THERMAL DIFFUSIVITY OF THICK FIBRE-ELASTOMER COMPOSITES

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Summary

The knowledge of thermal diffusivity data of thick fibre-elastomer composites is very important in heat conduction analysis of rubber products. The method of linear increase of surface temperature was used to determine the thermal diffusivity of thick fibre reinforced-rubber composites at temperatures ranging from 20 to 170°C.

In this paper the results of thermal diffusivity measurements of some rubber compounds reinforced with textile cords are presented. The values of the thermal diffusivity of thick fibre reinforced-rubber composite materials decrease with temperature. The thermal diffusivity parallel to the fibre direction is compared to the thermal diffusivity perpendicular to the fibre direction and to the thermal diffusivity of the matrix. It was found experimentally that the thermal diffusivity of rubber compounds reinforced with polyamide textile cords parallel to the fibre direction is approximately 1.6 time higher than the thermal diffusivity perpendicular to the fibre direction and the thermal diffusivity of the matrix. The effect of thermal contact resistance in textile cords on the thermal diffusivity perpendicular to the fibre direction was tested.

Key words: Thermal diffusivity, Composite materials, Reinforced rubber

Introduction

Thick fibre reinforced-rubber composites have been extensively used in rubber products such as tires and conveyer belts. Mathematical modelling of heat conduction in rubber products enables to reduce the time involved in the design of new products and to propose technological conditions for the manufacturing process approaching optimal conditions, all at reduced costs. For the mathematical modelling of transient heat conduction in rubber materials the knowledge of the thermal diffusivity of individual parts of products is necessary.

Generally, the reinforced parts of rubber products on the submacroscopic level are highly heterogeneous and anizotropic because they are composed of rubber compounds and textile or steel cords. Rubber compounds consist of natural or synthetic rubber, carbon black, curing agents, cure activators, cure accelerators, plasticizers, protective agents, and other ingredients. Textile cords used as reinforcement are consisting of fibres (usually polyamide, polyester viscose or rayon) and air entrapped between them. The cords used to reinforce rubber compounds, have a relatively great characteristic size (0.1-1 mm), compared to reinforcement of classical fibre composite materials. Figure 1 shows schematically the structure of reinforced rubber materials.

Both heat conduction in thick fibre reinforced–rubber composites and thermal diffusivity of these materials are influenced by several factors. The main of them, besides composition and temperature, are: direction of reinforcement, size, structure and pattern of the reinforcement arrangement, thermal contact resistance between individual fibres of cords, thermal contact resistance between reinforcement and matrix and thermal properties of individual components. For this reason, calculation of the thermal diffusivity on the basis of properties of components is not feasible. The only possibility to determine the thermal diffusivity of above given materials with an acceptable accuracy is the experimental determination of this quantity. In the experimental determination of the thermal diffusivity, reinforced rubber are considered to be orthotropic materials, because from the study of the heat conduction mechanism in thick fibre composite materials [3] follows that for the mathematical modelling of transient heat transfer in such materials the equation of heat conduction for orthotropic composite materials is the best relation.

In this paper the results of thermal diffusivity measurements of some rubber compounds reinforced with textile cords are presented. The thermal diffusivity parallel to the fibre direction, the thermal diffusivity perpendicular to the fibre direction and the thermal diffusivity of the matrix are compared.

Experimental Determination of Thermal Diffusivity

For determining the thermal diffusivity of thick fibre reinforced-rubber composites, the method of Linear Increase of Surface Temperature (LIST) was applied. This method was developed in house and originally provided the determination of the thermal diffusivity of composite materials with relatively great dimensions of the reinforcement. The details of the LIST method are given in work [1].

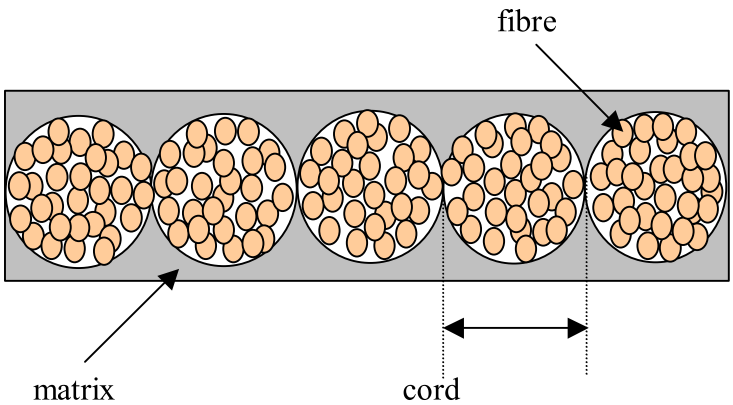

Figure 1: Structure of thick fibre reinforced-rubber composite materials

In estimating the thermal diffusivity by this method the experimental temperature field of the sample must be analysed. The values of the thermal diffusivity at different temperatures are obtained from the measured temperature fields by solving the equation of one dimensional transient heat conduction for time variable boundary conditions.

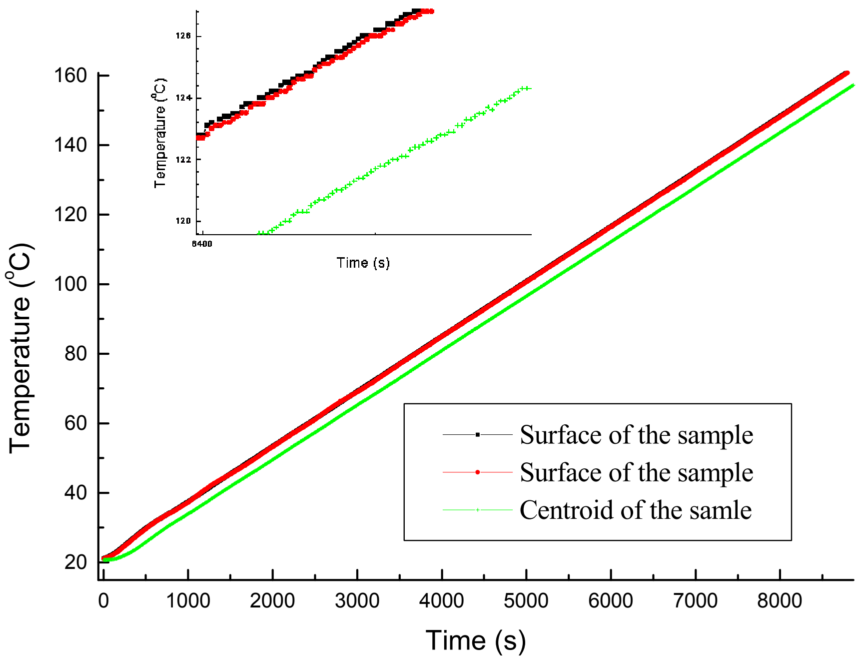

Figure 2: Record of measured temperature data

Figure 2 shows a typical example of measured temperatures on the surface of the sample and its centroid. The heat conduction equation used by the LIST method has the following form:

$$\frac{\partial^2 T}{\partial x^2} = a_x \frac{\partial T}{\partial t} \tag{1}$$

where a_x defined as:

$$a_x = \frac{\lambda_x}{\rho c_p} \tag{2}$$

is the thermal diffusivity in the direction perpendicular to the heating surface and the sample surface, T is the temperature, t is the time, , ρ is the density, c_p is the specific heat capacity and λ_x is the thermal conductivity in the direction perpendicular to the heating surface and the sample surface. Initial and boundary conditions, which take into account the physical arrangement of the experiment, are as follows:

$$\begin{aligned} &T(x, 0) = f(x) && 0 < x \le h && t = 0 \\ &T(0, t) = f(t) = b_0 + b_1 t && x = 0 && t > 0 \\ &\frac{\partial T}{\partial x}\Big|_{x=h} = 0 && x = h && t > 0 \end{aligned} \tag{3}$$

where h is half of the sample plate thickness, b_0 and b_1 are constants of the actual instrument arrangement. In calculating the first value of the plot *a=f(T),* the function *f(x)* has a value equal to the initial temperature of the sample. At further values, this function, however , describes the distribution of temperatures in the sample.

Equation (3) was solved numerically using the explicit finite difference method. From the measured data and by means of a mathematical model of the process the values of the thermal diffusivity at different temperatures were calculated using a PC software.

Samples

In estimating the thermal diffusivity by the LIST method, heat transfer from the heating plates into the sample must be one dimensional. This is considered if the sample has two dimensions of sufficient size. For determining the thermal diffusivity of thick fibre reinforced-rubber composites perpendicular to the fibre direction and parallel to the fibre direction the samples used were plates with sizes given in Figure 3. The reinforcement arrangement in the samples was the same as in real products of the tire industry. The samples have been already completely vulcanised.

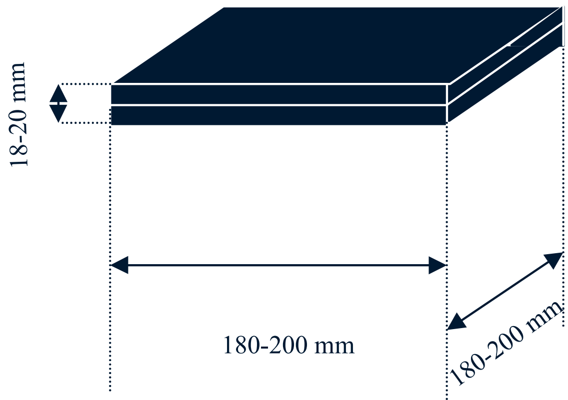

Figure 3: Sizes of the samples

Measured data

The relationships between the thermal diffusivity and the temperature for various types of thick fibre reinforced–rubber composites were measured at the temperature range 20-170^{o}C. It was found out that the thermal diffusivity of rubber composites decreases with temperature. A typical plot thermal diffusivity vs. temperature is shown in Figure 4. In case of practical applications, these temperature dependences were measured mostly for the thermal diffusivity perpendicular to the reinforcement layers.

Both composition and reinforcement arrangement of the samples were the same as in real products. In Table 1 are given the characteristics of the samples. Following matrixes composed of rubber compounds were used: type A containing: 61.5 wt-% of rubber, 23.6 wt-% of carbon black, 2.5 wt-% of vulcanising agent and 12.1 wt-% of other components, or type B containing: 58.9 wt-% of rubber, 21.6 wt-% of carbon black, 2.7 wt-% of vulcanising agent and 16.8 wt-% of other components. The material of the textile cords was polyamide 6. or polyamide 6.6. The thermal diffusivities of rubber composites with various composition and reinforcement arrangement are compared in Figures 5 and 6. The thermal diffusivity perpendicular to the cord layers is affected mostly by the properties of the matrix. The measured data of the thermal diffusivity given in Figure 6 show the effect of matrix composition for samples with the matrix type A and for samples with the matrix type B.

Polyamide textile cords used as reinforcement are consisting of a number of fibres and air entrapped between them. With the amount of entrapped air the thermal contact resistance between the fibres increases and the effective thermal diffusivity of composites perpendicular to the fibre direction decreases. The number of twists per one meter of the textile cord can have an effect on the amount of entrapped air. From the temperature dependence of measured thermal diffusivity data drawn in Figure 5 and characteristics of the samples given in Table 1 results that the values of the thermal diffusivity for a sample with a small number of twists are lower than the values of this quantity for other samples.

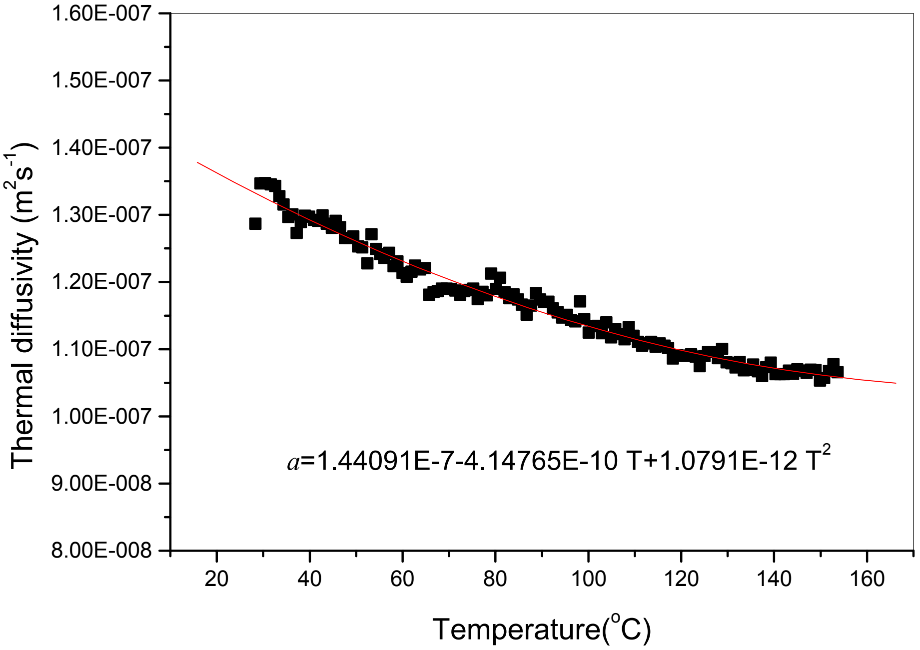

Figure 4: Example of the plot measured thermal diffusivity vs. temperature

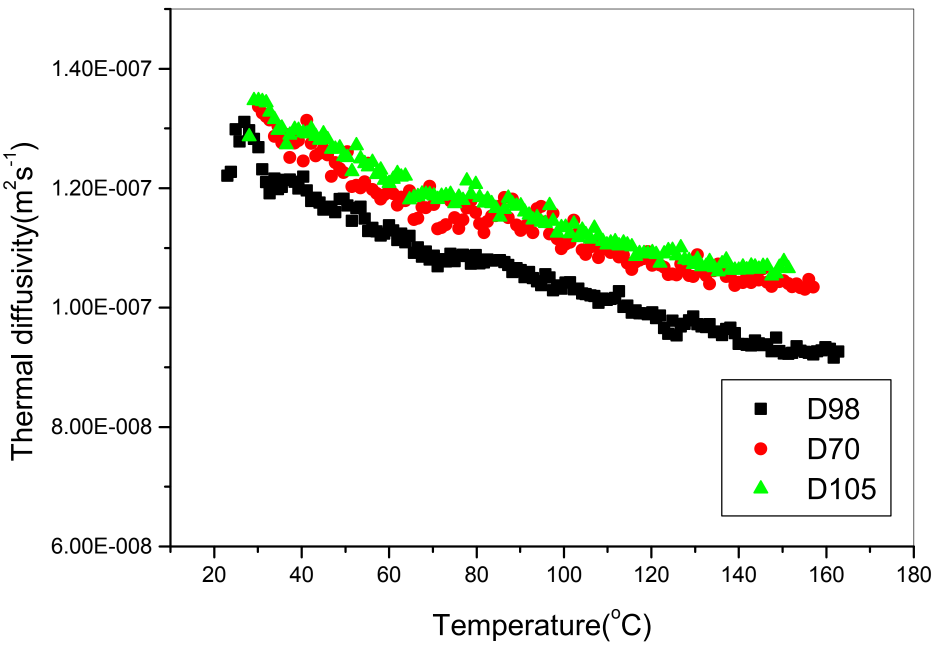

Figure 5: Thermal diffusivity of rubber compounds reinforced with various types of textile cords, perpendicular to the fibre direction. Effect of the thermal barrier resistance

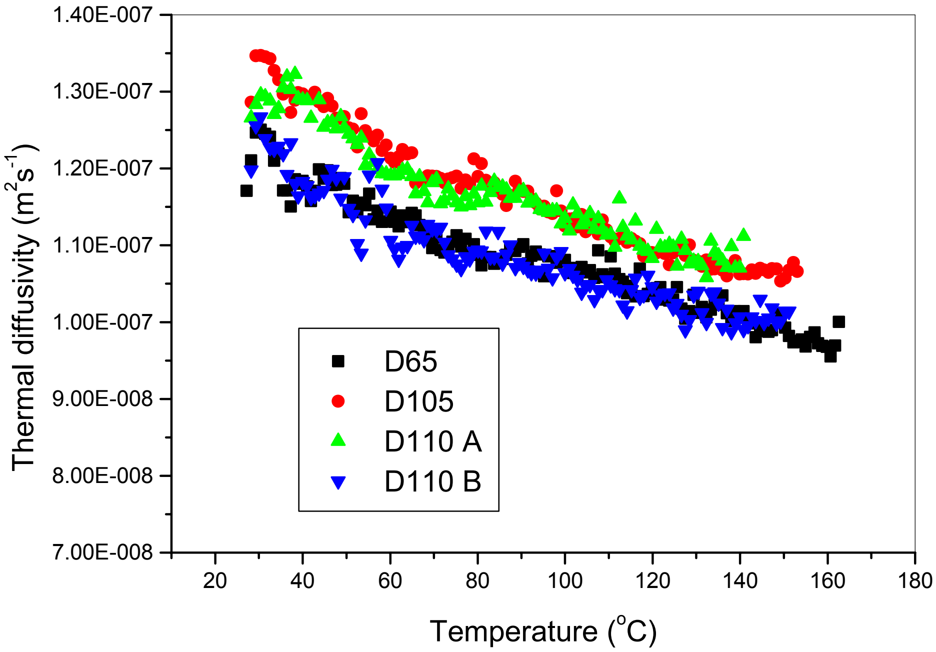

Figure 6: Thermal diffusivity of rubber compounds reinforced with various types of textile cords, perpendicular to the fibre direction. Effect of the matrix composition

Table 1: Characteristics of samples of thick fibre reinforced-rubber composites.

Sample identification	D65	D70	D98	D105	D108	D110 A	D110
Type of cord	94-1x2	188-1x2	180-1x3	188-1x2	188-1x2	140-1x2	140-1x2
Material of cord	PA 6	PA 6	PA 6	PA 6	PA 6.6	PA 6.6	PA 6.6
Wt (%) of cord	14.92	24.44	41.09	36.39	37.96	30.50	30.28
twists (1/m)	330	335	200	335	330	370	370
Picks (1/dm)	65	70	98	105	108	110	110
Weight of unrubbered fabric (g/m^2)	138	282	565	420	446	334	334
Thickness of unrubb. fabric (mm)	0.55	0.76	0.85	0.76	0.76	0.68	0.68
Thickness of rubbered fabric (mm)	0.88	1.13	1.38	1.13	1.13	1.05	1.13
Type of matrix	B	A	A	A	A	A	B

Figure 7 shows experimental data of the temperature dependence of the thermal diffusivity for a rubber compound, a rubber compound reinforced with polyamide cords, for heat flow perpendicular to the fibre direction and for a rubber compound reinforced with polyamide cords, in case of heat flow parallel to the fibre direction. These data indicate that the value for the thermal diffusivity of the composite parallel to the fibre direction is much higher than in the direction perpendicular to the fibre and also much higher than the corresponding value of the matrix. Such differences in the thermal diffusivity can be attributed to two effects. Firstly, the thermal conductivity parallel to the fibre direction is approaching the maximum value (upper bound) for such a composite, regardless of the relative value of the thermal conductivity of the components. Secondly, the conduction of heat perpendicular to the fibre direction is affected by the presence of a thermal barrier resistance.

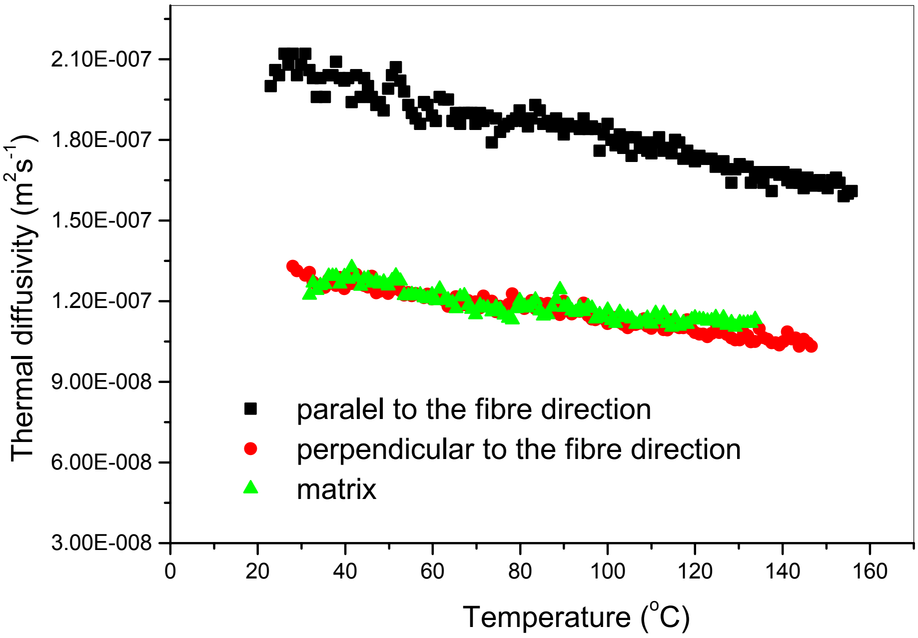

Figure 7: Thermal diffusivity of rubber compounds reinforced with polyamide textile cords. Influence of the reinforcement direction.

Conclusions:

The thermal diffusivity of thick fibre reinforced-rubber composite materials decreases with temperature. A comparison has been made between the thermal diffusivity parallel to the fibre direction and the thermal diffusivity perpendicular to the fibre direction. It was found experimentally that the thermal diffusivity of rubber compounds reinforced with polyamide textile cords parallel to the fibre direction is approximately 1.6 time higher than the thermal diffusivity perpendicular to the fibre direction and the thermal diffusivity of the matrix.

Both type and arrangement of the reinforcement have a crucial effect on the thermal diffusivity, mainly in the parallel direction to the fibre. For heat flow perpendicular to the fibre direction, the rate of heat conduction is limited by the properties of the matrix. Thermal diffusivity increases with the number of twists per one meter of cord length, because the thermal barrier resistance decreases with this parameter. The samples used in this work had the same arrangement as in commercial rubber product. In this case, sufficient experimental data must be available for the evaluation of various structural influences.

References

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