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Modelling of Thermal Behaviour of a Fabric Coated with Nanocomposites

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Abstract: A theoretical equation of the thermal resistance and adiathermic power of a coated fabric with nanocomposites is established. Samples, whose properties are analyzed by these equations, were constructed from commercial resins and Tunisian natural clay. Adiathermic power was determined by using a PASOD device measuring the necessary voltage to maintain a temperature difference between the inside and the outside of the fabric equals to 20°C. The mathematical equation, which modelling the coated fabric thermal behavior, contributes to analyze and explain the measured adiathermic power results by inserting the thermal resistance values. It was found that increasing quantity of clay enhance significantly the thermal insulation of a 400 g m^{-2} Sergey fabric 100% cotton. The calculated values show that the thermal resistances are in a good agreement with the measured adiathermic power values, which generally increases when the fabric becomes more resistant to the going through heat flow.

Key words: Nanocomposite, clay, coating, resin, thermal insulation, modelling

INTRODUCTION

The impetus behind a polymeric composite is their ability to be tailored to any system such as improved thermal resistance (Gao *et al*., 2007). As a load is applied to the continuous phase it is then transferred to the discontinuous, reinforcement phase. The choice and degree of reinforcing filler (in this study, clay) can then be assigned according to the requirements of the particular application. Superior performance and the resulting cost savings have allowed composites to be incorporated into nearly every aspect of our lives regarding the main environmental effects which are related to temperature, moisture, radiation and contact with various types of chemicals. These factors can affect the thermal and the mechanical properties of the composites in different ways (Selzer and Friedrich, 1995, 1997).

Heat transfer by radiation in materials was investigated theoretically by Mital *et al.* (1998). The heat transfer in materials was reported by Dietl *et al.* (1998).

The effective conductivity Keff is defined as below (Fricke *et al*., 1990):

$$Keff = Kcond + Kconv + Krad$$

Where:
Kcond = The conductivity due to conduction
Kconv = The conductivity due to convection
Krad = The conductivity due to radiation

The most of researchers like Mohammadi *et al.* (2003) neglect *Kconv* because the probability of a gas molecule movement through the structure is minimal. In this study, only Kcond will be studied and determined.

Other researchers like Zhou and Lucas (1995) investigated the physical mechanisms involved during the perception of composite and fabric dampness by studying the heat and moisture transfer in the fabric and at the fabric-skin interface (Li *et al*., 1995; Gautier *et al*., 1999), which has been performed by several apparatus such as thermal manikins (Bhattacharyya, 1980; Mastura, 1994) or other apparatus.

The purpose of this study is to establish a mathematical equation linking the adiathermic power of a nanocoated cotton fabric to clay percentage, fabric thickness, coating and the used resin conductivity and to show how the nanocomposite coatings enhances the thermal insulation of this new hybrid fabric in conjunction with the clay percentage and the sort of resin.

MATERIALS AND METHODS

Ten grams of Tunisian clay added to 100 mL of methylene chloride (CH_2Cl_2) have been ultrasonicated for 2 h at 25°C (freq. = 28 KHz), in order to have a good dispersion of clay particles. Then the prepared clay solution was added to the resin at different loadings of clay: 5, 20, 40 and 70%.

Five sorts of resin were selected to be mixed with clay: modified DMDHEU, Vinyl-Polyacetate (PVAv), Polyacrylate (PAC), elastic Polyurethane (PU1) and rigid Polyurethane (PU2).

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Table 1: Adiathermic power percentage in conjunction with the clay quantity, the deposited quantity and the sort of resin

	Clay (%)				
Resin	0	5	20	40	70
Deposited quantity (32 g m^{-2})					
PU1	18.30	20.61	21.74	22.00	22.56
PU2	18.88	22.1	22.80	23.07	
DMDHEU	15.29	15.8	16.60	19.59	
PAC	15.84	16.5	19.25	21.00	21.15
PVAc	18.52	23.8	23.90	24.80	26.25
Deposited quantity (172 g m^{-2})					
PU1	18.40	21.61	21.90	23.62	23.90
PU2	18.98	22.5	23.30	23.40	
DMDHEU	15.25	16.0	18.84	20.62	
PAC	16.04	17.5	20.25	21.10	22.00
PVAc	20.52	24.0	24.40	25.80	26.40
Deposited quantity (372 g m^{-2})					
PU1	18.51	21.85	22.00	23.62	24.10
PU2	19.00	22.7	23.70	23.95	
DMDHEU	15.70	16.06	19.00	20.92	
PAC	16.30	18.06	20.85	21.40	22.06
PVAc	21.40	24.2	24.90	26.00	26.80
Deposited quantity (540 g m^{-2})					
PU1	18.71	22.05	22.70	23.62	24.50
PU2	19.30	23.1	23.90	24.20	
DMDHEU	16.32	17.05	19.20	21.12	
PAC	17.26	19.6	21.36	22.00	23.00
PVAc	22.05	24.78	25.30	26.05	27.08
Reference	21.14	21.14	21.14	21.14	21.14

Mixtures PU2/70% clay and DMDHEU/70% clay failed because they became too thick

These different mixtures resin/clay were deposited on a cotton fabric Sergey (about 400 g m^{-2}) using a coating apparatus with rake pressure and deposited paste regulations. The deposited quantities of the mixtures are shown in Table 1. The polymerization of these coatings was carried out at 150°C during 5 min (Choi *et al*., 2001) and after a drying operation during 5 min permitting to water and CH_2Cl_2 to evaporate.

Then, the thermal isolation properties of the coated materials (three trials for each sample; $\sigma = 0.0344\%$) were determined by measuring the adiathermic characteristics using a PASOD device for measuring the adiathermic power (Table 1).

RESULTS AND DISCUSSION

The deposited quantity of nanocomposite on the fabric (Qc) and the Adiathermic Power (AP) are shown in Table 1.

Here, we want to calculate the adiathermic power in conjunction with the clay percentage, the deposited quantity and the used resin. Thus, knowing these parameters, the adiathermic power and using some equations, can be determined, without measuring. From Table 1, interpolation equations in this form

$$AP\% = A + B1x + B2x^2$$

Table 2: Adiathermic power percentage in conjunction with Qc: AP% = $A+B1x+B2x^2$

Resin coefficients	A/100	B1	B2x100	R^2
PU1				
Qc = 32 (g m^{-2})	0.1911900	0.1374	-0.10	0.8383
Qc = 172 (g m^{-2})	0.1942097	0.1686	-0.20	0.8410
Qc = 372 (g m^{-2})	0.1961213	0.1602	-0.10	0,8190
Qc = 540 (g m^{-2})	0.1988907	0.1613	-0.10	0.8170
PU2				
Qc = 32 (g m^{-2})	0.1964367	0.2836	-0.50	0.8028
Qc = 172 (g m^{-2})	0.1980265	0.3176	-0.60	0.8031
Qc = 372 (g m^{-2})	0.1984817	0.3422	-0.60	0.8268
Qc = 540 (g m^{-2})	0.2020413	0.3332	-0.59	0.7990
DMDHEU				
Qc = 32 (g m^{-2})	0.1542681	0.0229	0.202	0.9936
Qc = 172 (g m^{-2})	0.1512237	0.2254	-0.219	0.9967
Qc = 372 (g m^{-2})	0.1546083	0.2006	-0.158	0.9883
Qc = 540 (g m^{-2})	16.287810	0.1682	-0.118	0.9997
PAC				
Qc = 32 (g m^{-2})	0.1571587	0.2076	-0.186	0.9969
Qc = 172 (g m^{-2})	0.1637466	0.2006	-0.174	0.9712
Qc = 372 (g m^{-2})	0.1677377	0.2092	-0.194	0.9510
Qc = 540 (g m^{-2})	0.1802613	0.1738	-0.150	0.9165
PVAc				
Qc = 32 (g m^{-2})	0.2051270	0.1921	-0.162	0.7000
Qc = 172 (g m^{-2})	0.2169445	0.1704	-0.149	0.8230
Qc = 372 (g m^{-2})	0.2234094	0.1508	-0.127	0.8662
Qc = 540 (g m^{-2})	0.2303004	0.1264	-0.100	0.8260

Table 3: Coefficients A, B1, B2 in conjunction with Qc: (A, B1, B2) = $C+D1xQc+D2xQc^2+D3xQc3$

Coefficients	B2x100	B1	A/100
PU1			
C	-0.03761	0.12234	0.19086
D1	-0.00223	5.27E-04	1.73E-05
D2	9.16E-06	-1.81E-06	-5.07E-09
D3	-9.70E-09	1.79E-09	0
R_2	1	1	0.9818
PU2			
C	-0.45776	0.27258	0.19673
D1	-1.45E-03	3.42E-04	2.27E-07
D2	4.30E-06	-4.24E-07	1.69E-08
D3	-3.82E-09		0
R_2	1	0.9984	0.929
DMDHEU			
C	0.39184	-0.0667	-0.89554
D1	-0.00658	0.0031	0.04174
D2	2.10E-05	-9.64E-06	-2.96E-04
D3	-1.95E-08	8.72E-09	5.13E-07
R_2	1	1	1
PAC			
C	-0.19791	0.21461	0.15757
D1	4.42E-04	-2.59E-04	1.49E-05
D2	-2.28E-06	1.36E-06	4.77E-08
D3	3.01E-09	-1.89E-09	0
R_2	1	1	0.964
PVAc			
C	-0.16379	0.19491	0.20341
D1	6.40E-05	-1.26E-04	7.81E-05
D2	9.93E-08	2.26E-09	-5.44E-08
D3	0	0	0
R_2	0.9993	0.9925	0.982

where, x is the clay percentage and using the software Origin, can be determined (Table 2).

The coefficients A, B1 and B2 vary from deposited quantity to another. For this reason, the coefficients have to be interpolated too, in conjunction with Qc Table 3 in this form $PA\% = A+B1xQc+B2xQc^2$.

Table 4: Calculated and found AP of coated fabrics in conjunction with the clay percentages, the deposited quantities and the used resin

Calculated values			Found values			Errors		
	Clay (%)			Clay (%)			Clay (%)	
AP% Qc (g m^{-2})	2.5	15	AP% Qc (g m^{-2})	2.5	15	ΔAP/AP% Qc (g m^{-2})	2.5	15
PU1								
400	20.1	21.9	400	20.15	21.80	400	0.248	0.46
100	19.6	21.2	100	19.50	21.15	100	0.51	0.24
PU2								
400	20.8	23.7	400	20.65	23.45	400	0.73	1.07
100	20.4	23.0	100	20.40	22.95	100	0.00	0.22
DMDHEU								
400	20.7	20.9	400	16.00	19.05	400	29.38	9.70
100	15.5	15.6	100	15.45	16.10	100	0.32	3.10
PAC								
400	17.6	19.8	400	17.30	20.00	400	1.73	1.00
100	16.4	18.6	100	16.20	18.90	100	1.23	1.587
PVAc								
400	23.0	24.5	400	23.00	24.35	400	0.00	0.62
100	21.5	23.5	100	21.00	23.85	100	2.38	1.47

Model verification: In order to verify this model, some more samples have to be prepared:

The clay quantities 2.5 and 15% have been mixed with the same resins, but with different amounts, to make deposited quantities equal to 100 and 400 g m^{-2}. The obtained adiathermic powers and the corresponding errors are recorded in Table 4.

The model is reliable for all resins (except the DMDHEU resin), for error <2%. The thermal resistances can be easily deduced from a simple computing of the clay percentage and the deposited quantity on the fabric without any measure. This model is no more reliable for other resins or other fabrics.

CONCLUSIONS

In this study, we have developed a method of mathematical stimulating the fabric thermal resistance. The mathematical model has proved to be effective in predicting the fabric thermal resistance, which demands a long time to be evaluated by the concise measurement of the adiathermic power. This good agreement between these values has been demonstrated by mathematical formulas linking the clay percentage, coating, nanocomposite deposited quantities and the used resin. The result of theses computations indicates that clay application in nanocomposites proved its importance because the thermal insulation properties of the fabric are really enhanced according to the clay percentage in the coating. The average of this enhancement is about 20 to 30% and this is upon the used resin, the deposited quantity and the clay percentage present in the nanocomposite.

Besides, the clay percentage is a very important parameter since the high clay quantities in the nanocomposite generally present the better thermal resistances. Validation of these results is only possible through direct conductivity measurements. In this case, then, several parameters like α, β, γ and λ, predicting the percentages of the series and parallel models in the coated fabric, can be determined. Work is in progress to develop some theoretical model to evaluate these findings.

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