Low Formaldehyde Emission Particleboard Panels Realized Through a New Acrylic Binder

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ABSTRACT: The effectiveness of acrylic resins as low formaldehyde emission binders for particleboard production was explored. In particular, a multifunctional methacrylic monomer, ethoxylated bisphenol A dimethacrylate, classified as nonskin and eyes irritant, was selected and tested. In comparison panels realized with classic urea-formaldehyde (UF) binder were also prepared. No significant differences were found through the morpholocigal analysis of samples prepared with the two different binders. Moreover, particleboard panels realized with the acrylic binder showed better mechanical properties and lower water absorption and thickness swelling in comparison with corresponding panels realized with the UF binders. Furthermore, the replacement of the UF with the acrylic binder did not affect thermal insulation properties of the panels. Formaldehyde release tests revealed that particleboard panels obtained by applying the acrylic binder can be classified as E1 following the European classification and even *F***** following the stricter Japanese classification. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 122: 2779–2788, 2011

Key words: adhesives; composites; curing of polymers

INTRODUCTION

Particleboard is an engineered wood product manufactured from wood particles and synthetic resins or other suitable binders. Also called chipboard, particleboard is a panel product widely used in the manufacture of furniture, floor underlayment, home constructions, cabinets, stair treads, shelving, and many other civil and industrial applications.[1]

The production process of the particleboard panel can be summarized as follows. Wood particles are dried and after that oversized or undersized particles are screened out. Resin, in liquid form, is then sprayed onto the particles. The resin is sometimes mixed with other additives before being applied to particles, to make the final product waterproof, fireproof, insect proof, or to impart other specific performances.

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There are several classes of resins that have been tested for particleboard production. Nevertheless, more than 90% of particleboards are still obtained through urea-formaldehyde (UF) binders as they provide strong, durable bonds and at low cost.

Unfortunately, UF resins show drawbacks in terms of low water resistance and formaldehyde release.[2,3] In particular, formaldehyde emission (FE) is nowadays considered a severe limitation. In particular, this phenomenon is ascribed to the reversibility of the amino-methylene bond, which also explains the low resistance of UF against the influence of water and moisture, especially at high temperatures.[4]

Formaldehyde is released by degradation of methylol groups of UF resins during hot-pressing; free formaldehyde entrapped into the board slowly diffuses out during the lifetime of the particleboard. Furthermore, unreacted methylol groups and methylene-ether groups present in the cured resin can gradually break down to emit formaldehyde, with negative effects on the indoor air quality (IAQ) and the human health.[5–7]

In the last years several possible approaches have been proposed to reduce FE from boards, based either on the optimization of UF resin formulations and the particleboard production process[1,8] or on the application of different binders with an intrinsic

low FE. Within this last strategy, binders constituted by melamine modified urea formaldehyde (MUF) resins,[2,9] phenol-formaldehyde (PF) resins,[10,11] tannin based adhesives,[12–15] polymeric methylene diisocyanate (PMDI),[16–18] starch, and other natural based adhesives,[19–24] including bacterially derived biopolymers,[25–28] as well as mixtures of different binders[29–32] have been proposed, with alternating results, as possible low FE binders for particleboard production.

Among them, very interesting results have been shown by PMDI binders, in terms of both low FE and overall performances of the particleboards. However, the use of PMDI as a binder has a large number of disadvantages. The affinity of PMDI to metal is a problem as the glued particles and fibers can adhere to the press belts during hot-pressing. For this reason, it is necessary to work with expensive, properly coated press belts. The handling of PMDI also requires that strict work safety measures must be observed.

In this article a new safe and low FE acrylic resin has been tested as possible binder for particleboard production.

The curing parameters and the emission of formaldehyde from the resin have been evaluated through thermal characterization and environmental chamber methods, respectively. Moreover, the morphology of the realized panels, as well as the influence of this binder on mechanical properties, water absorption, thickness swelling and thermal insulation properties of spruce particleboards have been evaluated. All the tests have been carried out in comparison with classic UF binder.

MATERIALS AND METHODS

Materials

Spruce particles (*Pinea abies*), four mesh screened, were kindly provided by Fraunhofer Institute for Wood Research (WKI, Braunschweig, Germany).

Urea-formaldehyde (UF) resin, commercial name Kaurit 350, 50 wt % solid content, was kindly supplied by Basf (Cesano Maderno, Milano, Italy).

Acrylic (ACR) resin, commercial name Sartomer SR 348, 100% solid content, was purchased from Sartomer Europe (Paris, France).

Main characteristics of the selected UF, PF and ACR resins are reported in Table I.

TABLE I
Main Properties of the Urea-Formaldehyde (UF) and Acrylic (ACR) Resins used for Particleboard Production

Property	Resins	
	UF	ACR
Commercial name	Kaurit 350	SR 348
Producer	Basf	Sartomer
Dry content (wt %)	66.5 ± 1.0	>99
Water content (wt %)	<33	<0.2
pH (at 20°C)	8.5 ± 1.0	–
Maximum acid value	–	0.5 mg KOH/g
Viscosity (mPa s at 20°C)	350–600	600–1600

Preparation of the samples

Curing process of the resins

For the preparation of UF and ACR resin samples, each resin was mixed with the appropriate amount of catalyst and then oven-cured as follows.

UF resin (50 g) was mixed with ammonium sulfate (2.4 wt % with respect to the solid content of the resin). ACR resin (50 g) was mixed with dibenzoylperoxide (DBPO, 1.5 wt % with respect to the solid content of the resin).

The mixtures were then poured in Petri dishes and oven-cured for 30 min. For both UF and ACR resins two different curing temperatures were used: 140°C and 180°C.

Particleboard preparation

Spruce particles were oven-dried at 60°C for 7 days to reduce the water content of the particles before 0.2 wt %. Particles were then sprayed with the appropriate amount of UF or ACR resins previously mixed with the specific catalyst, as reported for the curing process of neat resins. For all the particleboard panels the target amount of solid resin was selected as 10 wt % with respect to the total weight of the panel. Chips sprayed with resins were then placed into a 300 mm × 300 mm frame.

A conventional hot platen press was used for the preparation of the particleboard panels. The pressing temperature was selected as 180°C either for UF or for ACR based panels. The pressing time was 10 min for all the panels.

Four values of target density were selected for the particleboard panels: 0.50, 0.63, 0.76, and 0.89 g cm^{-3}. Corresponding particleboard samples were prepared by varying the thickness of the samples through stop bars inserted among the platens of the press. For each resin and density three particleboard panels were prepared.

Testing methods

Thermal analysis

The optimal curing temperature of the selected resins and the effect of the specific catalysts were evaluated with a differential scanning calorimeter Mettler-Toledo DSC-30. The apparatus was calibrated with indium standard at various scanning rates. Dry

nitrogen gas with a flow rate of 20 mL min^{-1} was purged through the cell during measurements.

Neat resins (about 10 mg) and resins mixed with the appropriate amount of the specific catalyst were heated from 20 to 190°C at a scanning rate of 10°C/min.

To prevent that the endothermic peak due to water evaporation could mask the exothermic peak of the curing reaction, in the case of UF water-dispersed resin high-pressure crucibles[33,34] were used with a design tolerance of 150 bar. Standard aluminum crucibles were used for ACR resin whose formulation is free of water and organic solvents.

Curing onset temperature (T_{onset}) and peak temperature values (T_{peak}) were evaluated at the onset and at the maximum of the exothermic peaks of DSC traces. Curing enthalpy (ΔH_c) was measured by integration of the curing exothermic peak.[35]

Formaldehyde emission test on resin samples

Formaldehyde emission tests on resin samples were carried out using the small chamber method.[36] Each resin (3.4 g) were milled by means of a rotor miller (Retsch GmbH, Haan, Germany), placed in a Petri dish (90 mm diameter) and inserted in the test chamber (Inlemar, Paterna, Spain). The chamber parameters were: temperature 60.0 ± 0.5°C, relative humidity 3 ± 1%, air exchange 60 ± 3 L h^{-1}, over pressure 1200 Pa, air sampling each hour for 4 h from the beginning of the test.

For the formaldehyde determination the colorimetric method based on the use of acetylacetone, forming a green-yellow diacetyldihydrolutidine (DADHT) in presence of formaldehyde, was used. The amount of DADHT was quantified at 412 nm by means of a UV-Vis spectrometer (Jasco, Gross-Umstadt, Germany).

The amount of released formaldehyde was expressed as mg of formaldehyde per hour and per gram of neat resin (mg h^{-1} g^{-1}). Sampling and analyses were carried out in duplicate.

Morphological analysis

Morphological analysis was performed on the external surface of the samples by means of a Scanning Electron Microscope (SEM) FEI Quanta 200 FEG, operating in low vacuum mode. Accelerating voltage was set between 10 and 20 kV.

Density and moisture content

Particleboards were conditioned at 25°C and 60% relative humidity (RH) for 1 week and then tested for density and moisture content (MC) according to the following formulae:

$$\text{density}(\text{g/cm}^3) = \frac{W_a}{V_a} \tag{1}$$

$$\text{MC}(\%) = 100 \times \frac{W_a - W_0}{W_a} \tag{2}$$

where W_a is the weight after conditioning, V_a is the air-dried volume, and W_0 is the oven-dried weight of the particleboard samples.

Bending tests

Modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated on specimens 40 mm deep and 300 mm long. Before testing, specimens were conditioned for at least 1 week at 25°C and 60% RH. The bending test was carried out following the three-point bending method over an effective span of 180 mm, by means of an Instron dynamometer (model 5564), equipped with a load cell of 1000 kg, using a crosshead rate of 1 mm min^{-1}.[37]

MOE and MOR were determined using the following equations:

$$\text{MOE}(\text{MPa}) = \frac{L^3\, s}{4b\, d^3} \tag{3}$$

$$\text{MOR}(\text{MPa}) = \frac{3P\, L}{2b\, d^2} \tag{4}$$

where L is the support span (mm), s is the slope of the tangent to the initial straight-line portion of the load deflection curve (N/mm), b is the width of the specimen (mm), d is the depth of the specimen (mm), P is the load at rupture (N).

For each sample, five specimens were tested and the average values of MOE and MOR were reported.

Internal bonding test

Internal bonding (IB) tests were conducted on 40 mm ×40 mm specimens, cut from particleboard panels with target density values of 0.630 and 0.760 g cm^{-3}. Before testing, specimens were conditioned for at least 1 week at 25°C and 60% RH. Therefore IB tests were carried out according to DIN EN 319[38] at room temperature by means of an Instron dynamometer (model 5564), equipped with a load cell of 1000 kg, using a crosshead rate of 1 mm min^{-1}.

IB strength of particleboard specimens was determined using the following equation:

$$\text{IB}(\text{MPa}) = \frac{P}{A} \tag{5}$$

where P is the load (N) at which the specimen failed (N) and A the surface area of the specimen (m^2). For each sample, five specimens were tested and the average values of IB were reported.

Water absorption test and thickness swelling

Specimens with dimensions of 30 mm ×30 mm were used for the evaluation of the water absorption and the thickness swelling. Samples were dried in an oven at 90°C under vacuum for 24 h. Therefore, the weight (W_0) and the thickness (T_0) of the dried samples was measured. Then test specimens were placed into water and soaked for 24 h. The weight of the specimens was measured at various immersion times (W_t), while the thickness was measured again at the end of the soaking process (T_{24}).

Water absorption (WA) was calculated according to the following equation:

$$\mathrm{WA}(\%) = 100 \times \frac{W_t - W_0}{W_0} \quad (6)$$

Moreover the water absorption rate (WR) was calculated, as the slope of the WA curve in the first 15 s of absorption time.

Thickness swelling (TS) was determined by following equation:

$$\mathrm{TS}_{24}(\%) = 100 \times \frac{T_{24} - T_0}{T_0} \quad (7)$$

For each sample, WA and TS values were measures in triplicate, and the average values were reported.

Thermal conductivity

Thermal conductivity (λ) of particleboard panels was measured at room temperature using the multipurpose apparatus ISOMET (Applied Precision, Bratislava, Slovakia).[39] Measurements were performed at 25°C on samples conditioned at 60% RH for at least 1 week. For each sample, λ values were measured in triplicate on both sides of the panels, and the average values were reported.

Formaldehyde emission test on particleboard panels

Formaldehyde emission tests were also carried out on selected panels realized with the acrylic binder, following the standard EN 717-1 : 2004, in a 1 m^3 chamber.[40] Specimen dimensions were 200 mm × 280 mm. Tests were carried on four specimens for each composition. Average results were expressed in mg m^{-3}.

RESULTS AND DISCUSSION

The aim of this work was to explore the effectiveness of acrylic resins as possible low formaldehyde emission binders for particleboard production. Among several possible acrylic resins, the choice was pointed out on a class of resin with properties suitable for a possible direct industrial application.

In particular, the main characteristics considered for the selection of the resin were: viscosity suitable for spraying application; relative high stability at low temperature and in absence of catalyst; very low volatility; high boiling point; fast curing response, also in presence of small amount of water; optimal mechanical properties after curing; no toxicological risks.

On the basis of these requirements, a multifunctional methacrylic monomer (ethoxylated bisphenol A dimethacrylate) was selected, able to undergone to a fast curing process in presence of peroxides, classified as nonskin and eyes irritant.

The resin was characterized in terms of thermal and formaldehyde emission properties and then tested as binder for particleboard production, in comparison with classic UF and PF resins, currently widely used for industrial particleboard production.

Characterization of resin

Thermal analysis

To evaluate the optimal curing temperatures, dynamic DSC experiments were performed on the selected commercial resins, both neat and in mixture with the specific catalysts. In the case of UF resin, 2.4 wt % of ammonium sulfate was added.[41,42] The amount of catalyst was calculated with respect to the dry resin content. For the ACR resin, 1.5 wt % of dibenzoyl peroxide (DBPO) was added as catalyst, calculated with respect to the dry content of the resin.[43]

Under dynamic conditions, onset cure temperatures (T_{onset}) and peak temperatures (T_{peak}) of the curing reaction were evaluated, as well as the cure enthalpy (ΔH_{curing}). Cure enthalpy values have been corrected with respect to the dry content of the resin in the case of UF. The obtained results are summarized in Table II.

As reported, the effect of catalysts is well evident for both the resins. As well known, ACR resin does not undergo to a curing reaction in absence of catalyst: the DSC trace of the neat resin does not show any exothermic peak in the investigated range. For UF resin, the catalyst is able to promote the curing process, whose onset and peak temperature are shifted at lower values with respect to neat resin. Moreover an increase of the cure enthalpy was recorded for UF resin mixed with ammonium sulfate. This indicates that the curing reaction of the UF resin was strongly dependent on the catalyst content. This phenomenon could be explained by the increased reactivity due to the decrease of pH value obtained by addition of the catalyst.[44,45]

TABLE II
Onset Temperature (T_{onset}), Peak Temperature (T_{peak}), and Curing Enthalpy (ΔH_{curing}) of UF ACR Resins

Resin	Catalyst	T_{onset} (°C)	T_{peak} (°C)	ΔH_{curing} (J g^{-1})
UF	–	90	126	112.9
UF	$(NH_4)_2SO_4$	66	98	171.0
ACR	–	[a]	[a]	[a]
ACR	DBPO	70	95	204.5

[a] No curing process occurs

Formaldehyde emission tests on resin samples

Formaldehyde emission tests were carried out on resin samples cured at various temperatures using the small chamber method. In Table III results of formaldehyde emission tests are reported.

The mechanism of formaldehyde emission from UF resins has been widely investigated. The phenomenon can be explained by considering the reversibility of the amino-methylene bond in the UF resin, in particular at high water contents and high temperatures and in presence of acids that can act as catalysts for the depolymerization reaction.[4] On the other hand, the urea-formaldehyde ratio in the resin, as well as some other technological parameters, have been found to have significant effects on the formaldehyde emission of UF resins.[1,8]

In the case of the formulation used in this work, from data reported in Table III it can be observed that UF resin shows very high values of formaldehyde release both at lower and higher curing temperature. Moreover, stronger curing conditions seem to induce a slight increase of the formaldehyde emission, thus confirming that the stability of UF resin decreases with high temperature curing processes.

A very interesting result has been obtained by analyzing the acrylic resin. In fact, ACR shows the lowest levels of formaldehyde emission, both at lower and higher curing temperatures; in particular, stronger curing conditions seem to promote lower emission levels.

In fact, the acrylic resin cured at 180°C releases a formaldehyde amount that is less than 1/200 with respect to that released by the UF resin. This finding allows to assert that the proposed acrylic resin can be considered as a zero formaldehyde emission binder.

Particleboard characterization

Morphological analysis

Morphological analysis was performed on the external surface and in the inner part of the panel samples realized with the acrylic and the UF binder. In Figure 1 SEM micrographs of the samples with target density of 0.76 g cm^{-3} are reported.

In, Figure 1(a,c), the micrographs of the external surface of the panels are reported. The wood particles can be still distinguished, bonded each other through the selected binders. The use of the acrylic resin does not modify the surface morphology of the panel in comparison with the sample realized with the commercial UF resin.

The analysis of the inner part of the samples, whose micrographs are reported in Figure 1(b,d), clearly evidenced the presence of both the binders that do not form a uniform film on the surface of the particles. On the contrary, they join together adjacent wood particles. Some areas in which large size agglomerates of binders have been found both in the panels realized with the acrylic binder and in those realized with urea-formaldehyde. It must be also remarked that, in the case of the urea-formaldehyde, cracking phenomena of the UF binder have been observed.

The comparative analysis of particleboard panels with different target density values gave similar results. The distribution of the binder on the surface and within the panels is not significantly influenced neither by the density of the panels nor by the nature of the applied binder.

Density and moisture content

After conditioning at 60% RH for 1 week, particleboards were undergone to the evaluation of thickness, density, and moisture content (MC). Corresponding results are reported in Table IV.

As it can be observed, all the particleboards show low MC values that seem to be not significantly correlated with the panel density. In particular, particleboards realized with ACR resin show the lowest MC values, either with respect to panels obtained with UF. This finding underlines the intrinsic hydrophobic properties of ACR resin, able to reduce the moisture absorption of wood particles into the panels.

Mechanical tests

Modulus of elasticity (MOE) and modulus of rupture (MOR) of particleboard panels realized with UF, and ACR resins are graphed in Figures 2 and 3, respectively, as a function of particleboard density.

As it can be observed, for all the samples, both MOE and MOR increase as function of the panel

TABLE III
Formaldehyde Emission of UF and ACR Resins

Resin	Curing temperature	Formaldehyde emission[a] (mg h^{-1} g^{-1})
UF	140	4.0 ± 0.7
	180	5.3 ± 0.8
ACR	140	0.075 ± 0.010
	180	0.018 ±0.002

[a] Amount of CH_2O per hour per gram of cured resin.

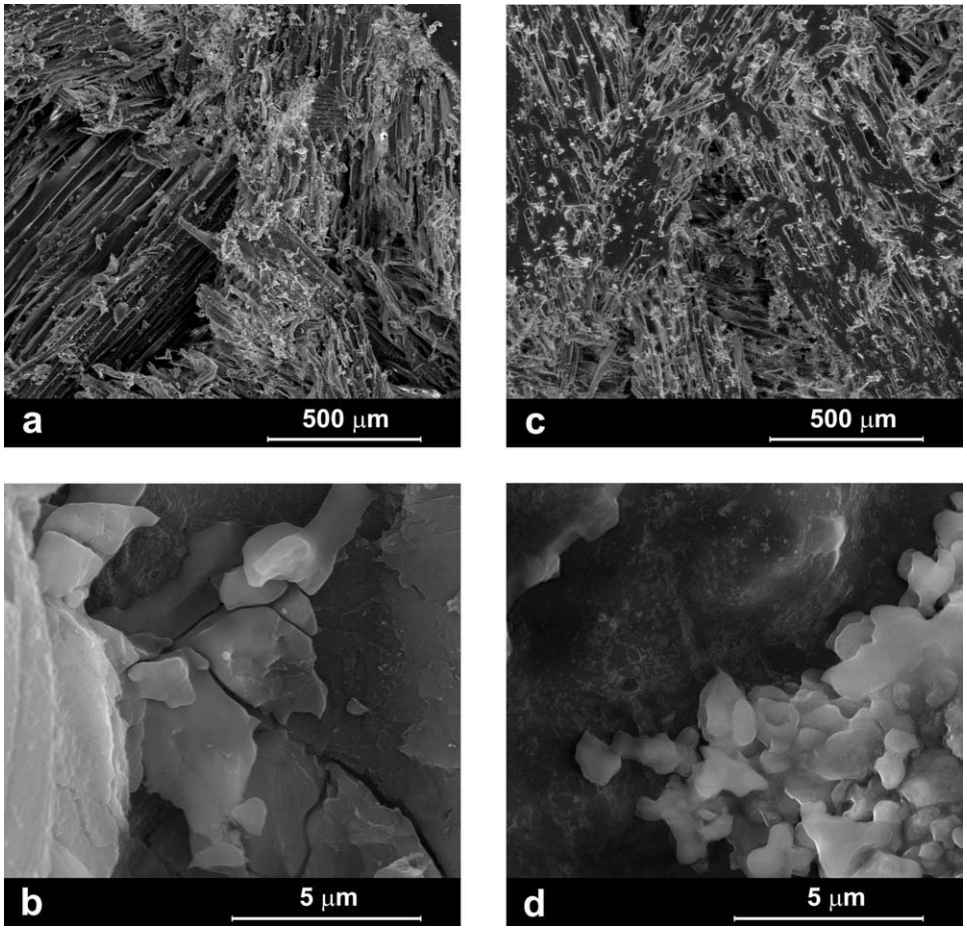

Figure 1 SEM micrographs of: a) surface of the particleboard panels realized with the UF resin; b) surface of the particleboard panels realized with the ACR resin; c) inner part of the particleboard panels realized with the UF resin; d) inner part of the particleboard panels realized with the ACR resin.

density. Moreover, both MOE and MOR are significantly improved by using the acrylic binder with respect to panels realized with UF resin. As an example, at the lowest density value (0.50 g cm^{-3}), MOE increases from about 480 MPa for the particleboards realized with the UF resin to about 875 MPa for the particleboards obtained with the acrylic binder. The same trend can be observed for the MOR: at the lowest density value (0.50 g cm^{-3}), MOR increases from about 5 MPa for the particleboards realized with the UF resin to about 9 MPa for the particleboards obtained with the acrylic binders.

The extent of the MOE and MOR improvement is very significant independently from the density of the panels: MOE and MOR curves for acrylic bonded panels fall above the corresponding curves obtained for panels realized with the UF resin in the whole range of investigated density values.

As concerning internal bonding, IB values for particleboards with target densities of 0.63 and

TABLE IV
Codes, Thickness, Density, and Moisture Content (MC) of the Particleboard Panels

Resin	Codes	Thickness (mm)	Density (g cm^{-3})	Moisture content (%)
UF	UF1	17.7 ± 0.1	0.495 ± 0.010	5.1 ± 0.2
	UF2	14.4 ± 0.1	0.620 ± 0.020	5.3 ± 0.2
	UF3	11.5 ± 0.1	0.770 ± 0.020	5.1 ± 0.1
	UF4	9.7 ± 0.1	0.910 ± 0.020	5.1 ± 0.2
ACR	ACR1	18.0 ± 0.1	0.495 ± 0.020	3.7 ± 0.1
	ACR2	14.5 ± 0.1	0.610 ± 0.010	3.5 ± 0.1
	ACR3	11.7 ± 0.1	0.755 ± 0.010	3.7 ± 0.2
	ACR4	9.1 ± 0.2	0.890 ± 0.040	3.4 ± 0.1

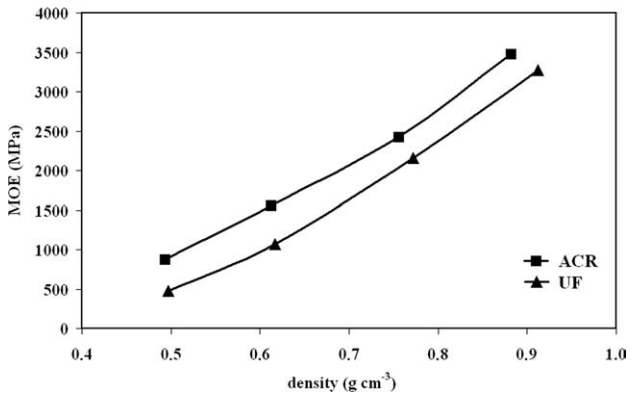

Figure 2 Modulus of elasticity (MOE) of particleboard panels realized with UF and ACR resins.

0.76 g cm^{-3} are listed in Table V. As it can be observed, also IB values are improved by using the selected acrylic resin as binder for particleboard production: the IB strength at the target density of 0.63 g cm^{-3} increases from 0.30 MPa for UF resin to 0.47 MPa for the particleboard realized with the acrylic resin. The same trend is observed at higher density, thus confirming that the use of the selected acrylic resin as binder is able to improve the overall mechanical properties of particleboard panels with respect to classic and currently used UF resins.

Water absorption test and thickness swelling

In Figure 4 water absorption curves of particleboards with various density values are reported, bonded with UF and ACR resins. As it can be observed, for all the density groups there is a considerable decrease of water absorption replacing UF with ACR resin.

This trend confirms once again that the acrylic resin is able to induce a superior hydrophobic properties with respect to the UF resin.

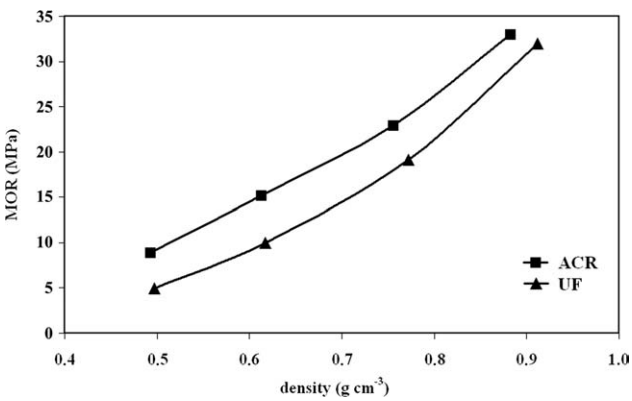

Figure 3 Modulus of rupture (MOR) of particleboard panels realized with UF and ACR resins.

TABLE V
Mechanical Properties of Particleboard Panels Realized with UF and ACR Binders

Sample	IB (MPa)
UF2	0.36 ± 0.2
ACR2	0.47 ± 0.2
UF3	0.43 ± 0.3
ACR3	0.56 ± 0.3

The effect of ACR on water absorption is more evident when the curve is observed at low water absorption times. For this purpose the water absorption rate (WR) has been calculated, as the slope of the WA curve at the first 15 s of water absorption time.

Values of WR are reported in Table VI together with the maximum water absorption (WA_{24}) and the thickness swelling (TS_{24}) after 24 h of soaking. As expected, it is evident that for each resin WR varies inversely with the density. Moreover, the more interesting differences of WR are recorded as a function of the nature of the resin: the acrylic resin strongly reduces the water absorption rate with respect to the UF binder, thus better evidencing the superior hydrophobic effect of ACR.

As far as the thickness swelling, no significant differences are evidenced by varying the density for each group of particleboards. More relevant differences are due to different resins used as binders: thickness swelling is higher for particleboard panels realized with UF binders, whereas it decreases by replacing UF with the ACR resin, thus confirming that panels obtained with the acrylic binder show higher water resistance with respect to panels realized with UF resins, and their properties are comparable or better with respect to particleboards bonded with other resins, such as PF or PMDI, generally considered binders suitable for outdoor applications, for which hydrophobization is considered a necessary property to ensure long-term durability and high performances.

Thermal conductivity

The influence of the binder nature on the thermal insulation properties of particleboard panels has been also evaluated. Thermal conductivity, λ, is directly related to the density of the board, the heaviest boards having the least insulating effect.[46] This tendency is generally explained with the evidence that lighter boards contains a large amount of voids, in which air, that is one of the poorest thermal conductors, is confined.

As reported in Table VII, no significant influence of the binder on the thermal conductivity of particleboards is evident. Thermal conductivity of panels

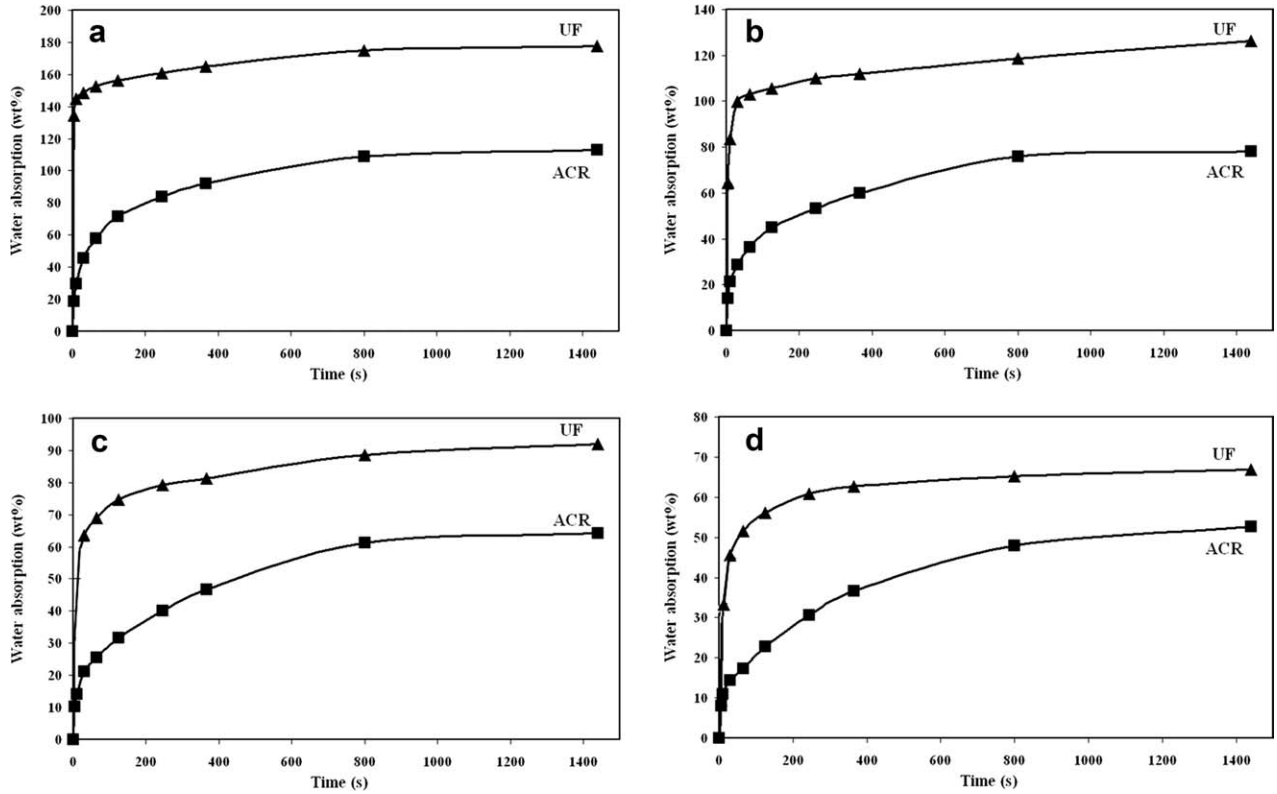

Figure 4 Water absorption curves of particleboard panels realized with UF and ACR resins at various density values: a) 0.50 g cm^{-3}; b) 0.63 g cm^{-3}; c) 0.76 g cm^{-3}; d) 0.89 g cm^{-3}.

obtained with UF and ACR resins with comparable density show similar values of λ.

To evaluate the effect of the density on the thermal conductivity of the panels, a linear regression analysis of λ versus density was performed, hypothesizing the following relationship[47] in the investigated range of densities:

$$\lambda = \alpha \times \text{density} \tag{8}$$

Therefore, the linear regression coefficient (α) as well as correlation coefficient (R^2) were calculated for each class of particleboard panels.

As it can be observed from results reported in Table VII, correlation coefficient values are very high, thus confirming the hypothesized linearity of λ with respect to density, within the range of investigated density values. Moreover, all the classes of particleboards show similar values of the linear regression coefficient, independently from the nature of the binder used, thus indicating the irrelevance of the binder nature on the thermal insulation properties of particleboard panels.

Formaldehyde emission test on particleboard panels

Finally, formaldehyde release was also evaluated by the chamber method on particleboard panels realized with the acrylic binder and characterized by target density values 0.63 and 0.76 g cm^{-3}. Very low formaldehyde release levels were measured: 0.011 ± 0.002 mg m^{-3} for panels with the lower density and 0.008 ± 0.001 mg m^{-3} for panels with the higher density.

These results are very interesting, in particular when compared to formaldehyde emission levels of commercial particleboard panels. As an example, interlaboratory tests described in a recent paper[40] show that commercial particleboard panels with different thickness (from 10 to 28 mm) and realized through UF resin, are characterized by average formaldehyde release ranging from 0.20 to 0.15 mg m^{-3}.

TABLE VI
Water Absorption Rate (WR), Maximum Water Absorption (WA_{24}) and Thickness Swelling (TS_{24}) of Particleboard Panels after 24 Hours of Soaking in Water

Sample	WR (% s^{-1})	WA_{24} (%)	TS_{24} (%)
UF1	9.7	177.8	33.7
UF2	5.8	126.2	28.8
UF3	3.7	92.1	29.9
UF4	2.4	66.8	27.1
ACR1	2.2	112.9	21.1
ACR2	1.5	78.1	18.4
ACR3	1.1	64.3	20.8
ACR4	0.8	52.6	21.5

TABLE VII
Thermal Conductivity (λ) at Room Temperature of Particleboard Panels and Results of the Linear Regression of Thermal Conductivity versus Density

		Linear regression $\lambda = \alpha \times$ density	
Sample	λ (W m^{-1} K^{-1})	α (W m^2 g^{-1} K^{-1})	Correlation coefficient (R^2)
UF1	0.119 ± 0.002	2.7×10^{-4}	0.971
UF2	0.148 ± 0.002		
UF3	0.180 ± 0.010		
UF4	0.240 ± 0.014		
ACR1	0.131 ± 0.003	2.6×10^{-4}	0.998
ACR2	0.158 ± 0.002		
ACR3	0.195 ± 0.010		
ACR4	0.231 ± 0.010		

Moreover, it must be considered that the Japanese limit for *F***** of 0.3 mg L^{-1} (in desiccator) is equivalent to 0.04 mg m^{-3} in the European chamber test.[40] Hence it can be observed that in the case of particleboard panels realized with the acrylic binder, either at 0.630 and 0.760 g cm^{-3} target density, formaldehyde release level are very low (27.5% and 20.0%, respectively) with respect to the *F***** limit.

In conclusion, the obtained results let to classify the particleboard panels realized with acrylate based binders as E1 following the European classification (UNI EN 13986 : 2005) and even *F***** following the more strict Japanese classification (JIS A 5908).

CONCLUSIONS

A multifunctional methacrylic monomer, ethoxylated bisphenol A dimethacrylate, classified as nonskin and eyes irritant, able to undergone to a fast curing process in presence of peroxides, was successfully tested as a potential zero formaldehyde emission binder for particleboard production.

The resin was characterized in terms of thermal and formaldehyde emission properties and then tested in comparison with classic UF resin, currently widely used for industrial particleboard production. On the corresponding particleboard panels mechanical properties, water absorption, thickness swelling, thermal insulation properties, and formaldehyde release were evaluated.

Particleboard panels realized with the acrylic binder showed better mechanical properties (modulus of elasticity, modulus of rupture, and internal bonding) in comparison with corresponding panels, having the same density, realized with UF binder. Moreover, water absorption and thickness swelling of the panels realized by applying the acrylate binder resulted drastically decreased with respect to corresponding panels realized through the UF binder.

As concerning thermal conductivity, the application of the acrylic binder to replace UF did not affect the thermal insulation properties of the panels.

Finally formaldehyde emission tests, carried out on both the neat acrylic resin and on the corresponding particleboard panels, showed very low formaldehyde release levels in comparison to the UF binder. Particleboard panels obtained by applying the acrylic binder and characterized by the chamber method were classified as E1 following the European classification (UNI EN 13986 : 2005) and even *F***** following the more strict Japanese classification (JIS A 5908).

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References

1. Nemli, G.; Ozturk, I. Build Environ 2006, 41, 770.
2. No, B. Y.; Kim, M. G. J Appl Polym Sci 2007, 106, 4148.
3. Myers, G.; Koutsky, J. A. Holzforschung 1990, 44, 117.
4. Dunky, M. Int J Adhes Adhes 1998, 18, 95.
5. Colak, S.; Colakoglu, G. Build Environ 2004, 39, 533.
6. Swenberg, J. A.; Kerns, W. D.; Mitchell, R. E. Cancer Res 1980, 40, 3398.
7. Chang, C. C.; Gershwin, M. E. Regul Toxic Pharm 1992, 16, 160.
8. Que, Z.; Furuno, T.; Katoh, S.; Nishino, Y. Build Environ 2007, 42, 1257.
9. Colak, S.; Colakoglu, G.; Guler, K. Holz Roh Werkst 2004, 62, 239.
10. Schmidt, R. G.; Frazier, C. E. Int J Adhes Adhes 1998, 18, 139.
11. Yanga, T. -H.; Linb, C. -J.; Wanga, S. -Y.; Tsaia, M. -J. Build Environ 2007, 42, 189.
12. Pizzi, A. Wood Sci Technol 2000, 34, 277.
13. Ballerini, A.; Despres, A.; Pizzi, A. Holz Roh Werkst 2005, 63, 477.
14. Roffael, E.; Dix, B.; Okum, J. Holz Roh Werkst 2000, 58, 301.
15. Trosa, A.; Pizzi, A. Holz Roh Werkst 2001, 59, 266.
16. Papadopoulos, A. N.; Hill, C. A. S.; Traboulay, E.; Hague, J. R. B. Holz Roh Werkst 2002, 60, 81.
17. Pan, Z.; Cathcart, A.; Wang, D. Ind Crop Prod 2006, 23, 40.
18. Sonnenschein, M. F.; Benjamin, A. E.; Wendt, L. Wood Sci Technol 2005, 39, 27.
19. Yang, I.; Kuo, M.; Myers, D. J.; Pu, A. J Wood Sci 2006, 52, 503.
20. Cheng, E.; Sun, X.; Karr, G. S. Compos A 2004, 35, 297.
21. El-Wakil, N. A.; Abou-Zeid, R. E.; Fahmy, Y.; Mohamed, A. Y. J Appl Polym Sci 2007, 106, 3592.
22. Duanmu, J.; Gamstedt, E. K.; Rosling, A. Compos Sci Technol 2007, 67, 3090.
23. Liu, Y.; Li, K. Int J Adhes Adhes 2007, 27, 59.
24. Peshkova S.; Li, K. J Biotechnol 2003, 102, 199.
25. Haag, A. P.; Maier, R. M.; Combie, J.; Geesey, G. G. Int J Adhes Adhes 2004, 24, 495.
26. Haag, A. P.; Geesey, G. G.; Mittleman, M. W. Int J Adhes Adhes 2006, 26, 177.
27. Avella, M.; Bogoeva-Gaceva, G.; Bužarovska, A.; Errico, M. E.; Gentile, G.; Grozdanov, A. J Appl Polym Sci 2007, 104, 3192.
28. Buzarovska, A.; Bogoeva-Gaceva, G.; Avella, M.; Gentile, G.; Errico, M. E. J Mater Sci 2007, 42, 6501.
29. Tomita, B.; Hse, C. -Y. Int J Adhes Adhes 1998, 18, 69.

30. Wang, S. -Y.; Yang, T. -H.; Lin, L. -T.; Lin, C. -J.; Tsai, M. -J. Build Environ 2007, 42, 2472.
31. Lei, H.; Pizzi, A.; Du, G. Holz Roh Werkst 2006, 64, 117.
32. Li, K.; Geng, X.; Simonsen, J.; Karchesy, J. Int J Adhes Adhes 2004, 24, 327.
33. Fischer, T. S.; Eisenreich, N.; Pfeil, A. Thermochim Acta 1999, 339, 35.
34. Gnanaraj, J. S.; Zinigrad, E.; Asraf, L.; Sprecher, M.; Gottlieb, H. E.; Geissler, W.; Schmidt, M.; Aurbach, D. Electrochem Commun 2003, 5, 946.
35. Vázquez, G.; González-Álvarez, J.; López-Suevos, F.; Freire, S.; Antorrena, G. J Therm Anal Calorim 2002, 70, 19.
36. Wiglusz, R.; Jarnuszkiewicz, I.; Sitko, E.; Nikel, G. Build Environ 2000, 35, 53.
37. Xu, J.; Widyorini, R.; Kawai, S. J Wood Sci 2005, 51, 415.
38. European Committee for Standardization. European Standard. DIN EN 319. Particleboards and Fiberboards; Determination of Tensile Strength Perpendicular to the Plane of the Board; European Committee for Standardization: Brussels, Belgium, 1993.
39. Luyt, A. S.; Molefi, J. A.; Krump, H. Polym Degrad Stabil 2006, 91, 1629.
40. Risholm-Sundman, M.; Larsen, A.; Vestin, E.; Weibull, A. Atmos Environ 2007, 41, 3193.
41. Siimer, K.; Kaljuvee, T.; Christjanson, P. J Therm Anal Calorim 2003, 72, 607.
42. Dukarska, D.; Lecka, J. Holz Roh Werkst 2006, 64, 403.
43. Avella, M.; Errico, M. E.; Gentile, G. Macromol Symp 2007, 247, 140.
44. Xing, C.; Deng, J.; Zhang, S. Y.; Riedl, B.; Cloutier, A. J Appl Polym Sci 2005, 982027.
45. Park, B. -D.; Riedl, B.; Hsu, E. W.; Shields, J. Polymer 1999, 40, 1689.
46. Xu, J.; Sugawara, R.; Widyorini, R.; Han, G.; Kawai, S. J Wood Sci 2004, 50, 62.
47. Venkateswaran, A. Wood Sci Technol 1974;8:50–55.