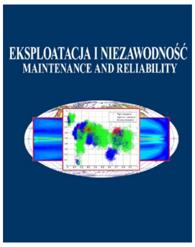

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A simulation strategy to determine the mechanical behaviour of cork-rubber composite pads for vibration isolation

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Highlights

- Use of modelling tools to determine compression behaviour of cork-rubber composites.
- Linear regression models to determine the effect of compound formulation.
- Prediction of the dynamic behaviour of different dimension samples through FEA.
- Comparison between experimental and numerical approaches.

Abstract

The present work aimed to determine the performance of new cork-rubber composites, applying a modelling-based approach. The static and dynamic behaviour under compression of new composite isolation pads was determined using mathematical techniques. Linear regression was used to estimate apparent compression modulus and dynamic stiffness coefficient of compounds samples based on the effect of fillers, cork and other ingredients. Using the results obtained by regression models, finite element analysis (FEA) was applied to determine the behaviour of the same cork-rubber material but considering samples with different dimensions. The majority of the regression models presented R^2 values above 90%. Also, a good agreement was found between the results obtained by the presented approach and previous experimental tests. Based on the developed methodology, the compression behaviour of new cork-rubber compounds can be accessed, improving product development stages.

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Keywords

cork-rubber composites, compression, vibration isolation, linear regression, finite element analysis.

1. Introduction

Cork is a natural material obtained from the harvest of *Quercus suber* L. trees and is typically applied in the manufacturing of stoppers for the wine industry. Surplus from the harvest and stoppers production can be introduced in the manufacture of composite materials, like agglomerates and cork-polymer composites, due to cork characteristics like good thermal and acoustic behaviour, high compressibility and recovery characteristics, low Poisson's ratio, impact energy absorption, among others [8, 25, 30]. One example of cork composites is cork-rubber or rubber-cork. The introduction of cork into a rubber mixture improves its compressibility and recovery characteristics as well as the chemical stability of rubber [16, 30].

The manufacture of cork-rubber composites is similar to other rubber-based materials. During mixing stage, cork granules are introduced into a rubber compound with fillers, processing aid ingredients and vulcanizing agents. Several works have been developed to study the effect of rubber compound ingredients on the physical and mechanical properties of vulcanizates, such as the quantity of fillers (carbon black [24], calcium carbonate [5], silica and nanoclay [4], for example), plasticizer [5] and vulcanizing agents and accelerators [4, 5]. Also, several authors have investigated the effect on the rubber properties with the introduction of natural based-materials like bamboo [14], cereal straw [21], mengkuang and wood fibers [29, 31] and also cork powder [12]. Generally, with the increase of fillers quantity and the utilization of smaller particles, an increase in hardness is observed.

In vibration isolation systems, elastomeric materials, like cork-rubber composites, can be applied between structure and potential vibration sources to reduce or avoid vibrations transmission. In order to achieve this requirement, the material must have specific characteristics in terms of static and dynamic performance [15]. One of the first requirements to be met is the capacity to support the structure without exceeding the static deformation allowed of the material, which typically ranges a maximum value between 10 to 15% of the pad thickness in compression, in order to be able to provide efficient dynamic isolation (low stiffness) and avoid the increase of deflection over long periods of time (creep) [15, 27, 28].

An illustrative description of the behaviour of a system composed of a cork-rubber composite subjected to compressive loading is presented in Figure 1. Like other rubbery materials, the mechanical performance of cork-rubber materials is dependent on the sample's hardness and geometry. In terms of quasi-static compression, the increase of hardness usually leads to the increase of Young's modulus (E_0), as accounted by several studies regarding rubber materials [11, 17, 26]. Analytical models describing Young's modulus as a function of a

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single variable hardness have been developed in [11, 26]. The model proposed by Kunz and Studer [17] additionally takes into account the Poisson's ratio of the rubber material.

When rubber materials are subject to static compression between bonded surfaces, the effect of geometry can be described by applying a variable designated by shape factor: ratio between loaded area and total area free to bulge. Several authors have derived and presented mathematical relations between the shape factor and the compression behaviour of rubber blocks [10, 13, 19, 32]. Analytical models differ in terms of material assumptions, such as considering total incompressibility ($\upsilon = 0.5$) [10, 13] or the effect of a smaller Poisson's ratio ($\upsilon < 0.5$) [19, 32]. Also, mathematical models vary according to the block geometry: circular and rectangular cross section blocks as presented in [13, 19]. The performance of these materials is usually described by apparent compression modulus (E_c). Considering the same material, samples with high shape factors present higher stiffness when compared to smaller shape factors.

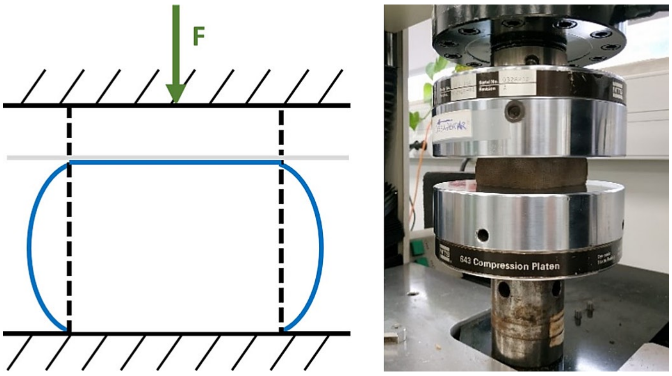

Fig. 1. Compression of cork-rubber composites with frictional contact between surfaces

Another requirement that must be considered when developing a vibration isolation system is its dynamic performance. The dynamic stiffness of cork-rubber composite materials is related to their static behaviour, so it is expected that hardness and shape factor also play a role in the dynamic performance of cork-rubber composites. A measurement for the dynamic performance used is the ratio between dynamic and static stiffness, also known as the dynamic stiffness coefficient (K) [28]. In the case of bearing pads, DIN 53513 [6] is applied to measure the dynamic stiffness of the materials.

In terms of product development, the application of computational resources, namely modelling techniques, in the early stages of a project, can have a positive impact in terms of sustainability and development time. There is a reduction in the number of prototypes developed, industrial tests, raw materials used and project-related costs and time, rather than following a typical trial and error approach.

Besides compound formulation and evaluation of requirements, the application of modelling tools is also present in other aspects like the design and manufacture of rubber products. For example, design of experiments and regression analysis has been used as a method for evaluating mixing [22] and vulcanization related variables [1] and to analyse different design configurations of composite products like conveyor belts [2, 3]. Also, numerical methods have been applied to determine the evolution of the rubber vulcanization process [7] and to assess the behaviour of rubber products under different loading conditions [18].

The goal of this article is to present a modelling approach for the prediction of cork-rubber composites performance, in terms of static and dynamic compression as vibration isolation pads, based on their compound formulation. Variation of fillers and cork granules on a cork-rubber composite was studied using design of experiments. Regression models were derived to predict apparent compression modulus and its relationship with dynamic compression modulus (E_d). The results obtained by regression models, combined with finite element analysis, allow determining the dynamic behaviour of other samples of the same material. To validate the approach, comparisons between experimental and simulation results are presented and discussed.

The present article is structured in the following order: in section 2, the materials and methods applied in this study are described, followed by the presentation of results and discussion in section 3. Finally, the conclusions of this developed study are presented.

2. Materials and methods

To study the influence of compound ingredients on the properties of the cork-rubber composites, a cork-rubber formulation was examined, divided into two groups to be analysed separately: fillers and cork granules. A cork-natural rubber compound formulation with hardness around 60 Shore A was selected as the base formulation of two separate experimental designs focused on finding differences in relation to fillers and cork granules (compound B). The same rubber compound without the addition of cork granules was also considered for this study (compound A).

Regarding fillers study, two variables were analysed: type and quantity of filler. According to the type and origin of the filler used, differences between compounds regarding mechanical properties were expected. In addition to these two parameters, it was also considered a third parameter concerning the effect of the filler activator quantity on the formulation. To analyse this system, a 2^3 factorial design was employed.

Two variables related to cork granules applied in a rubber formulation were also considered in a separate design of experiments. Granulometry and quantity of cork granules were the factors to be analysed through a 2^2 factorial design.

A summary of all cork-rubber composite samples produced in this study is presented in Table 1. In total, eight cork-rubber composites (1A, 1B, …, 1H) were characterized regarding fillers analysis. Related to cork analysis, four cork-rubber composites (2A, 2B, 2C and 2D), and also compound A, were used to determine regression models. For each factorial design, the maximum and minimum values are coded with + and – symbols, respectively. The original quantities of filler and cork granules applied in the base formulation (compound B) are represented by x_f and x_c, respectively. Compound B and other additional compounds (V1, V2, ..., V5) were also produced and characterized to compare with the results given by developed regression models.

2.1. Production of samples

The samples created for the experimental studies were manufactured and evaluated in pilot scale. The production of the cork-rubber samples with dimension 200x200x10 mm was executed following this procedure: weighing of all formulation components, mixture in an internal mixer (Banbury) and in a two-roll open mill, cutting of slab in a square shape of 200x200 mm, placement of the slab inside a mould in a compression moulding press to proceed to vulcanization at 150°C. The vulcanization times were defined based on the optimum cure type determined by Moving Die Rheometer (MDR) and the sample's final thickness.

2.2. Characterization of samples

Five samples with 60×60×10 mm were taken from each vulcanizate, to be use in both static and dynamic compression tests. After a conditioning period of at least 24 h at 23°C @ 50% RH, quasi-static compression tests were performed first. Load-displacement compression curves were obtained from a universal testing machine, with a load cell of 50 kN, until a maximum load level was achieved. Tests were performed at a rate of 5 mm/min and the maximum load applied was around 30 kN. No lubricant or rough surface was applied, it was only considered dry surfaces. For the same sample, three consecutive compression tests were performed, but only the third test was recorded. Due to the linear-like behaviour of the cork-rubber compos-

Table 1. Summary of samples produced, characterized and/or simulated for this study

Compound	Fillers			Cork granules	
	Type	Filler Quantity (phr*)	Activator Quantity (phr)	Type	Quantity (phr)
A	F1	x_f	-	n/a	
B	F1	x_f	-	C1	x_c
Fillers study (1A-1H)	F1 / F2	- / +	- / +	C1	x_c
Cork study (2A-2D)	F1	x_f	-	C1 / C2	- / +
V1	F1	-	x_{aint}	C1	x_c
V2	F1	+	x_{aint}	C1	x_c
V3	F2	-	x_{aint}	C1	x_c
V4	F2	+	x_{aint}	C1	x_c
V5	F1	x_f	-	C2	x_c
V6	F1	x_f	-	C2	x_{cint}

**phr – parts per hundred rubber*

Filler quantity: Level - < x_f < Level +

Cork quantity: Level - < x_c < Level +

Cork granulometry: C1 > C2

x_{aint} : mean activator quantity between levels – and +

x_{cint} : mean cork quantity between levels x_c and +

ites until 10% strain [20], the apparent compression modulus for each sample was calculated by Equation 1:

$$E_c = \frac{\sigma}{0.1} \tag{1}$$

where σ corresponds to the stress at 10% strain in Pa units.

The specimens used in the static compression test were then subjected to a dynamic compression test to evaluate the performance of a mechanical system composed of a mass and the material (acting like a spring-damper system). The tests were performed recurring to a hydraulic universal testing machine. The test procedure consisted of retrieving the resultant signal of displacement when a sample was loaded with a sinusoidal force with a 10% load amplitude at 5 Hz. For each sample, the test was performed six times, with compression stress ranging from 0.5 to 3 MPa, after being pre-conditioned at 5 Hz and a mean stress of 1.8 MPa with 10% load amplitude. Data obtained from the last twenty cycles were retrieved and analysed, calculating parameters like dynamic elastic stiffness (k_d in N/m), dynamic compression modulus and natural frequency of the system (f_n in Hz) when subject to certain stress (Equations 2 to 4).

$$k_d = \frac{F_a}{d_a}\cos\delta \tag{2}$$

$$E_d = \frac{k_d L}{A} \tag{3}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_d g}{F_m}} \tag{4}$$

where F and d are load (in N) and displacement (in m), δ is the phase shift between load and displacement, a and m are subscripts for the amplitude and mean values of the sinusoidal curves, L (in m) and A (in m^2), are the initial thickness and loaded area of the sample, respectively, and g is the gravitational acceleration (in m/s^2).

Based on the compression tests results, the value of dynamic stiffness coefficient was determined by Equation 5:

$$K = \frac{E_d}{E_c} \tag{5}$$

2.3. Regression models: 60×60×10 mm samples

Due to the amount of data obtained by the application of design of experiments and easiness of implementation compared to other techniques, linear regression was chosen as a first approach method to develop mathematical models. Furthermore, this method has been applied in other works, relating the variation of composition elements with the final properties of rubber products, such as in [4, 5].

Regression models were developed based on the data obtained by the characterization of cork-rubber materials related to fillers and cork granules analysis. Also, compound A results were used as additional data to the latter study. R statistical software was applied to develop all regression models.

After a preliminary study about the main factors, the development of linear regression models was accessed for fillers and cork granules analyses, regarding static and dynamic properties of 60×60×10 mm samples. Independent variables related to filler or cork granules type were treated as dummy variables: value of 0 for type 1 and value of 1 for type 2. The chosen dependent variable related to the static compression performance was the apparent compression modulus (E_c), at 10% strain because, until this point of deformation, all tested materials presented an almost linear behaviour [20]. Concerning dynamic performance, the ratio between dynamic compression modulus and apparent compression modulus at 10% strain, defined as dynamic stiffness coefficient (K), was considered as the dependent variable. In the latter case, it was also considered another additional independent variable: compressive stress imposed during the dynamic test.

In a first approach, the least squares method was applied. To evaluate the prediction capacity of each regression model, coefficient of determination (R^2) and adjusted coefficient of determination (R$^2_{\text{adj}}$) were determined. Several combinations of predictor variables were used to develop regression models. The inclusion of some interaction and quadratic terms was considered in the development of some of the models presented in this work. An example of a model combining main factors, interactions and quadratic terms is presented in Equation 6:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_1^2 x_2 + \beta_7 x_1 x_2^2 \tag{6}$$

where y represents the dependent variable, x_1 and x_2 the dependent variables, and β_0 to β_7 represent the regression model coefficients.

Considering a 95% confidence level, a significant regression model with the highest values of R^2 and R$^2_{\text{adj}}$ was selected for each analysis. If the assumption that the residuals are normally and independently distributed with mean zero and constant variance was not met, instead of using the least squares method (function *lm* from R package *stats*), other regression methods were employed. In the case of failure of the assumption of residuals normally distributed, the robust regression method using Huber M-estimator (function *rlm* from R package *MASS*) was applied (more information about robust regression in [9, 23]. If the assumption of homoscedasticity was not verified, the method of weighted least squares (WLS) method was applied (function *lm* from R package *stats*) (more information about WLS in [23]). In this case, due to the existence of replicates, at each combination of predictor variables, the weights corresponded to the inverse of sample's variances of the dependent variable.

Regression models with a coefficient of determination above 90% were used to predict apparent and dynamic compression moduli.

2.4. Simulation of mechanical behaviour of samples with different dimensions

The developed regression models are only applicable to the same sample's geometry, a squared cross section specimen 60×60 mm with 10 mm thickness since all data utilized for its development came from experimental data of these specimens. To evaluate the static and dynamic compression behaviour of other samples, with squared cross-sections but with different dimensions, a procedure including the application of finite element analysis was employed.

Based on the results of apparent compression modulus provided by the regression models developed for 60×60×10 mm samples, estimates of Young's modulus of cork-rubber composites were determined. To do that, the relation between moduli presented in [20] was applied. For other squared cross section samples with different dimensions of the same cork-rubber composite, the apparent compression modulus was determined using the same method, according to its shape factor.

To determine the dynamic properties under compressive loading of squared cross section samples with different dimensions, a methodology presented in Figure 2 was applied. Similarly to the procedure applied for determining static properties, the results of the dynamic stiffness coefficient of 60×60×10 mm sample obtained from the regression model were used to determine an equivalent dynamic Young's modulus $(E_{0_{eq}})$, according to the shape factor of 60×60×10 mm samples and the compression stress level imposed and based on a single degree of freedom model (SDOF). Together with the sample's final thickness obtained through the application of the static compressive load, finite element analysis (using Harmonic Response module of Ansys Workbench) was applied to determine a displacement amplitude value, which allowed the calculation of dynamic compression modulus. Recurring to Equation 2 and 4, dynamic stiffness and natural frequency, correspondent to the dynamic experimental test, were calculated.

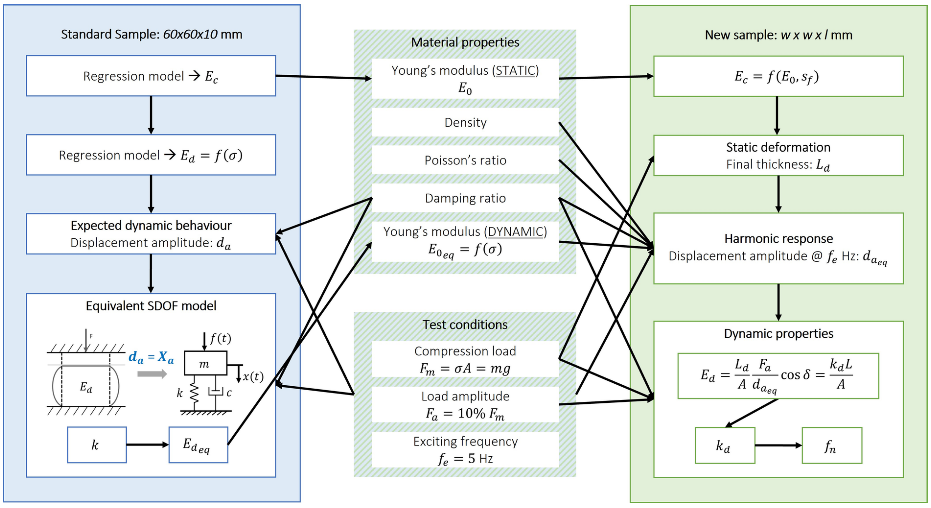

Fig. 2. Methodology to determine the dynamic properties correspondent to the experimental testing of samples with a squared cross section of a cork-rubber composite material

The finite element model was composed of a solid block, representing the cork-rubber specimen. A mass point correspondent to the stress level imposed on a cork-rubber specimen during dynamic experimental tests was added to the top surface of the block. A fixed support condition was considered on the opposite surface of the block. The numerical analysis consisted of simulating the application of a sinusoidal load with an amplitude of 10% of the mean applied load, recording as output the displacement amplitude of the system at the value of the exciting frequency used in experimental tests of the standard sample. The 3-D finite element model are presented in Figure 3, respectively.

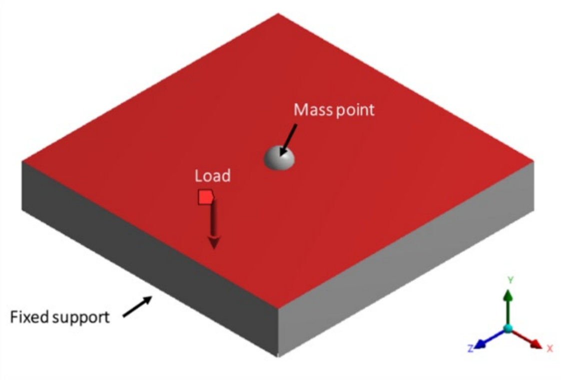

Fig. 3. Dynamic compression of a cork-rubber sample: finite element model.

For this study, the following properties were assumed for cork-rubber materials. All cork-rubber composites presented the same final density: 1000 kg/m^3. Poisson's ratio of compound B was determined through the measurement of lateral deformation when subjected to compressive load. Poisson's ratio of samples with 60×60×30 mm and 60×60×50 mm were determined considering a maximum axial strain of 20%. As the obtained results presented similar results in both transversal directions, the average value was assumed as the Poisson's ratio of a cork-rubber composite, considering isotropic behaviour. Since no significant differences between composite B and other cork-rubber composites were detected, due to small variations on compound formulations, the value obtained for compound B was considered and applied in all simulations: 0.31. Preliminary dynamic mechanical analysis results showed that the loss factor of cork-rubber samples varied from 0.05 to 0.13, depending on amplitude strain (ranging from 0 and 20%) and disturbing frequency (between 5 and 15 Hz). A constant damping ratio (ξ) was considered for all analyses. The damping ratio value was calculated through the average loss factor (η), as presented in Equation 7:

$$\xi = \frac{\eta}{2} = \frac{0.09}{2} = 0.045 \tag{7}$$

3. Results and Discussion

In this section, results obtained by linear regression and simulation approach are described. For cork-rubber squared cross section samples of 60×60×10 mm, the developed regression models are presented. Based on the results obtained through the application of some of the regression models, predictions about the static and dynamic behaviour of cork-rubber samples with different compound formulations and/or dimensions are reported, as well as their comparison with experimental results related to some materials.

3.1. Development of regression models

Four regression studies were performed to achieve mathematical models able to predict the static and dynamic behaviour of cork-rubber composites, according to fillers and cork granules included in the same rubber formulation.

3.1.1. Fillers

Concerning the fillers study, multiple linear regression models were developed to predict apparent compression modulus (E_c). In a first approach, data from a screening experiment were used considering three independent variables: filler type (t), filler quantity (f) and filler activator quantity (a). Using the least squares method, the model with the best fit presented a R^2 value of 92.36% and a R^2_{adj} of 91.24%. Due to the residuals' lack of normality observed, robust method using Huber M-estimator was applied. The resultant equation is presented in Equation 8. The obtained value of the coefficient of determination R^2 for this model was 91.82%.

$$E_c = 9.583 + 0.582t + 0.159f + 0.613a + 0.484ta - 0.014fa \quad (8)$$

Multiple linear regression was also applied to determine the dynamic stiffness coefficient (K). Besides the three independent variables applied in the static behaviour model, stress applied to the sample was also added during model development, as well as some quadratic terms. Using the least squares method, the best model obtained a R^2 value of 96.23% and R^2_{adj} of 96.08%. Due to the assumption of residuals normality not being fully met, the application of robust regression method using Huber M-estimator was considered. The resultant model given by the application of the robust method is presented in Equation 9. The obtained value of the coefficient of determination R^2 for this model was 96.09%.

$$K = 1.084 + 0.283\sigma - 0.170t + 5.27\times10^{-5}f - 0.024a + 0.046\sigma^2 - 0.002\sigma f + 0.007tf - 0.007ta + 0.001fa \quad (9)$$

3.1.2. Cork granules

For each type of cork granules, a simple linear regression model was determined, in which the independent variable was cork quantity (c), and the dependent variable was the apparent compression modulus of the vulcanizate (E_c). In a first step, least squares method was used. The model of cork-rubber compounds with type C1 cork granules is very limited for the determination of new predictions since the value of R^2 obtained was 48.57%. On other hand, the model for cork-rubber compounds with type C2 granules presented a R^2 of 89.16%. However, the homoscedasticity assumption did not seem to be met based on the model's residuals analysis. To overcome this issue, weighted least squares method was implemented using the same data. The resultant R^2 value for the type C2 model was 93.47%. The models obtained for type C1 and C2 cork granules are presented in Equations 10 and 11, respectively:

$$E_c = 13.293 + 0.041c \quad (10)$$

$$E_c = 13.371 + 0.101c \quad (11)$$

As it is possible to verify through the obtained regression models, the use of cork granules of smaller granulometry and larger quantities increases the static stiffness associated with these compounds.

Regarding the dynamic compression behaviour, multiple linear regression was applied for each type of cork granules. Like in the fillers analysis, another independent variable, the stress imposed on the specimen, was added to the model's development for the prediction of the ratio between dynamic and apparent compression moduli. Some quadratic terms were considered in the two models. Using least squares method, the values of R^2 obtained were 96.90% ($R^2_{adj} = 96.72\%$) and 98.11% ($R^2_{adj} = 97.95\%$) for the models regarding compounds with type C1 and type C2 cork granules, respectively. Due to the lack of residuals normality observed, the model correspondent to the compounds with type C1 cork granules was developed using the robust method with Huber M-estimator. The resultant R^2 value for type C1 robust model was 96.88%. The equations regarding each cork-rubber compound, using type C1 and C2 cork granules, are presented in Equations 12 and 13, respectively:

$$K = 1.508 + 0.205\sigma - 0.084c + 0.062\sigma^2 + 0.004c^2 + 0.005\sigma c \quad (12)$$

$$K = 1.410 + 0.331\sigma - 0.053c + 0.030\sigma^2 + 0.003c^2 - 0.023\sigma c + 4.62\times10^{-4}\sigma c^2 + 0.005\sigma^2 c \quad (13)$$

3.2. Prediction of mechanical behaviour of cork-rubber composite samples

The results related to the application of the previous regression models and simulation approach presented in section 2 are described in the following sections, considering squared cross section samples with 60×60×10 mm or other dimensions.

3.2.1. Static behaviour

3.2.1.1. Samples 60×60×10 mm

To evaluate the performance of previous fillers models, predictions were made about the apparent compression modulus, regarding other cork-rubber composites produced in the same conditions and with the same geometry (60×60×10 mm) as the samples whose data were used to create the regression models. The results obtained by the model presented in Equation 8 and respective error in comparison with experimental results are presented in Table 2.

The regression results obtained for cork-rubber composites with fillers F2 (V3 and V4) are closer to the experimental data when compared with the other cork-rubber compounds produced with fillers F1 (B, V1 and V2). For two of the three cork-rubber compounds with filler type F1, the application of the regression model provided higher values of apparent compression modulus (higher static stiffness) than the results of the experimental samples, exceeding a 10% error.

Due to the high value of R^2, a prediction about the static performance of cork-rubber composites produced with type C2 cork granules

Table 2. Fillers analysis: comparison between experimental and regression model results for apparent compression modulus

Compound	Apparent compression modulus E_c (MPa)		Relative error	Young's modulus E_0 (MPa)**
	Prediction by Equation 8	Experimental*		
B	16.722	14.481 ± 0.829	15.5%	12.962
V1	14.885	12.743 ± 0.224	16.8%	11.538
V2	17.194	16.164 ± 0.404	6.4%	13.327
V3	16.919	17.441 ± 0.596	-3.0%	13.115
V4	19.228	18.828 ± 0.885	2.1%	14.904

** Mean of five samples*

*** Based on Equation 14*

Table 3. Cork granules analysis: experimental and regression model results for apparent compression modulus

Compound (type C2)	Apparent compression modulus E_c (MPa)		Relative error	Young's modulus E_0 (MPa)**
	Prediction by Equation 11	Experimental*		
V5	14.379	15.198 ± 0.150	-5.4%	11.145
V6	14.882	-	-	11.536

** Mean of five samples*

*** Based on Equation 14*

is presented, based on the regression model obtained for the 60×60×10 mm geometry. The static performance of a cork-rubber composite, containing half of the maximum quantity of cork incorporated of all produced composites, was compared with experimental data. The results obtained by the model presented in Equation 11 and respective error in comparison with experimental results are presented in Table 3.

3.2.1.2. Other dimensions

Based on the results obtained in [20] and the shape factor of the samples 60×60×10 mm, estimates of the correspondent Young's modulus (E_0) can be determined for each cork-rubber composite. For a squared cross-section pad with a shape factor of 1.5, the relation between Young's and apparent compression modulus is given by Equation 14. The Young's modulus results are presented in Table 2, corresponding to the results provided by the fillers regression model.

$$E_c = 1.29 E_0 \tag{14}$$

To determine the static behaviour of another squared cross-section sample with different dimensions, the relation between Young's and apparent compression moduli varies according to its shape factor. As an example, the values of apparent compression modulus of samples made from cork-rubber composite material B are presented in Figure 4.

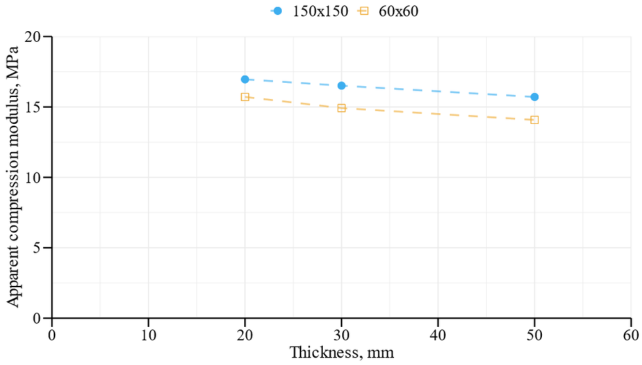

Fig. 4. Simulation results for cork rubber composite B squared cross section samples with different dimensions

Young's modulus results, related to the regression results from the cork granules study, are also presented in Table 3 and were determined based on the relation presented in Equation 14. Using the correspondent relation between Young's and apparent compression moduli, the apparent compression modulus of samples with different dimensions was determined. The results obtained for cork-rubber composites V5 and V6 are presented in Figure 5.

The increase of cross section area subjected to compressive load, increases the sample's apparent compression modulus, comparing samples with equal thicknesses. The decrease of thickness also increases stiffness, concerning equal cross section areas. Regarding squared cross section samples, the shape factor is proportional to the area and inversional proportional to the sample's thickness. Thus, according to the results presented, higher values of apparent compression modulus are obtained for samples with the highest shape factors, and these results are in agreement with the observed mechanical behaviour in experimental and theoretical works regarding the compression of elastomers between bonded or frictional surfaces [10, 13, 19, 32].

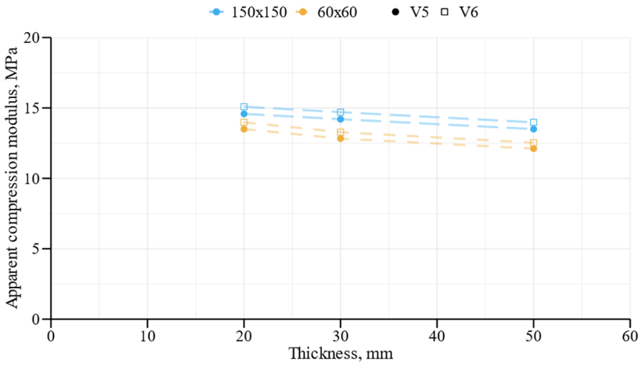

Fig. 5. Simulation results for cork-rubber composites V5 and V6 squared cross-section samples with different dimensions

3.2.2. Dynamic behaviour under compressive load

3.2.2.1. Samples 60×60×10 mm

Before predicting other samples behaviour, a comparison between predicted and experimentally observed dynamic compression behaviour of samples with 60×60×10 mm was performed. Based on the estimates of apparent compression modulus regarding the fillers study, presented in the previous section, and the results of the ratio between compression moduli, obtained by the application of the regression model presented in Equation 9, dynamic compression modulus of these cork-rubber composites under compressive loads were calculated and compared with results from experimental tests. The results for the different compounds are presented in Figures 6 and 7. The maximum error obtained was 7.5%, which demonstrates a good correlation between experimental tests and the results obtained by applying the regression models for all five cork-rubber composites.

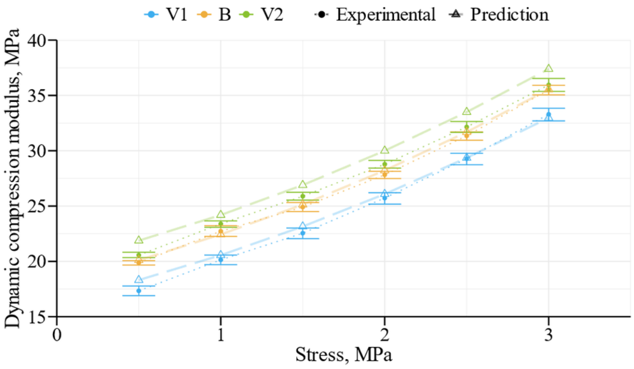

Fig. 6. Simulation results for cork-rubber composites V1, B and V2 squared cross section samples with different dimensions

Regarding the type C2 of cork granules, dynamic compression modulus was determined based on the prediction of apparent compression modulus and regression model presented in Equation 13. A prediction of the dynamic compression behaviour of the two cork-

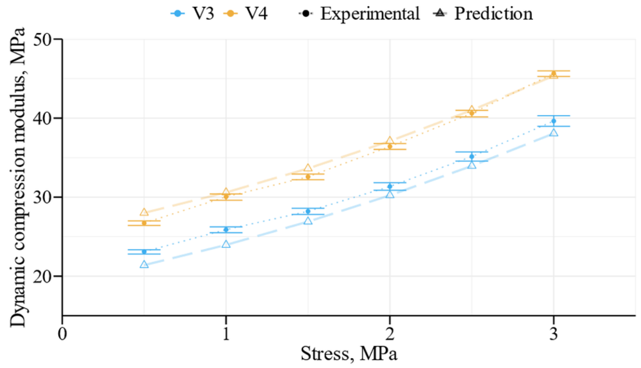

Fig. 7. Simulation results for cork-rubber composites V3 and V4 squared cross section samples with different dimensions

rubber composites 60×60×10 mm samples (V5 and V6), at different stress ranges, is presented in Figure 8.

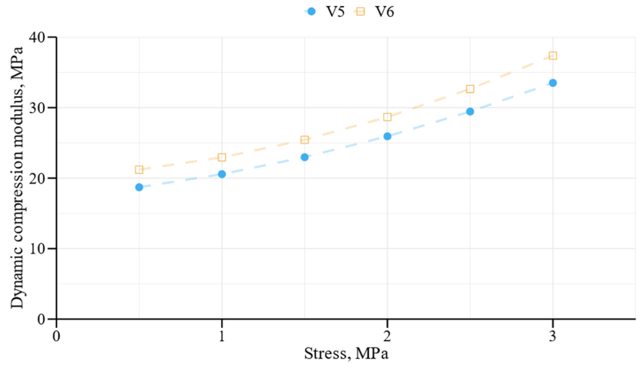

Fig. 8. Results of dynamic compression modulus results based on regression model (Equation 13) for compounds V5 and V6 samples of 60×60×10 mm

3.2.2.2. Other dimensions

Based on the previous results for each 60×60×10 mm cork-rubber compound, obtained by regression models, values of an equivalent Young's modulus were determined, according to the level of stress imposed, and used as input for the application of finite element analysis.

Together with the expected final thickness of a sample submitted to compressive load, finite element analysis was conducted. Based on the output of finite element analysis - displacement amplitude -, the equivalent properties of the experimental dynamic test were determined based on the procedure presented in section 2.4 of the article. The results of natural frequency concerning two of the five different cork-rubber composites samples (V1 and V4), with different cross-section areas and thicknesses, are presented in Figure 9.

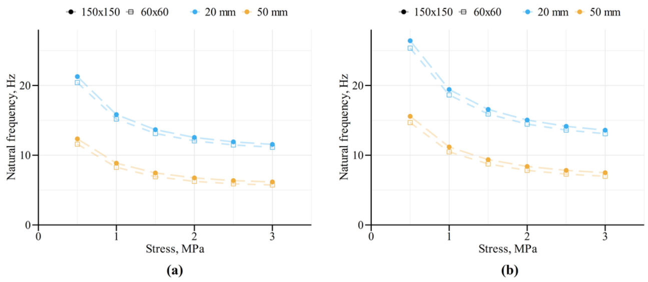

Fig. 9. Simulation results of squared cross section samples with different dimensions: a) cork-rubber composite V1; b) cork-rubber composite V4

Using data related to the cork granules study and applying the same simulation procedure to determine the dynamic behaviour of different dimension samples, the results obtained for cork-rubber composite material V5 and V6 are described in Figure 10.

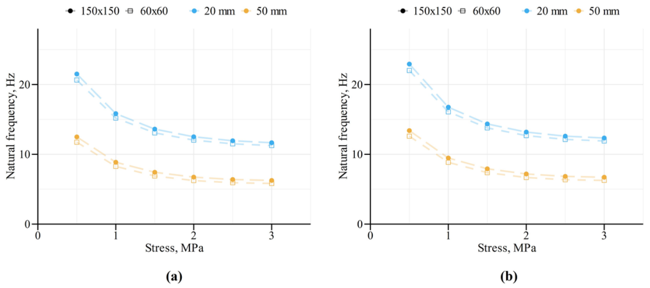

Fig. 10. Simulation results of squared cross section samples with different dimensions: a) cork-rubber composite V5; b) cork-rubber composite V6

Generally, and as expected, higher values of dynamic stiffness are related to the compounds that presented higher values of apparent compression modulus and to samples with higher values of shape factor.

4. Comparative analysis between experimental and simulation approaches

In contrast to what happens following a typical experimental trial and error methodology, where the compounds are fabricated first and then tested throughout several iterations, the systematic approach provided by the application of modelling techniques contributes to a broader understanding of the performance of cork-rubber composites. Also, it contributes to the definition of a more focused plan towards the achievement of specific requirements during product development stages.

The application of the proposed methodology does not fully replace the use of experimental tests since it depends on some of their results (standard sample) to create the regression models relative to the dynamic performance of different cork-rubber compounds. Different formulations need to be dynamically tested. However, with the application of the simulation strategy presented in this study, there is no longer the necessity of materially testing a lot of samples with different dimensions of the same compound in the early stages of product development, since the employed methodology already gives an indication about their expected performance, reducing development time and costs. Although, this does not exclude further experimental tests on the final stages of the product development for validation purposes.

5. Conclusions

A novel approach is presented to predict the static and dynamic performance of cork-rubber composites used as vibration isolation pads. The developed approach uses two modelling techniques for the prediction of material properties: linear regression and finite element analysis.

Based on some data obtained from two experimental designs related to the study of fillers and cork granules in a natural rubber compound, regression models were developed to predict the apparent compression modulus and dynamic stiffness coefficient (ratio between dynamic and apparent compression moduli). Regarding filler models, the independent variables of the models included filler type and quantity, filler activator quantity and, additionally for the dynamic behaviour model, compressive stress imposed on the samples. Using data related to the variation of cork granules quantity, four regression models were determined for static and dynamic compression behaviour, according to the granulometry of cork granules applied in the rubber compound. Most of the regression models presented R^2 values above 90%, except for the case of the regression model for apparent compression modulus concerning compounds with higher size cork granules (R^2 <50%). Regarding the latter result, there could be other variables related to the inclusion of larger cork granules influencing the static behaviour of cork-rubber samples, such as the geometry and porosity of particles and their dispersion on the rubber compound. Another study involving more samples and other variables must be considered in future works to develop a more reliable regression model.

The results obtained by the application of regression models allowed to determine the expected behaviour of new cork-rubber composites, according to their formulation. The application of the developed models is restricted to determine the behaviour of squared cross section samples with 60×60 mm^2 area and 10 mm thickness. A comparison with experimental results of other cork-rubber compounds was carried out and revealed a good approximation with simulation results. Finite element analysis was applied to determine the static and dynamic behaviour of new cork-rubber composites samples with different cross section areas and/or thicknesses, based on the results of the regression models and the dependence of the mechanical behaviour of these elastomers with the sample's shape factor.

Future works may include the application of these methods to other cork-rubber composites formulations, the introduction and analysis of other variables relevant to the final properties, and also the application of these modelling techniques to assess other properties, for example.

Although the methodology and results presented in this article are limited to few formulation variations of a single cork-rubber composite and one type of geometry (blocks with squared cross section area), the application of modelling techniques demonstrated to be a valuable tool during the development of this kind of materials. Potentially, it can decrease the number of iterations during development stages, minimizing resources, energy consumption and saving time.

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