The Influence of Microfungi on Physicomechanical Properties of Particleboards

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This study concerns the influence of selected fungi on changes in physical and mechanical properties of type P2 particleboards intended for use in dry conditions. The tested fungi included *Aspergillus niger* van Tiehgem, *Chaetomium globosum* Kunze et Fr., *Trichoderma viride* Persoon ex S.F., Gray *aggr*., and *Penicillium funiculosum* Thom. The incubation process lasted for 16 weeks, yet samples for the strength test were selected after a period of four weeks. The degradation level of boards was estimated by measuring the decrement of initial mass and changes in physicomechanical properties. The obtained results showed that mechanical strength of the investigated boards affected by the tested fungi decreased by 15% to 20%. However, the differences in DSC thermographs indicate that it is cellulose that mainly undergoes degradation in the wood of the investigated boards. Based on the changes in mechanical properties and DSC analyses, we consider *T. viride and A. niger* as the most aggressive fungal species.

Keywords: DSC; Mechanical properties; Microfungi; Particleboard; SEM

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INTRODUCTION

Particleboards of type P2 are intended for use as interior furnishings, including furniture, in dry conditions. If laminate or furniture foil is properly affixed to the board surface, type P2 particleboards can also be used in the production of furniture that can be exposed to the action of higher humidity (*e.g.* in laundries, bathrooms, and kitchens). Nevertheless, this protective layer can be damaged, uncovering the raw particleboard and producing favourable conditions for fungi to grow. According to Lutomski and Ważny, the major fungal species occurring on the surface of wood-based materials are *Aspergillus* spp., *Penicillium* spp., *Alternaria* spp., *Paecilomyces* spp., and *Phoma* spp. (Lutomski 1995; Ważny 1994, 2003). Out of these species, *Aspergillus niger* is considered dangerous for people's health (Baran 1998).

The decay level of wood is defined by three types of rots: brown rot, soft rot, and white rot; in each case there is a different fungal species involved causing a different kind of damage and having a different course. Brown-rot fungi are the most damaging, because by breaking down cellulose (Ericsson *et al.* 1990) they cause a decrease in mechanical strength of wood, which cracks in various directions and, in the final phase, it turns into powder (Perez *et al.* 1993; Blanchette 1995; Kim and Newman 1995). White rot is a less harmful type of decay (Highley *et al.* 1984; Schmidt *et al.* 1997; Worrall *et al.* 1997; Lehringer *et al.* 2011a,b; Halis *et al.* 2012), because it is caused by fungi that break down mainly lignin. Rotted wood becomes soft and therefore its compressive strength is decreased. The most common type of decay is soft rot (Levi and Preston 1965; Mouzouras 1989; Terziev and Nilsson 1999). Soft-rot fungi cause a greenish or greyish coating on the wood surface that is usually 2 to 4 mm thick. This kind of rot is commonly noticed on unprotected wooden fences, window frames, or benches. Soft-rot fungi produce cellulase, an enzyme that breaks down cellulose, yet it does not damage lignin. One should be aware of the fact that wood is one of the major construction materials for building engineering; the growth of fungi on the wood surface not only deteriorates aesthetic value and weakens the structure of a building (Clausen *et al.* 2003), but it also unfavourably affects the health of people who spend their time in places attacked by fungi.

The extensive literature on the subject refers mainly to issues related with the decay of wood caused by the specific-rot fungi and efficient methods of protecting wood from fungal attacks. There are only few publications that present the influence of fungi on mechanical properties of wood, and even fewer of them discuss those aspects with reference to wood-based materials. Thus, the purpose of the present paper is to determine the influence of microfungi on properties of one type of commonly-used wood-based materials, namely particleboard.

EXPERIMENTAL

For the purposes of the present investigation, type P2 particleboards with a nominal thickness of 6 mm produced under industrial conditions were employed. Boards were selected with such a thickness value because, on the one hand, the dimension of samples should be appropriate to determine bending strength after the incubation period according to the EN 310 (1993) standard; on the other hand it should be easy to carry out the inoculation and incubation process. In the latter case, smaller samples facilitate the preparation of the incubation process. Although 6-millimeter-thick boards are not a perfect example of furniture particleboards, they concurrently meet both the above-mentioned requirements. The prepared samples with the dimension of 170×50×6 mm (length×width×thickness) were inoculated with the test microfungi, *i.e*. *Aspergillus niger* van Tiehgem, *Chaetomium globosum* Kunze et Fr., *Trichoderma viride* Persoon ex S.F., Gray aggr., Pe*nicillium funiculosum* Thom, according to *AS*T*M* D *55*90 (1994). They are soft-rot fungi which often occur on the wood surface, but generally have been disregarded in studies on the biodegradation of wood. The inoculated samples were placed in an incubator with temperature of 28±1°C and relative humidly of 90%. The clean control samples were put in a separate incubator to determine the effect of incubation conditions on physicomechanical properties of the investigated particleboard. The incubation process lasted for 16 weeks. However, every four weeks a test sample was taken out and, after returning to normal conditions, its basic physicomechanical properties were determined, *i.e*. modulus of rupture (MOR) according to EN 310 (1993), modulus of elasticity (MOE) according to EN 310 (1993), internal bond (IB) according to EN 319 (1993), and swelling in thickness after immersion in water (TS) according to EN 317 (1993). Table 1 shows the initial values of the inoculated board. The presented data indicate that its physicomechanical properties were far better than those required by the standard EN 312 (2011). However, it is quite obvious that properties of thin boards exceed the standard requirements to a greater extent than those of the thick ones.

Table 1. Initial Values of the Particleboard Used in the Investigations

Property	Testing method	Unit	x	σ
ρ	EN 323	kg m^{-3}	760	15
TS	EN 317	%	17.0	1.15
MOR	EN 310	N mm^{-2}	15.88	1.1
MOE	EN 310	N mm^{-2}	2290	100
IB	EN 319	N mm^{-2}	0.72	0.05

For each board the mass decrement caused by the action of fungi was also determined. Moreover, samples were taken for DSC analysis from the samples that had been incubated for 16 weeks and then subjected to MOR tests, since the goal was to determine changes occurring in particleboards attacked by fungi (Gemelin 1999). The investigations were made within open aluminum melting pots with use of the LABSYS TM thermobalance produced by Setaram. The samples of powdered boards of 20 mg mass were heated with the rate of 10 °C min^{-1} in the temperature range 20 to 600 °C in a helium atmosphere with constant flow of 2 dm^3 h^{-1}.

When evaluating the effect of incubation time and type of fungi on the considered properties, it was decided to use the relative difference (1) of a given property (X),

$$\delta_x = \frac{X_0 - X_C}{X_0} \cdot 100\% \tag{1}$$

where X_0 is the average value of a given property for the control sample, and X_C is the average value of a given property for the particular incubation time or type of microfungi.

The statistical analysis was made with use of the dedicated application Statistica 10. The evaluation of findings, according to the formulated hypotheses, was made at the significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

Evaluating the initial mass decrement is the basic index for evaluating the degradation degree of the investigated material. Table 2 presents the results of the relative mass decrement caused by the action of the test fungi on the investigated particleboards.

The data show that after 4-week incubation the mass increment amounted to 2.6%, and after 6 weeks it ranged from 3.41% to 4.67%. The intensity of action of the investigated fungi was not the same throughout the whole investigation process. Fungal species *P. funiculosum* and *Ch. globosum* caused a greater mass decrement after 4 weeks than *A. niger* and *T. viride*. However, in the next 12 weeks, a more serious decay was caused by the latter. If one considers the mass decrement after 16 weeks as the main criterion for the action intensity, it can be inferred from the investigation that within this scope the greatest changes were caused by *A. niger* and the slightest are caused by *Ch. globosum*. The overall value of changes observed in samples attacked by fungi was twice as large as that presented in the publication of Chung *et al.* (1999); in fact, it was at the similar level as in case of plywood and OSB.

Table 2. Relative Weight Loss of Particleboard due to the Action of the Test Fungi

Kind of fungus	Time [Weeks]							
	4		8		12		16	
	δ_W	υ^*	δ_W	υ^*	δ_W	υ^*	δ_W	υ^*
	%							
1 Chaetomium globosum	2.69	5.07	2.96	3.35	3.13	1.62	3.41	2.15
2 Aspergillus niger	2.62	2.47	3.82	1.93	4.25	2.81	4.67	3.04
3 Trichoderma viride	2.49	3.51	3.56	3.17	4.47	3.36	4.59	2.99
4 Penicillium funiculosum	2.73	4.59	3.50	3.11	3.75	3.16	4.07	2.68

$\upsilon^{*\ +\ coefficient}$ of variation

Chung's research shows that the aggressiveness of *T. viride* and *A. niger* towards particleboards is at the similar level. However, the authors' own investigations indicate that *A. niger* is a far more aggressive fungus. In the case of wood, mass decrement translates to decrement in wood mass; however, in terms of wood-based material it is difficult to estimate to what extent the decay refers to wood and how strongly it affects the bonding agent. Although the basic adhesives used for wood-based materials are characterized by higher bio-resistance than wood, it seems that even if the decay of adhesive joints is only a small fraction of the overall mass decrement, it may strongly affect the mechanical properties of the boards. The work of Fojutowski *et al.* (2009) indicates that wood-based materials glued with pMDI are more resistant to the action of fungi *Coniophora puteana* (Schum. ex Fr.) than those glued with urea-formaldehyde resin (UF). The PB boards used in the present investigations were glued with UF resin, which means that they may be more prone to the decay caused by fungi. Nevertheless, Chung *et al.* (1999) do not provide any information on the type of resin the investigated boards were glued with.

Tables 3 to 7 show the mechanical properties of the particleboards subjected to the action of test fungi. The data show that all the test fungi caused statistically significant changes of the investigated mechanical properties ($p < 0.05$). Moreover, the analysis of contrasts shows that the 4-week incubation period, regardless of the type of fungi, induced significant changes in relation to the control board for each of the investigated properties.

Table 3. Effect of Incubation Time on the Mechanical Properties of Particleboard Attacked by *Chaetomium globosum* Kunze et Fr. Fungus

Property	F(4; 55)	P	Tukey's HSD		0 ⇐4*	4 ⇐8	8 ⇐12	12⇐16
MOR	653.61	0.000	THT		0.000129	0.494252	0.030426	0.007700
	MS**=0.42579		δ_{MOR}	%	60.8	63.5	68.5	74.4
MOE	1883.9	0.000	THT		0.000129	0.093162	0.753465	0.925763
	MS=4030.8		δ_{MOE}	%	75.1	78.0	79.3	78.4
IB	160.85	0.00	THT		0.000129	0.068608	0.006802	0.912367
	MS=0.00158		δ_{IB}	%	32.0	37.8	45.4	47.2

*- changes in relation to the board in the preceding study period, **- Error - MS intergroup

However, the results obtained for Tukey's test, for the subsequent measurement periods, indicate that between week 4 and week 12, the intensity of decay caused by the action of fungi did not increase so rapidly; in relation to the previous measurement periods, the observed changes were not statistically important. Nevertheless, quite unexpectedly, the intensity of the action of fungi, especially *T. viride*, increased in the last analyzed incubation period.

Table 4. Effect of the Incubation Time on the Mechanical Properties of Particleboard Attacked by *Aspergillus niger* van Tiehgem Fungus

Property	F(4; 55)	P	Tukey's HSD		0 ⇐4*	4 ⇐8	8 ⇐12	12⇐16
MOR	976.17	0.000	THT		0.000129	0.155920	0.006801	0.872964
	MS**=0.37125		δ_{MOR}	%	70.9	74.5	80.1	81.6
MOE	2862.9	0.000	THT		0.000129	0.007078	0.440403	0.005365
	MS=3193.3		δ_{MOE}	%	80.6	84.2	85.9	89.5
IB	463.98	0.000	THT		0.000129	0.179267	0.000130	0.048988
	MS=0.00098		δ_{IB}	%	45.6	49.4	59.8	64.6

*- changes in relation to the board in the preceding study period, **- Error - MS intergroup

Table 5. Effect of Incubation Time on the Mechanical Properties of Particleboard Attacked by *Trichoderma viride* Persoon ex S.F. Fungus

Property	F(4; 55)	P	Tukey's HSD		0 ⇐4*	4 ⇐8	8 ⇐12	12⇐16
MOR	860.09	0.000	THT		0.000129	0.005464	0.174311	0.010216
	MS**=0.42088		δ_{MOR}	%	68.5	74.5	78.3	84.0
MOE	2835.3	0.000	THT		0.000129	0.287040	0.998716	0.030547
	MS=3240.6		δ_{MOE}	%	83.0	85.0	85.3	88.4
IB	569.99	0.000	THT		0.000129	0.427730	0.000129	0.000129
	MS=0.0101		δ_{IB}	%	44.3	47.2	61.9	76.7

*- changes in relation to the board in the preceding study period, **- Error - MS intergroup

Table 6. Effect of Incubation Time on the Mechanical Properties of Particleboard Attacked by *Penicillium funiculosum* spp. Fungus

Property	F(4; 55)	P	Tukey's HSD		0 ⇐4*	4 ⇐8	8 ⇐12	12⇐16
MOR	701.47	0.000	THT		0.000129	0.000129	0.004958	0.909011
	MS**=0.48618		δ_{MOR}	%	59.3	70.8	77.2	78.7
MOE	2062.8	0.000	THT		0.000129	0.022348	0.011064	0.000859
	MS=4087.3		δ_{MOE}	%	75.5	79.1	82.9	87.8
IB	439.01	0.000	THT		0.000129	0.000519	0.000141	0.175567
	MS=0.00103		δ_{IB}	%	42.6	50.2	60.0	63.8

*- changes in relation to the board in the preceding study period, **- Error - MS intergroup

Table 7. Influence of Incubation Conditions on Changes in the Properties of Particleboards

Property	F(4; 55)	P	Tukey's HSD		0 ⇐4*	4 ⇐8	8 ⇐12	12⇐16
MOR	369.47	0.000	THT		0.000129	0.154540	0.000147	0.016337
	MS**=0.56684		δ_{MOR}	%	45.6	50.1	60.6	66.8
MOE	853.58	0.000	THT		0.000129	0.474232	0.100261	0.000249
	MS=6831.1		δ_{MOE}	%	61.8	64.2	67.9	75.0
IB	220.34	0.000	THT		0.000129	0.011178	0.000129	0.162292
	MS=0.00119		δ_{IB}	%	20.6	26.9	44.1	48.3

*- changes in relation to the board in the preceding study period, **- Error - MS intergroup

The greatest changes, regardless of the incubation period, were observed for modulus of elasticity. In this case, after a 4-week incubation the relative changes reached over 75%. However, the relative changes in internal bond in the corresponding period of time never exceeded 46%. After 16 weeks, the greatest changes in modulus of rupture and internal bond were caused by the action of *T. viride*, and *A. niger* affected mostly modulus of elasticity. Nevertheless, if one considers only the final value of changes, there is no explicit indication of which fungus caused the largest degradation of the investigated boards. That is why an additional statistical analysis was carried out: it was a two-factor analysis (time, fungus) of the observed mechanical properties of the boards. The data from Wilks lambda distribution (Fig. 1a to c) shows that the scale of the observed changes in the investigated properties of boards can be associated with the type of fungus.

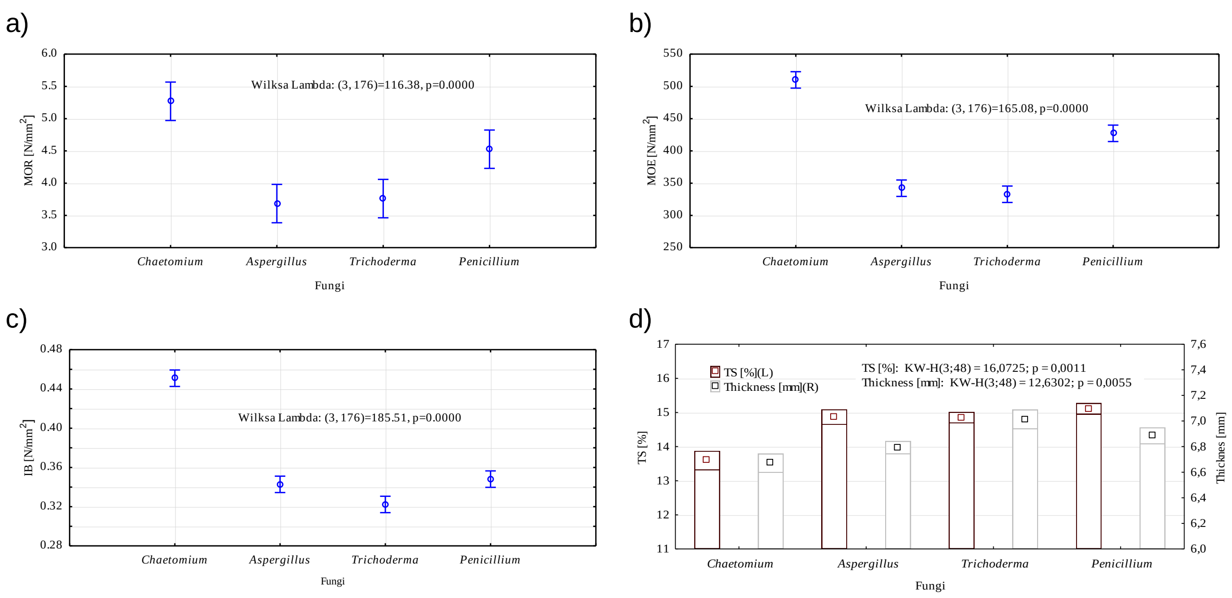

Fig. 1. Effect of the fungus type on the properties of the particleboard after 16-week incubation (a) modulus of rupture, (b) modulus of elasticity, (c) internal bond, (d) thickness swelling

In case of modulus of rupture and modulus of elasticity, there were no statistically significant differences in the boards incubated with *A. niger* and *T. viride* (MOR-THT: 0.860520, MOE-THT: 0.732113); however, as far as internal bond is concerned, *T. viride* turns out to have been a far more aggressive fungus. This seems rather strange because *A. niger* caused greater mass decrement of the investigated boards. The statistical analysis taking into consideration three factors, *i.e.* type of fungus, incubation time, and investigated mechanical properties, makes it clear that the intensity of action was similar for the both types of fungi (Tukey's HSD test – 0.735779, intergroup MS = 667.89, df = 528.00). Nevertheless, Figure 1d shows that *A. niger* contributed to greater swelling in thickness than *T. viride*: in case of the latter fungus, after 16-week incubation there was a smaller increase in the thickness of the boards. Owing to the permanent increment of the thickness of the boards, caused by, for instance, the process factors, the values of such properties as MOR and MOE are decreased (Wu 1998). Thus, the greater changes in the thickness of boards clearly confirm the deep changes in the structure of particleboards affected by fungi.

The incubation conditions are very demanding as for the boards of P2 type. This kind of board is intended for use in dry conditions, and moreover it is surfaced under pressure with a solid material that enhances its resistance to moisture. The data shown in Table 6 indicate that after four weeks of incubation the mechanical properties of these boards deteriorated by 20 to 60 per cent. In every consecutive measurement period further decrease in these values was observed and, in most cases, the changes were statistically significant. Therefore, only 20 to 30% of the observed changes in the mechanical properties of the boards can be ascribed to the action of the test fungi.

The thermogravimetric analysis of wood makes it possible to determine the changes in its structure and composition that occur during biodegradation caused by enzymes released from microfungi (Popescu *et al.* 2010). Figure 2a shows the results of DTG analysis, and Fig. 2b presents results of DSC analysis. The course of the DTG and DSC curves for the board unaffected by fungi is similar to the curve for pine wood (Lee *et al.* 2000). The TG/DTG thermograms made it possible to determine the characteristic temperatures of thermolysis, and the results of these measurements are shown in Table 8. One can infer from these data that the investigated particleboards are characterized by varied thermal characteristics depending on the aggressiveness of fungi inoculated on their surface.

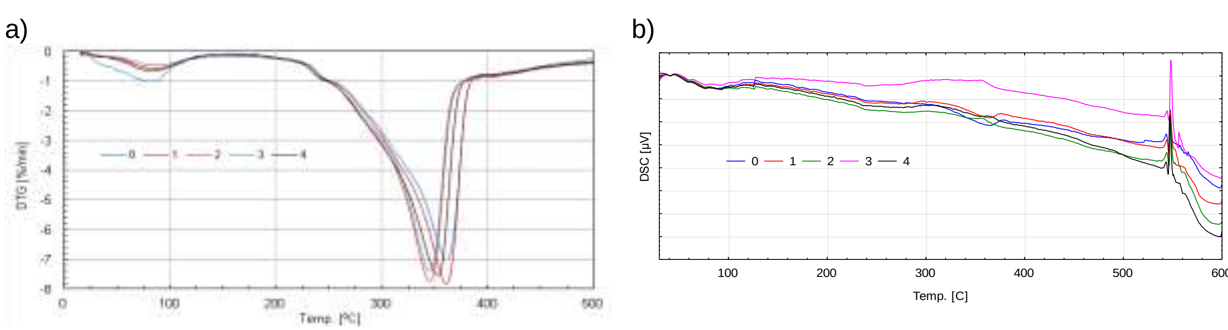

Fig. 2. DTG (a) and DSC (b) spectra of a particleboard infected by microfungi: *1 – Chaetomium globosum*, *2 – Aspergillus niger*, *3 – Trichoderma viride*, *4 – Penicillium funiculosum*, *0* – control sample

Table 8. Thermal Characteristics of Particleboards Affected by the Selected Strains of Microfungi

Parameter	Kind of Microfungus				
	- *	*Chaetomium globosum*	*Aspergillus niger*	*Trichoderma viride*	*Penicillium funiculosum*
T_i [°C]	164.3	178.5	184.4	184.7	180.9
W_{Ti} [%]	6.0	3.9	3.7	3.1	4.0
T_{max} [°C]	362.5	361.0	345.1	345.2	353.6
W_{Tmax} [%]	45.3	46.0	39.7	37.5	44.0
T_f [°C]	397.0	393.1	384.8	383.5	385.1
W_{Tf} [%]	57.9	55.8	52.7	49.4	54.9
W_T [%]	64.2	66.1	62.5	58.9	64.6

* sample of particleboard unaffected by microfungi
T_i – the initial temperature of thermal decomposition, T_{max} – the temperature of the maximum rate of mass decrement, T_f – final temperature of thermal decomposition, W_{Ti}, W_{Tmax} – mass decrements in the above-mentioned temperatures, W_{max} – the total mass decrement

The analysis of the courses of the TG/DTG curves demonstrates that in the considered temperature range (20 to 600 ºC) there are three areas of decomposition of the investigated samples. In the lower temperature range, up to 130 ºC the thermolysis of all the samples proceeded in a similar manner.

Remarkable differences in the course of thermolysis were recorded only in the range of temperatures 140 to 400 °C responsible for the thermal decay of cellulose and lignin included in the wood. Therefore, the active thermolysis proceeding in this area is the overall effect of numerous superimposing decay processes occurring in the investigated material. Data included in Table 8 indicate that the decomposition of the control particleboard was unaffected by fungi. However, when the material was incubated with *Ch. globusom*, a higher temperature was required than in case of boards attacked by other microfungi. These findings were demonstrated as lower final temperatures (T_f) and temperatures corresponding to the maximum rate (T_{max}) of the thermal degradation of boards attracted by *A. niger* and *T. viride*. The course of the DTG curves shows that, in this range of temperatures, the thermal effects that accompanied the decay of the control sample and a sample affected by *Ch. globosum* were of endothermic character (Fig. 2a). In the other cases, there were small exothermic peaks, suggesting changes in the cellulose of both quantitative and qualitative nature. It is also significant that in this range of temperatures the most intensive decay of the applied resin (UF) took place.

The temperature range of over 400 ºC is the third area in which changes were observed in the course of DSC curves. Here, all the curves of the samples attacked by fungi were characterized by a slightly different curse than the curve of the particleboard unaffected by fungi. The most distinct changes were observed for the sample attacked by *T. viride*: in this case an exothermic peak was clearly visible with its maximum at 557 °C. Although the soft rot fungi are considered less aggressive, the changes they cause in the structure of cell walls contribute to changes in mechanical strength of the attacked wood.

The concentration analysis (Fig. 3a) for DTG curves indicated a similarity in the changes of thermal resistance for the samples attacked by *A. niger* and *T. viride,* which is consistent with the observed changes in the mechanical properties of the boards. Quite unexpectedly, however, the analysis highlights changed in the course of DTG caused by

P. furniculosum, while changes caused by *Ch. globosum* were considered much less important, although the observed changes in the mechanical properties were in both cases similar. The cluster analysis provided a different evaluation of the courses of DSC curves (Fig. 3b). In this case, the courses for *P. furniculosum* and *Ch. globosum* were considered similar, which is compatible with the earlier observations. Yet, the DSC curves for the samples attacked by *A. niger* and *T. viride* were considered to be much different.

a) b)

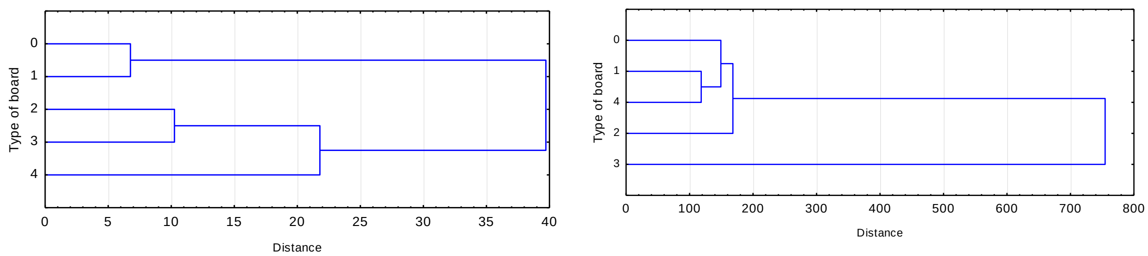

Fig. 3. Cluster analysis of DTG (a) and DSC (b) spectra of the particleboards infected with microfungi: 1 – *Chaetomium globosum,* 2 – *Aspergillus niger,* 3 – *Trichoderma viride,* 4 – *Penicillium funiculosum, 0 – control sample*

The small amount of fungi used in the investigation does not facilitate a fully correct analysis of regression. However, the values R^2, attained for linear regression, that amount to 0.9765 and 0.9711, respectively for the systems $DTG_{Euclidean\ distance}/\delta_W$ i $\delta_{MOR*MOE*IB}/\ DTG_{Euclidean\ distance}$ are compliant with the expectations. That is because proportionally to the mass decrement of the boards, one should expect changes in their mechanical properties.

CONCLUSIONS

1. P2 type particleboards show certain susceptibility to the action of fungi. Nonetheless, it seems that in this case the conditions under which the fungi grow and attack play the most important role.
2. The investigations show that the incubation conditions strongly affect the decay process of particleboards. The decrease in mechanical properties of the board attacked by the test fungi is estimated at 15 to 20%. Here, greater changes are observed in terms of modulus of rupture and modulus of elasticity than in case of internal bond.
3. The samples affected by fungi are also characterized by the permanent increase in the board thickness, and the scope of this change depends on the kind of fungi.
4. The analysis of DSC and DTG curves of the board samples attacked by fungi and the control samples, shows that there were significant differences in the thermal stability of the investigated samples. This was indicated by the changes observed in the course of curves in these ranges of temperature where the decay of cellulose occurs.

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Article submitted: June 28, 2014; Peer review completed: August 13, 2014; Revised version received and accepted: August 26, 2014; Published: September 2, 2014.