematical model.

Table 6. Calculation values of the statistics for the evaluation of the mathematical model

Std. Dev.	0.14
Mean	-1.99
C.V. %	7.22
PRESS	1.76
R-Squared	0.9812
Adj R-Squared	0.9779
Pred R-Squared	0.9681
Adeq Precision	53.276

The value of regression coefficients of the mathematical model, the standard error, 95% confidence intervals and the Variance inflation factor (VIF) of regression coefficients are presented in Table 7.

Table 7. Values of coefficients of the mathematical model and confidence intervals

Factor	Coefficient Estimate	df	Standard Error	95% CI		VIF
				Low	High	
Intercept	-1.25	1	0.042	-1.33	-1.17	
A-f	1.58	1	0.093	1.39	1.77	9.55
B-d	1.55	1	0.087	1.38	1.73	11.02
AB	0.26	1	0.044	0.17	0.35	1.43
A^2	-0.38	1	0.054	-0.49	-0.27	1.10
B^2	-0.30	1	0.051	-0.40	-0.19	1.33
A^2B	-0.84	1	0.076	-0.99	-0.68	3.17
AB^2	-0.41	1	0.072	-0.55	-0.26	2.76
A^3	-0.36	1	0.100	-0.57	-0.15	8.30
B^3	-0.32	1	0.087	-0.50	-0.15	9.03

The final equation of the mathematical model which adequately describes the dependence of the sound absorption coefficient of recycled rubber on the frequency and the material thickness is:

$$Ln(\alpha) = - 1.69947 - 4.40877E{-}003*f - 131.00232*d + 0.23296*f*d + 3.93762E{-}006*f^2 + 4089.88397*d^2 - 7.68280E{-}005*f^2*d - 1.37867*f*d^2 - 9.03081E{-}010*f^3 - 40439.17333*d^3 \quad (3)$$

The diagnostics of statistical characteristics of the model (diagram of normal distribution of residuals, Box-Cox diagram, etc.) show that residuals are normally distributed and that the model has satisfactory statistical characteristics (Figures 4 and 5).

The graphical presentation of the mathematical model described by Eq. (1) is shown in Figures 6 and 7.

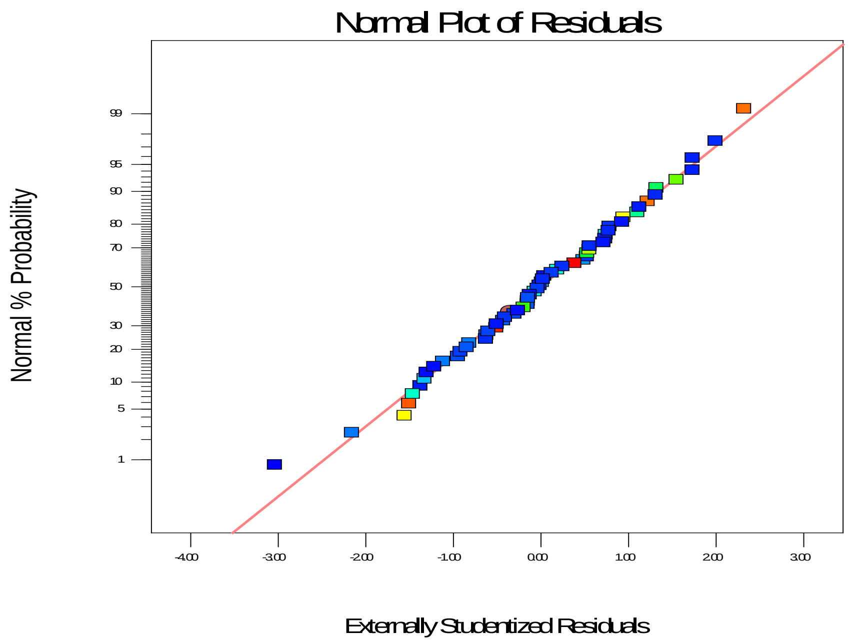

Figure 4. Diagram of the normal distribution of residuals

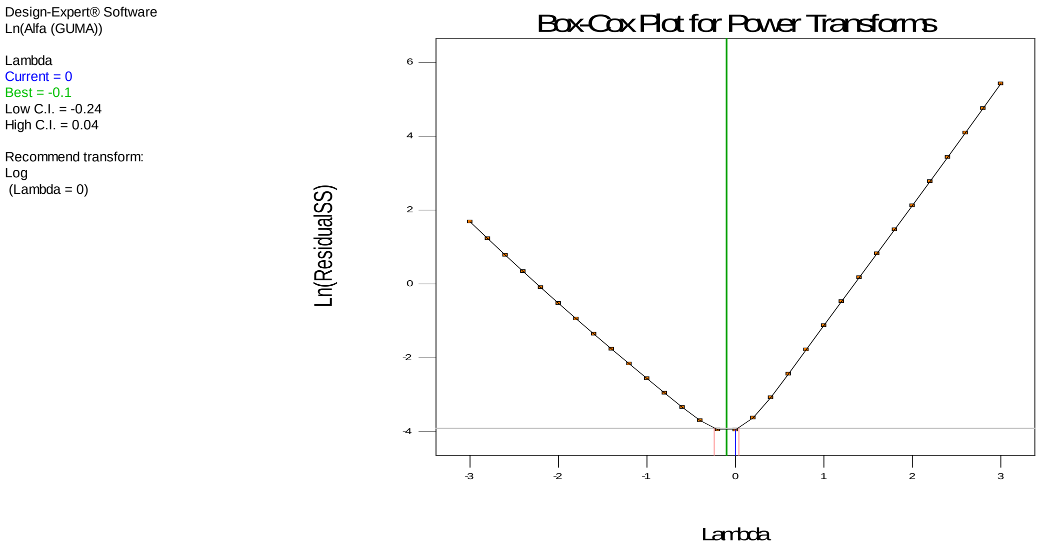

Figure 5. Box-Cox diagram for the corrected model for recycled rubber

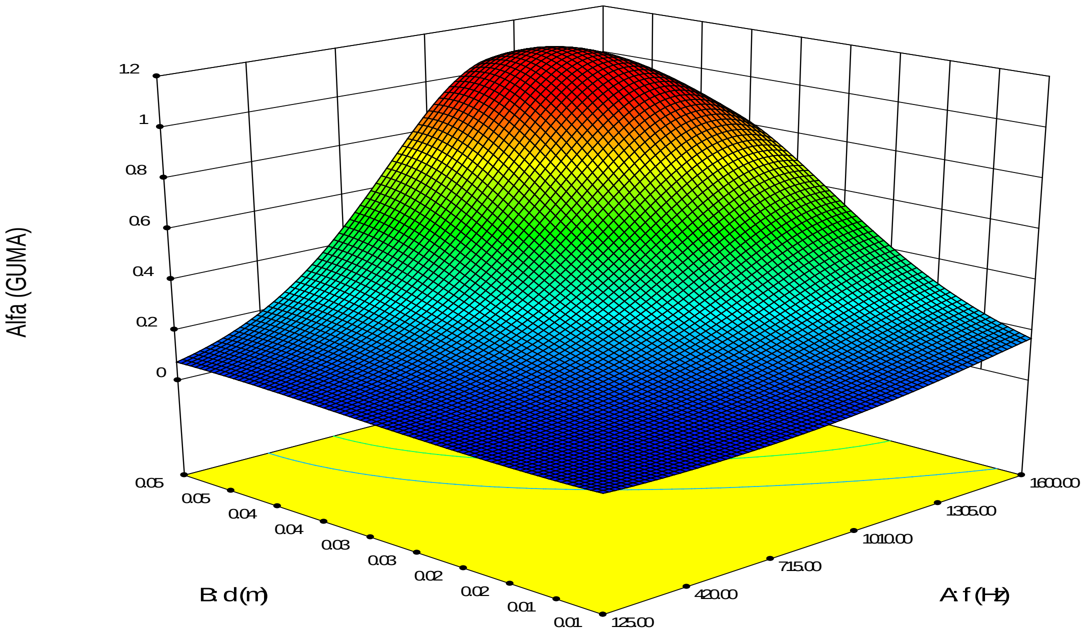

Figure 6. 3D graphical presentation of the dependence of the absorption coefficient on the material thickness in the examined frequency range

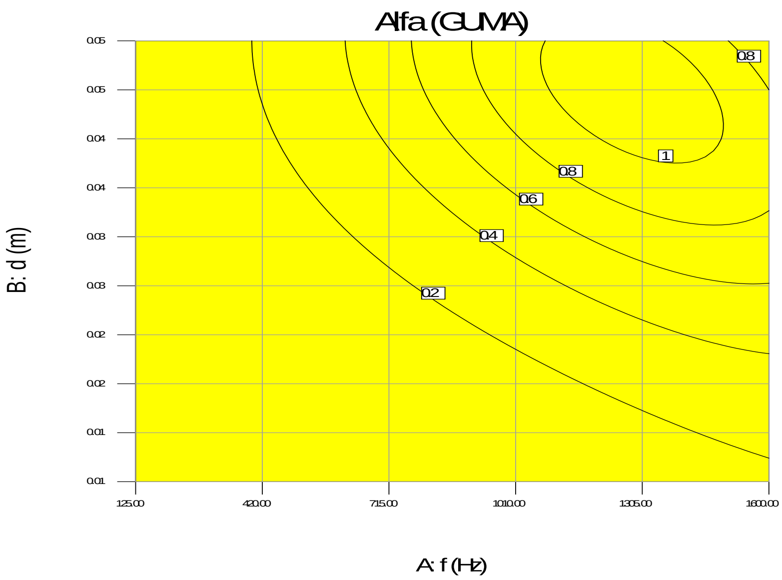

Figure 7. Contour 2D presentation of the mathematical model for recycled rubber

4. CONCLUSION

Experimental results show that the absorption coefficient of recycled rubber increases with the increase in frequency up to the value of 1300Hz, and after that it decreases. The best values are obtained in the interval from 800Hz to 1600Hz, which justifies the application of recycled rubber as the absorption material for noise protection.

As for the influence of material thickness, it can be stated that the increase in thickness has its purpose up to 45mm, and after that the absorption coefficient decreases. It also confirms why the examination was carried out on the samples up to 50mm thick.

Further work will imply new examinations with samples with varying dimensions of rubber granules, pressing forces while forming the samples, parameters of installation, etc., as well as examination of mechanical properties, fire resistance, thermal conductivity, etc.

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