Christian R. Welzbacher, Christian Brischke, Andreas O. Rapp, Silvia Koch, Sabine Hofer

Performance of thermally modified timber (TMT) in outdoor application – durability, abrasion and optical appearance

Ponašanje termički modificiranog drva u vanjskim uvjetima primjene – trajnost, abrazija i izgled

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ABSTRACT • *Thermally modified timber (TMT) is increasingly offered in Europe as an alternative to preservative treated timber. TMT durability in field tests as well as its moisture sorption behaviour in façade application was determined so as to consider its suitability for outdoor use. Additionally, abrasion and crack-formation of TMT deckings were examined and the optical appearance of a TMT façade was evaluated after 5 years of service. After 7.5 years exposure in ground contact, the various TMT materials tested were classed as "slightly durable" to "not durable" whereas the classification in above ground exposure was "very durable" to "moderately durable", which was in line with the reduced moisture sorption of TMT in weathered application. Moreover, the TMT-decking showed less abrasion and crack-formation compared to references, though the TMT façade revealed considerable discoloration by weathering. Hence, the suitability of TMT for above ground use is suggested, but a surface treatment is obligatory if discoloration is objectionable.*

Key words: *blue stain, cracks, decking, façade, weathering*

SAŽETAK • *Termički modificirano drvo (TMT) sve se više nudi u Europi kao alternativa kemijski zaštićenom drvu. Za ocjenu prikladnosti TMT-a za vanjsku upotrebu ispitivana je biološka trajnost u vanjskim uvjetima, kao i sorpcija vode u elementima fasade. Dodatno je ispitivana otpornost na abraziju i nastajanje pukotina u TMT podovima, te je napravljen vizualni pregled TMT fasade nakon petogodišnje upotrebe. Nakon 7,5 godina izloženosti u dodiru s tlom, različiti TMT materijali ocijenjeni su kao "slabo otporni" do "neotporni" dok su ocjene tog istog materijala za izlaganje iznad tla bile "vrlo otporno" do "srednje otporno". Dobivene su ocjene, u skladu sa smanjenom sorpcijom vode TMT materijala u vanjskoj upotrebi. Štoviše, TMT podovi pokazali su manju abraziju i pukotine od referentnog drva, iako su TMT elementi fasade pokazali veću diskoloraciju uzrokovanu abiološkom razgradnjom. Dakle, TMT je u vanjskim uvjetima i iznad tla preporučljiv za upotrebu, ali uz obveznu površinsku obradu ako se želi izbjeći diskoloracija.*

Ključne riječi: *plavilo, pukotine, polaganje podova, fasade, abiološka razgradnja*

[1] Authors are Associate Professor, Associate Professor and Professor at Faculty of Architecture and Landscape Sciences, Leibniz University Hannover, Hannover, Germany. [2]Author is Wood Science Graduate, Alte Poststraße 32, D 53721 Siegburg, Germany. [3]Author is Wood Science Graduate, Billhorner Mühlenweg 13 b, D 20539 Hamburg, Germany.

[1] Autori su, redom, izvanredni profesor, izvanredni profesor i profesor Fakulteta arhitekture i uređenja krajobraza, Sveučilišta Leibniz u Hannoveru, Hannover, Njemačka. [2]Autorica je diplomirana inženjerka drvne tehnologije, Alte Poststraße 32, D 53721 Siegburg, Germany. [3]Autorica je diplomirana inženjerka drvne tehnologije, Billhorner Mühlenweg 13 b, D 20539 Hamburg, Germany.

1 INTRODUCTION
1. UVOD

The ability of thermal modification processes to improve the resistance of wooden products against fungal decay has been intensively investigated and promoted in recent years (Syrjänen and Kangas, 2000; Boonstra and Tjeerdsma, 2006; Del Menezzi and Tomaselli 2006). On account of the increased durability of thermally modified timber (TMT) compared to untreated material, its application above ground in use class 3 (EN 335-1, 2006) has often been recommended (i.a. Jämsä and Viitaniemi, 2001; Wienhaus, 1999). On the other hand, the applicability of TMT for use in ground contact (use class 4, EN 335-1, 2006) is still a matter of controversial discussion, because TMT is frequently classed as "very durable" to "durable" (durability class 1-2, EN 350-2, 1994) in laboratory tests (e.g. Boonstra and Doelman, 1999; Tjeerdsma *et al,* 2000), which would in theory allow an application in soil contact (EN 460, 1994). Additionally, various industrial suppliers promote their TMT products with unlimited suitability for use in ground contact, which also emphasizes the uncertainty of consumers.

However, besides typical applications in use class 3 like claddings and façades, TMT is mostly used for horticultural products, e.g. wooden decks and floorings. Concerning these non- or less-load bearing applications, the resistance to abrasion becomes the decisive mechanical property of the material used, since numerous authors referred to an increase in brittleness and occurrence of splinters and flake offs compared to untreated wood (*i.a.* Jämsä and Viitaniemi, 2001; Militz, 2000).

Alongside durability and mechanical properties, the optical appearance of TMT in use is increasingly spotlighted by consumers, because the brownish color of uncoated TMT is non-stable against UV irradiation (Sailer *et al,* 2000; Junghans and Niemz, 2005) and TMT exhibits discoloration and staining in weathered exposure.

This paper presents the results of field tests after 7.5-year exposure in use class 3 and 4, results regarding the moisture sorption behaviour of TMT in façade application as well as the outcome of abrasion tests and visual observations regarding the optical performance of a TMT-façade after 5 years in service in order to contribute to the discussion on the suitability of commercially available TMT for outdoor application.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Moisture sorption behaviour of TMT façade boards
2.1. Ponašanje TMT elemenata fasade s obzirom na sorpciju vode

Determination of moisture behaviour in weathered application was performed with boards of 500x122x22 mm³ from European larch heartwood (*Larix decidua* Mill.), Scots pine sapwood (*Pinus sylvestris* L.), Norway spruce sapwood (*Picea abies* Karst.) and Oil-Heat-treated spruce sapwood (220°C, 1h). These materials (*n*=9) were mounted with stainless screws as weather boarding on a house façade in East, West and South orientation in Kiel, North-Germany, in 9 different locations in the year 2000 (Figure 1).

Polyamide coated stainless steel cables as electrodes were glued in the reverse side of the boards with graphite containing glue mixtures according to Brischke *et al.* (2008). The wood moisture content (MC) was determined and recorded daily over a period of one year (April 2000 to April 2001) by measuring the electrical resistance, as described by Pöhlmann (2001).

In 2007, the boards were removed from the façade and were exposed freely suspended to natural weathering at Hamburg University in Hamburg-Lohbrügge for a period of 4 months, from March 2007 to July 2007. The MC of specimens was measured gravimetrically during this exposure.

2.2 Durability tests
2.2. Testovi biološke otpornosti

Field trials in soil contact and above ground were installed in 2001 to examine the durability of the various TMT materials (Table 1) in differently severe exposure conditions.

Figure 1 East and South-West orientation of the house facade in Kiel; Arrows point to the location of TMT boards with glued-in electrodes for long-term moisture recording
Slika 1. Istočno i jugozapadno pročelje kuće u Kielu: strelice pokazuju mjesta promatranih TMT elemenata fasade s ugrađenim elektrodama za dugotrajno praćenje sadržaja vode u drvu

Table 1 Abbreviations in tables and figures (Abbr.), corresponding to wood species, process description and supplier of the thermally modified material
Tablica 1. Kratice u tablicama i slikama koje odgovaraju vrsti drva, postupku modifikacije i dobavljaču (proizvođaču) termički modificiranog drva

Abbreviation *Kratica*	**Wood species** *Vrsta drva*	**Modification process** *Postupak modifikacije*	**Supplier** *Dobavljač (proizvođač)*
Plato	*Picea abies* Karst.	PLATO process	Plato Hout B.V., Netherlands
Thermowood	*Pinus sylvestris* L.	Thermowood process	Kestopuu Oy, Finland
NOW	*Pinus maritima* Mill.	Retification process	S.A. NOW, France
OHT	*Pinus sylvestris* L.	Oil-Heat process*	Menz Holz, Germany

* Rapeseed oil-retention was minimized to less than 5 kg/m³ / *Retencija repičina ulja svedena je na minimum (manje od 5 kg/m³).*

The number of replicates was *n*=20 for each test set-up, the dimension of the specimens was 500x50x25 mm³ (except NOW: 500x50x20 mm³). According to EN 252 (1990) the samples for field tests in ground contact were planted in the field at the Federal Research Centre for Forestry and Forest Products, Hamburg at a distance of 30 cm to each other. The durability of the different materials above ground in use class 3 (EN 335–1, 2006) was tested using the double layer test method according to Augusta and Rapp (2005), in which samples were shifted by one sample half to create an artificial water trap between both horizontal layers.

Decay on samples from field tests in use class 4 and 3 was determined yearly according to EN 252 (1990) using the five step rating scheme, which classifies depth and distribution of decay (0=sound, 1=slight attack, 2=moderate attack, 3=severe attack, 4=failure). These decay ratings were taken as basis to determine the durability. According to EN 252 (1990) x-values are used to calculate the durability based on the mean lifetime. Since the mean lifetime was not yet obtained for all tested materials after 7.5 years, the durability was calculated as the quotient of the decay rate of the controls and the decay rate of the material tested (durability factor *f*), as shown in equation 1 and 2.

$$decay\ rate = \frac{mean\ decay\ rating}{time\ of\ exposure} \quad (1)$$

$$durability\ factor\ f = \frac{decay\ rate_{\text{control}}}{decay\ rate_{\text{tested specimens}}} \quad (2)$$

Decay types were determined according to DIN CEN/TS 15083-2 (2005).

2.3 Abrasion tests
2.3. Testovi abrazije

For the abrasion tests, commercially heat treated beech (*Fagus sylvatica* L., Thermowood, 230°C for 4h) was applied besides beech controls and larch heartwood (*Larix decidua* L.), which is a typical softwood species for decking applications. Heat treated beech was used in this study, since this mechanically strong and abrasion-resistant European hardwood species with improved durability and dimensional stability by the thermal modification is increasingly used as decking material to substitute tropical timber. Two tests were performed to characterize the abrasion performance: the “Shaker” test according to Brischke *et al.* (2006) and the Taber abraser test according to DIN EN 438-2 (1992).

The resistance to abrasion after the Shaker-method was determined as follows: 5 specimens of 35x10x10 mm³ were oven dried, weighed and put into a polyethylene flask of 0.5 l together with 400 g of steel balls of 6 mm diameter (Figure 2). The filled flasks were put in an overhead shaker and rotated with 28 min^{-1} for 72 hours. Afterwards, the specimens were cleansed of wood dust by air pressure, oven dried and weighed again to determine the abrasion in terms of mass loss. Five specimens were weighed together and gave one replicate, ten replicates were used.

The following modifications of the Taber abraser test were made in order to allow testing of solid wood: Specimens of 100x100x7 mm³ were prepared and conditioned in 20°C/65%RH. The tree rings of all specimens were oriented 45° to their cutting edges. After weighing and measuring the thickness at 4 points, the specimens (*n*=10) were clamped into the Taber abraser

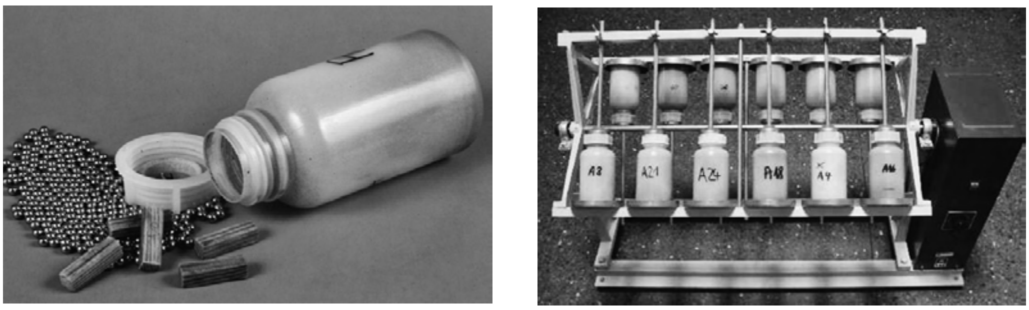

Figure 2 Polyethylene flask, steel balls, specimens and over-head shaker used in Shaker-tests
Slika 2. Polietilenske bočice, čelične kuglice, uzorci i uređaj za ispitivanje abrazije

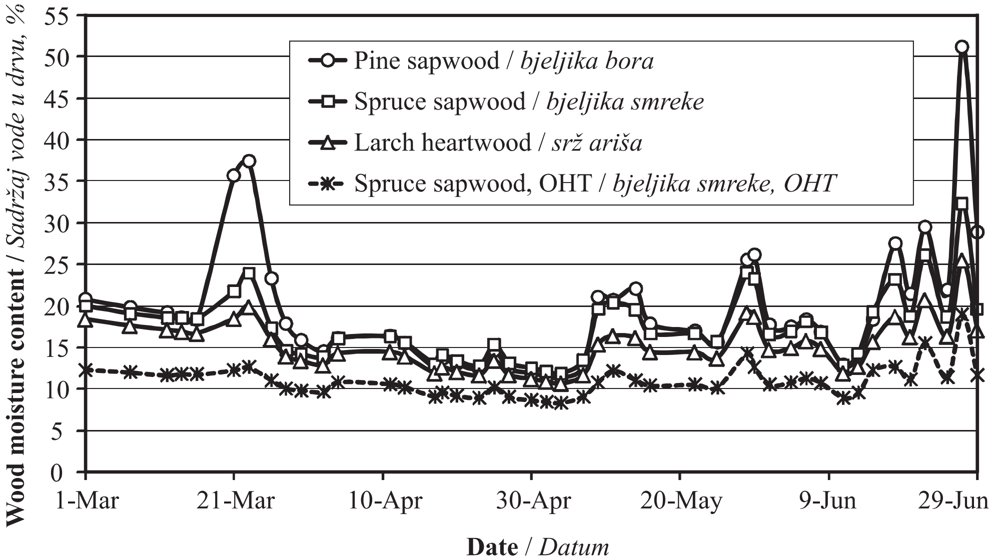

Figure 3 Course of gravimetrically determined wood moisture content of façade boards in vertical exposure (Hamburg, 2007)
Slika 3. Krivulja sadržaja vode vertikalno izloženih elemenata fasade određena gravimetrijski (Hamburg, 2007)

and were abraded with sanding paper S-42 with approx. 60 min^{-1} for 1000 rounds. Afterwards the mass loss and the decrease in thickness by abrasion were determined.

2.4 Optical appearance of a TMT façade in service
2.4. Izgled elemenata fasade od TMT materijala u upotrebi

The TMT in façade application was made out of unsorted pine (*Pinus sylvestris* L.) boards of 4500x140x28 mm³, thermally modified at 212°C for 2 h (Thermo-D, Stellac Oy, Mikkeli, Finland). Stainless steel screws were used to attach the TMT boards to the façade of the Technical Centre of the Fire Brigade in Beelitz-Heilstätten, Germany, with a façade area of approx. 1000 m². Additionally, TMT-gluelam (4500x100x70 mm³) was used as an accessible apron around the building.

The TMT-façade was built in 2002, the visual evaluation focusing on discoloration, formation of cracks, staining and decay was carried out after 5 years in service in July 2007.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Moisture behaviour during natural weathering
3.1. Sorpcija vode tijekom izlaganja vanjskim uvjetima

The evaluation of the daily recorded wood moisture content (MC) in 2001 clearly pointed to the reduced moisture induced risk for fungal decay of thermally modified timber: Oil-Heat-treated (OHT) spruce did not exceed a MC of 20% over the measuring period of one year (Table 2).

Table 2 Number of days below 15% and above 20% wood moisture content (MC) during 365 days of natural weathering; MC was determined electrically and recorded daily
Tablica 2. Broj dana u godini tijekom izlaganja vanjskim uvjetima, kada je TMT drvo imalo manje od 15 % i više od 20 % sadržaja vode: sadržaj vode (MC) mjeren je električki i svakodnevno je bilježen

Number of days *Broj dana*	**Pine sapwood** *Bjeljika bora*	**Spruce sapwood** *Bjeljika smreke*	**Larch heartwood** *Srž ariša*	**Spruce sapwood, OHT** *Bjeljika smreke termički modificirana u ulju*
< 15% MC	34	48	47	68
≥ 20% MC	194	131	119	0

Table 3 Number of days below 15% and above 20% wood moisture content (MC) during 121 days of natural weathering; MC was determined gravimetrically
Tablica 3. Broj dana tijekom 121-dnevnog izlaganja vanjskim uvjetima, kada je drvo imalo sadržaj vode niži od 15 % i viši od 20 %; sadržaj vode (MC) mjeren je gravimetrijski

Number of days *Broj dana*	**Pine sapwood** *Bjeljika bora*	**Spruce sapwood** *Bjeljika smreke*	**Larch heartwood** *Srž ariša*	**Spruce sapwood, TMT** *Bjeljika smreke termički modificirana u ulju*
< 15% MC	30	33	65	117
≥ 20% MC	64	30	4	0

Table 4 Percentage of occurrence of decay rating and prevailing decay types (of decayed samples) after 7.5 years of exposure in double layer tests
Tablica 4. Postotak pojavnosti ocjene razgrađenosti i prevladavajuća vrsta truleži na zaraženim uzorcima nakon 7,5 godina izlaganja u *double layer* testovima

Material *Materijal*	**Percentage of decay rating, %** *Pojavnost ocjene, %*					**Percentage occurrence of prevailing decay type** *Udio pojavnosti prevladavajuće truleži*		
	0	**1**	**2**	**3**	**4**	white rot	soft rot	white rot/ soft rot
Plato	10	30	30	25	5	28	17	55
Thermowood	10	10	45	35	0	80	0	20
NOW	55	25	15	5	0	67	0	33
OHT	60	40	0	0	0	75	0	25
Pine control *kontrolna borovina*	0	0	0	0	100	30	30	40

Table 5 Percentage of occurrence of decay rating and prevailing decay types (of failed samples) after 7.5 years of exposure in ground contact
Tablica 5. Postotak pojavnosti ocjene razgrađenosti i prevladavajuća vrsta truleži na zaraženim uzorcima nakon 7,5 godina izlaganja u dodiru s tlom

Material *Materijal*	**Percentage of decay rating, %** *Pojavnost ocjene, %*					**Percentage occurrence of prevailing decay type** *Udio pojavnosti prevladavajuće truleži*		
	0	**1**	**2**	**3**	**4**	white rot	soft rot	white rot/ soft rot
Plato	0	0	0	25	75	100	0	0
Thermowood	0	0	0	5	95	100	0	0
NOW	0	0	0	0	100	100	0	0
OHT	0	5	0	20	75	93	0	7
Pine control *kontrolna borovina*	0	0	0	0	100	10	35	55

Similar results were found in studies by Brischke (2003), where the weekly course of MC for Oil-Heat treated specimens and matched untreated controls was examined, showing that the alteration of the MC due to climate changes was less pronounced for the OHT materials going along with significantly lower amplitudes of the MC. However, these changes in moisture sorption behaviour of heat treated timber is explained by a lesser amount of moisture accessible hydroxyl groups of TMT compared to controls (Boonstra and Tjeerdsma 2006).

The gravimetric determination of MC of façade boards after 7 years in service showed, that the protective mechanism behind the increased durability of TMT, the reduced MC, was not changed by weathering impacts compared to its initial state (Figure 3).

The MC of OHT specimens was below 20% during the complete measuring period, whereas controls showed a significantly higher number of "wet days" above 20% MC (Table 3).

The improved moisture sorption properties in weathered application above ground clearly point to the suitability of TMT for façade application.

3.2 Decay rating and decay types in field tests
3.2. Ocjena biološke razgrađenosti i vrsta štetočinja u drvu u vanjskim uvjetima izlaganja

Decay was found at all TMT materials exposed in the double layer test set-up in use class 3 after 7.5 years. The prevailing type of decay at TMT in use class 3 was white rot and combinations of white and soft rot, whereas decay by brown rot was not found (Table 4).

Table 6 Provisional classes of natural durability (DC) calculated on the basis of the durability factor *f* after 7.5 years of exposure in use class 3 and use class 4
Tablica 6. Privremeni razredi biološke otpornosti (DC) izračunani na bazi čimbenika otpornosti (*f*) nakon 7,5 godina izlaganja u razredima upotrebe 3 i 4

Material *Materijal*	**Use class** *Razred upotrebe 3*	**Use class** *Razred upotrebe 4*
Plato	3	5
Thermowood	4	5
NOW	1	5
OHT	1	4
Pine control *kontrolna borovina*	5	5

Among the TMT materials, Thermowood and Plato samples exhibited the strongest decay with an average decay rating of 2.1 and 1.9, respectively, whereas NOW and OHT showed lower average decay ratings of 0.7 and 0.4. Pine sapwood controls failed completely after 7.5 years of exposure. In soil contact white rot was predominantly responsible for decay in the Hamburg test field, which has a high potential for white and soft rot (Table 5).

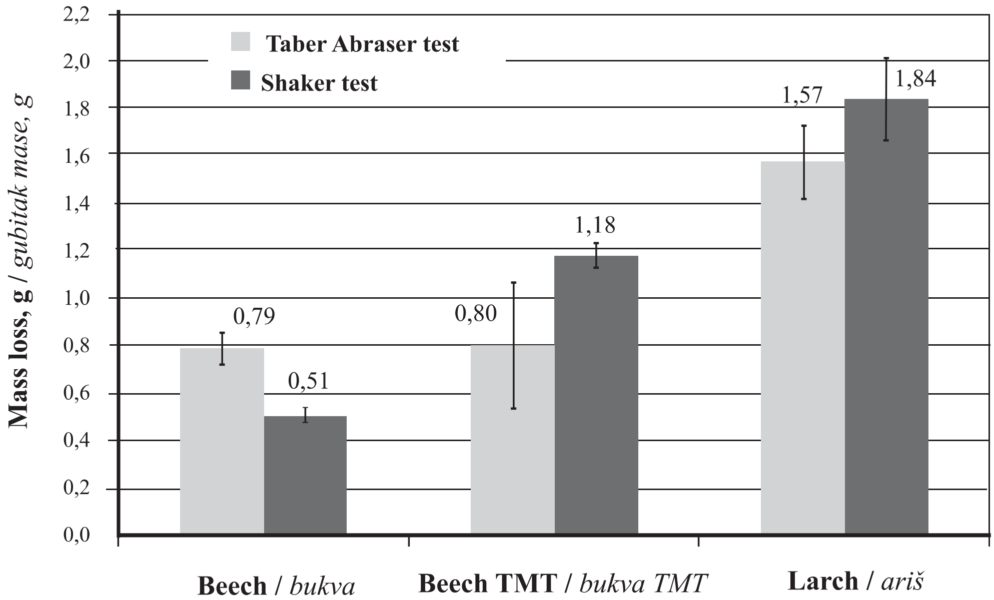

Figure 4 Mass loss by abrasion of beech, beech TMT and larch after laboratory abrasion tests
Slika 4. Gubitak mase uzoraka bukovine, termički modificirane bukovine i ariša zbog testiranja otpornosti na abraziju

The decay evaluation after 7.5 years in soil gave average decay ratings of 3.8 for Thermowood, 3.6 for NOW, 3.5 for Plato and 2.9 for OHT, whereas pine sapwood controls already failed after 5.5 years of exposure.

The dominant role of white rot decay on TMT in field tests was also reported by Augusta and Rapp (2005) and Westin *et al.* (2004), where TMT was tested in different fields. This clearly points on the weakness of TMT for white rot decay in real-life situations.

3.3 Durability classification
3.3. Razredba biološke otpornosti

The calculated classes of natural durability are listed in Table 6. It is obvious that the obtained durability classes differed significantly, dependent on the test situation above ground or in soil contact. In the double layer exposure (use class 3) OHT and NOW were classed as very durable (DC 1) classification, on the other hand Plato was moderately durable (DC 3) and Thermowood was only slightly durable (DC 4).

In contrast to the double layer test, soil contact tests resulted in a lower durability classification: OHT was slightly durable (DC 4), Thermowood, Plato and NOW were not durable (DC 5).

3.4 Abrasion of beech TMT
3.4. Abrazija termički modificirane bukovine

The results from the Taber abraser tests showed no difference in resistance to abrasion between beech and beech TMT, whereas a significantly higher mass loss by abrasion of beech TMT compared to controls was determined by the Shaker test (Figure 4).

However, in both cases the abrasion in terms of mass loss of beech TMT was significantly lower compared to larch heartwood, which represents a commonly used decking material. When comparing the typical damage caused by the Taber abraser and by the Shaker method (Figure 5a and 5b) with examples of worn wood in service (Figure 5c and 5d), it becomes obvious, that more realistic abrasion stress is induced by the Shaker method, e.g. occurrence of broken and rounded edges of specimens, as it is typical for decking boards.

3.5 Optical performance of a pine TMT façade
3.5. Vizualni rezultat fasade od TMT borovine

Machining of the pine TMT boards and installation of the façade was carried out without any problems in the year 2002. Neither the increased brittleness of TMT, nor the occasional occurrence of slight inner radial cracks due to the thermal modification process turned out to be restrictive.

After 5 years in service the weathered façade revealed a significantly changed appearance compared to its initial state: The façade areas, which were directed to the North and West, showed substantial graying. Discoloration due to chemical reactions, e.g. corrosion of the mounting material, was not found, since stainless steel screws were used exclusively.

Compared to the North and West orientation, which is the main weather side, the façades to the South and East showed less graying and retained a more or less brownish color but also showed substantial growth of blue stain in the sapwood of the pine TMT (Figure 6).

The distinctive occurrence of blue stain in TMT in outdoor exposure was also mentioned in the studies by Junghans and Niemz (2005), which stands in contrast to numerous laboratory examinations which did not reveal the susceptibility of TMT to blue staining fungi (Bächle *et al,* 2004; Boonstra *et al,* 2007). However, decay was not found after five years, although the façade construction exhibited no wood protection by construction since it was not covered by roof overhangs and ended straight at the ground in direct contact to splash water.

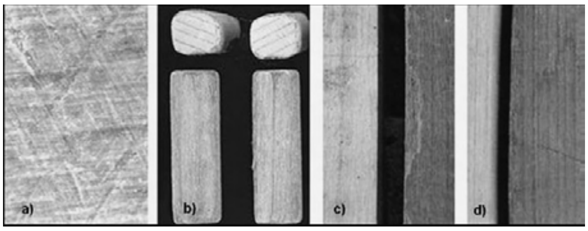

Figure 5 Abraded specimens: a) surface of a heat treated beech specimen after 1000 rounds in the Taber abraser (x10); b) heat treated specimens after 72 h abrasion in the shaker; c) broken edges of beech TMT after 3 month in service as decking; d) rounded edges of beech TMT after 3 month in service as decking

Slika 5. Uzorci nakon testiranja abrazivnosti: a) površina termički modificirane bukovine nakon 1000 okretaja uređaja (povećanje 10 puta); b) termički modificirani uzorci nakon 72 sata abrazije u uređaju; c) polomljeni bridovi TMT bukovine nakon 3 mjeseca upotrebe kao podne obloge; d) zaobljeni bridovi TMT bukovine nakon 3 mjeseca upotrebe kao podne obloge

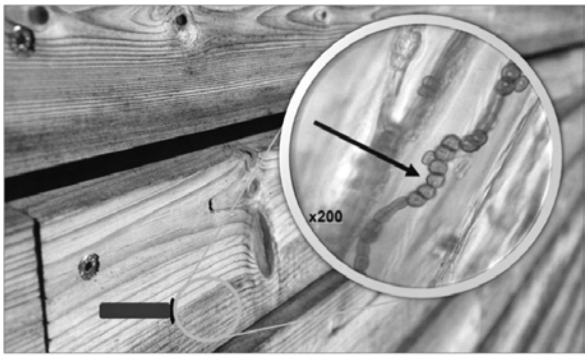

Figure 6 Staining of pine TMT sapwood by blue stain and microscopic identification of blue stain hyphae in tracheids (x200)

Slika 6. Plavilo TMT bjeljike bora prouzročeno gljivama plavila i mikroskopsko prepoznavanje hife gljiva plavila u traheidama (povećanje 200 puta)

Figure 7 Rounding of edges and break ups of TMT-gluelam in service

Slika 7. Zaobljenje rubova i otvaranje sljubnica TMT lamela u upotrebi

No remarkable formation of cracks by weathering or occurrence of flake offs was found, which points to the decreased dimensional changes of the façade due to reduced sorption of TMT. In contrast, the accessible TMT-gluelam apron showed substantial wear, caused by rounding of edges and break ups of the edges (Figure 7).

Here, the reduced mechanical strength (Bengtsson *et al,* 2002) and the decreased resistance to abrasion of TMT (Brischke *et al,* 2006) had a significant impact on the service ability in a heavy duty exposure.

4 CONCLUSIONS
4. ZAKLJUČCI

On the basis of 7.5 years field testing, TMT (independent from the treatment process and supplier) appears to be not suitable for in ground contact applications, whereas the suitability of TMT for out of ground usage in use class 3 was ascertained and is recommended. This recommendation is supported by results from abrasion tests and by the visual evaluation of the optical performance of a TMT façade after five years in service, which accounted for the increased dimensional stability and durability of TMT. However, TMT is subjected to restrictions with respect to its limited mechanical load capacity and regarding to discoloration by UV-irradiation and other weathering impacts (e.g. rain or hail).

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Zahvale

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Corresponding address:

Associate Prof. CHRISTIAN R. WELZBACHER, PhD

Leibniz University Hannover
Faculty of Architecture and Landscape Sciences
Institute of Vocational Sciences in the Building Trade (IBW)
Section Wood Technology
Herrenhäuser Str. 8
D – 30419 Hannover, Germany
e-mail: welzbacher@ibw.uni-hannover.de