Eur. J. Wood Prod. (2012) 70:279–286
DOI 10.1007/s00107-011-0554-y

ORIGINALS ORIGINALARBEITEN

Modification of beech veneers with N-methylol melamine compounds for the production of plywood: natural weathering

Hien Mai Trinh · Holger Militz · Carsten Mai

Received: 18 November 2010 / Published online: 11 June 2011

Abstract Beech (*Fagus sylvatica* L.) veneers were treated with two formulations based on N-methylol-melamine (NMM): (1) NMM solution (NMM-1, 10% solid content), (2) fatty acid modified NMM dispersions containing paraffin (with an aluminium salt as catalyst, mNMM-2, 5% solid content). Five veneers were glued with a phenol formaldehyde adhesive to produce plywood. The plywood specimens were weathered outdoors over a period of 18 months according to EN 927-3 (2006). The moisture content of the treated plywood was clearly reduced during the exposure as compared to panels from water treated veneers (controls). As a consequence, the treated plywood displayed higher form stability and less cracks and delamination than the control plywood. Coated, NMM-treated plywood panels displayed remarkable lower degrees of discoloration than the coated controls. These differences between the treated, coated and the coated control panels were not so clearly observed in the case of uncoated panels. The treatment with NMM compounds additionally led to reduced surface colonisation by staining fungi on the indirectly weathered reverse sides of the plywood panels.

Modifizierung von Buchenfurnieren mit N-Methylol-Melamin-Verbindungen zur Herstellung von Sperrholz: Natürliche Bewitterung

Zusammenfassung Buchenfurniere (*Fagus sylvatica* L.) wurden mit zwei auf N-Methylol-Melamin (NMM) basierenden Formulierungen behandelt: (1) NMM-Lösung (NMM-1, 10 % Feststoffgehalt), (2) Fettsäure-modifizierter NMM-Dispersion mit Paraffin (mit einem Aluminiumsalz als Katalysator, mNMM-2, 5 % Feststoffgehalt). Fünf Furniere wurden mit Phenol-Formaldehyd-Harz zu Sperrholz verklebt. Die Sperrholzproben wurden über einen Zeitraum von 18 Monaten gemäß EN 927-3 (2006) im Freiland exponiert.

Die Holzfeuchte der behandelten Sperrhölzer war während der Exposition im Vergleich zu den Platten aus wasserbehandelten Furnieren (Kontrollen) deutlich reduziert. Dies hatte eine höhere Formstabilität und ein geringeres Maß an Rissbildung und Delaminierung der behandelten Sperrhölzer zur Folge. Beschichtete, NMM-behandelte Sperrhölzer zeigten ein auffallend geringeres Maß an Verfärbung als die beschichteten Kontrollen. Diese Unterschiede zwischen behandelten, beschichteten Proben und beschichteten Kontrollproben waren bei den unbeschichteten Platten nicht so klar erkennbar. Die Behandlung mit NMM-Verbindungen führte zusätzlich zu einem geringeren Oberflächenbefall durch verfärbende Pilze auf den indirekt bewitterten Rückseiten der Sperrhölzer.

1 Introduction

When wood is exposed outdoors, above ground, it undergoes many complex processes such as photo-degradation, hydrolysis and leaching of cell wall polymers, swelling and shrinking, deformation as well as discoloration by blue stain fungi and moulds. The appearance of unprotected wood changes considerably after only few months of weathering exposure (Derbyshire and Miller 1981; Feist 1983; Sudiyani et al. 1999). As with solid wood, the surface of plywood undergoes photochemical degradation by solar radiation and discoloration by staining fungi; moreover plywood is more vulnerable to moisture changes than is solid

---

H.M. Trinh · H. Militz · C. Mai (✉)
Wood Biology and Wood Products, Burckhardt-Institute, Georg August University of Göttingen, Büsgenweg 4, 37077 Göttingen, Germany
e-mail: cmai@gwdg.de

wood due to the adhesive bonding between the veneer layers (Williams 2005). To protect plywood from deterioration due to weathering, the most common way is to prevent weathering factors from reaching the wood. Wood coatings provide good protection by partly or completely obstructing the light to reach the wood surface and excluding water from penetration (Xie 2005; Deka et al. 2007; Williams 1999).

When solid wood is directly exposed to weathering, the cyclic changes in wood moisture and its dimension are most pronounced at the wood surface. This results in surface tensile stresses whose magnitude depends on the moisture gradient between the surface and the interior layers (Feist 1983; Evans and Urban 2007). If these stresses exceed the strength of wood perpendicular to the grain, checks or cracks occur at the wood surface. Moreover, exposure to UV and visible light increases the tendency of wood to crack because photo-degradation weakens the wood surface and degrades its micro-structure (Evans 2008).

Likewise solid wood, unprotected plywood exhibits surface cracks in the early stage of weathering (Feist 1983). In addition, plywood contains micro-cracks on the veneer surface caused during processing when veneer is peeled or cut off the stem. The cycles of wetting and drying with subsequent swelling and shrinking magnify the micro cracks on veneer surfaces of plywood. The surface cracking could be inhibited by application of exterior wood finishes, however, surface cracks sometimes extend through the coating and lead to early coating failure (Williams 1999). Therefore, water repellent treatment might restrict surface cracking for both coated and uncoated plywood.

Delamination and deformation occur when plywood is exposed to weathering mainly due to cyclic changes of moisture content. The adjacent veneer layers of plywood are bonded in different grain directions with different shrinkage coefficients. Thus, mechanical stresses in the glue joint result from the differences in swelling and shrinking of the adjacent veneers under changes of moisture content. These stresses may develop and be great enough to rupture glue bond or wood veneers resulting in delamination and deformation of plywood (Vick 1999). It is known that beech wood exhibits extreme swelling and shrinking in tangential and radial directions which have negative effects on the durability of the bonding in beech plywood (Gryc et al. 2008). One approach to increase the dimensional stability of plywood in order to reduce cracking, delamination and deformation is to chemically modify the veneers (Dieste et al. 2009).

For many years, the treatment with N-methylol-melamine (NMM) compounds has been shown to bring about remarkable improvements of solid wood such as enhanced water repellence and dimensional stability, increased hardness, modulus of elasticity and bending strength (Deka and Saikia 2000; Gindl et al. 2004; Inoue et al. 1993). In addition, the treatment with water-based melamine increased the resistance of solid wood against wood destroying fungi (Lukowsky et al. 1999; Rapp and Peek 1996) and weathering degradation (Pittman et al. 1994; Rapp and Peek 1999). Melamine-treated wood exhibited reduced discoloration after accelerated weathering (Hansmann et al. 2006; Inoue et al. 1993) and greying after natural weathering (Nguyen et al. 2007; Pittman et al. 1994; Rapp and Peek 1999). It is assumed that the penetration of NMM molecules into the cell wall lessens UV-degradation and washing out of degradation products (Hansmann et al. 2006) as well as staining fungi colonisation (Rapp and Peek 1999).

Chemical modification of solid wood with another N-methylol compound, 1,3-dimethylol-4,5-dihydroxyethylene urea (DMDHEU), also improved the resistance towards weathering degradation (Xie 2005; Xie et al. 2008). DMDHEU-treatment stabilised the cell wall of pine wood and reduced surface erosion during weathering exposure. Water uptake and sorption during the exposure was reduced and treated panels displayed less cracking, roughness and deformation (cupping).

In this study, control and NMM-treated plywood, both uncoated and coated, were exposed to natural weathering in order to evaluate the influence of the veneer treatment on the outdoor performance.

2 Materials and methods

Methylated N-methylol-melamine (NMM-1) was Madurit MW 840/75 WA (Ineos Melamines, Frankfurt/Main, Germany). It was supplied as an aqueous stock solution with a solid content of ca. 75%. The fatty acid modified N-methylol-melamine dispersions containing paraffin (mNMM-2) was Phobotex VFN (Ciba, Basel, Switzerland). A commercial catalyst solution (Catalyst RB, Ciba, Basel, Switzerland) was used for the curing of Phobotex VFN. The phenol formaldehyde (PF) resin used for the bonding of veneers was Prefere 4976 (Dynea, Erkner, Germany).

2.1 Plywood production

Rotary cut beech (*Fagus sylvatica* L.) veneers measuring $1.5 \times 420 \times 420\ \text{mm}^3$ ($R \times L \times T$) were impregnated in an autoclave under vacuum (60 mbar) for 30 min and subsequently under pressure (12 bar) for 2 h with the following solutions: (1) N-methylol-melamine (NMM) solution (NMM-1, 10% solid content), (2) fatty acid modified NMM dispersions containing paraffin (mNMM-2, 5% solid content) with catalyst RB (1.7% of the commercial stock solution). Water impregnated veneers were used to produce control plywood. The impregnated veneers were pre-dried at 40°C to a moisture content of 3–8% and subsequently $160\ \text{g m}^{-2}$ phenolic

Table 1 Coating systems applied to test the natural weathering performance of plywood panels
Tab. 1 Beschichtungssysteme zum Test des Verhaltens der Sperrhölzer in der natürlichen Bewitterung

No.	Type	Coating system	Color	Binder	Solvent	Application	Wet amount (g/m^2)
1	Stain	Cetol WP 560/006	Brown	Acrylic	Water	Primer	72.8
		Cetol WF 950/006	Brown	Acrylic	Water	Top coat	159.2
2	Paint	Rubbol WP 176	White	Acrylic	Water	Primer	78.5
		Rubbol WF 380	White	Acrylic	Water	Top coat	162.4
3	Stain	Novatech 006	Brown	Alkyd	Organic	Top coat	155.5

resin (Prefere 4976, Dynea, Erkner, Germany) was applied per veneer. Afterwards, 5-layer-plywood was produced in a hot press (130°C) at 1.5 N mm^{-2} pressure (10 min pressing time).

2.2 Natural weathering

Natural weathering was performed according to EN 927-3 (2006) using plywood panels of 7.5 × 100 × 375 mm^3 dimensions. The edges of the panels were sealed with the coating Wapex 660 (Akzo Nobel Decorative Coatings, Wunstorf, Germany). Per treatment, a group of four panels was uncoated, and three groups of four panels were coated (on the front face) with a paint or a stain (Akzo Nobel Decorative Coatings, Wunstorf, Germany) as shown in Table 1. The primers (one time) and the top coats (twice) were applied with a brush. After each coating step, the finishes were dried at room temperature. The amount of the freshly applied finish on each sample was recorded by weighing the finish can and the brush before and after each application. Then, all panels were stored in a climate chamber (65% RH, 20°C) for about two weeks to establish equilibrium moisture content. One panel of the four replicates per treatment was left in the climate chamber (65% RH, 20°C) as a reference. The other three replicates were placed on the weathering racks (facing to the south and inclined at 45° from the horizon) in the test field of the Wood Biology and Wood Products Department, Georg-August-University, Göttingen (Germany) for 18 months (from July 2007 to January 2009). Every 3 months during the exposure, the panels were weighed and the moisture content was related to the oven-dry weight of the panels before the weathering test. Afterwards, the panels were conditioned in a climate chamber (65% RH, 20°C) for about 2 weeks. Both sides of the panels were then scanned in an EPSON Expression 10000 XL (EPSON, Japan) scanner (300 dpi resolution) in order to evaluate the colour and (fungal) staining.

2.2.1 Surface appearance and colour measurement

The scanned surfaces (see above) were analyzed with Adobe Photoshop 7.0 (Adobe, USA) using the histogram function in Lab mode. The absolute colour change was calculated as follows:

$$\Delta E = \sqrt{(L_t - L_0)^2 + (a_t^* - a_0^*)^2 + (b_t^* - b_0^*)^2} \tag{1}$$

where, ΔE: the overall colour change; L_0, a_0^* and b_0^*: the CIE Lab values at the beginning of the weathering test; L_t, a_t^* and b_t^*: the CIE Lab values at an exposure time t (Ghosh et al. 2008).

Crack formation on the weathered surfaces was evaluated according to ISO 4628-4 (2003). The evaluation scale ranged from 0 to 5 (CR = 0: no cracks and CR = 5: dense pattern of cracks).

2.2.2 Colonisation by staining fungi

The scanning images of the reverse side of the panels were analyzed with an image analysis software GIMP 2.6.4 (GNU Image Manipulation Program) in a manner that the images were converted into black and white. The percentage of the staining area was automatically calculated from the number of pixels.

3 Results and discussion

3.1 Macroscopic surface appearance

3.1.1 Surface appearance of the uncoated plywood panels

After 18 months of outdoor exposure, all uncoated plywood panels showed the typical grey discoloration of weathered wood. The formation of a uniform grey surface colour is attributed to the combined effect of photo-bleaching due to lignin decay and colonisation of the bleached surface by staining fungi such as *Aureobasidium pullulans* (Sell and Leukens 1971; Feist 1983; Schoeman and Dickinson 1997; Xie et al. 2008; Evans 2008). The treatment of the veneers with both NMM formulations did not significantly change the colour of the resulting plywood panels. After weathering, the controls and the mNMM-2 treated panels displayed a dark grey colour, while the NMM-1-treated panels showed a lighter grey. It was previously shown that wood panels

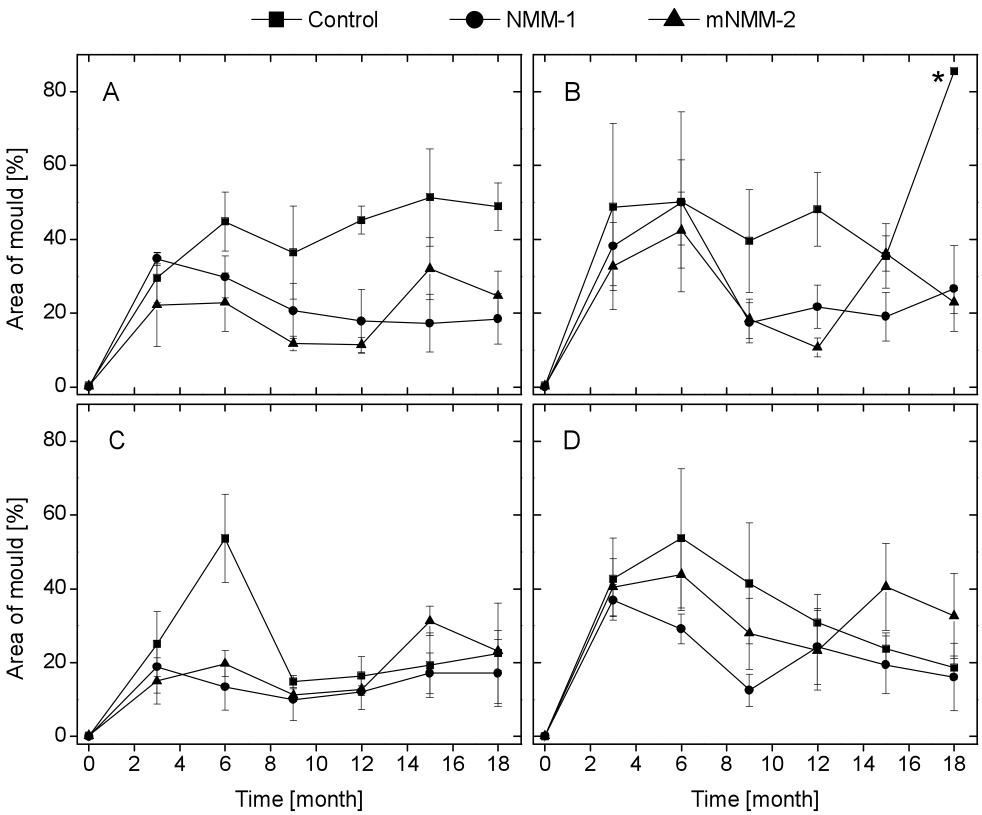

Fig. 1 Area proportion of mould colonization on reverse surfaces of weathered plywood panels after 18 months of weathering. (**A**) acrylic stain WF 950; (**B**) acrylic paint WF 380; (**C**) alkyd stain Novatech 006; (**D**) uncoated (*only one panel left) ($n = 3$, mean values ±SD)

Abb. 1 Flächenanteil des Schimmelpilzbefalls auf den Rückseiten der bewitterten Sperrholzproben nach 18 Monaten Bewitterung. (**A**) Acryllasur WF 950; (**B**) Acryllack WF 380; (**C**) Alkydlasur Novatech 006; (**D**) unbeschichtet (*nur eine Platte übrig) ($n = 3$, Mittelwert ±SD)

treated with mNMM-2 at higher solid content (approx. 3 times) were considerably less discoloured than the control panels (Nguyen et al. 2007) and those used in this study. It was, however, found that the relatively great size of the emulsion particles of mNMM-2 limited the penetration into the deeper parts of the wood and caused an aggregation of the solid parts on the surface. For this reason mNMM-2 was used in a low concentration in this study. Treatment with both NMM formulations also reduced cracking and deformation of the upper veneer; this was more pronounced with NMM-1-treated plywood (see below).

The reverse, indirectly weathered sides of all plywood panels exhibited inhomogeneous staining through mould fungi. The degree of colonisation decreased in the succession controls, mNMM-2 to NMM-1-treated plywood. The colonisation by moulds was evaluated as percentage of mould area (Fig. 1). The area of mould growth did not steadily increase over the exposure time but even decreased due to varying availability of moisture.

In the case of the uncoated panels NMM-treatment caused a moderate reduction in mould colonisation (Fig. 1D). This might be explained by the fact that less rain water penetrated from the weathered surface through the plywood so that the reverse sides of the treated panels were dryer. NMM-1 tended to be somewhat more efficient in reducing mould colonisation, because of the higher treatment concentration and the lower degree surface cracking.

It was previously shown that the indirectly weathered sides of solid wood panels treated with DMDHEU (Xie et al. 2008), with NMM-1 (Rapp and Peek 1999) or with nNMM-2 (Nguyen et al. 2007) were colonised by moulds in a minor degree than the control panels. The degree of mould reduction caused by NMM-treatment on plywood panels was lower than that observed for solid wood. The same tendency was found when the weathered sides of the panels were coated (Fig. 1A–C). Obviously, the four glue lines of phenolic resin between the veneers acted as moisture barriers and limited the penetration of moisture through the panels so that the effect of NMM-treatment or coating was less distinctive as with solid wood.

3.1.2 Surface appearance of the coated plywood panels

The stain-coated NMM-treated panels revealed considerably less discoloration and cracking than the coated control panels. The alkyd-based stain Novatech 006 and the acrylic white paint WF 380 revealed the same tendency (not shown). Likewise in the case of uncoated plywood, NMM-1-treatment imparted the highest surface stability. The strong crack formation in the coatings of the control plywood obviously resulted in a high degree of surface colonisation by staining fungi. The staining fungi grew along the cracks developed in the coating film of both control and treated panels. However, the fungal staining was denser in the cracks of the control panels than of the treated ones.

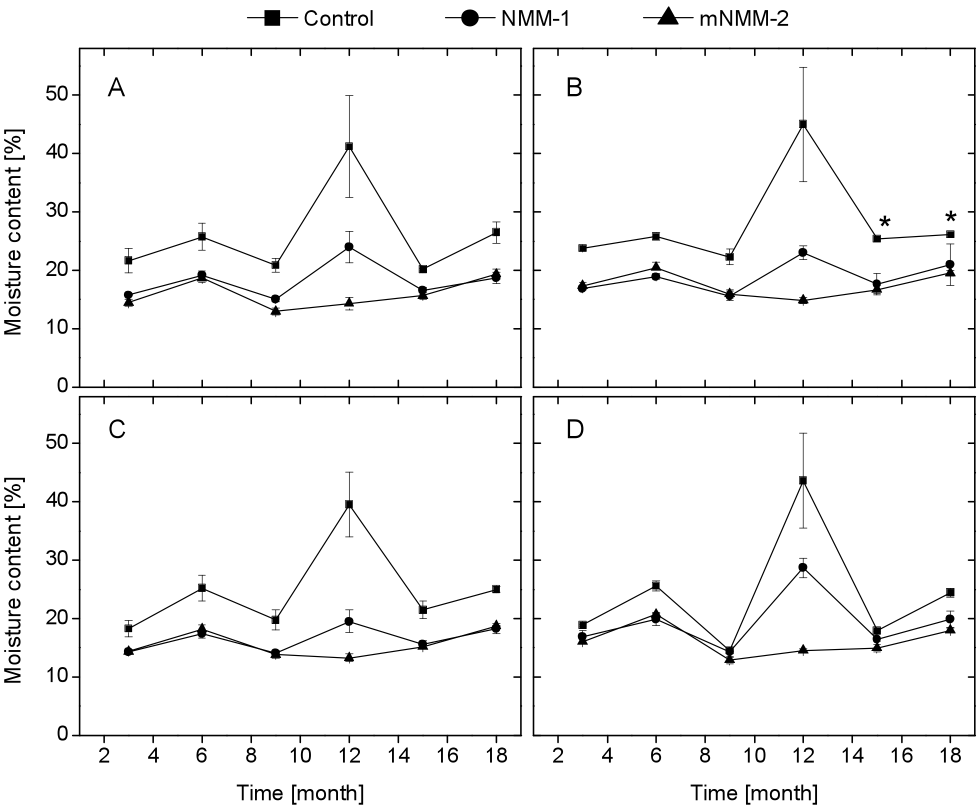

Fig. 2 Moisture content of the plywood panels during the course of weathering. (**A**) acrylic stain WF 950; (**B**) acrylic paint WF 380; (**C**) alkyd stain Novatech 006; (**D**) uncoated (*only one panel left) ($n = 3$, mean values ±SD)
Abb. 2 Holzfeuchte der Sperrhölzer im Laufe der Bewitterung. (**A**) Acryllasur WF 950; (**B**) Acryllack WF 380; (**C**) Alkydlasur Novatech 006; (**D**) unbeschichtet (*nur eine Platte übrig) ($n = 3$, Mittelwert ±SD)

Photo-degradation of lignin at the interface between the wood surface and the coating was indicated to weaken the adhesion causing flaking of the coating film (Evans 2008). Flaking, however, was neither observed on the control panels nor on the NMM-treated panels after 18 months of weathering.

3.2 Moisture content

Water accelerates surface degradation by washing out degradation products; furthermore changes in the moisture content generate stresses leading to checking and splitting (Evans and Banks 1988; Feist et al. 1991; Sudiyani et al. 1999; Williams and Feist 1985). Thus, water plays an important role in weathering degradation because it facilitates light penetrate into accessible regions and opens up inaccessible regions of the cell wall for photo-oxidation (Evans 2008; Hon 2001). Hence, hydrophobation of the surface and reduction in moisture content during the weathering exposure may improve weathering resistance for the treated plywood.

During the course of weathering, the control panels always displayed higher moisture content and higher fluctuation between the wet and dry periods than the treated ones, regardless of the surface protection system (Fig. 2). The maximum moisture content of the controls reached 49.1%, whereas that of the treated panels was 28.7% (uncoated NMM-1 treated panels). The maximum fluctuation in moisture content amounted up to approx. 30% in the controls, while it was only 11% in the treated panels (uncoated NMM-1 treated panels). Treatment with nNMM-2 resulted in lower moisture content than NMM-1-treatment during the weathering exposure. These findings are in agreement with the reduction in water uptake observed in a laboratory submersion test (Trinh et al. 2010) and are attributed to the stronger water repellent effect of the fatty acid modified melamine derivative and paraffin in nNMM-2 as compared to NMM-1.

At low ambient humidity, the plywoods treated with NMM-1 and mNMM-2 displayed similar moisture contents; at higher humidity (e.g., 12 months of weathering) mNMM-2 was more effective in reducing moisture uptake. It is assumed that the low moisture content at low RH is due to sorption of water vapour, while the high moisture content is due to capillary uptake of rain water. Particularly nNMM-2 acts as a repellent for liquid water but is hardly able to reduce moisture sorption because it was used in low concentrations and does not penetrate the cell wall. NMM-1 should have a somewhat stronger effect on moisture sorption due to partial cell wall penetration but this is hardly recognisable in the results (Fig. 2). Rapp and Peek (1999) also reported on a low efficiency of NMM-treatment with regard to the reduction in moisture content.

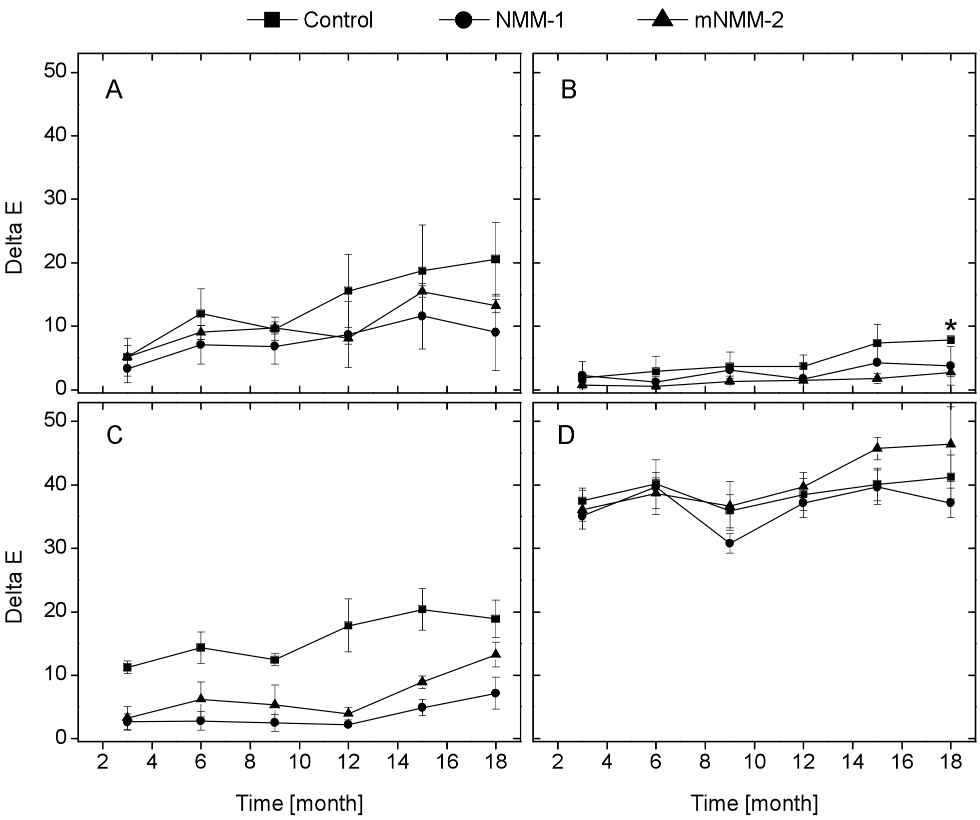

Fig. 3 Overall colour change (ΔE) of the plywood panels during 18 months of weathering. (**A**) acrylic stain WF 950; (**B**) acrylic paint WF 380; (**C**) alkyd stain Novatech 006; (**D**) uncoated (*only one panel left) ($n = 3$, mean values ±SD)
Abb. 3 Gesamtfarbänderung (ΔE) der Sperrhölzer im Laufe einer 18-monatigen Bewitterung. (**A**) Acryllasur WF 950; (**B**) Acryllack WF 380; (**C**) Alkydlasur Novatech 006; (**D**) unbeschichtet (*nur eine Platte übrig) ($n = 3$, Mittelwert ±SD)

3.3 Discoloration of weathered surfaces

The surface colour of the controls and the treated panels was not stable over the exposure time; especially after 9–12 months of weathering, the overall colour changes (ΔE) increased regardless if the panels were coated or uncoated (Fig. 3). The discoloration of panels (ΔE) was significantly reduced through the application of the coatings. Paints provide higher protection levels to wood than stains because they contain more pigments and form coating films which totally block the UV radiation (Williams 1999, 2005; Deka et al. 2007). As a consequence, the discoloration of the plywood panels coated with the stains WF 950 (acrylic) and Novatech 006 (alkyd) was much stronger than that of the plywood panels coated with the acrylic paint WF 380 (Fig. 3A–C). The discoloration of the stain-coated panels (WF 950, Novatech 006) displayed remarkable differences between the controls and the treated plywood, while these differences were not clearly observed in the uncoated panels. These results coincide with those from outside weathering tests with DMDHEU modified plywood (Dieste et al. 2009). The higher colour stability of the coated NMM-treated panels is attributed to a lower degree of fungal staining. In both cases of the coated and uncoated panels, the NMM-1 treated panels generally revealed less discoloration than the mNMM-2 treated ones even though the moisture content of the mNMM-2 treated plywood was lower during the exposure.

Table 2 Visual cracking evaluation (CE) of weathered surfaces of plywood panels after 18 months of weathering; CE = 0: no cracking; CE = 1: very few cracks; CE = 2: a few cracks permitted; CE = 3: a moderate amount of cracks permitted; CE = 4: a considerable amount of cracks permitted; CL = 5: dense pattern of cracks (according to ISO 4628-4)
Tab. 2 Visuelle Rißbewertung (CE) der bewitterten Oberflächen von Sperrhölzern nach 18 Monaten Bewitterung; CE = 0: keine Risse; CE = 1: einzelne Risse; CE = 2: wenig Risse; CE = 3: mäßig viele Risse; CE = 4: viele Risse; CL = 5: sehr viele Risse (nach ISO 4628-4)

Treatment	WF 950	WF 380	Novatech 006	Uncoated
Control	4	3	4	5
NMM-1	1	1	2	3
mNMM-2	2	1	2	3

3.4 Surface cracking

Cracking of coated and uncoated panels was reduced by both NMM formulations as compared to the controls but it was not completely prevented (Table 2). The uncoated control panels displayed the highest density of large cracks, while the uncoated NMM-1 and mNMM-2-treated panels exhibited fewer and smaller cracks. Studies on weathering of solid wood reported on reduction of cracking for formulations comparable to NMM-1 (Hansmann et al. 2006) and nNMM-2 (Nguyen et al. 2007). Of all coating systems, the paint (WF 380) showed the best limitation of cracking for

Table 3 Number of delaminated plywood panels (per total of 3 plywood panels/ coating/ treatment) over 18 months of weathering

Tab. 3 Zahl der delaminierten Sperrhölzer (von insgesamt 3 Sperrhölzern /Beschichtung/ Behandlung) über 18 Monate Bewitterung

Weathering time (months)		3	6	9	12	15	18
Stain-acrylic WF 950	Control	0	0	0	1	1	1
	NMM-1	0	0	0	0	0	0
	mNMM-2	0	0	0	0	0	0
Paint-acrylic WF 380	Control	0	0	0	1	2	2
	NMM-1	0	0	0	0	0	0
	mNMM-2	0	0	0	0	0	0
Stain-alkyd Novatech 006	Control	0	0	0	0	1	1
	NMM-1	0	0	0	0	0	0
	mNMM-2	0	0	0	0	0	0
Uncoated	Control	0	0	0	1	2	2
	NMM-1	0	0	0	0	0	0
	mNMM-2	0	0	0	0	0	0

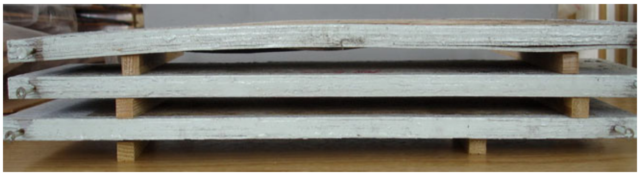

Fig. 4 Delamination and deformation of uncoated plywood panels after 18 months of weathering (*from top to bottom*: control, NMM-1 treated, mNMM-2 treated)

Abb. 4 Delaminierung und Deformation der unbeschichteten Sperrhölzer nach 18 Monaten Bewitterung (*von oben nach unten*: Kontrolle; 2: NMM-1-behandelt; 3: mNMM-2-behandelt)

both the treated and control panels. Only in one case (acrylic stain WF 950) NMM-1 was more effective than nNMM-2 in reducing cracking.

The reduction in cracking is primarily attributed to the increased dimensional stability of the NMM-treated panels, which reduces tensile stresses on the surface formed because of different degrees of swelling on the surface and subjacent layers. Higher dimensional stability caused by nNMM-2 is mostly due to the water repelling effect during the exposure. NMM-1, however, is additionally able to penetrate the cell wall and to reduce moisture sorption (Lukowsky 2002).

3.5 Delamination and deformation

Regardless of coated and uncoated panels, delamination of the control plywood started from the twelfth month of weathering exposure (Table 3). In contrast, the plywood treated with NMM-1 and mNMM-2 did not undergo any delamination and exhibited greater form stability after 18 months of weathering (Fig. 4). In general, application of the coatings resulted in less deformation due to weathering but the number of delaminated control panels was not reduced. NMM-1 imparted slightly higher form stability than mNMM-2 (not shown). The high stability towards deformation and delamination is attributed to the hydrophobing effect of both NMM-formulations which resulted in lower water uptake and thickness swelling (Trinh et al. 2010). In addition, NMM-1-treatment increased the bonding strength with a phenolic resin, while nNMM-2 strongly decreased it as compared to the control plywood (Trinh et al. 2010). In this study the hydrophobing effect of nNMM-2 and the high dimensional stability obviously offset the decrease in bonding with regard to delamination under weathering conditions.

4 Conclusion

The treatment of veneers with NMM-1 and mNMM-2 improved the weathering performance of plywood produced thereof as compared to those from control veneers. The treatments reduced discoloration and fungal staining as well as cracking, deformation and discoloration of uncoated and coated plywood panels during 18 month outdoor weathering conditions. These effects are mainly attributable to the reduction in water uptake, which increases dimensional stability.

The positive effects of NMM-treatment on the weathering performance of solid wood have previously been shown by several authors (Rapp and Peek 1999; Nguyen et al. 2007; Pittman et al. 1994; Hansmann et al. 2006). Problems, however, might arise due to inhomogeneous distribution of NMM in solid wood. During drying and curing the aqueous NMM is likely to migrate in the capillary tubes from the core to the surface. The resulting inhomogeneous distribution of rigid NMM resin in wood might cause additional stresses resulting in crack formation during longer periods of outdoor exposure. These problems of solid wood in bigger dimensions, however, can be avoided by modifying veneers in a hot press because the possibility of gradient formation is limited due to the low thickness. Thus, NMM-treated plywood panels exhibit a high potential for outside application in hazard class 3 according to the European standard EN 335 (2006).

References

Deka M, Saikia CN (2000) Chemical modification of wood with thermosetting resin: effect on dimensional stability and strength property. Bioressource Technol 73(2):179–181

Deka M, Tomažič M, Petrič M (2007) Photo-degradation of modified and non-modified wood, coated with water borne acrylic coatings during artificial light exposure. In: Proceedings of the international research group on wood preservation. Document No: IRG/WP 07-30416

Derbyshire H, Miller E (1981) The photodegradation of wood during solar irradiation. Holz Roh- Werkst 39(8):341–350

Dieste A, Krause A, Bollmus S, Kloeser L, Militz H (2009) Beech plywood modified with DMDHEU: anti-swelling efficiency, mechanical properties, gluing ability and protection against weathering discoloration. In: Proceedings of the 4th international symposium on veneers processing and products, Espoo, Finland, pp 243–250

EN 335 (2006) Durability of wood and wood-based products. Definition of use classes

EN 927-3 (2006) Paints and varnishes—coating materials and coating systems for exterior wood—Part 3: Natural weathering test

Evans PD (2008) Weathering and photoprotection of wood. In: Schultz TP, Militz H, Freeman MH, Goodell B, Nicholas DD (eds) Development of commercial wood preservatives: efficacy, environmental, and health issues. American Chemical Society, Washington, pp 69–119

Evans P, Banks W (1988) Degradation of wood surfaces by water changes in mechanical properties of thin wood strips. Holz Roh- Werkst 46(11):427–435

Evans P, Urban K (2007) The effect of solar radiation on the surface checking of wood. In: Proceedings of the international research group on wood preservation. Document No: IRG/WP 07-40356

Feist WC (1983) Weathering and protection of wood. In: Proceedings of the 79th annual meeting of the American Wood Preserver's Association, Kansas, USA

Feist W, Rowell RM, Ellis W (1991) Moisture sorption and accelerated weathering of acetylated and methacrylated aspen. Wood Fiber Sci 23(1):128–136

Ghosh SC, Militz H, Mai C (2008) Natural weathering of Scots pine (*Pinus sylvestris* L.) boards modified with functionalised commercial silicone emulsions. Bioressource Technol 4:659–673

Gindl W, Hansmann C, Gierlinger N, Schwanninger M, Hinterstoisser B, Jeronimidis G (2004) Using a water-soluble melamine-formaldehyde resin to improve the hardness of Norway spruce wood. J Appl Polym Sci, Appl Polym Symp 93(4):1900–1907

Gryc V, Vavrčík H, Gomola Š (2008) Selected properties of European beech (*Fagus sylvatica* L.). J For Sci 54(9):418–425

Hansmann C, Deka M, Wimmer R, Gindl W (2006) Artificial weathering of wood surfaces modified by melamine formaldehyde resins. Holz Roh- Werkst 64(3):198–203

Hon DN-S (2001) Weathering and photochemistry of wood. In: Hon DN-S, Siraishi N (eds) Wood and cellulosic chemistry. Dekker, New York, pp 513–546

Inoue M, Ogata S, Nishikawa M, Otsuka Y, Kawai S, Norimoto M (1993) Dimensional stability, mechanical-properties, and color changes of a low-molecular-weight melamine-formaldehyde resin impregnated wood. Mokuzai Gakkaishi 39(2):181–189

ISO 4628-4 (2003) Paints and varnishes—evaluation of degradation of coatings—designation of quantity and size of defects, and of intensity of uniform changes in appearance—Part 4: Assessment of degree of cracking

Lukowsky D (2002) Influence of the formaldehyde content of water-based melamine formaldehyde resins on physical properties of Scots pine impregnated therewith. Holz Roh- Werkst 60:349–355

Lukowsky D, Büschelberger F, Schmidt O (1999) In situ testing the influence of melamine resins on the enzymatic activity of basidiomycetes. In: Proceedings of the international research group on wood preservation. Document No: IRG/WP 99-30194

Nguyen HM, Militz H, Mai C (2007) Protection of wood for above ground application through modification with a fatty acid modified N-methylol/paraffin formulation. In: Proceedings of the international research group on wood preservation. Document No: IRG/WP 07-40378

Pittman CU, Kim MG, Nicholas DD, Wang LC, Kabir FRA, Schultz TP, Ingram LL (1994) Wood enhancement treatments 1. Impregnation of Southern yellow pine with melamine-formaldehyde and melamine-ammeline-formaldehyde resins. J Wood Chem Technol 14(4):577–603

Rapp AO, Peek RD (1996) Melamine resins as preservatives—results of biological testing. In: Proceedings of the international research group on wood preservation. Document No: IRG/WP 96-40061

Rapp AO, Peek RD (1999) Melaminharzimprägniertes sowie mit Wetterschutzlasur oberflächenbehandeltes und unbehandeltes Vollholz während zweijähriger Freilandbewitterung. Holz Roh- Werkst 57(5):331–339

Schoeman MW, Dickinson DJ (1997) Growth of *Aureobasidium pullulans* on lignin breakdown products at weathered wood surfaces. Mycologist 11:168–172

Sell J, Leukens U (1971) Untersuchungen an bewitterten Holzoberflächen—2. Mittlg.: Verwitterungserscheinungen an ungeschützten Hölzern. Holz Roh- Werkst 29:23–31

Sudiyani Y, Tsujiyama S, Imamura Y, Takahashi MMK, Kajita H (1999) Chemical characteristics of surfaces of hardwood and softwood deteriorated by weathering. J Wood Sci 45(4):348–353

Trinh HM, Militz H, Mai C (2010) Modification of beech veneers with N-methylol melamine compounds for the production of plywood. Eur J Wood Prod (submitted)

Vick CB (1999) Adhesive bonding of wood materials. In: Wood handbook. Wood as an engineering material, Forest Products Laboratory, Department of Agriculture, Forest Service, US, pp 9/1–9/24

Williams RS (1999) Finishing of wood. In: Wood handbook. Wood as an engineering material, Forest Products Laboratory, Department of Agriculture, Forest Service, US, pp 15/1–15/37

Williams RS (2005) Weathering of wood. In: Rowell RM (ed) Handbook of wood chemistry and wood composites. CRC Press, Boca Raton, pp 139–211

Williams RS, Feist WC (1985) Water repellents and water-repellent preservatives for wood. General Technical Report FPL-GTR-109, Forest Products Laboratory, Department of Agriculture, Forest Service, US

Xie Y (2005) Surface properties of wood modified with cyclic N-methylol compounds. PhD thesis, Wood Biology and Wood Technology Institute, Georg–August University, Göttingen, Germany

Xie Y, Krause A, Militz H, Mai C (2008) Weathering of uncoated and coated wood treated with 1,3-dimethylol-4,5-dihydroxyethyleneurea (mDMDHEU). Holz Roh- Werkst 66:455–464