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Hydrothermal recycling of waste and performance of the recycled wooden particleboards

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Abstract

Recycling today constitutes the most environmentally friendly method of managing wood waste. A large proportion of the wood waste generated consists of used furniture and other constructed wooden items, which are composed mainly of particleboard, a material which can potentially be reused. In the current research, four different hydrothermal treatments were applied in order to recover wood particles from laboratory particleboards and use them in the production of new (recycled) ones. Quality was evaluated by determining the main properties of the original (control) and the recycled boards. Furthermore, the impact of a second recycling process on the properties of recycled particleboards was studied. With the exception of the modulus of elasticity in static bending, all of the mechanical properties of the recycled boards tested decreased in comparison with the control boards. Furthermore, the recycling process had an adverse effect on their hygroscopic properties and a beneficial effect on the formaldehyde content of the recycled boards. The results indicated that when the 1st and 2nd particleboard recycling processes were compared, it was the 2nd recycling process that caused the strongest deterioration in the quality of the recycled boards. Further research is needed in order to explain the causes of the recycled board quality falloff and also to determine the factors in the recycling process that influence the quality degradation of the recycled boards.

1. Introduction – The need to recycle wood

Today's rapid technological growth has led to dangerous degradation of the environment, which constitutes a serious threat for upcoming generations. Environmental pollution, the reduction in natural resources and the general disturbance of the ecological balance constitute problems that should be taken into serious consideration by our society (Lykidis and Grigoriou, 2005).

The increase in CO_2 and CH_4 emissions, resulting from the over-consumption of fuel, from forest fires and from the decomposition of waste, are, to a large extent, responsible for the 'greenhouse phenomenon' which involves overheating of the planet and extreme meteorological and climatic events (Grigoriou, 2000). In order to prevent such events, many countries from all over the world agreed to sign the Kyoto protocol, with the result that by the year 2010, there should be a decrease in greenhouse gas emissions of 8% compared with 1990 levels (European Cooperation in the field of Scientific and Technical Research, 2002; Jungmeier et al., 2004). Apart from the factors already mentioned, the carbon balance on earth is also considerably influenced by photosynthesis. Forests, via photosynthesis, absorb large quantities of CO_2 from the atmosphere and as a result they constitute an enormous natural carbon reservoir with an important role in regulating the 'greenhouse phenomenon' (Grigoriou, 1996). The crucial contribution of forests to the ecological balance also arises from the fact that they facilitate water storage, they are great recreation areas and, of course, they provide wood, a valuable raw material used in the manufacture of furniture and many other products. Changes in economic and demographic growth, combined with the many advantages of wood compared with other construction materials,

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have resulted in an increase in demand for wood worldwide combined with an increase in the generation of wood waste (Fig. 1). Nevertheless, wood waste can potentially constitute a valuable resource for the production of various materials and products.

2. The recycling of wood products

The current strategies in managing wood waste and their impact on the environment are presented in Table 1 (European Commission, 1997). Landfilling of organic material leads to CH_4 emissions, which result in greenhouse gas potential 21 times higher than that of CO_2 (European Cooperation in the field of Scientific and Technical Research, 2002). Furthermore, Risholm-Sundman and Vestin (2005) reported that during the combustion of particleboard it is important to have the appropriate conditions; otherwise incomplete combustion can result in the formation of toxic compounds. Other researchers have also stated that the alternatives to incineration or the disposal of wood waste in landfills constitute low-profit solutions that can also be hostile to the environment (Rowell et al., 1993; Michanickl, 1996b; Grigoriou, 1998) in contrast with recycling, which causes less harm to the environment. On the other hand, the growing shortage of low-price wood, in combination with the continuously rising cost of raw materials, creates considerable problems for wood-based panel manufacturers. As a result, they are seeking alternative sources of raw material and they are turning to the option of wood waste recycling (Wolff and Siempelkamp, 2000; Boehme, 2003).

Fig. 1. Typical wood-waste (Auburn Machinery, 2003).

A large part of wood waste is composed of old wooden constructions, including furniture, which, when they have outlived their usefulness, are available for exploitation (Michanickl and Boehme, 1996). The above constructions are mainly manufactured from urea–formaldehyde (UF) bonded particleboards and fiberboards (Riddiough, 2002). Since these boards consist of at least 90% wood, the recovery and recycling of wood from used wood-based panels in the production of new ones constitutes the most rational means of wood waste exploitation.

Various researchers have dealt with the possibility of recycling wood-based panels as well as re-using board production residues. Sandberg (1965) and Pfleiderer Unternehmensverwalt (1994) have presented methods which make possible the re-use of board residues, after steaming, in the production of particleboard or other wood-based material. In a related patent published by Moeller (1993), a method for the recycling of wood products and waste containing wood is described. The application of the method includes mechanical handling of waste followed by processing for the production of by-products or end-products. Roffael (1996) presented a method for re-using wood particles and fibers derived from waste panels bonded with tannin-based adhesive. The formaldehyde required to crosslink the tannin was generated by the hydrolytic decomposition of adhesives of the waste boards during hot pressing. Boehme and Michanickl (1998, 2003) presented a method with which it is possible to recover particles and fibers from waste containing wood, old furniture and other wood-product residues. The wood waste is comminuted and is then impregnated with a solution consisting of urea, ammonia and soda. After this impregnation, the wood products are heated in order to dissolve the adhesive bonds between the fibers and particles. A project named "Envirofiber" was introduced by Fibersolve Ltd proposing the hydrothermal pulping of waste wood panels in order to recover wood fibers that could be used as raw material for the production of medium density fiberboard (Riddiough and Kearley, 2001; Riddiough, 2002). Related work has also been conducted by Sandison (2002) who presented a patent for the recovery of wood particles from waste particleboards and MDF using a vacuum prior to the heat treatment. A patent related to the recycling of wood products published by Hesch (2002) relates to a method that uses

Table 1
Wood waste management techniques and their most significant results for the environment (European Commission, 1997)

	Environmental impacts		
	Air	Water	Soil
Landfilling	CO_2 and CH_4 emissions (greenhouse gases), Unpleasant smells	Toxic compound pollution of subsoil water	Build up of hazardous substances in soil, land take up
Incineration	Emits CO_2, CH_4, SO_2, NO_X, HCl, dioxins	Fallout of hazardous substances into surface water	Dumping of incinerator ashes and smoke – cleaning residues
Recycling	No such environmental impact		

an apparatus for breaking down wood products such as used furniture into usable individual components such as chips and fibers.

3. Aim

The aim of the present research was to investigate the properties of recycled particleboards made from recovered wood particles. For the recovery of the wood particles, four different particle-recovery hydrothermal treatments were utilized. This applied particle-recovery method differed from other related methods (Moeller, 1993; Boehme and Michanickl, 1998, 2003; Riddiough and Kearley, 2001; Riddiough, 2002; Hesch, 2002) due to the fact that during the recycling process, the original boards were neither comminuted nor impregnated with any solution that would assist in their degradation. Research was also carried out to assess the influence of a 2nd recycling process on the quality of the recycled boards.

4. Materials and methods

For the purposes of this research, one-layer laboratory particleboards with dimensions of 350 × 300 × 12 mm and with a nominal density of 0.65 g/cm^3 were manufactured. The wood particles used were obtained from a particleboard manufacturer and produced by chipping poplar, fir, pine and waste wood. In order to minimize potential fine material loss, which would alter the results during the production of the boards, the particle fraction of $k < 1.5$ mm was removed. A commercial liquid urea–formaldehyde (UF) resin of E2 grade with 50% solids content was applied to the particles in a proportion of 7% (dry resin weight per dry weight of particles). The ammonium chloride (NH_4Cl) hardener was incorporated at 2% per dry weight of adhesive. During hot pressing a maximum pressure of 2.5 N/mm^2 was applied to the boards at a temperature of 185 °C for 240 s.

To carry out particle recovery, the laboratory boards were treated with four different hydrothermal (steam) treatments in various pressure–temperature-duration conditions. The combinations of conditions applied were: 2 bar/119 °C/480 min, 4 bar/140 °C/120 min, 6 bar/156 °C/45 min, and 8 bar/167 °C/20 min. The selected temperature range of the treatments was between 110 and 170 °C, because temperatures under 110 °C would result in the slow decomposition of UF bonds, while temperatures over 170 °C would result in fast thermal decomposition of the wood (Goldstein, 1973). The treatment durations varied due to the fact that lower temperatures require relatively larger time intervals compared to higher temperatures. Under the effects of saturated steam, the UF adhesive bonds were hydrolytically degraded, thus resulting in the detachment of wood particles which could then be re-used for the production of new (recycled) particleboards. Utilizing the particles recovered from each of the four different hydrothermal treatments, new laboratory particleboards were produced under the same conditions as the original. From each of the four groups of the recycled particleboards produced, three boards were separated in order to determine their properties (1st recycling boards), while the rest of them were used in the production of new boards (2nd recycling boards), after the same steam treatments. Moreover, for the evaluation of effects caused only by hydrothermal treatments (without recycling) on the board properties, boards were manufactured using wood particles that had previously been hydrothermally treated at 6 bar/156 °C/45 min. All of the hydrothermal treatment–recovery–board production plans are shown in Fig. 2.

The particleboard hydrothermal treatments for wood-particle recovery took place inside the reactor of a laboratory autoclave (Fig. 3), which has the ability to produce saturated steam at temperatures ranging from 100 to 170 °C and absolute pressures ranging from 1 to 8 bars.

For all of the types of particleboards produced, determination of mechanical (internal bond, screw holding strength, modulus of rupture and modulus of elasticity in bending) and hygroscopic (thickness swelling and absorption of water within 24/48 h, permanent thickness swelling) properties and also formaldehyde content (Perforator method) were performed according to the current European Norms (EN). Certain particle characteristics (fraction analysis and bulk density) were also determined.

The results for each property were expressed in mean and standard deviation values. Statistical analysis (t-test) with a confidence level of 95% was performed to determine whether significant differences among the mean values of the tested parameters occurred.

5. Results

The results concerning the bulk density and fraction analysis of the recovered wood particles are presented in Table 2. The recovered particles showed higher levels of $k < 1$ mm in comparison with the original (control) material, which probably means that the recycling process involves a slight reduction in wood particle size. The reduction in particle size can degrade some mechanical properties of the panels (mostly modulus of rupture). In most cases, the recovered material, when compared to the original (control), showed higher amounts in the fraction $k > 4$, which can be attributed to the fact that the former included a limited number of clustered particles. The recovered material, due to particle size reduction, showed higher values of bulk density than the control.

The results of the determination of board mechanical-hygroscopic properties and formaldehyde content are presented in Tables 3 and 4.

As can be observed from Tables 3 and 4, the recycling of particleboards with wood particle recovery via hydrothermal treatments in conditions 2 bar/119 °C/480 min, 4 bar/140 °C/120 min, 6 bar/156 °C/45 min and 8 bar/167 °C/20 min influenced the quality of recycled boards negatively, both with regard to mechanical properties (with the exception of the modulus of elasticity) and hygroscopic proper-

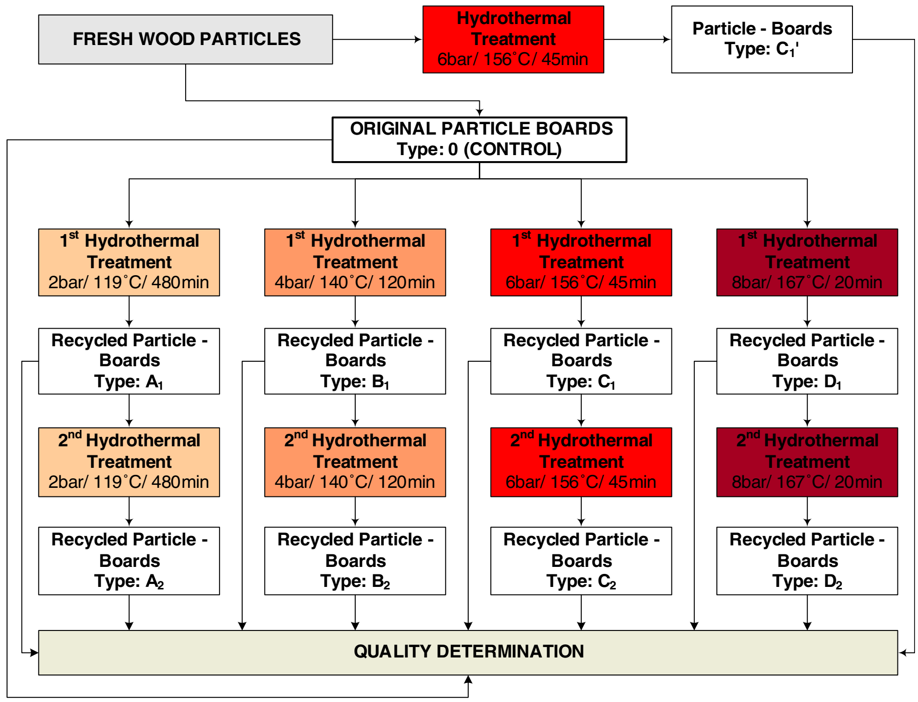

Fig. 2. Hydrothermal treatments and laboratory board production plans.

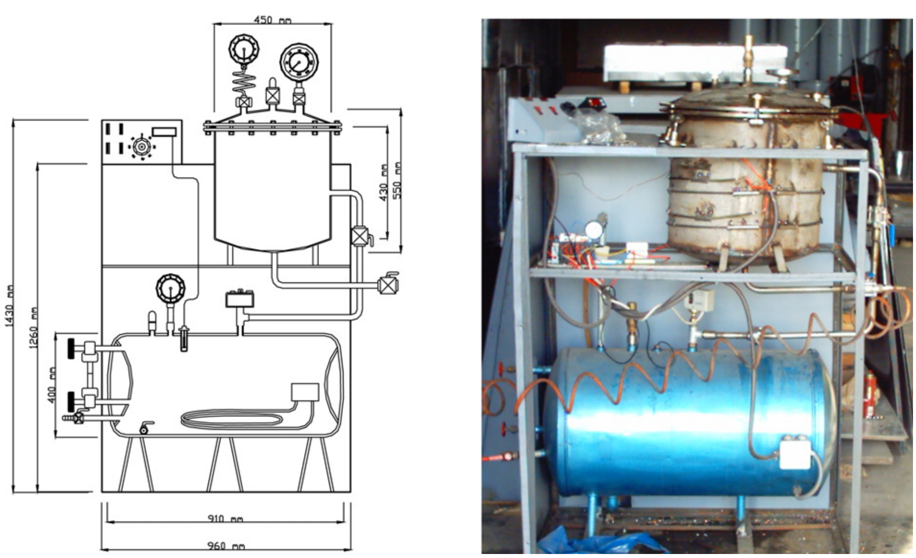

Fig. 3. Laboratory autoclave used for the steam-recovery of wood particles.

ties. More specifically, in comparison with non-recycled boards (control), the internal bond, the screw holding strength, and the modulus of rupture in static bending of recycled boards decreased considerably (showing statistically significant differences), a finding which corresponds with results reported by other authors (Michanickl, 1996a; Boehme and Michanickl, 1998). The decrease in mechanical properties could be mainly attributable to the thermal decomposition of wood during the hydrothermal treatments (Yilgor et al., 2001). In addition, some other factors such as particle size reduction, the occurrence of clustered particles and residues of hardened resin on the surface of recovered particles could have a negative effect on the recycled panel properties. In contrast, the modulus of elasticity in static bending of the recycled boards showed a statistically significant improvement compared with the control boards, which is also reported in related research (Boehme and Michanickl, 1998; Michanickl, 1996a). This improvement is probably a result of the increased wood elasticity of the hydrothermally treated wood particles.

Regarding hygroscopic properties, the recycled particle-boards showed a statistically significant increase in thickness swelling, water absorption and permanent thickness swelling in comparison with the control boards. The

Table 2
Bulk density and fraction analysis of the particles used for the production of the laboratory particleboards

Board type	Bulk density (g/cm^3)	Particle fraction analysis			
		$K > 4$ mm (%)	$4 < K < 2$ mm (%)	$2 < K < 1$ mm (%)	$K < 1$ mm (%)
0	0.124	2.60	28.23	61.32	7.79
A_1	0.160	9.09	31.15	51.07	8.67
B_1	0.160	5.43	27.56	55.98	11.01
C_1	0.157	8.98	30.83	50.97	9.31
C_1'	0.134	1.54	25.73	61.60	11.00
D_1	0.151	7.73	31.49	51.38	9.46
A_2	0.182	3.25	26.69	58.26	11.78
B_2	0.175	6.08	28.28	54.68	10.83
C_2	0.182	2.66	27.10	57.53	12.67
D_2	0.178	2.28	26.80	59.05	11.74

above-mentioned factors, which cause a reduction in the mechanical properties of recycled panels, are probably also responsible for the deterioration in their hygroscopic properties. The strongest deterioration in both the mechanical and hygroscopic properties of the recycled boards was caused when particle recovery was carried out by the hydrothermal treatment of 6 bar/156 °C/45 min.

As far as the formaldehyde content is concerned, the recycled boards had considerably lower values compared with the control boards, which indicates that they could release lower levels of formaldehyde if used as construction material in interior fittings. The above-mentioned result was similar to results found by other researchers already referred to (Michanickl, 1996a,b). The reduction in formaldehyde content of the recycled particleboards, compared to the original ones, in combination with the fact that the boards produced from hydro-thermally treated wood particles (board type C_1') showed almost the same formaldehyde content as the original ones, leads to the probable conclusion that the residual resin (mostly urea, due to volatility of formaldehyde) which exists on the recovered particles acts as a formaldehyde scavenger.

Comparison of the 1st and 2nd recycled particleboards showed that as regards the internal bond, the screw holding strength, the modulus of rupture in static bending and the hygroscopic properties, the 2nd recycling process caused further deterioration (statistically significant differences) in the board properties. On the contrary, the modulus of elasticity in static bending showed no statistically significant differences between the 1st and 2nd recycling boards.

Boards made from wood particles hydrothermally treated in conditions 6 bar/156 °C/45 min were of significantly better quality than recycled particleboards produced from particles that were recovered using the same hydrothermal treatment (compare board types C_1' and C_1). This fact leads one to the conclusion that besides the wood particle chemical degradation caused by hydrothermal treatment, there are obviously some other factors related to the recycling

Table 3
Mechanical properties of laboratory particleboards

Board type	Thickness (mm)	Density (g/cm^3)	Modulus of rupture (N/mm^2)	Modulus of elasticity (N/mm^2)	Internal bond (N/mm^2)	Screw holding strength (N/mm)
0	11.66 [a]	0.65	17.15	2137	0.938	96.72
	(0.062)[b]	(0.048)	(2.034)	(180.707)	(0.150)	(14.786)
A_1	11.43	0.67	14.24	2248	0.652	77.29
	(0.130)	(0.039)	(2.013)	(208.693)	(0.099)	(14.260)
B_1	11.34	0.67	13.28	2357	0.518	76.24
	(0.072)	(0.036)	(1.690)	(274.302)	(0.081)	(9.479)
C_1	11.47	0.66	12.11	2343	0.379	68.51
	(0.137)	(0.037)	(1.317)	(219.177)	(0.064)	(13.454)
C_1'	11.40	0.67	13.03	2198	0.712	78.90
	(0.151)	(0.048)	(2.172)	(320.921)	(0.099)	(9.755)
D_1	11.32	0.69	13.15	2402	0.501	72.18
	(0.095)	(0.048)	(2.014)	(361.943)	(0.098)	(15.160)
A_2	11.25	0.68	13.55	2379	0.504	73.49
	(0.076)	(0.043)	(2.023)	(348.273)	(0.082)	(12.813)
B_2	11.31	0.67	12.55	2518	0.382	65.69
	(0.132)	(0.038)	(1.512)	(261.986)	(0.068)	(12.761)
C_2	11.38	0.67	9.52	2453	0.177	47.37
	(0.223)	(0.044)	(2.203)	(551.661)	(0.067)	(8.772)
D_2	11.24	0.65	11.47	2581	0.262	62.49
	(0.106)	(0.045)	(1.736)	(389.895)	(0.062)	(13.551)
n[c]	60	60	15	15	20	20

[a] Mean value.
[b] Standard deviation.
[c] Number of specimens.

Table 4
Hygroscopic properties and formaldehyde content of laboratory particleboards

Board type	Thickness swelling		Water absorption		Permanent thickness swelling (%)	Formaldehyde content (mg/100 g)
	24 h (%)	48 h (%)	24 h (%)	48 h (%)		
0	28.45[a] (2.561)[b]	29.73 (2.768)	82.71 (7.100)	89.77 (8.456)	19.28 (2.147)	10.16
A_1	37.03 (4.226)	38.82 (4.050)	92.47 (7.053)	97.75 (7.398)	24.82 (2.811)	3.95
B_1	38.89 (2.861)	40.79 (3.019)	95.43 (5.801)	101.45 (6.110)	25.32 (2.413)	2.70
C_1	42.10 (2.941)	44.17 (3.143)	101.33 (5.463)	110.81 (5.768)	28.05 (2.443)	1.61
C_1'	26.18 (0.025)	27.09 (0.026)	78.97 (0.060)	83.42 (0.062)	17.49 (0.021)	10.26
D_1	37.20 (4.125)	38.78 (4.280)	95.08 (7.858)	101.96 (14.279)	24.11 (3.016)	2.78
A_2	39.21 (3.343)	40.48 (3.671)	93.76 (6.323)	98.90 (6.974)	23.79 (2.870)	1.60
B_2	39.87 (2.959)	41.80 (3.042)	96.01 (5.070)	101.88 (5.374)	24.72 (2.397)	2.31
C_2	59.11 (4.847)	61.21 (4.754)	119.61 (4.933)	125.56 (10.363)	41.10 (3.707)	2.11
D_2	47.62 (3.888)	48.83 (3.973)	105.44 (7.941)	113.90 (9.097)	29.42 (3.166)	1.75
n	20[c]	20[c]	20[c]	20[c]	20[c]	2[d]

[a] Mean value.
[b] Standard deviation.
[c] Number of specimens.
[d] Number of repetitions.

Fig. 4. Color difference between original (left) and recycled (right) particleboards.

process which have a negative influence on the properties of recycled boards. Further research is needed to determine these factors more specifically. However, possible factors could be the clusters that may occur in the recovered material and also the residual hardened resin on the surface of the recovered wood particles. The latter may have a negative effect on particle bondability.

Comparison of board types C_1' and 0 leads to the conclusion that boards produced from hydrothermally treated particles offer improved hygroscopic properties compared to boards produced with particles that have not been hydrothermally treated. This fact can be attributed to the chemical modification of wood components caused by hydrothermal treatment.

As a result of hydrothermal treatment, the recovered particles, and thus the recycled boards, obtained a darker color (Fig. 4), the darkness of which depended on the temperature and the duration of treatment.

6. Conclusions

Particleboards produced from steam-recovered wood particles showed a quality (with the exception of the modulus of elasticity in static bending and the formaldehyde content) inferior to that of particleboards made from original particles (control). The 2nd recycling process caused further quality degradation in the boards compared with the 1st recycling process. Among the four hydrothermal treatments applied for particle recovery, the treatment of 6 bar/156 °C/45 min resulted in the strongest degree of quality deterioration in the recycled boards. There is the need for further experimental studies in order to explain the causes of degradation occurring with regard to some properties. With that aim in mind, the next step in this research is to carry out chemical analysis so as to define the possible cellulose, lignin and hemicellulose content changes in order to achieve a clearer view of the facts.

Regarding the exploitation of the above results, the recycling methodology presented in this work can be applied in industry, by not fully replacing fresh wood particles but by using mixtures of recovered and fresh wood particles in such proportions so as to avoid a significant deterioration in the quality of the boards produced and still meet with current specifications. The degree of degradation in the quality of recycled particleboards can be significantly reduced by using milder conditions during hydrothermal treatments for particle recovery.

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