Book of Abstracts

LIVING WITH MODIFIED WOOD

COST Action FP1407
Final Conference

Belgrade, Serbia
12-13 December 2018

University of Belgrade – Faculty of Forestry

COST Action FP1407

Understanding wood modification through an integrated scientific and environmental impact approach (ModWoodLife)

Living with modified wood

Final COST Action FP1407 International Conference

Belgrade, Serbia, 12 – 13th December 2018

Book of Abstracts

Editors: Goran Milić, Nebojša Todorović, Tanja Palija, Andreja Kutnar

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Local organiser preface

It is both a pleasure and a privilege for the Department of Technologies, Management and Design of Furniture and Wood Products, Faculty of Forestry to host the final conference of COST Action FP1407. This honour has given us an opportunity to establish a more visible position within the European network of wood related institutions.

Wording of the title - "Living with modified wood" - signifies that the time in which we live has provided us with technologies of wood modification that will ensure that never again will this material be regarded as a lesser material with a short life-span. Wood, as one of the rare living materials, is experiencing a worldwide renaissance, one that could not have been considered possible just a generation ago. For these very reasons, the primary goal of this conference is to foster, forge and encourage the cooperation and exchange of ideas between wood modification researchers and experts in related fields and, hopefully, help them grow.

Belgrade, as a city with a long and rather eventful history, is an environment where sparse moments of peace and prosperity have instilled a way of thinking that appreciates the little things in life. This setting emphasises even more the pressing need of the modern age to live more organically, ethically and above all, ecologically – and what better way than living with an organic material such as wood.

Success of this event would not have been possible without the effort of the entire team of my colleagues. I would like to thank them and to express my deepest gratitude to Andreja Kutnar, Chair of COST FP1407, for leading this fantastic Action, and for her continuous help in organising this Final Conference.

Last but not least I would like to thank all of the participants and contributors of the Final COST FP1407 Conference. I wish you to have a memorable time in Belgrade.

So let us look forward to an exciting conference!

Goran Milić

Preface

Welcome to the fourth and final international conference of COST Action FP1407 "Understanding wood modification through an integrated scientific and environmental impact approach" (ModWoodLife). This conference, "Living with modified wood", held in Belgrade, Serbia December 12 and 13, 2018 brings researchers and professionals together to share and disseminate their work. Their research contributes significantly to our Action's objectives. It is especially rewarding too see contributions that have resulted from collaborations developed and strengthened through this network. Since the beginning of the Action in 2015, we have delivered new knowledge in the field of wood modification and environmental impact assessment. We can all be proud that during our Action, the European Union recognized the need to strategically approach activities, research, and policy to reduce climate change. Among the key strategies that were accepted in the past three years are the Circular Economy (2015), the Paris Agreement (2016), the Research and Innovation Roadmap 2050 – A Sustainable and Competitive Future for European Raw Materials (2018), as well as the recently renewed Bioeconomy strategy. Although our Action did not directly contribute to these documents, I am convinced that the activities of our network and its participants accelerated their adoption. At the same time, it is clear that our collaboration must continue after the Action ends on March 9, 2019. Going forward we should jointly contribute to "closing the loop" of product lifecycles through greater recycling and re-use and bring benefits for both the environment and the economy.

I would like to thank you for your great collaboration. Besides the new knowledge we created, our new friendships will continue for many years more!

Wishing you a successful and memorable conference in Belgrade.

Andreja Kutnar
Chair, COST FP1407

Conference Program

COST Action FP1407 Final Conference: “Living with modified wood”

Wednesday, December 12th, 2018

9:00 - 9:30	Registration
9:30 - 9:40	Welcome to University of Belgrade – Faculty of Forestry: **Goran Milić & Ratko Ristić, dean**
9:40 - 9:45	Welcome from COST Action FP1407 Chair: **Andreja Kutnar**
9:45 - 10:15	Keynote lecture: “Shift Your Thinking for Research Innovation”, **Eric Hansen**

10:15 - 11:15	***Session 1: Modified wood in use*** **Chairs:** E. Kegel, T. Palija	
	Human interaction with wood – what to measure, how to measure?	**A. Sandak**, J. Sandak, A. Landowska, V. Kotradyová
	Can modified wood compete with untreated wood in preference of people?	**D. Lipovac**, M. Burnard, A. Kutnar, A. Sandak
	EcoModules - an on-line Eco-design Tool	**T. Räty**, M. Laajalahti, M. Saarinen, K. Usva
	Online tool for generating Environmental Product Declarations (EPD-tool) for modified wood products	**L. Tellnes**, O. Iversen

11:15 - 11:45 **Coffee break**

11:45 - 13:00	***Session 2: Novel modification technologies*** **Chairs:** G. Mantanis, A. Sandak	
	Review: wood modification techniques based on cell wall bulking with non-toxic chemical reagents	**K. Peeters**, E. Fredon, P. Gérardin, C. Grosse, C.A.S. Hill, C. L’Hostis, M. Humar, D. Jones, E. Larnøy, M. Noël, A. Sandak
	The potential application of Maillard-type reactions during thermal modification treatment	**D. Jones**, D. Kržišnik, M. Hu-mar, L. Nunes, S. Duarte, C-M. Popescu

	Effect of polymerization temperature during ε-caprolactone modification on wood properties	M.A. Ermeydan, O. Gonultas, **M. Yildirim**, Z. Candan
	Wood sawdust and alkali activated slag bio-composite	**D. Vaičiukynienė**, A. Kielė, R. Bistrickaitė, G. Tamošaitis
	Wood protection from the olive industry	**M. Schwarzkopf**, M. Burnard

13:00 - 14:15 **Lunch**

14:15 - 15:45	***Session 3: Projections and monitoring of modified wood*** **Chairs:** C.Ganne-Chédeville, L.Tellnes	
	Projection of the effects of climate change on decay risk of external timber: United Kingdom case study	**S. Curling**, G. Ormondroyd
	State of the art of wood modification in Spain. Researches, industrial treatments and examples of end uses in real cases	**D. Lorenzo**, A. Lozano, J. Benito, M. Touza, J. Fernán-dez-Golfín, R. Herrera
	Monitoring of the performance of thermally modified wood in buildings	**M. Humar**, B. Lesar, D. Kržišnik
	Durability of modified wood and bio-based materials under outdoor conditions	**H. Kallakas**, K. Visnapuu, T. Poltimäe, J. Kers, A. Sandak
	Furfurylated wood durability in a cyclic hydrothermal environment	**A. Morozovs**, A. Ķeķe, L. Fišere, U. Spulle
	Termite and decay resistances of bioplast-spruce green wood plastic composites	**K. Candelier**, A. Atli, J. Alteyrac

15:45 - 16:15 **Coffee break**

16:15 - 17:30	***Session 4: Beyond wood modifications*** **Chairs:** A. Dias, M. Petrič	
	Wastewater remediation with formaldehyde free tannin-furanic foam powders	T. Sepperer, J. Eckardt, J. Neubauer, **G. Tondi**
	The application of water pretreatment in the pellet production process	J. Popović, **M. Popović**, M. Điporović-Momčilović, A. Prahin, V. Dodevski, I. Gavrilović-Grmuša

	Charring of Norway spruce wood surface as a surface modification technique	**J. Žigon**, M. Pavlič, M. Petrič
	Wood modification related researches at the University of Sopron	**R. Németh**, M. Bak, J. Ábra-hám, F. Fodor, N. Horváth, M. Báder
	Networking in European wood research	**P. Rademacher**

17:30 **Closing of the first day**

17:30 - 18:00 **Core group meeting**

18:30 - 20:00 **Sightseeing**

20:00 **Conference dinner**

Thursday, December 13th, 2018

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	Engineered wood products in contemporary architecture	**M. Kitek Kuzman**, D. Sandberg
	Effect of silane treatment on mechanical properties of degraded wood	**M. Broda**, M.J. Spear, S.F. Curling
	The impact of temperature increasing rate during ther-mal modification on wood surface-coating interaction	**T. Palija**, G. Milić, T. Schabel, D. Djikanović
	Cutting forces assessment when machining wood over all grain orientations – example of thermally modified poplar	**R. Curti**, B. Marcon, A. Scippa, M. Fioravanti, G. Campatelli, L. Denaud, G. Goli
	Experimental and numerical analysis of fracture toughness of thermally modified beech in mode II	**V. Sebera**, M. Redon, M. Brabec, D. Děcký, P. Čermák, J. Milch, J. Tippner
	Mechanosorptive creep tests on thermally modified wood	**C.F. P. Nziengui**, G. Goli, R.M. Pitti, E. Fournely, J. Gril
	Characterisation of subfossil oak wood from central Serbia using SEM and FTIR spectroscopy	**M. Veizović**, A. Straže, N. Todorović, K. Čufar, M. Merela, G. Milić

	Generalised thermal modification kinetic model of poplar wood under different technologies	**B. Marcon**, L. Procino, G. Goli
	Properties of multi-layer plywood made from combinations of densified and non-densified veneers in one structure	**E.A. Salca**, P. Bekhta
	Decay and insect resistance of modified wood with epoxidized plant oils	G.K. Demirel, **A. Temiz**, S. Palanti, N. Terziev

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	Volatile organic compounds emitted from heat and vacuum- heat treated wood	**H. Sivrikaya**, D. Tesařová, E. Jeřábková, A. Can
	In-service performance of floorings with modified wood top layer	R. Németh, **M. Bak**
	Thermo-hydro mechanical densification process of *Nothofagus pumilio* and *Nothofagus antarctica* and the effect of annual width ring on modulus of hardness, and dynamical mechanical properties	**J.G. Pečnik**, M. Schwarzkopf, A. Kutnar
	Enhancing outdoor durability of heat treated wood surface by photo-stabilization by waterborne acrylic coating using bark extract	**Ö. Özgenç**, E. Bilici
	Changes in wood surface properties caused by aging techniques	**A. Rozanska**, A. Barski
	Photostability of thermally modified poplar wood coated with alkoxysilanes	**D. Lechowicz**, B. Mazela, W. Perdoch
	Wood properties and extractive exploitation from thermally modified Chestnut wood	**P. Cetera**, M. D'Auria, L. Milella, D. Russo, L. Todaro
	Antimicrobial particleboards – part 1: preparation and strength	**J. Iždinský**, L. Reinprecht
	Antimicrobial particleboards – part 2: resistance to bacteria and fungi	**L. Reinprecht**, Z. Vidholdová

	Selected mechanical properties of lignocellulosic layered composites produced in various temperature conditions	**A. Gumowska**, M. Krakowski, G. Kowaluk
	Assessment of lignocellulosic-substrate fungi-based materials	**L. Marrot**, M. Mikuljan, F. Pohleven
	The compressive resistance of low density mycelium boards	**Z. Vidholdová**, J. Iždinský, R. Lagaňa
	Variability of hemp concrete material performance: a focus to modulus and their calculation methods	**C. Niyigena**, S. Amziane, A. Chateauneuf
	Characterization of two liquefied agricultural wastes	**S.H. Fuentes da Silva**, I. Egües, J. Labidi
	Influence of hydrothermal modification on the properties of cellulose and lignin after-service-life valorisation of wood	**E. Robles**, R. Herrera, J. Fernández, O. Gordobil, J. Labidi
	Improving hydrophobicity and thermal stability of wood through esterification with fatty acids	**R. Herrera Díaz**, O. Gordo-bil, P.L. de Hoyos-Martinez, J. Labidi, R. L. Ponte
	Preservation of wood structures in non-controllable environ-ment by the example of pre-stressed laminated timber bridge deck with two curved geometry	**T. Teppand**
	Sensitivity and reliable design of a timber beam considering crack growth and environmental effects	**Y. Aoues**, H. Riahi, S.E. Ha-mdi, T.B Tran, E. Bastidas, R.M. Pitti
	Creep response of European species under environ-mental and mechanical loadings in outdoor conditions	CF.P. Nziengui, M.A. Ella, **R.M. Pitti**
	Understanding shrinkage and fracture process of green wood using X-ray-microtomography	JG Mambili, S.E. Hamdi, **R.M. Pitti**
	Modified wood – research on selected physical and mechanical properties	**I. Burawska-Kupniewska**, M. Grzeskiewicz, P. Boruszewski
	Paper tissue reinforcement – coating with nanocellulose and silanes	**Z. Cao**, B. Mazela, W. Perdoch
	Preliminary analysis of bio-sourced hybrid resins as coatings for wood protection	**P.L. de Hoyos-Martínez**, R. Herrera, J. Labidi, F. Charrier-El Bouthoury
	Nano-modified adhesives for composite wood panels manufacturing	**D. Janiszewska**, P. Hochmańska

11:35 - 12:15 **Coffee break**

12:15-13:00	**Session 5: Thermally modified wood – properties** **Chairs:** D. Sandberg, A. Rozanska	
	Influence of heating rate during thermal modification on some properties of maple wood	**G. Milić**, M. Glišić, M. Veizović, N. Todorović
	The evaluation of the quality control methods for thermally modified wood	**D. Kržišnik**, B. Lesar, G. Rep, R. Repič, R. Cerc Korošec, M. Humar
	Physical and elastomechanical properties of full-size fir (*Abies alba*) sawnwood after heat treatment with different intensities	**A. Straže**, G. Fajdiga, B. Gospodarič

13:00 - 14:00 **Lunch**

14:00 - 14:45 **Working group meetings (WG1, WG2, WG3, WG4)**

14:45 - 15:15 **Reports of WG leaders and conference conclusions**

15:15 - 15:45 **Coffee break**

15:45 - 17:00 **MC meeting**

18:00 - 22:00 **Nikola Tesla Museum & Dinner**

Keynote

Shift Your Thinking for Research Innovation

Eric Hansen[1]

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Keywords: innovation, creativity, functional fixedness

Introduction

As this COST Action closes and your community of researchers moves onto the next generation of research, I hope to provide each of you with an insight or two that can help you develop innovative ideas for your future research. COST Actions are designed for: 1) "building capacity by connecting high-quality scientific communities throughout Europe and worldwide; 2) providing networking opportunities for early career investigators; and 3) increasing the impact of research on policy makers, regulatory bodies and national decision makers as well as the private sector." Accordingly, COST Actions are an example of a tool to diversify thinking via exposure to different people, different expertise, and different contexts. Innovation thrives when different perspectives, backgrounds, expertise areas are brought to bear on a problem. Now that this COST Action has collectively mastered the networking pathway to innovation, it is time to explore other avenues.

Functional fixedness is a psychology term describing a cognitive bias that limits one's use of an object to its customary use (Duncker 1945). There is a certain parallel to this in the famous line from Maslow (1966), "I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail." Considering different ways of using the tool (hammer) or alternative ways to describe the problem (nail) can lead to different and potentially better solutions. Ultimately, creativity and learning to think differently can be critical in overcoming the bias of functional fixedness and can be a key benefit to wood researchers.

Creativity Exercise

As humans, we tend to follow norms and the customary ways of doing things – and as a result fail to think outside the box. Creativity exercises can serve to jump-start thinking and remind us to always try look at things differently and from different angles. The aircraft creativity exercise provides insights into developing out-of-the-box thinking.

Think Shift Exercise

McCaffrey and Pearson (2015) provide a unique approach to thinking differently via the example of the famous ocean liner, The Titanic. Could different thinking from the Captain and the crew of the Titanic have resulted in the survival of more passengers? If so, what sort of solutions might they have developed? What solutions might wood modification researchers develop to save passengers of the Titanic?

Conclusion

These two exercises provide food for thought as the wood modification field contemplates its future research endeavours. Employing these concepts can ultimately provide a positive boost to research creativity in many fields, including wood modification.

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Maslow A.H. 1966. The Psychology of Science. p. 15.

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Session 1: *Modified wood in use*

Human interaction with wood – what to measure, how to measure?

Anna Sandak[1,2], Jakub Sandak[1,2], Agnieszka Landowska[3], Veronika Kotradyová[4]

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Keywords: wood perception, wearable sensors, preference test

Incorporating nature into the built environment, either directly or indirectly, can reduce physiological and psychological indicators of stress, while increasing productivity, creativity and self-reported levels of well-being (Mcsweeney *et al*. 2015). Research in this area provides an evidence base of positive health impacts of wood use in the built environment (Burnard and Kutnar 2015). However, the measurement of perception of aesthetical quality of materials is challenging. The majority of research related to materials interaction consider sensory perception using a single, two, three or more modalities (Fujisaki *et al.* 2015). In fact, people use all their senses in order to explore the surrounding world. The richness of subjective experience depends on the number of sensory modalities received at once. This attitude is particularly useful while designing new products. Customers perceive product characteristics through the sensory modalities that are closely connected to material properties. Hence, visual, tactile and olfactory stimuli play a major role in the case of wood. The visual impression of material includes perception of the surface colours, glossiness and pattern. The tactile sensing includes an object's weight, temperature, roughness and hardness. Smell impressions depend on perceiving the volatile molecules that are emitted from in the material. For that reason, at the initial step of new product development, customized scenarios of the sensory events that occur when a person meets a product or uses it are prepared (MacDonald 2002).

Several methods for verification of user preferences might be implemented including surveys and hedonistic/preferences tests. They might provide quantitative and/or qualitative feedback. Selection of materials, as well as target groups of respondents, should be carefully planned in order to obtain reliable results. Tests can be performed with prior training of the responders or without any preparation. Assessment can be performed by using only visual stimuli or including other senses (in both cases use of real or virtual samples can be implemented). Using real samples and employing more senses than only vision (hearing, taste, smell and/or touch) during the assessment is a superior approach. In preference tests attractiveness of materials/products is ranked in comparison to the set of alternative samples representing the variability range of available choices. Respondents might perform two types of comparison: single-attribute or multi-attribute comparison. Human perception tests might be supported by measuring physiological responses in order to provide a more complete picture of human emotions (Landowska 2014, Kotradyová *et al*. 2017, Landowska *et al.* 2018). Tests of preferences might be designed in a more complex way and combined with other than aesthetics factors influencing the customer choice. These may include economic issues (investment cost, maintenance frequency) or environmental awareness (local/imported resources or natural/modified wood) (Sandak *et al*. 2015). It is also necessary to provide sufficient isolation from other environmental stimuli in the testing environment in order to ensure that the responses are mostly due to the tested stimuli.

Preference test approach can be considered as a very useful tool for conservation/maintenance scheduling. In this case the goal of the test is to define limits for the customers' tolerance for surface defects due to ageing, usages or deterioration. This research provides an overview on recent state of the art methods suitable for assessment of interaction between human and materials from the perspective of materials aesthetics and function. The review is combined with presentations of case studies conducted by authors. Furthermore, the influence of economic, environmental and cultural aspects on the preference changes is discussed.

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Can modified wood compete with untreated wood in preference of people?

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Keywords: wood modification, perception, evaluation, preference, well-being

Visual or tactile contact with pleasant materials can improve our affective states and decrease our physiological arousal. Accordingly, pleasant materials may have a protective or restorative role in human stress responses. Current evidence suggests that tactile and visual contact with wood leads to healthier affective and physiological outcomes when compared to other common materials (Burnard and Kutnar 2015, Demattè *et al.* 2018, Ikei *et al.* 2017). Recently, however, modified wood has become widespread due to its improved properties, such as enhanced durability and dimensional stability (Sandberg *et al.* 2017). Importantly, these changes are accompanied by alterations of the material's visual and tactile qualities (Bakar *et al.* 2013), which influence human perception and evaluation of materials. Is modified wood, with its visual and tactile changes, still liked among people when compared to untreated wood? Are some modification processes better than others in creating appealing materials?

To gain insight into these questions, we prepared 30 wood samples (approximately 7 x 15 x 1 cm) from several species that are either untreated or treated (i.e., thermally modified, chemically modified, impregnated, coated, or treated with a combination of these methods) (Fig. 1). As a first step, a group of experts rated all samples based on several sensory (e.g., glossy, dark) and evaluative (e.g., natural) attributes. After completing this step, we conducted the study in two phases. First, we presented all 30 samples to 25 participants simultaneously and asked them to choose their favourite five materials to be used as an outdoor table top surface based on their combined tactile and visual inspection (and rank these five favourite materials from their most to least favourite). From the initial group of 30 materials, we selected 10 samples that on average received the highest rankings. These 10 samples were then ranked by a new group of 50 participants, similarly as in the first phase.

The presented results will demonstrate how modified wood fares against untreated wood in terms of preference. In addition, we will present associations between preference rankings, wood modification processes, wood species, as well as sensory and evaluative attributes of wood.

Figure 1: Wood samples used in the study.

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EcoModules - an on-line Eco-design Tool

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Keywords: LCA, Eco-design, EcoModules

The European Union is intensifying its rows in product life cycle assessment (LCA). The goal is that more durable products and businesses will stand out in the market - and more reliably. Luke has developed impact assessments and the new EcoModules tool to speed up and facilitate on-line product life cycle assessment.

The inventory for LCA is usually created as a rather demanding experiment and a considerable amount of effort is put forward to create a model for impact assessment and reporting. All this is usually left safe for the next trial after several years, whereas LCA could be made for use in daily R&D activities and monitoring of environmental performance. The EcoModules approach is to keep inventory creation and modelling as live processes. The product/producer inventories are stored in a modular cloud service respecting autonomy and data ownership of actors in the chain, but also following common rules that guarantee comparability of the results. It thereby ensures the possibility to link together different inventories and/or impact assessments to facilitate eco-design of the products and processes. With tailored applications, users can easily simulate the impacts of production alternatives, conditional to different suppliers, technologies in locations or transportation needs, to name a few.

Data Sharing

The EcoModules data sharing service is unique in the life cycle assessment applications field. It connects the chain of actors to each other so that the environmental indicators generated by an actor can be used by other chain operators in their own calculations. This enables real-world, knowledge-based assessment at all stages of the chain, in modules, up to consumer products.

Sharing the data provides the basis for a chain of co-operation to manage the environmental impact of products. Any actor of the chain can initiate co-operation. Assuring confidentiality, EcoModules does not distribute LCI data but only module-specific outcomes.

Data sharing is supported with generic data from Luke. This is usually the case for the primary flows, e.g. wood procurement, energy and transportation.

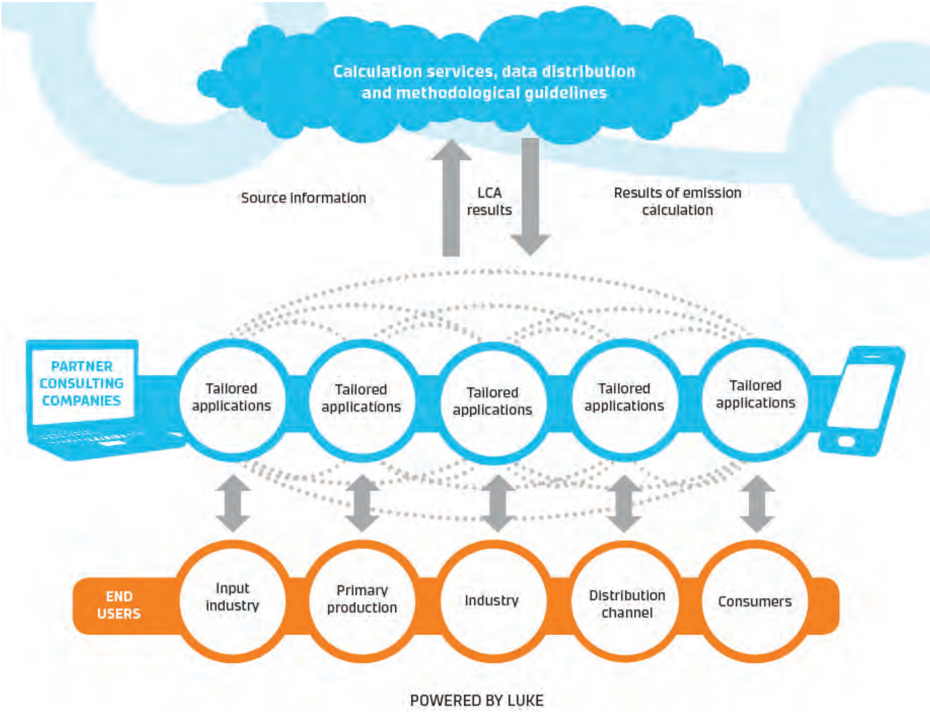

Figure 1: EcoModules work flow.

Tailored user applications

EcoModules follows SOA (Service-oriented Architecture) enabling flexible communication between data services as well as system-independent performance. Primary producers or industry designers can simply connect to the service via web browser for the update of their inventory or create new calculations using the data made available from the chain or the EcoModules system manager. EcoModules meets these demands through automation and centralized calculation, without sacrificing data specificity or quality. A tailored application can even integrate LCA with an Enterprise Resource Planning (ERP) application.

In this presentation we will show an application of Ecomodules, based on a wood-plastic composite value chain.

Online tool for generating Environmental Product Declarations (EPD-tool) for modified wood products

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Keywords: environmental product declarations (EPD), modified wood products, life cycle assessment (LCA)

With an increased demand for objective documentation of building product environmental properties, Environmental Product Declarations (EPD) have become available for many more products. Since 2012, the amount of verified EPD according to EN 15804 has risen from about 500 to more than 5000 in 2018 (Anderson 2018). For modified wood products, some of the larger manufacturers have developed EPD for their main products and markets. The EPD can, for instance, be used to compare the carbon footprint of modified wood with preservative treated wood, taking service life and maintenance into account (Tellnes *et al.* 2018). The objective of this work is to show the potential for making EPD development easier for modified wood products through an EPD-generator (Fig. 1).

Figure 1: General illustration of the EPD-generator concept (LCA.no AS).

The practice of developing EPD has, to a large extent up until now, been what can be called "manual EPD." This EPD work is heavily dependent on LCA-consultants for each company and gives companies difficulties when their product range has large variations and is applied under various scenarios. The solution for several producers is to have an EPD-tool or EPD-generator. In Norway, this has been developed both for whole industries and by individual companies. The use of an EPD-generator can make it possible for larger companies to declare their full range of products with scenarios especially for each building project or market. Since more work is done by the companies themselves, the costs per EPD is much lower than manual EPD. For smaller companies, the involvement of trade associations would normally be a solution to share the initial cost of establishing the EPD-generator and providing training courses. The development of an EPD-generator involves several parts such as software, database and company data, quality control and verification by an EPD-program operator. An overview of the technical system is shown in Fig. 2.

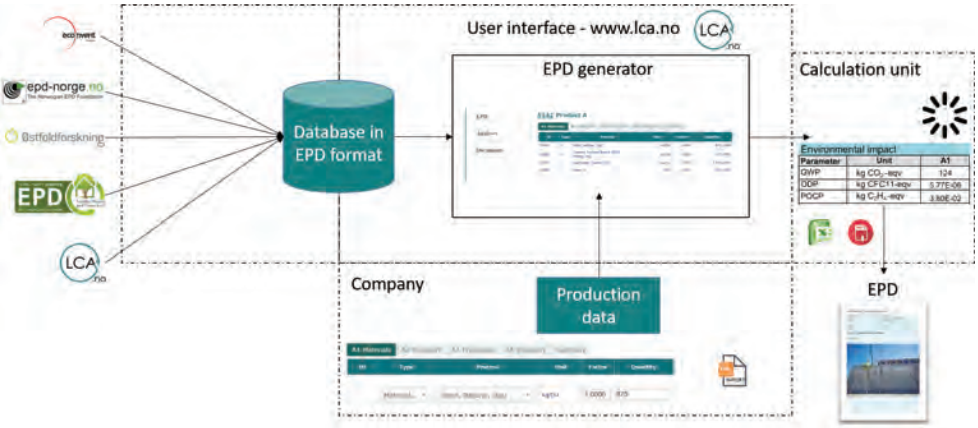

Figure 2: System overview EPD-generator (LCA.no AS).

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Session 2: *Novel modification technologies*

Review: wood modification techniques based on cell wall bulking with non-toxic chemical reagents

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Keywords: cell wall bulking, esterification reaction, Maillard reaction, non-toxic reagents, wood modification

Wood modification is used to improve key properties of wood used as building material. Recently, developments in the area of cell wall bulking with chemical reagents have grown considerably. By cell wall bulking, a dimensionally stable material is created because the cell wall itself will be in a permanently swollen state that will attract no or very little water. Often the treated wood is no longer recognised as a nutrient medium by the specific enzyme systems of degrading fungi or the lowered equilibrium moisture content prevents decay. Several impregnation methods are available (some already commercialized), however development of new, enhanced treatments is still on-going, mostly in steering the modification systems to meet following criteria:

- use of cheap, readily available (coming from renewable resources), non-leachable, non-toxic and small enough to penetrate the cell wall chemical reagents;
- economically and ecologically feasible (no use of solvents, expensive or harmful catalysts or strong acids/ bases) impregnation technology;
- recyclability at the end of its life cycle (absence of heavy metals).

The focus of this abstract is to present information regarding the different types of bulking treatments which try to meet those criteria, and their progress.

One system fulfilling above requirements is based on esterification reactions by a condensation of hydroxide groups from chemical reagents or wood with carboxylic acids under moderate temperatures. In NIBIO (Norway), they examined the potential of the polyesterification of sorbitol and citric acid in wood as a wood modification process. Pine wood was impregnated with the aqueous reagent solution and was cured at 103 or 140°C for 18 hours. Impregnated samples cured at 140°C showed a permanent (leach-resistant) increased dimensional change, but samples treated at 103°C did not. However, samples treated at both temperatures showed resistance to white-rot (*Trametes versicolor*) and brown-rot decay (*Postia placenta*) even after a leaching procedure. The leached and non-leached samples were also less susceptible to blue-stain fungi.

At the Bern university (Switerland), they studied the use of bio-polyesters for wood chemical modification by the vacuum/pressure impregnation of mono- or oligomers of lactic acid (LA) or oligomers of polybutylene succinate (PBS), in bulk or water solutions. Subsequently, thermal treatment enables the LA to diffuse into the cell wall, whereas wet heat treatment is necessary for PBS diffusion. Optimized treatments confer excellent biological resistance and dimensional stability, with good fixation in wood. Slight increase in material brittleness and diminished ability to gluing and coating must still be overcome. Easier to implement (simple treatment process), LA modification is considered for industrial up-scaling, which would allow positioning new modified wood variant with intermediate properties, between thermo-treated wood and chemically modified wood.

Dealing as well with poly-esterification, the university of Lorraine (France) investigated the combination of glycerol (G) with citric acid (CA), tartaric acid (TA) or succinic anhydride (SA). Waterborne mixture (about 40% solid ratio) were vacuum/pressure impregnated in wood, then thermal treatment was performed to induce in situ polymerization. For each variant, molar ratio, temperature and duration were optimized regarding material properties. Best results were obtained using GCA and GSA formulations, keeping leaching under 1%, reducing swelling up to 60%, ensuring high durability against white and brown rot fungi and maintaining bending mechanical performances compared to untreated wood. 160°C and 6h were found to be the optimum curing conditions. On-going research is focused on the extension to other biobased monomers and the preparation to numerical modelling-supported up-scaling, which will ensure optimal material performances.

Another possibility to bulk wood cell walls is the Maillard reaction, where amine groups are reacted with the reductive ends of sugars according to a complex mechanism. The feasibility thereof was recently investigated by InnoRenew CoE (Slovenia) and NIBIO. They scanned different combinations of chemical reagents and found that the combination of 0.1 mg L^{-1} lysine/glucose/ citric acid reacted at 120°C obtained the highest weight percentage gain, albeit with significant leaching. In continuation, they found that at 120°C mainly esterification between glucose and citric acid occurs and a reaction temperature of 160°C is necessary to achieve Maillard reaction and no leaching. Another reagent combination (0.1 mg L^{-1} ascorbic acid/Trizma base/citric acid) appeared to work, but SEM images showed that it could damage the wood. On-going research is focused on the resistance of the treatment against fungal decay and obtaining a repeatable, high-volume change.

Whilst the Maillard reaction classically involves primary amines, secondary amines could be used, too. On-going studies between LTU in Sweden and University of Ljubljana in Slovenia are considering how to combine these Maillard-type reactions within a thermal modification process. Initial experiments considered tricine and the tertiary amine bicine, and whilst the work has yet to be fully published, spectroscopic analysis by FTIR has identified that some degree of reaction has occurred.

The potential application of Maillard-type reactions during thermal modification treatment

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Keywords: thermal modification, Maillard reaction, bicine, tricine

The concept of thermal modification of wood has been well established over the past decades, with several commercialised processes now supplying the market. Whilst the process results in more dimensionally stable material with increased biological resistance, its use where mechanical properties are required often causes problems. Many of these mechanical properties lost during thermal modification are maintained during chemical modification, such as with methylol/melamine resins, silicon polymers, or DMDHEU. Recent work (Hauptmann *et al*. 2015) has considered the use of tricine for the modification of wood. This reagent is apparently capable of binding with reduced sugars via a Maillard reaction, though studies have been limited to a maximum temperature of 103 ^{o}C. Recent work (Peeters *et al*. 2018) investigated the Maillard reaction at low temperatures. These concurrent studies investigated if compounds such as tricine could be impregnated into wood prior to conventional thermal modification.

Experiments were carried out on two different species, spruce (*Picea abies*) and beech (*Fagus sylvatica*), with impregnation of two chemicals (tricine and bicine) undertaken in an aqueous solution of 10 wt% bicine/tricine. Tricine was chosen as an extension of previous work (Hauptman *et al*. 2015), whilst bicine (a tertiary amine) was chosen to investigate if this could undergo a similar Maillard-style reaction. A summary of the reaction parameters is shown in Table 1, with modification temperatures limited to 160 ^{o}C to minimise thermal degradation of the compounds.

Some of the results will be presented from this study, along with FT-IR spectral analysis and investigations into the effect on termite attack.

Table 1: Summary of reaction parameters

Spruce		Beech	
Code	Treatment description	Code	Treatment description
S_C	control	B_C	control
S_HT	Heat treatment only	B_HT	Heat treatment only
S_B	Bicine pre-treatment and drying	B_B	Bicine pre-treatment and drying
S_B_HT	Bicine pre-treatment and heat treatment	B_B_HT	Bicine pre-treatment and heat treatment
S_T	Tricine pre-treatment and drying	B_T	Tricine pre-treatment and drying
S-T_HT	Tricine pre-treatment and heat treatment	B-T_HT	Tricine pre-treatment and heat treatment

Spectral analysis (Popescu *et al*. 2018) of the thermally and thermo-chemically modified wood suggested the occurrence of the reactions between the functional groups from bicine and tricine and those present in wood structure, which for bicine would suggest that there was chain displacement to create the Amadori products and activation of the N via a quaternary ammonium intermediate. Moreover, it was observed that the softwood samples were more susceptible to chemical/thermal modification than the hardwood samples, indicated both by the increased WPG values, but also by the infrared spectra. Termite experiments (Duarte *et al*. 2018) focussed on the analysis of termite hindgut flagellate protist community. Both bicine and tricine are recognised zwitterionic buffers, which may hinder the ways in which the protists work. As such the most "effective" treatment was the combination of bicine and heat treatment in both beech and spruce.

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Effect of polymerization temperature during ε-caprolactone modification on wood properties

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Keywords: ε-caprolactone, graft polymerization, ring opening polymerization, temperature, wood modification

Wood is one of the best engineering materials due to its specific strength and has been used since almost the beginning of human age of our planet. Many products such as indoor/outdoor furniture, decks, sidings, fences, insulation panels, sport-products, etc. are only some utilization fields of wood. However, hygroscopic and hydrophilic nature of wood due to its chemical structure limits long-term usage, especially at outdoor fields. Cracks and splitting may occur in a year; also, water absorption ability makes wood susceptible to biodegradation.

Hydrophobic poly(ε-caprolactone) modification of wood is one of the chemical modification methods established recently (Ermeydan *et al*. 2014). Water repellence and dimensional stability can be both improved up to 50% and 45% respectively, by in-situ grafting hydrophobic ε-caprolactone monomer inside spruce, pine or poplar wood cell walls (Ermeydan *et al*. 2014, 2017). The main factors of reaction conditions of ring opening polymerization of ε-caprolactone are, i.e., the nature of the initiator, type of solvent, reaction temperature, etc. It is known that temperature above 100 °C is critical for wood mechanical properties and mild temperatures are generally preferred (Hill 2006). In this research, economically valuable poplar wood is modified with a pretty new modification method by grafting hydrophobic poly(ε-caprolactone) (PCL) with different temperature ranges (75-85-95 °C) to assess the optimal conditions for complete polymerization and minimal wood degradation. To find the possible effects of temperature, (Dynamic Mechanic Thermal Analysis) DMTA of wood samples was characterized. The results obtained in this study showed that the modulus values increased as the modification temperature increased. It is already reported that storage modulus of PCL modified poplar was increased about 14% at 105 °C as shown in Fig. 2 (Candan *et al.* 2017). Better mechanical performance is expected with slightly lower temperatures. Besides, water absorption, dimensional stability (ASE) of modified wood was found in order to observe temperature dependence. On the other hand, native wood components was investigated to observe possible changes; hot-water solubility, contents of Klason lignin, holocellulose, α-cellulose, and ash will be determined as shown by Gonultas *et al*. (2017) in Table 1 which gives critical information.

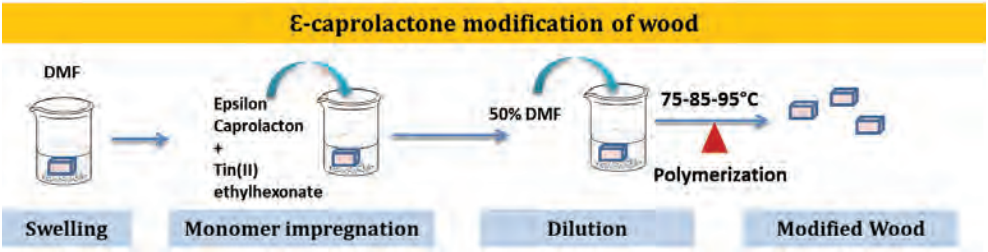

Figure 1: ε-caprolactone modification of wood.

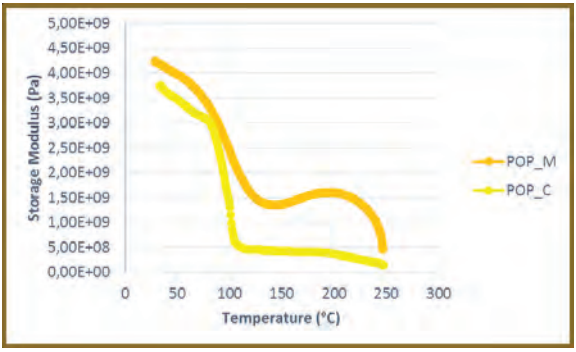

Figure 2: Storage modulus values of modified (POP_M) and control (POP_C) poplar wood samples (Candan *et al.* 2017).

Table 1: Chemical properties of the materials (Based on extracted dry wood, %, Gonultas et al. 2017).

Sample	Ash content	Hot water solubility	Klason Lignin	Holocellulose	α-cellulose
Control Poplar	0.82	2.87	22.49	79.09	47.54
Modified Poplar	1.85	3.37	21.19	81.94	41.36

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Wood sawdust and alkali activated slag bio-composite

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Keywords: wood sawdust, alkali activated slag, bio-composite

Alkali-activated materials are a rapidly emerging sustainable alternative to Portland cement binder because of their high strength and durability and low environmental impact. There is a growing interest in the development of new cementitious binders, which enhance optimal utilization of industrial by-products, such as slag and wood sawdust. Great interest in alkali-activated materials resulted in a large amount of waste recycling.

According to literature review, the influence of sawdust on the properties of alkali activated materials varied. One group of researchers stated that sawdust has positive effect on the main properties of alkali activated materials, but the other group published negative effect. Halas *et al*. (2011) showed that sawdust can be used as one of the possible fillers to alkali-activated materials based on fly ash. However, it also showed that growing quantity of sawdust decreases the compressive strength of the samples. Duan *et al*. (2016) stated that sawdust is beneficial for the resistance to cracking and drying shrinkage. Sawdust exhibited positive effect on compressive and flexural strength after 28 days and it led to the formation of an optimal microstructure. Feltz *et al*. (2005) investigated particleboards composed of sawdust and Geopolymer resin. The results indicated that it is possible to manufacture and engineer these types of composite beams to obtain a specified strength and to satisfy fire requirements. Kong *et al*. (2018) synthesized the geopolymer composites formed by two industrial wastes, namely red mud and sawdust. Sawdust was chemically treated with alkali for the removal of lignin and subsequently bleached, before forming composite with acid-modified red mud. The geopolymer matrices with high compressive strength of 8.3-138 MPa were obtained, which is comparable to Portland cement (compressive strength of 9-20.7 MPa).

Bio-composite which is made of sawdust and alkali activated slag is presented in this paper. In this case, 5 % of phosphogypsum addition was added. Relationships between density, compressive strength, bending strength and sawdust content were observed.

In this study milled granulated blast furnace slag was used as cementing component. According to XRD data, the biggest amount of oxides CaO and SiO_2 were found. High amounts of amorphous SiO_2 and Al_2O_3 made slag a good raw material for alkali-activated binding material. XRD analysis showed the peaks of quartz, hydrotalcite and calcite. Semi-hydrate phosphogypsum generated by fertilizer plant in wet-process of phosphoric acid production was used in the study. Hardwood sawdust was taken in amount of: 0%, 5%, 10%, 15% and 20% by slag mass. Samples were hardened for one day in ambient conditions, second day at 60 °C temperature and the last 26 days in ambient conditions again. The samples were covered with polyethylene material to prevent water from evaporation (Fig. 1).

Figure 1: The samples of wood sawdust and alkali activated slag bio-composite

The results of the study showed that bio-composite from alkali-activated slag blended with sawdust has a great potential in the construction materials area. It could be used as alternative construction material to ordinary Portland cement as well. It is possible to recycle sawdust, slag and phosphogypsum in alkali-activated slag blends.

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Wood protection from the olive industry

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Keywords: modification, olive oil, protection, wood

The European olive industry produces the majority of the olive oil in the world. The process by which the oil is obtained separates the oil phase of the olive from the solid phases comprised of the stone, fleshy parts of the olive, and residual leaves. All of these materials contain phenolic compounds which provide good flavour and human health benefits, however, they may serve another purpose: providing protection against degradation of wood products. Recently, Schwarzkopf *et al*. (2018) explored the use of these olive mill by-products for use in the protection of wood. In this study two maleinisation techniques were used to chemically modify low-value lampante oil to limit leaching when impregnated in wood. Scots pine (*Pinus sylvestris*) and European beech (*Fagus sylvatica*) were then impregnated with the modified oils (Fig. 1) and underwent leaching, accelerated weathering, and decay tests. The two oil modification treatments increased the potential for the oil to react with the hydroxyl groups of the wood, making them less likely to leach from the wood. Leaching of the oils was relatively low compared with other experiments and beech wood specimens impregnated with a direct maleinisation oil showed improvement in leaching performance compared to control specimens. In addition, it was found that the modified oils were not completely removed from the wood after solvent extraction indicating that they could potentially be used as an immobilisation agent in combination with other treatments to reduce the required quantity of active component of protective agents.

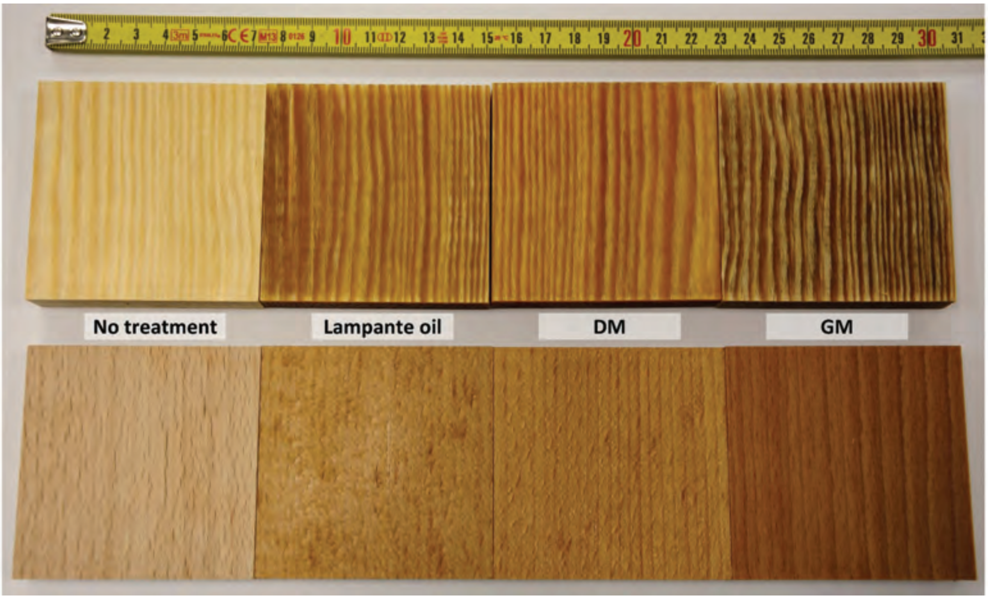

Figure 1: Pine (upper row) and beech (lower row) specimens treated with modified oils. DM signifies direct maleinisation and GM signifies maleinisation preceeded by a glycerolysis step.

These results have prompted further interest in this topic leading to Horizon 2020 funding in an active Bio-Based Industries project entitled ‘ProEnrich’. Rather than focusing on the oil, this project targets the pomace and wastewater coming from the olive mill. These waste materials have higher phenolic content than the oil, making them more attractive for further processing. The objective of the project is to create a value chain from the olive farmer to the end user who would buy refined phenolic compounds. These phenolics can then be used by industries including food, cosmetics, pet care, and wood protection.

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Session 3: *Projections and monitoring of modified wood*

Projection of the effects of climate change on decay risk of external timber: United Kingdom case study

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Keywords: durability, climate change, timber, climate index

Decay fungi require certain conditions (an adequate temperature and a moisture source) to enable them to decay wood. For exterior timber exposed out of ground contact, these factors are determined by the climatic conditions. A number of models have been used to determine climate risk and service life (Viitanen *et al*. 2009, Brischke and Rapp 2010, Brischke *et al.* 2011) and have shown that the UK (particularly western areas) is in a zone with some of the highest Decay Climate Indices in Europe. One of the earliest and simplest modelling methods is the Scheffer Climate Index (SCI) (Scheffer 1971) that determines regional decay risk based on temperature and precipitation data. Whilst not a perfect predictor of decay likelihood, the SCI is a useful tool and in this paper is determined for different regions of the UK using both historic data from the UK meteorological office and various scenarios using climate projections.

Determination of the historic and current SCI was calculated using publicly available data from the UK Metrological office. For temperature, data was obtained from 1931, from a number of weather stations around the UK (from at least 1 station in each region). Precipitation data was extracted from the regional HadUKP data set (Alexander and Jones 2001). The annual SCI was then calculated for each station, with means calculated for regions where possible, based on approximate 30 year ranges ending in 1960, 1990 and 2017.

Projections of the increase in SCI were also made for the same regions of the UK using projections detailed in The UK Climate Projections (UKCP09) with low and high emission scenarios utilised to calculate possible SCI for the mid 2020's and the mid 2050's (Fig.1b).

The data shows that the climate index for decay in the UK has increased from 1990 to 2017 and this implies an associated rise in decay hazard. Projections suggest a significant increase in the SCI and the associated decay hazard under projected climate change scenarios, although again it must be remembered that localised conditions ultimately determine the decay hazard.

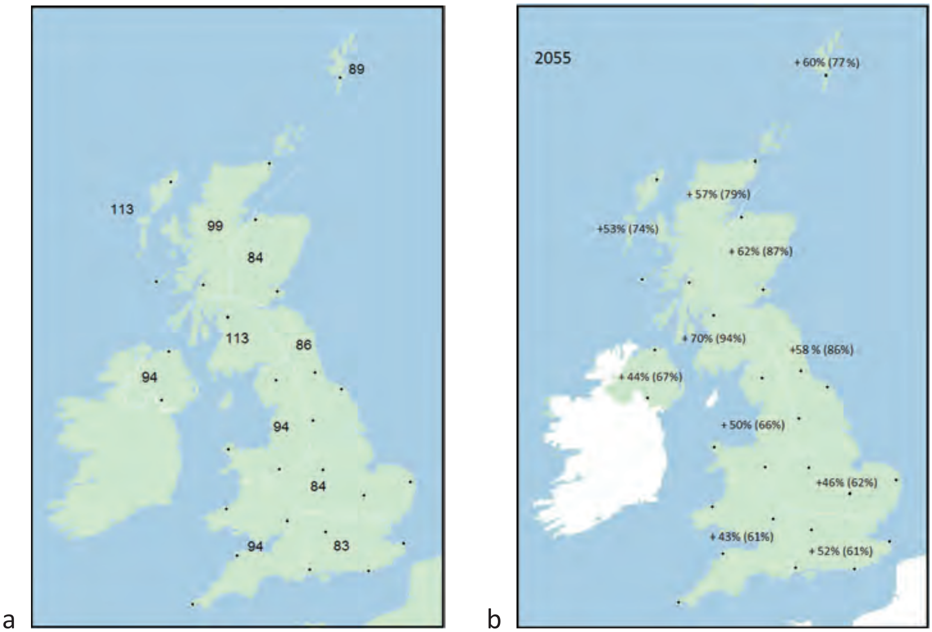

Figure 1: Current SCI values (a) and projections (b) of percentage increase for mid 2050's based on low and high emission climate scenarios (values in brackets).

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State of the art of wood modification in Spain. Researches, industrial treatments and examples of end uses in real cases

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Keywords: Spain, wood, modification, research, treatments

In Spain there are small research groups studying different aspects related to modified wood and its processes. In the University of the Basque Country, Chemical and Environmental Engineering Department, is doing researches of modified wood, focussing in thermal modified radiate pine. The Forest Research Centre (CIFOR)-National Institute for agricultural and Food Research and Technology (INIA) is working in Spanish research projects related mainly to the performance of thermal modified wood in test devices of use class 3, deckings. Forest and wood Galician Research Centre CIS-Madeira is conducting different researches of modified wood related to performance of real cases of acetylated modified facades, studying real examples in different Spanish locations.

Concerning the situation of the wood modification industrial treatments plants, there are actually only 3 industrial plants in Spain. In the Basque country, the company "Maderas Torresar" produces thermally modified products, mainly in radiata pine, in a medium industrial scale plant under the brand *Termogenik*. The process involves using a Mahild chamber of30 m^3 capacity with steam as heating medium, and modifying wood at temperatures between 192 and 212 °C. The company "Mariano Hervás Parquets", located in Sigüenza, modifies thermally eucalyptus and ash wood between 180 and 220 °C for outdoor applications, in a small plant scale (no data provided). The company "LOSAN group", in Galicia, is testing thermal modified eucalyptus and other wood species in a small plant (no data provided). Some projects regarding the installation of new thermal industrial facilities in Spain are planned for the future. Different products from chemical modification processes (acetylation and furfurylation) and thermal modified wood are commercialized and available in the market in Spain, where is possible to find different examples of modified wood in real cases for indoor and outdoor applications, mainly as facades and deckings.

Figure 1: View of thermally modified radiata pine wood elements in a passive house.

Monitoring of the performance of thermally modified wood in buildings

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Keywords: thermally modified wood, moisture performance, thermal performance, buildings

Thermally modified wood is frequently used for various building applications such as windows, doors, façades and decking. Wood in these applications is exposed to several biotic and weathering factors. Hence, it is of great importance to predict changes of thermally modified wood in real conditions and describe possible changes. The aim of the presented paper was to elucidate the overall performance of thermally modified (TM) spruce in building applications and compare it to the performance of untreated Norway spruce wood.

The research was performed on wall, decking, façade and window elements. Decking elements were positioned horizontally on copper-treated spruce beams 0.5 m above ground in monolayer using steel fasteners. Façade elements were fixed on all sides of the model house. The model house is located in Ljubljana (46.048721, 14.479568). Façade and decking were exposed in October 2013. Timber window with a frame width of 68 mm, produced by Slovenian company M SORA d.d., was made of spruce and TM spruce. The window was installed in a test object with a regulated internal temperature of approximately 24 °C. In addition, the performance of thermally modified wood was assessed in the first building made of modified wood in Slovenia (2009) in Mozirje, and on the façade of the new building of the Department of Wood Science and Technology in Ljubljana (2015). For moisture monitoring, insulated electrodes (stainless steel screws) were applied at various positions and depths and linked to electrical resistance measuring equipment (Gigamodule, Scanntronik Mugrauer GmbH, Germany).

In order to determine moisture performance of TM spruce and spruce on different application scenarios, the moisture content (MC) of façade and decking applications were monitored for periods between 2 and 5 years. It can be resolved from figures 1 and 2, that MC of thermally modified wood was considerably lower through all monitoring procedure. None of the application in UC 3.1 exposure did exceed 25% limit within the exposure. The only exceptions were decking elements (Fig. 3), where moisture performance decreases through the years. There were small cracks formed on the surface of TM wood that resulted in decreased durability. However, lower moisture performance can be overcome with better inherent durability. In the last year of the monitoring, MC of spruce wood increased, predominately due to prominent decay.

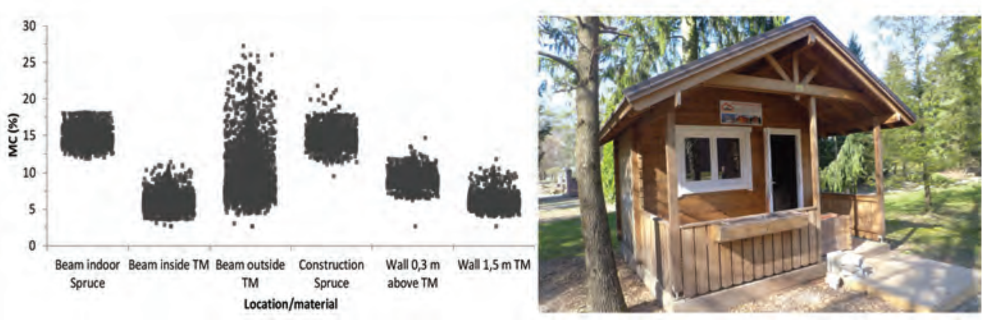

Figure 1: Moisture content distribution in the log house made of thermally modified wood in Mozirje (right). On every location, 2500 measurements were performed in the period between March 2015 and June 2018.

Figure 2: Moisture content distribution in the window (right) made of non-modified spruce and thermally modified wood in Ljubljana. On every location, 12.000 measurements were performed in the period between October 2013 and October 2018.

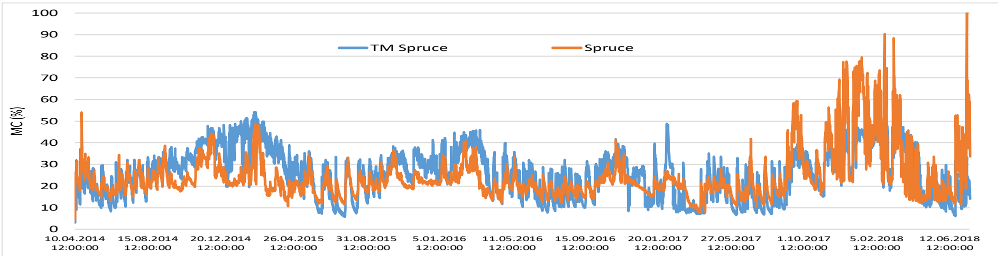

Figure 3: The moisture content of decking elements made of non-modified and thermally modified spruce in Ljubljana in the period between October 2013 and October 2018.

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Durability of modified wood and bio-based materials under outdoor conditions

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Keywords: modified wood, bio-based materials, natural weathering, durability, façade performance

Recent advances in the biomaterials modifications processes have delivered several innovative solutions for the building sector. However, in order to increase confidence for their use, a deep understanding of the material properties, structure, assembly, formulation and its performance along the service life is indispensable. This research was conducted in collaboration with BIO4ever, where the performance of 120 selected façade materials provided by over 30 industrial and academic partners was evaluated during an experimental campaign of natural weathering. Natural weathering was conducted in 2 different locations: Tallinn (Estonia) and San Michele (Italy). Additionally, durability field tests according to EN 252 standard were carried out in Oleron Island (France), Guadeloupe (France) and San Michele (Italy). The experimental samples were classified in seven categories, according to the type of material and treatment applied: natural wood (or other bio-based material), composites, chemically modified, thermally modified, impregnated, coated and/or surface treatment and hybrid modified materials. The last one included a combination of at least two different treatments.

This abstract presents a part of the natural weathering experiment conducted in Tallinn according to standard EN 927-3. Samples were exposed on the racks, inclined at an angle of 45° to the horizontal level and facing the southern direction. Evaluation protocol was similar as proposed by Round Robin Test conducted within COST Action FP1303. The materials performance was evaluated by measurement of the color change, visual assessment and the evaluation of cracks formation during outdoor exposure. High resolution photos were taken every month in order to document appearance changes during the test.

The performance of investigated samples after 12 months of exposure was varying depending on materials class and treatment process. The color measurement results indicated that the most durable test-specimens were the coated materials (belonging to the class of surface treatments). The cracks occurred on 45 specimens among 120 tested façade materials. Natural wood of different species, as well as thermally modified wood, were among specimens changing appearance in the most apparent way. This included changes of the color parameters as well as cracks presence. Impregnated samples (e.g. furfurylated wood) and some of the hybrid modifications of samples (e.g., thermally modified + colored wood with ferrous sulphate) became patchy. The appearance of selected material (in this case belonging to composite class) is presented in Fig.1. As it can be seen, that this particleboard lost its bamboo coating entirely. Outdoor exposure tests for wood-based materials are still on-going and will be confronted with the natural weathering results from San Michele (Italy).

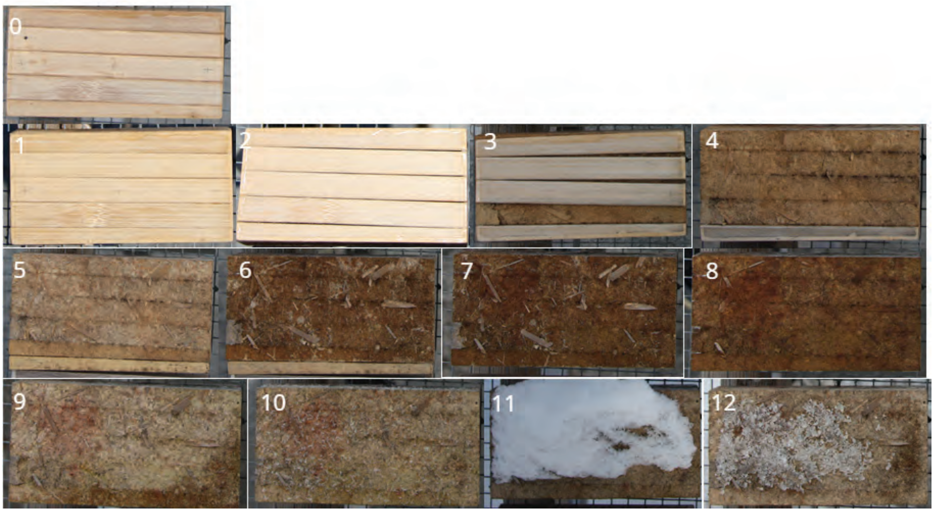

Figure 1: Change of appearance of particleboard with bamboo cladding during 12 months of exposure.

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Furfurylated wood durability in a cyclic hydrothermal environment

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Keywords: cyclic hydrothermal environment, formic acid, furfuryl alcohol, pine wood

Wood as a renewable resource has been widely used since time immemorial to provide people with heat and shelter construction. Almost three quarter parts of wood dried mass is composed of cellulose and hemicelluloses rich in hydroxyl groups (Fengel and Wegener 1984). Hydrogen bonds among wood carbohydrates and water induce anisotropic wood swelling that is a drawback for wood construction longevity. Therefore, considerable research on wood modification has been carried out to find practical and economical methods to reduce the natural tendency of wood to shrink and swell with changes in ambient humidity (Sandberg *et al*. 2017). Wood chemical modification is the result of chemical reactions that provoke cross-linking between wood constituents or substitution of wood hydroxyl group hydrogen atom with bulking agents to reduce dimensional alterations. Furfuryl alcohol (FA) with maleic anhydride (MA) catalyst is used for wood furfurylation (Schneider, 2012). Wood dimensional stabilization is supposed as result of FA polymers grafting to cell wall polymers. Modification of wood with FA is one of the modification techniques on an industrial production level that is now in the phase of product improvement and development of new application areas (Sandberg et al. 2017).

The objectives of the given research were: 1) to attain maximal modification of wood cell wall by saturation with FA with subsequent polymerization catalysed by formic acid vapours and 2) evaluation of FA modified wood hydrothermal durability by cycles of hydrothermal impact (HTI).

Two different series: 1) oven dried and 2) with moisture content of 13.4%, pine (*Pinus silvestris* L.) wood specimens were continuously impregnated with FA. Then FA excess was removed from wood by conditioning at temperature of 100 °C during 1 day. Afterwards, FA in wood was cured in formic acid vapours at 100 °C for 1 day. After modification, wood specimens were dried at temperature of 103 °C for 3 days.

The dried modified and reference specimens were exposed to the severe HTI. The HTI cycle consisted of: exposure to hot water at temperature of 75 °C, freezing at temperature of -20 °C and drying at temperature of 103 °C. Duration of the each stage was 3 days (total 9 days). Wood sample mass or volume was rationed against untreated, initial oven-dried mass or volume before treatment. The ratio of furfurylated and unmodified wood sample mass or volume was used for modification impact assessment in each HTI cycle.

Hot water absorption in the furfurylated wood was less than for reference wood 3 during the initial four HTI cycles. It indicates that FA polymers blocked the penetration of water into wood voids. The initial water anti-absorbance efficiency of modified wood was 85% and decreased to 75% during cyclic HTI, probably due to increase of voids accessibility to water.

The grafting with wood or bulking effects of FA polymer decreased the swelling in furfurylated wood in smaller degree in comparison to reference wood. Anti-swelling efficiency (ASE) decreased from 42% to 33% during eleven HTI cycles. ASE was 1.7 times lower than in acetylated wood in analogous conditions. The swelling of reference wood to furfurylated wood diminished from 1.7 to 1.5 times in the same HTI cycles.

Wood two stage furfurylation with extended FA absorption into wood cell wall and curing in the formic acid vapours did not protect wood cell components against interaction with water so well in comparison with wood acetylation. This result can be related to greater modification reagent volume irrespective of the high mass percent gain by furfurylation (128±3%).

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Termite and decay resistances of Bioplast-spruce green wood plastic composites

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Keywords: decay resistance, optical microscopy, termite resistance, water uptake, wood-plastic-composites (WPCs)

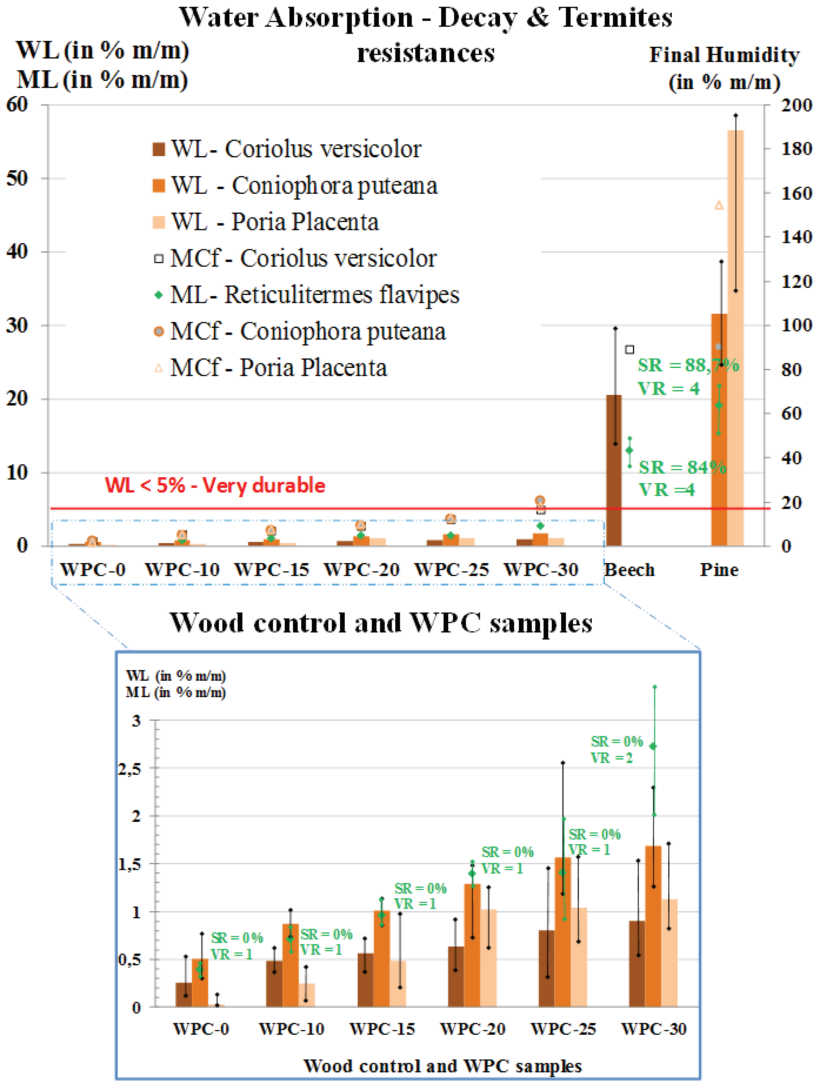
Wood-plastic-composites (WPCs) are very promising and sustainable green materials to achieve durability without using toxic chemicals. These materials, produced by blending biopolymers and natural fillers, permit us not only to tailor the desired properties of materials, according to the characteristics and ratios of wood and polymers, but are also the solution to meet environmental and sustainability requirements.

This study is focused on the durability evaluation of green WPCs made from a blend of an entirely biodegradable biopolymer (Bioplast GS2189 supplied by Biotec-Germany) and spruce wood sawdust. The spruce sawdust with different amounts (from 0 to 30% of total weight) was introduced into Bioplast and the obtained blends were injected into injection molds in order to manufacture the samples which are eco-friendly materials and are biodegradable in specific conditions. To determine the biological resistance of the produced WPCs, the decay and termite resistance tests, conducted according to screening tests adapted from European Standards, were carried out in relation to the wood content.

The results showed an increase of fungal and termite degradation levels with increasing amounts of wood in Bioplast. It also showed (Fig. 1) a relationship between the water uptake due to fungi growth and a decrease of the resistance against fungal and termites.

The optical microscopy observations performed on WPC specimen surfaces highlighted the presence of micro-cracks on the surface of WPCs, after their decay exposure, resulting in an embrittlement of the composite containing high wood content. These observations were discussed in order to understand the pathways of degradation mechanisms in our WPCs.

Although Bioplast partial substitution by wood decreased the resistance of WPCs to fungal and termite attacks, the elaborated WPCs in this study were still in the class of strongly durable material.



MCf = Moisture content after fungal exposure
SR = Termites Survival Rate
VR = Visual rating from termite degradation [0, no attack ; 1, attempted attack ; 2, slight attack ; 3,average attack ; 4, strong attack]
WL = Weight Loss due to decay degradation
ML = Mass Loss due to termite attacks

Figure 1: Water absorption (WA) and Weight loss (WL) due to Coniophora puteana, Poria placenta and Coriolus versicolor exposures, Mass loss (%) due to termite attacks of control and WPC samples, according to composite wood contents.

Acknowledgments: We gratefully thank to our colleagues Drs. S. Simon, P. Lourdin and C. Rigollet from ECAM Lyon (France) for helpful discussion and our students M. Blanchard and T. Tetaz for their contribution to this work.

Session 4: *Beyond wood modifications*

Wastewater remediation with formaldehyde free tannin-furanic foam powders

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Keywords: modified bio-resource, pollutant absorption, polyphenols, water remediation

Materials of a new generation have to be integrated into favourable life cycles. This means that every product has to be exploited as much as possible, considering extensive cascade usages and long serving time (Höglmeier *et al.* 2014).

Tannin foams are copolymers of two bioresources, tannin extract and the furfuryl alcohol obtained by dehydration and catalytic reduction of hemicellulose moieties. This material can be produced with tailored chemical and physical process parameters so that the range of product obtainable is very broad (Tondi and Petutschnigg 2016). These foams can be considered for the insulation of buildings because of their lightness (40-50 kg/m³), their good thermal conductivity (30-40 mW/m. K) and their good fire resistance (Tondi *et al.* 2016). From the chemical viewing angle, these foams have a strong aromatic and hydrophilic character due to the presence of flavonoid and furanic components in their matrix (Reyer *et al.* 2016).

Three different tannin extract from Acacia mimosa and namely, industrial original extract (OIE), methanol soluble (MeS) and acetone soluble (AcS) fractions, have been foamed with furfuryl alcohol under acid environment at 90 °C. The formaldehyde free foams were then pulverized, repeatedly washed with water and ethanol to remove any impurities and unreacted material and finally dried before undergoing the pollutant absorption capacity test.

Riboflavin and methylene blue have been selected as new generation pollutants. The adsorption trials were conducted as follows: An equivalent of 1 mg tannin foam powder was mixed with 5 ml of pollutant solution containing riboflavin or methylene blue at a concentration of 20 ppm and magnetically stirred for 48 h in the dark. Concentration of the pollutants was determined by UV/vis spectroscopy at 450 nm for riboflavin and 656 nm for methylene blue before and after the foam treatment.

In Fig. 1 the absorption capacity of tannin foams against the two pollutants is reported as percentage of removal. Standard deviation is indicated by error bars.

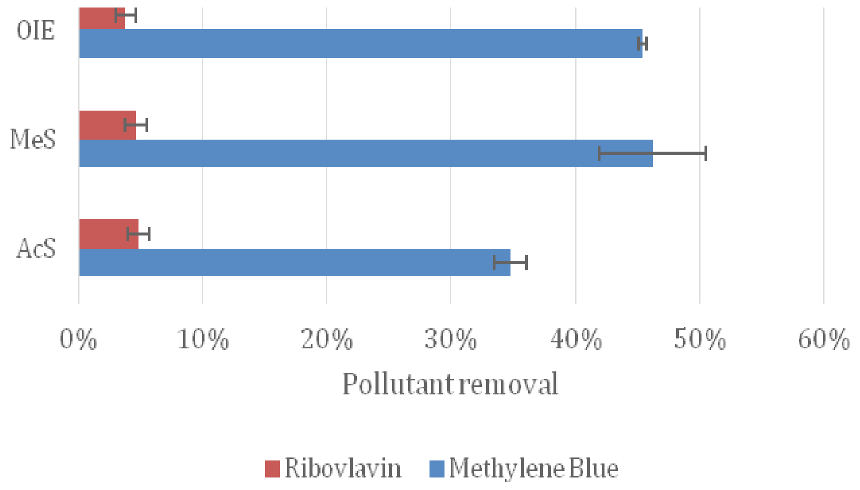

Figure 1: Pollutant removal by different foams.

It can be observed that generally the presented tannin foam powders contained absorption of Riboflavin (< 5%) but also showed very interesting absorption of methylene blue (> 30%).

This result suggests that the interaction between the tannin polymers and methylene blue is stronger, possibly because of the aromatic chemical structure presenting and charge distribution, while the riboflavin has a significant branch of aliphatic alcohols and it interacts more weakly with the tannin-furanic network.

Further, we can also observe that that the foams present similar absorptions against the two pollutants independently on the purification. Hence, the purification degree has no influence in case of absorption of riboflavin, while a decrease was observed by the foam produced with the tannin soluble in acetone (roughly 35% compared to 45%).

According to our previous research (Sepperer *et al.* 2018), this tannin fraction is poorer of proteins suggesting a possible involvement of the latter in the absorption process.

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The application of water pretreatment in the pellet production process

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Keywords: water pretreatment, pellet, properties, heating value

The properties of wood pellets depend on the processing parameters, but also on the characteristics of wood raw material, such as: size, chemical composition and moisture content (Stelte 2011). The application of pretreatment can change the structure of wood in such a way to enable the process optimization, improve the properties of end product and increase the utilization ratio of raw material. For example, the pre-extraction process removes part of hemicelluloses, which have the lowest heating value due to their high oxidation degree (Grammelis 2011). This results in the increase of the heating value of ligno-cellulosic raw material.

This paper presents the research on the effects of hot water treatment of beech particles on the properties of pellets. Sawmill residues from beech wood processing were comminuted using hammer mill. Obtained wood particles were then treated with water (wood:water = 1:4) in the autoclave, during 60 minutes at the temperature of 150 °C. After the treatment, particles were washed in plain water and air dried until the appropriate moisture content.

The size distribution of untreated and treated particles was determined on the laboratory vibrating sieve machine with the series of screens (1.2; 1.0; 0.5; 0.4 mm and blind screen), and since it did not differ significantly, this parameter was presumed to have no influence on the pellet properties. Water treatment did however reduce the content of hemicelluloses for 10.02%.

Three series of pellets were produced under the same processing conditions. Two pellet series were produced from the treated beech particles with different initial moisture content of 10.54 % (PT 10) and 20.46% (PT 20), while the third series was produced from the untreated beech particles (PNT). The pellets were produced in the pellet pressing machine equipped with flat matrix die of 40 mm in thickness and with the 6 mm diameter of holes. The temperature of the matrix was about 97 °C during processing. The characteristics of produced pellets are given in the Table 1.

Table 1: Characteristics of pellets produced from untreated (PNT) and water treated beech particles (PT 10 and PT 20)

Sample	Diameter* [mm]	Bulk density [kg/m³]	Equilibrium moisture content* [%]	Ash content [%]	Heating value, [MJ/kg]
PNT	6.34 ± 0.11	605.13 ± 4.37	10.40 ± 0.21	1.32 ± 0.14	18.266
PT 10	6.07 ± 0.04	729.63 ± 8.57	7.08 ± 0.17	1.00 ± 0.24	19.332
PT 20	5.95 ± 0.18	667.11 ± 4.84	10.60 ± 0.23	1.08 ± 0.08	18.445

* after conditioning (68%, 20.1 °C)

Diameter of the pellets PT 10 and PT 20 slightly differs from the nominal diameter (6 mm), which implies that the elasticity of treated particles has decreased. Consequently, the bulk density of the PT 10 and PT 20 pellet series has increased for 20.57% and 10.24%, respectively, in regard to the untreated pellets (PNT series). The ash content of both PT 10 and PT 20 pellets was about 20% lower than for the PNT pellets, since a large portion of mineral substances have been dissolved in water during pretreatment. Heating value of the PT 10 and PT 20 pellets (made from treated wood particles) was increased for 5.84 % and 0.98 %, respectively, in regard to the PNT samples. The samples of PT 10 pellets had the lowest equilibrium moisture content of 7.08%, after conditioning (68%, 20.1 °C). The moisture content between other two pellet series was similar, and significantly higher than for the PT 10 pellets, suggesting that the moisture content of raw wood material had significant influence on this property of pellets.

According to the results, it could be concluded that the water treatment has increased bulk density and heating value, and decreased the ash content of pellets. The moisture content of treated particles has influenced the pelleting process, thus affecting the properties of pellets, especially in regard to equilibrium moisture content, which also reflected on the heating value of pellets.

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Charring of Norway spruce wood surface as a surface modification technique

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Keywords: charring, scorching, surface, wettability, wood

If wood is subjected to sufficient heat, a process of thermal degradation (pyrolysis) occurs. Charring (also known as scorching) of wood substrate is a modification technique performed with a source of heat, which due to wood's low thermal conductivity, is limited to its surface (Lowden and Hull, 2013). As a protection technique for wood, it was used in most civilisations in history against influences of abiotic and biotic factors (Millis 2013). Wood's behaviour and its time-dependent thermal degradation is quantified by the charring rate, mainly determined by the type of wood (Frangi and Fontana 2003) or its microstructure, respectively (Zicherman and Williamson 1981). Another much more widespread protection technique is thermal modification. Thermally modified (TM) wood is well-known and widely used due to its appearance, better dimensional stability, and resistance to insects and fungi. After TM of normal wood, the surface and the bulk become dark brown and the surface is more hydrophobic. During both modification processes (charring and thermal modification) combustible gases are generated, accompanied by a loss in mass and cross-section dimensions (Frangi and Fontana 2003).

The aim of the present study was to compare the crucial surface properties of charred, TM and non-modified wood. Also, the question was whether the surface, prepared by charring, is similar in its properties to the surface of TM wood and if it can be surface-finished in the same way.

In the experimental part, samples of Norway spruce (*Picea abies* (L.) Karst.) wood with semi-radial orientation and dimensions of 300 × 75 × 20 mm were used. For the comparison of their surface properties, three types of specimens were prepared: charred, TM, and non-modified. Charring of the surface was performed with the flame of a gas (mixture of butane and propane) burner, and the surface was first gently scrubbed (to remove charcoaled part) and sanded afterwards. TM process was performed in vacuum at 230 °C i.a.w. Rep *et al.* (2012). Later, different analyses of the surfaces were performed: CIELAB colour measurements, contact angle (CA) measurements of water, diiodomethane and formamide droplets, calculation of the surface free energy, and FT-IR analysis. At the end, a transparent commercial water-based polyurethane coating was applied on the samples and adhesion strength of the created films was measured.

The results showed that the surface of wood after the described charring and sanding procedure was darker than the surface of TM wood. In general, colour changes are the result of reactions taking part through the thermal degradation of wood components, which combine caramelisation and Maillard reactions (Millis 2013).

The results of water droplet CA measurements showed that the process of TM and charring made the wood surfaces quite more hydrophobic, since the average CA on both modified wood types were about 20° higher than at non-modified wood (Fig. 2).

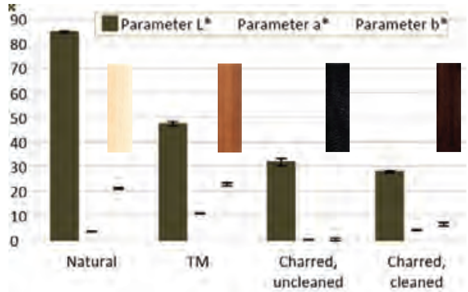

Figure 1: Colour parameters and appearance of different Norway spruce wood types.

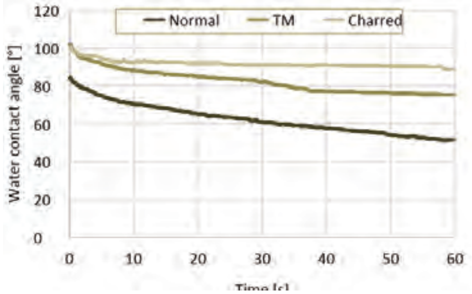

Figure 2: Water contact angles on different Norway spruce wood types.

FT-IR analysis showed that chemical reactions of wood structure in a thin layer under the charred surface are very likely, because of a probable anoxic environment (Nishimiya *et al.* 1998), similar to those of TM wood in vacuum. Adhesion strength of the coating system on charred and TM wood was lower in comparison to that on non-modified wood.

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Wood modification related researches at the University of Sopron

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Keywords: acetylation, densification, heat treatment, impregnation, pleating

Wood is a biodegradable material. Many traditional treatments currently exist to prevent these deteriorations, but they are based mostly on toxic materials. The aim is to get better performance of the wood, resulting in improvements in dimensional stability, decay resistance, weathering resistance, etc. Wood modification in different ways dates back decades at the University of Sopron (Simonyi Károly Faculty of Engineering, Wood Sciences and Applied Arts, Institute of Wood Science). During the last years, special attention was given to heat treatment processes in different media, acetylation, some impregnation processes and application of nano-scale materials as well as compression of wood perpendicular and parallel to grain. The main topics are described below:

- *Heat treatment in gaseous atmospheres*: Our autoclave is suitable for heat treatments up to 250°C temperature in vacuum, inert gases and steam. So far, the investigated wood species are oak, turkey oak, black locust, poplar, hornbeam, beech, maple, pine and spruce. By means of heat treatments exotic and homogeneous colour can be achieved in whole cross-section of the wood, for producing flooring elements. As a result of the treatments, durability improved, swelling decreased, and both tensile strength and impact bending strength decreased.
- *Heat treatment in different fluids*: Wood was heat treated in rapeseed-, linseed- and sunflower oil at 160-200°C. Swelling properties decreased by 20-60% and strength decreased less than by heat treatment in gaseous atmospheres. Colour changes were similar than by heat treatments in gaseous atmospheres. Further advantage of a heat treatment in vegetable oils is the short treatment time (Bak and Németh 2012). With applying paraffin as heat treatment medium, similar results were achieved, and moisture uptake decreased further (Németh *et al*. 2012).
- *Compression perpendicular to the grain (densification)*: In terms of low-density wood species, for example poplar, the property which limits the indoor utilization is the surface hardness, so the goal was to ensure the low-density material a high surface hardness. Using heat and steam treatment before densification of poplar wood by 30% (Thermo-Hygro-Mechanical treatment) hardness increased by 120% and reached the hardness of maple. In addition, the wood colour became brownish in 2-3 mm depth (Ábrahám *et al.* 2010).

- *Compression parallel to the grain (pleating)*: Before the compression procedure the high-density hardwoods have to be plasticized. The compression ratio is 15-25% of the original length, but the remaining shortening is always lower. The sample can be held compressed for a while (relaxation), which increases the property changes. During the process, the cell walls are deforming and the name “pleating” comes from this phenomenon (Báder and Németh 2018). Pleating results in a high decrease of modulus of elasticity and a high increase in pliability.
- *Acetylation of wood*: Acetylation changes hydroxyl groups to acetyl groups. Focusing on poplar, its swelling decreased by 70%, and the mechanical properties remained unchanged. Black locust could not be effectively treated. However, as veneer or flake, good results were achieved. Equilibrium moisture content and fibre saturation point of hornbeam decreased by 58% and 33%, respectively, beside a slight increase in the density (Fodor et al. 2017). Its shrinkage decreased by 60-80%. Weight loss by three types of fungal decay was below 1%.
- *Other wood modification processes*: Impregnation of wood with nanoparticles improved the decay-resistance significantly, using already very low agent concentrations. Better results could be achieved by using zinc borate compared to zinc oxide. Impregnation with beeswax decreases the moisture uptake of wood significantly (10-40%) and it increases the durability in short term applications, thus it can be a natural-based preservative for wood (Németh et al. 2015).

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Networking in European wood research

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Keywords: European wood research network, 66.6% of EU economy average, wood property improvement, wood modification, bio-economy

International relationships and networking play more and more an important role in Europe (not only in the bio-economy research field) in order to be successful in European calls, project implementations, publications, conferences and stakeholder-interactions. The demands to do this are not only limited to mainly Southeast EU-countries with an economy average < 66.6% in order to be supported by EU-countries with an average of > 66.6% in scientific, technological and financial ways. The EU-countries > 66.6% can also gain from this relationship in making accessible new EU calls and projects by involving Southeast-European partners and helping to implement innovative products and open new markets in this region.

In our field of wood research, focussing on the investigation of wood and bio-materials and their property improvement by wood modification, the COST Action FP 1407 and the InnoRenew activities are predominant examples of successful research networks, also including Southeast European partners, who function here partly or mainly as project leaders.

Important network examples in wood research, joined by our Brno-group and participated, established or led by SE-European research institutions, are Slovenian-led projects:

- COST Action FP1407 ModWoodLife; Lead: University of Primorska (SI)
- InnoRenew CoE (GA 739574); Lead: InnoRenew-Group/ Izola (SI)
- EFOP-3.6.1 (Improving research, development & innovation); Lead: Sopron-Univ. (HU)
- Danube Network-Wood Research Centres (No. 01DS17011); Lead: HNE-Eberswalde (DE)
- Hungarian Danube-Co-financing (EU_KP_16-1-2017-0009); Lead: Sopron-Univ. (HU)
- HARDIS (bilateral CZ-AT-project in mechanical wood processing); Lead: Mendel-Univ. (CZ)
- InWood “The Establishment of an International Research Team for the Development of New Wood-based Materials” (CZ.1.07/2.3.00/20.0269); Lead: Mendel-Univ. (CZ).

Examples of two integrating Hor2020-projects, just under development as proposals, in the ERA-Net: ‘Wood Value Chain’ (Participants: DE, SE, UK, AT, CZ, SI; Lead: HNE-Eberswalde) and ‘TWINNING’ (Participants CZ, SE, DE, AT; Lead: MENDELU in Brno), enable the Brno research team to deepen and widen their network activities in wood research and the bio-economy (Fig. 1).

Figure 1: Implementation of the Brno-Group into the European Wood Research Network.

Important research fields and outcomes our research network is focussing on:

- Widening the utilization of lesser-used wood species (Robinia, Eur. Chestnut, Poplar)
- Characterization of wood properties for traditional and future applications
- Improving wood properties by wood modification with non-biocide impregnation agents from native origin (plasticisation, densification, thermal-treatment, chemical impregnation; Rademacher et al. 2017a & b).
- Application of new material in music instruments, furniture, flooring, and exterior utilizations.

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Session: *Short Term Scientific Missions*

Engineered wood products in contemporary architecture

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Keywords: EWPs, architecture, modified wood, case studies

We often talk about an idea for a building, a structure with integrated materials where shape is the result and not the reason. Aesthetics is the aspect of design and technology that most closely relates to art, where colour, shape, texture, contrast, form, balance, cultural references and emotional response are important aspects. Architecture, of which construction is a part, is the responsible handling of nature and landscape to combine “the place and the use”, a truly meaningful combination of place and experience. It is possible to build something with a fine feeling where everything is built in relation to use and function, where design and technology diverge from art in their aim to create a product that is both useful and attractive, meeting the challenge of holding together the values of practical utility and aesthetic appeal. By using validated eco-friendly materials, e.g. engineered wood products (EWPs), in combination with innovative methods of modifying wood, new business opportunities for the timber construction industry can be created. Contemporary timber architecture mirrors the conversion from classical construction techniques to the use of new wood-based materials. EWPs offer technical and spatial innovations and make possible the use of materials and constructions as new standards for the future (Fig. 1).

Figure 1: Examples of innovative timber constructions, from the left: a) La Seine Musicale in Paris, b) House of bread in Asten, Austria, and c) Kilden Performing Arts Centre in Kristiansand, Norway.

EWPs offer greater design freedom and address the design requirement of ensuring that all places offer the same quality, helping to bridge the divide between function and hierarchy. EWPs are an ideal material for Restorative Environmental and Ergonomic Design (REED) because they satisfy the general tenets of the design concept (pattern, standard and idea), sustainability and a connection to nature. There are different types of interior environments in which occupants benefit from restorative environment and REED (Fig. 2).

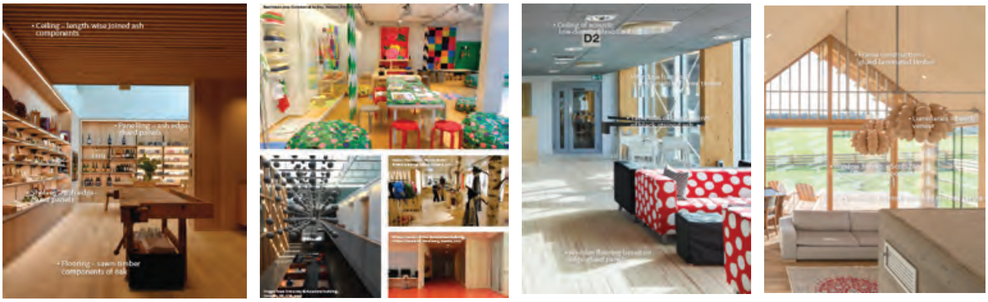

Figure 2: The use of EWPs in interiors as a result of fruitful cooperation between architecture and engineering (Kitek Kuzman *et al.* 2018; Sandberg *et al*. 2018).

Wood modification is a process used to improve the physical, mechanical or aesthetic properties of sawn timber, veneer or wood particles used in the production of wood composites and EWPs (Fig. 3). The reason for wood modification is to meet increasing global environmental concerns, and wood modification must therefore fulfil three aspects:

1. the modified wood should not exhibit toxicity in service,
2. the modified wood should not release toxic materials at the end of service, and
3. the modified wood should be non-biocidal in providing biological resistance.

Nowadays, EWPs illustrate the system and its specific application in contemporary architecture, i.e. integrated design and construction with aesthetics tied to the construction system and methodology. The case studies where a timber construction meets the goals of sustainability through its architecture provide an understanding of the use of EWPs and modified wood.

Figure 3: Examples of modified wood in construction, from the left: a) The Moses Bridge of acetylated wood in Fort De Roovere, the Netherlands, b) façade of thermally modified timber, private house in the Netherlands, and c) Outlook tower of acetylated timber in Fort De Roovere.

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Effect of silane treatment on mechanical properties of degraded wood

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Keywords: degraded wood, silane treatment, visco-elastic behaviour, Dynamic Mechanical Analysis

The results of a study on new methods for waterlogged wood conservation clearly showed that organosilicon compounds with different functional groups can effectively stabilise the dimensions of waterlogged wood during drying (Broda *et al*. 2018). However, to establish this kind of treatment as a practical method of conservation, better understanding of the properties of the treated degraded wood is needed, including its mechanical characteristics. This was the aim of the presented research.

The studied material was chemically degraded pine wood, treated with a solution of 50% silane in 96% ethanol using the oscillating vacuum-pressure method. Three organosilicon compounds were used for wood modification: Methyltrimethoxysilane (MTMS), (3-Mercaptopropyl)trimethoxysilane (MPTES) and 1,3-Bis(diethylamino)-3-propoxypropanol)-1,1,3,3-tetramethyldisiloxane (DEAPTMDS). Untreated and sound pine samples were used as a control.

Dynamic Mechanical Analysis (DMA) was performed using a Triton Technology DMA. The samples of dimensions ca. 20x10x3 mm (r x l x t) were analysed using a single cantilever mode in the temperature range from -150°C to 150°C. A dynamic force of 0.5 N was used.

DMA is a technique which enables determination of glass transition temperature (T_g) of a homogeneous polymer system and of the individual thermal transitions within a heterogeneous material, such as the amorphous components of wood (lignin and hemicelluloses). Moreover, the effect of various diluents on the visco-elastic response of wood can also be observed using this method (Kelley *et al*. 1987). This allows better understanding of the contributions made by individual wood components and the applied silane within the treated wood.

Example output from the performed DMA analyses is presented in Fig. 1. In the untreated wood, the lowest peak in tan δ, or the γ dispersion, can be attributed to molecular motion in the polysaccharides (amorphous cellulose and hemicellulose), while the β peaks (at intermediate temperatures from -38 to +66°C) relate to site exchange of moisture (Kelley *et al*. 1987). Silane treatment of samples decreased wood moisture content, and this is commonly reported in silane modification systems. Therefore, in the case of the treated samples, a slight shift of the γ peak towards higher temperatures, and change in location of β peaks was observed, in comparison with untreated wood.

In Fig.1b tan δ response for the treated samples, an additional peak was observed, which was presumably associated with the presence of particular silanes. The location of this peak was distinctly different for the three silanes studied. For example, in the case of the MPTE-treated samples, a sharp decrease of storage modulus (E’) at a temperature of about -100°C can be observed. It further indicates that the tan δ peak which occurs at this temperature is associated with T_g related to the silane, as it is characteristic for a large-scale segmental motion which is specific for a glass transition (Kelley *et al.* 1987). However, in the case of chemically degraded wood treated with the same silane the decrease of E’ was not visible. This could be explained by the different chemical reactivity of the silane with particular wood polymers. As sound and degraded wood differ in their chemical composition, the reactivity with chemicals can also be expected to differ.

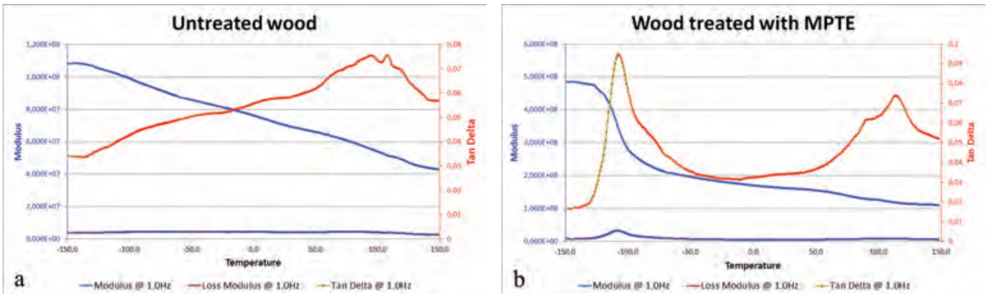

Figure 1: Storage modulus (E’), loss modulus (E”) and tan δ response of: (a) untreated and (b) MPTE-treated sound pine.

The experiment highlighted several phenomena relating to the effect of silane and moisture content on the observed DMA results in sound and degraded wood. This study undertaken during an STSM has led to planned additional experiments, which will be performed in the near future to explain additional phenomena observed from the DMA analyses.

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The impact of temperature increase rate during thermal modification on wood surface-coating interaction

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Keywords: thermal modification, temperature increase rate, coating penetration, adhesion strength

The properties of thermally modified wood (TMW) are affected by characteristics of the substrate and parameters of the thermal modification treatment (TMT) process. The duration of the TMT process can be reduced by the increase of the speed of reaching the treatment temperature. This approach can be significant from an economical point of view for industrial (commercial) use. On the other hand, lowering of the total process time of TMT by reduction of time needed to reach the treatment temperature can be justified only if the properties of TMW during use are not threatened. This paper analyses how the speed of reaching the specified temperature during TMT of wood affects the interaction of coating and wood surface.

Samples of ash (*Fraxinus excelsior* L.) and maple (*Acer pseudoplatanus* L.) wood were treated at temperature of 200°C, with a difference in the time required to reach specified treatment temperature. In the short-term regime (I treatment) the total process lasted for approximately 4 days, while in the long-term regime (II treatment) the total process time was approximately 6 days. For the purpose of comparison of effects of different types of coating, half of the samples were finished with water-based (WB) coating and the other half with polyurethane (PU) coating.

FT-IR spectroscopy revealed differences in spectra of TMW in comparison to untreated ones for both wood species. Between samples of TMW, the changes in samples modified by II treatment were more accentuated, especially at wavenumbers related to functional groups within the lignin molecules.

The difference in the penetration depth of coatings was found between unmodified samples of ash (limited to the first row of cells) and maple wood (1 to 2 rows of cells underneath the surface). In the case of TMW samples, the deeper penetration (from 2 to 6 rows of cells) was found for samples of II treatment for both types of coatings. The difference in penetration depth of different types of coating was not observed for TMW samples. For samples of II treatment, deeper penetration was observed in maple samples compared to ash samples, which can be related to higher quantity and easier accessibility of vessels in the maple samples.

The measurements of adhesion strength using a pull-off test resulted in cohesive failure of TMW. These results confirm the finding of previous research that pull-off test results are influenced by the reduced strength of TMW as a substrate rather than being solely determined by the interface bonding (Altgen and Militz 2017). In addition, it was stated that cohesive failure in elements of wood-coating system can be expected when heat treated ash samples were finished with waterborne coating (Herrera *et al.* 2015).

The cross-cut tests revealed that the adhesion strength between coating and wood surface was affected by TMT process (Fig.1), for both types of coating. Higher penetration depth of coating into wood samples modified by II regime did not lead to increase in adhesion strength (measured by cross-cut test).

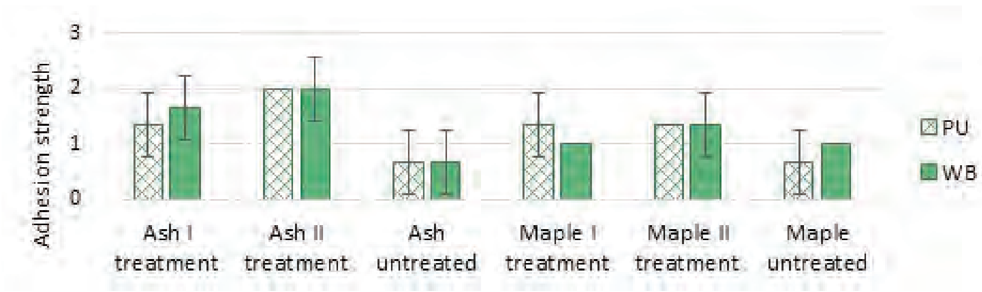

Figure 1: Adhesion strength between coating on surface of untreated and TMW samples of ash and maple wood measured by cross-cut tests.

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Cutting forces assessment when machining wood over all grain orientations – example of thermally modified poplar

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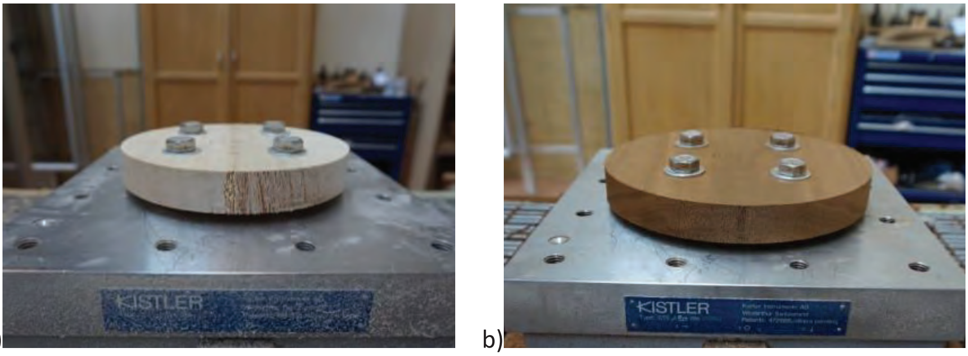
Keywords: cutting forces, milling, grain orientation, poplar wood, thermal modification

The use of thermally modified wood today is getting more and more frequent in different uses: internal furniture because of the darker colour or internal use in wet conditions and external use because of its higher durability and dimensional stability. It is also getting easier and easier to find this product on the market. Even if thermally modified wood is not a new product, the efforts of researchers until now have been focused mainly on treatment processes, chemical analysis, durability assessment, dimensional stability assessment or mechanical assessment. The machining of modified wood is something not very explored yet. Some information about handling, machining and gluing of this material can be found on Finnish ThermoWood Association (2003). The quality after machining has also been assessed as described in Sandak *et al*. (2017). The cutting forces as well as the specific cutting coefficients are however not investigated. In this paper, a new method based on the machining of a wood disk was used. The general approach was described in Goli and Sandak (2016). This study focuses on the force signal acquisition and the development of a data analysis system able to calculate accurate cutting forces and specific cutting coefficients for various grain orientations. The process was tested over different wood species and wood-based products. Among them, we considered machining of unmodified and thermally modified poplar. The disks were fixed on a tri-axial dynamometric platform for the measurement of cutting forces. The same disks (one for thermally modified wood and one for unmodified wood) (Fig. 1) were machined with different cutting depths (0.3, 0.7 and 1.1 mm) and the forces were measured on two axes in order to calculate the specific cutting coefficients when machining this product with different grain orientations.

a) 

b)

Figure 1: Massive (a) and thermally modified poplar samples (b) after machining.

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Experimental and numerical analysis of fracture toughness of thermally modified beech in mode II

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Keywords: thermally modified beech, fracture toughness, crack, digital image correlation, finite element analysis

Thermally modified timber (TMT) has been long recognized as an efficient and eco-friendly alternative to tropical species and wood treated by other techniques. Nevertheless, the range of feasible applications for TMT is limited by undesired side effects, such as reduction of mechanical properties including the fracture properties such as energy release rate (Majano-Majano *et al.* 2012). For examination of the fracture properties of wood in shear mode II, there has been developed a unique procedure based on so-called equivalent crack length to obtain fracture energies from global mechanical response (Wang and Qiao 2004, de Moura *et al.* 2006). The procedure is implemented in end-notched tests with three-point bending set-up. Such tests provide R-curves and may also be used to derive cohesive zone models for finite element analyses of fracture problems (Arrese *et al*. 2010). Therefore, this paper aims to evaluate the fracture properties TM beech wood in mode II by coupling three-point bending test and optical technique based on digital image correlation (DIC) and implementing the experimental data into the numerical model for later assessment.

As depicted in Fig. 1 right, the forces and deflections of the non-treated wood samples are greater than the thermally modified specimens. Additionally, the image data from the 3-D DIC provided additional data such as displacement and strains helping in the analysis of the crack development. Fig. 1 left shows distribution of the shear strain (ε_{xy}) at maximal force (at effective strength). We see the highest shear strain is allocated at the crack tip. The crack development is not possible to see by naked eye, but using DIC, we may obtain the opening by listing horizontal displacements below and above the crack. The single-factor Analysis of Variance (ANOVA) on a level of $\alpha = 0.05$ showed that all three groups (reference, modified at 180 °C and 200 °C) differ significantly in terms of maximal strain energy release rate. Further, a numerical model of crack propagation was built based on the experimental data of cohesive law obtained using results from standard testing and

DIC. The numerical model uses special adhesive finite elements that enable to define bi-linear behaviour of crack propagation.

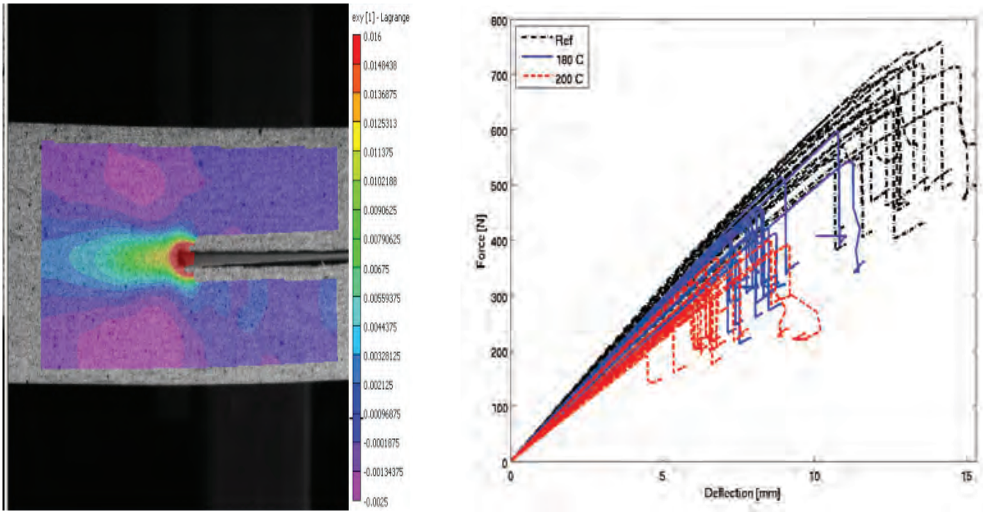

Figure 1: Shear strain at crack tip obtained using DIC (left) and force vs. deflection diagrams for all three tested groups.

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Mechanosorptive creep tests on thermally modified wood

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Keywords: creep, mechanosorption, poplar, thermally modified wood

Aim of the STSM

The aim of this study is to show the principal advantages brought by the use of thermally modified wood in the field of construction and to develop mathematical models able to predict the long-time mechanical behaviour of this type of material.

Material and Methods

Mechanosorptive creep tests have been performed on unmodified and thermally modified wood in 3-points bending (Fig. 1). The specimens were cut by splitting in order to get a straight grain and sized to 15×5×160 mm³ (RxT×L). This geometrical configuration, with a small thickness, was chosen to speed up moisture diffusion in the sample. Then the specimens were loaded at 10% of rupture load (Saifouni *et al*. 2016). Elastic modulus and bending strength were estimated from literature data.

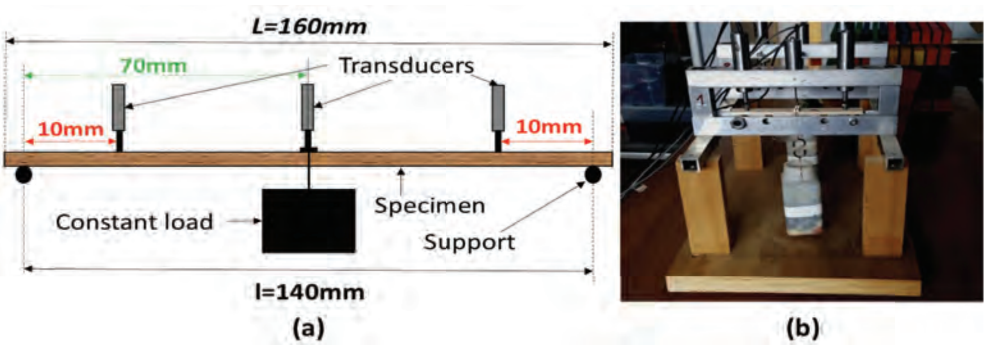

Figure 1: Experimental setup.

The tests were performed in a climatic chamber, where relative humidity (RH) can be varied between 35% and 80%. In our case, three RH levels were used (45%, 55% and 75%). The initial RH was 55%. After 19 hours of creep it was set to 75%. This RH level was kept constant for 5 h, then brought back to 55%. Again after 19 h, a second RH cycle was applied, with a drying period at 45% RH during 5 h, and the chamber brought back to 55% RH. Finally the load was removed and RH kept at 55%.

Results

Fig. 2 shows the results of a complete test with variations under load and recovery after unloading. It was performed on unmodified (PT10) and thermally modified (PM8 – 24h at 200°C – ThermoVacuum system) Poplar wood (*Populus Alba L.*). Although no clear conclusion can be drawn due to the lack of repetition, the results suggest a stiffening effect of the thermal modification. A more detailed analysis of the results is under way.

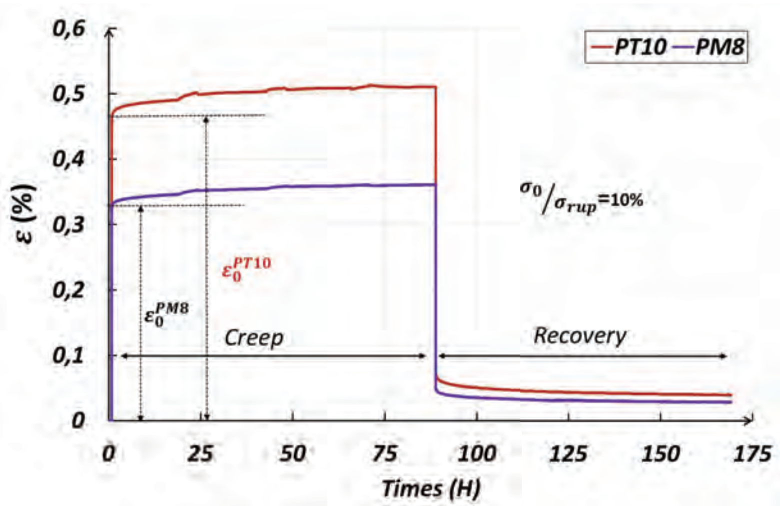

Figure 2: Mechanosorptive behaviour of thermally modified (PM8) and unmodified poplar wood (PT10).

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Characterisation of subfossil oak wood from central Serbia using SEM and FTIR spectroscopy

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Keywords: subfossil oak, FTIR spectroscopy, SEM

It is known that the conditions in which the subfossil wood was deposited have a major influence on its properties. For this reason, analysis of subfossil wood from central Serbia will contribute to the entire community which is engaged in the research of this material. A better knowledge of the properties of this material will affect the improvement of its preservation and processing technology, as well as its better utilization. Previous studies conducted on this material have shown that its properties are different from the recent oak. Although the density of the subfossil oak is not significantly lower than the density of the recent oak, its mechanical properties are lower by about 10% to 40% (Veizović *et al*. 2018), while dimensional changes are almost twofold. SEM analysis and FTIR spectroscopy techniques were used in order to indicate the chemical and anatomical changes that have taken place in the subfossil wood. This could reveal the cause of the change in all properties of the material. Images made using SEM showed the changed structure of the subfossil oak wood (Fig. 1). The collapse of subfossil wood cell wall is clearly visible. The cell collapse can be one of the explanations for increased dimensional changes of subfossil wood. Some cell walls are completely degraded, which is probably a consequence of biotic factors (fungi or bacteria). It can also be seen that lignin in the middle lamella is highly degraded. Some cell walls in subfossil oak wood were detached from the middle lamella (ML). The obtained spectra of the subfossil oak were compared with the spectra of recent oak. There was no big difference in lignin ratio which was for recent oak 0.92 and for subfossil 0.95. The hemicellulose ratio of recent oak was 1.82, compared to 0.59 for subfossil wood. This significant difference shows that there was clear loss of hemicelluloses during aging of wood. Similar results were also shown by Hudson-McAulay (2016). In Figure 2, it can be visually determined that the size of the hemicellulose tip for recent oak is higher compared to the subfossil oak which matches the data about hemicellulose ratio. This suggests that the absorption of infrared light due to the C = O binding of hemicellulose to the subfossil oak wood is lower, which could also mean their smaller proportion, comparable to lignin and cellulose. All these anatomical and chemical changes coincide with changes in mechanical and physical properties of this material.

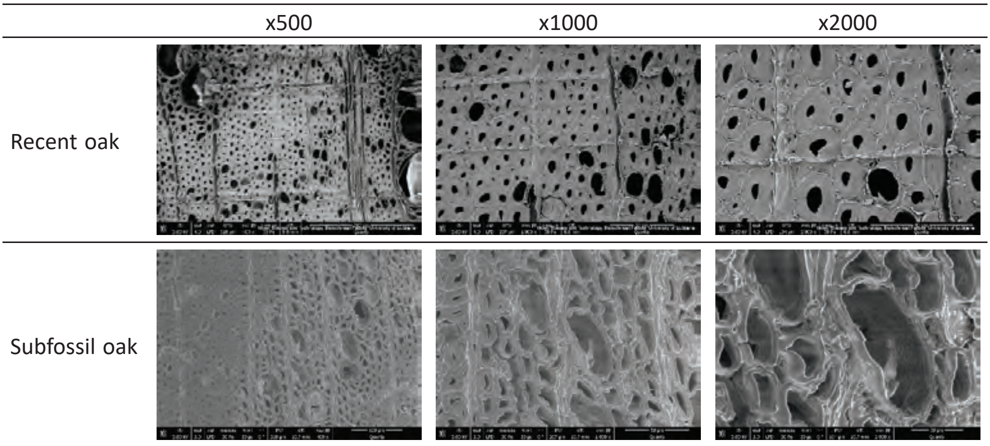

Figure 1: SEM images of Recent and Subfossil oak (Group 2 – high density and high dynamic MOE., Group 3 – high density and low dynamic MOE). Recent oak images (Novak 2018)

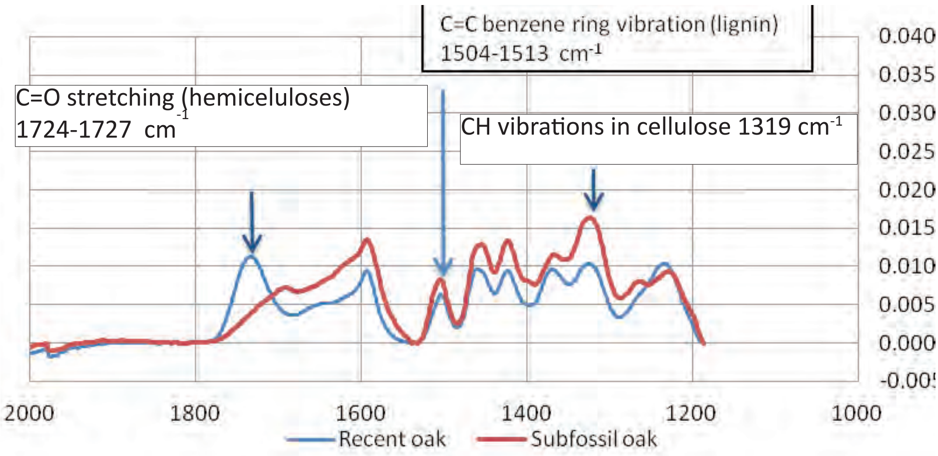

Figure 2: Recent oak (Belec 2017) and Subfossil oak FTIR spectra

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Generalised thermal modification kinetic model of poplar wood under different technologies

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Keywords: wood, thermo-hygro modification, kinetic model, energy of activation, mass variation

Wood modification kinetic modelling is of major interest to assess different technologies to modify solid and engineered wood products to improve given properties as well as environmental impacts. The present research extends the work of (Goli *et al.* 2014; Marcon *et al.* 2018). These works provided a model of the degradation kinetics when thermally modifying wood in a conventional ventilated oven. In the present study, 2 different wood modification processes, applied to poplar wood (*Populus Alba* L.) from the same tree, were assessed through mass variation kinetics: ventilated open air oven and saturated steam in autoclave. Mass variation was chosen as physical descriptor to assess the wood’s final quality because it is already proven by (Candelier *et al.* 2016) that the mass loss is a good descriptor of thermal modification.

Experiments and Results

The measured dry mass variation in ventilated oven and autoclave are plotted in Fig. 1(a). Those kinetics are modelled using the time-temperature superposition method exposed in (Goli *et al.* 2014; Marcon *et al.* 2018) taking into account a temperature effect on the pre-exponential factor to enhance the predictive ability of the model (not considered in kinetic models up to now).

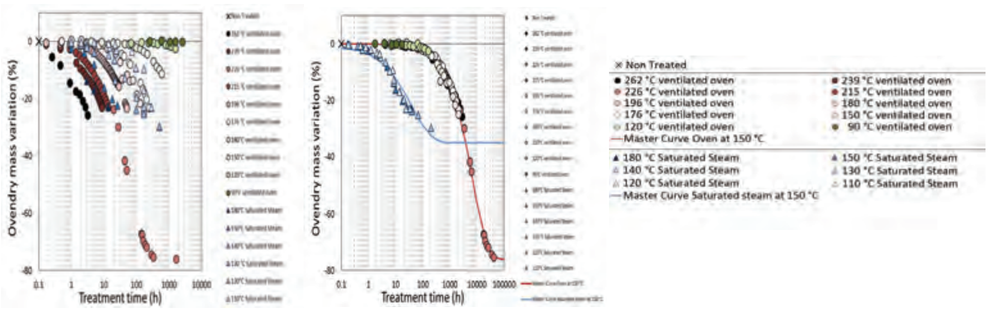

Figure 1: (a) Experimental mass variations at oven dry state after exposition to ventilated oven and saturated steam in autoclave treatments; (b) Master curves identified on the experimental mass variation measured after time shifting to the reference temperature T_{ref} = 150 °C for the ventilated oven and saturated steam heat treatment conditions.

Thus, master curves at the same reference temperature of 150 °C are identified for both kinds of treatment (open-air at dry state and saturated steam) and represented in Fig. 1(b).

Conclusions

The main results concerning the study and Fig. 1-2 are summarized as:

- Saturated steam conditions are exhibiting rather faster modification than ventilated open-air conditions.
- The maximum mass variation that can be expected for poplar solid wood under saturated steam conditions is only about 35% compared to the maximum mass loss in open air oven reaching 76%. This is the consequence of the presence of oxygen in the oven and not under saturated steam; oxidation reaction cannot occur under saturated steam environment.
- Both heat treatments mass variations can be accurately modelled using time-temperature equivalency and Arrhenius' law as described in (Goli *et al.* 2014) and later improved in (Marcon *et al.* 2018).

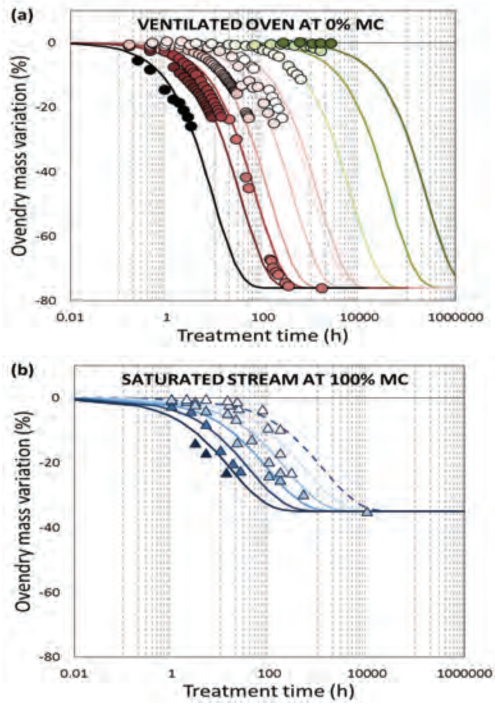

Fig. 2: Mass variation kinetics models prediction confronted to the corresponding experimental data.

A generalised kinetic model, taking into account in its formalism physically based elements such as the treatment temperature (Marcon *et al.* 2018), the calorific media heat capacity, the humidity (Zeniya *et al.* 2019) and the oxygen concentration (Goli *et al*. 2014), is the final goal and outcome of this ongoing research work.

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Properties of multi-layer plywood made from combinations of densified and non-densified veneers in one structure

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Keywords: black alder, birch, densification, plywood

The aim of the study was to evaluate selected physical and mechanical properties of multi-layer plywood samples made as combinations of densified and non-densified veneers within the same plywood structure. Defect free samples of rotary-cut veneers made of birch (*Betula verrucosa* Ehrh.) and black alder (*Alnus glutinosa* L.) were used. To densify the veneers, a constant hot-pressing schedule was applied under laboratory conditions, such as a temperature of 180°C under a constant pressure of 2MPa for 3 min time span. The plywood samples made of 5 veneer layers were manufactured using a commercial urea-formaldehyde (UF) resin under laboratory conditions. A constant hot-pressing schedule was applied while the glue spreading rate varied as a function of the plywood type as shown in Table 1. The adhesive ratios were reduced to almost 50% of the recommended glue spreading rate used under industrial conditions. Two plywood panels were manufactured for each one of the plywood types.

Prior to any process step and test, both veneers with and without pre-treatment and the produced plywood structures were kept under constant room conditions at 20±2°C and 65±5% relative humidity for a week. The bending modulus of rupture (MOR) and the modulus of elasticity (MOE) have been determined according to EN 310 standard. The reported results represent the average of ten samples for each plywood type. In the case of black alder, the bending strength and the modulus of elasticity have been enhanced once the process of densification was applied to veneer before plywood production and also for the combined plywood structures made of both densified and non-densified veneers. It appeared that the selected glue consumption values provided relevant results in terms of mechanical properties. Such findings are in accordance with the specialty literature for plywood made of densified veneers (Bekhta *et al.* 2009, Chen *et al.* 2015, Arruda and Del Menezzi 2016). In the case of birch, only a small decrease was noticed for the same mechanical properties (Fig. 1 a, b). Such plywood structures resulted in improved physical and mechanical properties of the final product when using decreased glue consumption. A positive environmental impact based on low emissions of toxic compounds as part of the low cost of the value-added finished product is expected.

Table 1: The pressing parameters for plywood manufacturing

Type of plywood	Veneer type	Code	Density [kg/m³]	Glue spreading [g/m²]	Pressure [MPa]	Temperature [°C]	Pressing time [s]
Control non-densified	black alder	AN	628.2 (20.8)	80	1.8	130	270+60
	birch	BN	727.8 (18.0)				
Control densified	black alder	AD	590.4 (10.7)	60			
	birch	BD	737.2 (15.9)				
Combinations ± densification	black alder	±A	630.7 (8.3)	70			
	birch	±B	724.8 (19.7)				

Values in parenthesis are standard deviations

a)

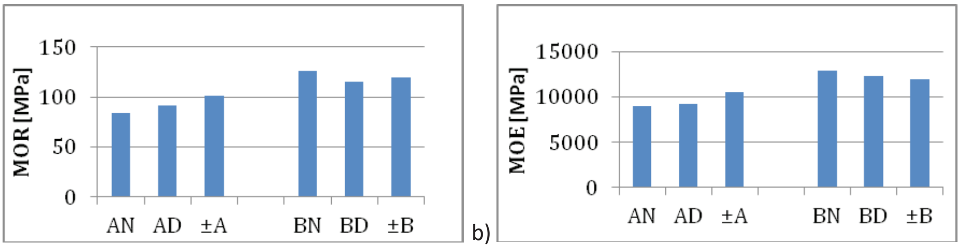

Figure 1: Results of bending strength (MOR) (a) and modulus of elasticity (MOE) (b) as a function of plywood type and species.

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Decay and insect resistance of modified wood with epoxidized plant oils

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Keywords: epoxidation, plant oils, decay and insect test

In this study, the efficiency of modified wood with epoxidized plant oils against fungi and insects was investigated. Unsaturated double bonds in linseed and soybean oils were epoxidized with hydrogen peroxide. Samples of Scots pine sapwood (*Pinus sylvestris* L.) were treated with epoxidized plant oils by means of empty cell process. Two different retention levels: 80-140 kg/m^3 (A) and 170-270 kg/m^3 (B) were targeted. In order to improve the plant oils performance against fungi and insects, secondary impregnation with boric acid and oil-boric acid emulsions were employed. Modified wood samples (15×25×50 mm (R×T×L)) were tested against brown rot (*Coniophora puteana* BAM Ebw15) and white rot fungi (*Trametes versicolor* CTB 863A) according to EN 113 (1996) standard. Prior to decay, half of the samples were leached in water according to EN 84 (1980). Samples were subjected to fungal attack for 16 weeks in a climate room (22 ±2 °C and 70±5% RH).

The insects test was carried out according to EN 47 (2005) standard for determining the efficiency of epoxidized and non-epoxidized oils against larvae of *Hylotrupes bajulus.* Sample with dimensions of 15 × 25 × 50 mm along the grain were conditioned at 20±2 °C and 65 ± 5% RH prior to the test. Three openings, approximately 3 mm deep, were drilled in a diagonal pattern on the upper longitudinal face of each test sample. A newly hatched larva of *H. bajulus* was carefully inserted head first in each opening. After exposure to the larvae, the test specimens were placed on a filter paper dish in jars and stored in a controlled chamber at 20 ± 2 °C and 65 ± 5% RH for 4 weeks. After the exposure, each sample was examined by X-rays to check for dead larvae or presence of frass, which is a sign of an initial larval activity. The state of larvae (dead, living, not recovered) was recorded for all test samples.

Decay test results against *C.puteana* and *T.versicolor* revealed that the modified wood samples with epoxidized oils improved fungi resistance when compared with untreated samples, but boric acid treatments significantly decreased weight losses (Table 1).

According to the insects test results, modified wood samples with epoxidized oils showed resistance against larvae of *Hylotrupes bajulus*.

Table 1: Decay test results

Treatment		Coniophora puteana		Trametes versicolor	
		Leached [%]	**Unleached** [%]	**Leached** [%]	**Unleached** [%]
3% BA+ ELO	A	2,19 (0,81)*	1,94 (0,31)	1,81 (0,61)	2,76 (0,40)
	B	2,50 (0,27)	2,99 (0,34)	2,54 (0,32)	3,84 (0,48)
3% BA + LO	A	3,02 (0,22)	2,23 (0,24)	2,71 (0,37)	2,87 (0,31)
	B	2,14 (0,39)	0,64 (0,34)	3,08 (0,83)	1,42 (0,29)
ELO/ 3% BA emuls.	A	2,99 (0,34)	2,16 (0,32)	3,23 (0,43)	2,94 (0,80)
	B	4,19 (0,72)	4,03 (0,62)	3,09 (0,57)	4,80 (1,28)
ELO	A	12,32 (0,54)	6,45 (0,06)	13,95 (1,98)	8,91 (1,53)
	B	7,64 (0,37)	8,19 (0,24)	10,17 (0,79)	10,40 (1,99)
LO	A	4,95 (1,52)	3,00 (0,33)	9,56 (1,86)	3,75 (0,21)
	B	2,90 (0,33)	3,30 (0,79)	5,33 (1,88)	2,67 (0,17)
3% BA	-	2,77 (0,23)	1,86 (0,32)	4,71 (1,87)	1,79 (0,64)
3% BA+ ESO	A	2,71 (0,60)	2,81 (0,32)	3,76 (0,34)	3,16 (0,31)
	B	3,91 (0,69)	4,00 (1,82)	4,10 (0,58)	7,28 (3,20)
3% BA + SO	A	2,39 (0,50)	2,22 (0,28)	2,56 (0,45)	2,79 (0,36)
	B	3,42 (1,04)	2,93 (0,56)	3,60 (0,61)	2,57 (0,28)
ESO/ 3% BA emuls.	A	3,65 (1,06)	3,22 (0,49)	3,23 (0,88)	3,71 (0,91)
	B	3,23 (0,43)	7,64 (1,31)	2,84 (0,57)	7,79 (0,85)
ESO	A	6,02 (0,75)	10,80 (1,25)	9,68 (1,17)	10,27 (1,83)
	B	7,18 (0,21)	9,04 (0,66)	11,62 (1,17)	9,53 (0,37)
SO	A	3,81 (0,06)	3,47 (0,39)	10,48 (2,04)	4,58 (0,89)
	B	3,69 (0,70)	3,25 (0,39)	9,96 (0,96)	3,64 (0,48)
Control	-	-	61,47 (6,62)	-	23,35 (6,53)

ELO - Epoxidized linseed oil; ESO - Epoxidized soybean oil; LO - Linseed oil; SO - Soybean oil; and BA - Boric acid; A - retention level 80-140 kg/m^3; B - retention level 170-270 kg/m^3
* Numbers in parenthesis are standard deviations.

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Poster **Session**

Strategies for improvement of visibility and acceptance of modified wood

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Keywords: modified wood, interaction with materials, human perception, product visibility

Perception is defined as a recognition and interpretation of sensory information. Perception also includes how we respond to the information and how we interact with the surrounding environment. Knowledge about human sensory perception of materials is playing an increasingly important role in the selection and combination of materials within manufactured products (Zuo *et al*. 2016). One of the main recent advances in wood technology is the development of modified wood. New products offer enhanced durability and improved performance in unique ways. Wood modification includes several treatments that change material properties on different levels (Hill 2006). They include active modifications, that change chemical nature of materials (e.g., chemical, thermal, enzymatic), or passive, that do not alter materials chemistry (e.g., impregnation, surface treatments). Consequently, various properties of wood are changed to different extents.

A previous study demonstrated that not only physical characteristics of materials are important in materials experience, but also sensory properties of materials and the meanings and emotions triggered by them (Karana *et al*. 2015). Customers formulate a perception of the product partly based on its sensory properties (e.g., colour, texture, sound, smell, taste) when experiencing the product for the first time. Sijtsema *et al*. (2016) highlighted the importance of obtaining insight into perceptions of laypeople about new technologies. In some cases (e.g., genetic modification), new technologies are not generally accepted and might even be rejected by consumers, even if professionals see many benefits in them. Similarly, "modified wood" might impair the impression due to specific background knowledge (e.g., containing "chemistry" and/or manipulated/no more natural). Material perception shall be investigated in certain contests and applications. Modified wood used for food contact materials should be safe for human health and do not transfer organoleptic characteristics of food (European Comission, 2004). Therefore, the selection of materials with particular sensory properties and placing them in certain usage contest might enhance the product's overall image and the market's perception of its value (Zuo *et al*. 2001). The project "Perception of modified wood" is a joint project of seven partners with the overall goal to investigate reception of modified wood in order to improve its visibility and acceptance. Within this research, we aim to investigate preferences in using modified wood from psychological, physiological and cultural perspectives. Influences of modification processes on human health and wellbeing will be investigated with preference tests by using both virtual and real samples. Special focus will be directed towards implementing alternative assessment methods (e.g., wearable sensors that can capture physiological responses) while assessing respondents.

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Volatile organic compounds emitted from heat and vacuum-heat treated wood

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Keywords: Scots pine, heat treatment, vacuum-heat treatment, volatile organic compounds

Heat treatment improves dimensional stabilization and decay resistance of wood, but reduces mechanical properties due to the higher temperatures from 180 °C to 260 °C (Hill 2006). Vacuum-heat treatment is carried out in a chamber in which oxygen is reduced by the application of vacuum. *Termovuoto*, a new process, has been introduced to wood modification using vacuum (Ferrari *et al*. 2013). In recent years, the production of heat treated wood has increased with several methods such as Thermowood, Platowood or Retified wood. Heat treated wood can emit various volatile compounds (VOCs) depending on the wood species and treatment conditions. Releasing volatile organic compounds from wood can present a health concern (Hofmann *et al*. 2013). However, there are a relatively small number of studies dealing with the volatile organic compounds emitted from heat treated wood.

In the present study, Scots pine (*Pinus sylvestris* L.) sapwood and heartwood samples were exposed to heat and vacuum-heat treatment at 180 °C and 200 °C for 2 hours. The field and laboratory emission cell (FLEC) and gas chromatography–mass spectrometry (GC-MS) system were used subsequently in detection of VOCs. Based on the obtained results, the increase in heat treatment temperature increased the total volatile organic compound (TVOC) emitted from the wood samples. The analysed samples resulted in 35 volatile organic compounds. The VOCs, pentanal, hexanal, α-pinene, β-pinene, camphen and limonene were found in higher quantities compared to other compounds. Some compounds such as benzene, trichlorethylen, furfural, ethylbenzene, myrcen, and octanal were emitted in very low quantities from sapwood and heartwood after heat treatment. Pfenol and 1,4-dichlorobenzen were not detected in the samples before or after heat treatment.

The effect of vacuum-heat treatment was evident particularly in the heartwood samples. Vacuum-heat treated samples released higher TVOC from heartwood samples compared to heat treated samples. α-pinene was the major compound in higher quantity released from the heartwood samples by vacuum-treatment.

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In-service performance of floorings with modified wood top layer

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Keywords: steaming, abrasion resistance, indoor service test, deformation

From recently, oak (*Quercus petraea* and *Quercus robur*) has been the most widely used wood species in European parquet production as a face layer. It is possible to use other wood species for this purpose which are primarily used as firewood due to their smaller dimensions or lower yield (large ratio of wood defects), but still provide the necessary technical parameters for parquet production. The smaller log diameter is not a big problem in the field of parquet production because of the small dimensions of the parquet friezes. Furthermore, wood defects can be easily removed in production. The following wood species are suitable for parquet production: hornbeam (*Carpinus betulus*), turkey oak (*Quercus cerris*) (Todaro 20121), and black locust (*Robinia pseudoacacia*). By investigating different production technologies for oak face layers, it was found that 80% to 85% of the costs are raw material costs (Orłowski and Walichnowski 2013). This result shows the importance of raw material selection.

Due to its extraordinary hardness, decorative appearance and small available dimensions, black locust wood is expected to be an excellent material for strip parquet flooring. The steaming of the black locust face layers was done in an industrial scale steaming chamber at atmospheric pressure and at two different temperatures. Temperatures were: 85 °C (light steamed) and 95 °C (dark steamed), with the same duration of 48 hours. Four different face layers were investigated: oak (O), natural (unsteamed) black locust (N), light steamed black locust (L), and dark steamed black locust (D). The core and bottom layer was made of spruce. Flooring was installed in a heavy-wear student dormitory stair landing (Fig. 1.). Through normal use in a busy student dormitory stair landing, the flooring elements have changed colour rapidly but have not suffered significant changes in structure and performance.

Based on this experiment, the effect of steaming on abrasion resistance of flooring top layers was not found to be significant. Oiling significantly increased the abrasion resistance of the steamed specimens, but the differences in abrasion resistance are more likely due to differences in density and annual ring orientation (radial, tangential) than to surface treatment. This makes the evaluation of abrasion tests difficult, but this shortcoming could be compensated by a different experimental design, which includes density as one of the variables and a larger sample size. In general, the measured differences between samples, although sometimes statistically significant, were small from a practical point of view. This is especially true when comparing the abrasion properties of black locust with those of oak, as with one method oak attained superior ratings, while with the other black locust performed better. After the service period, tests were conducted to show how indoor service affects Brinnel-Mörath hardness (HBM). As seen in (Fig. 2), a significant decrease in surface hardness can be observed.

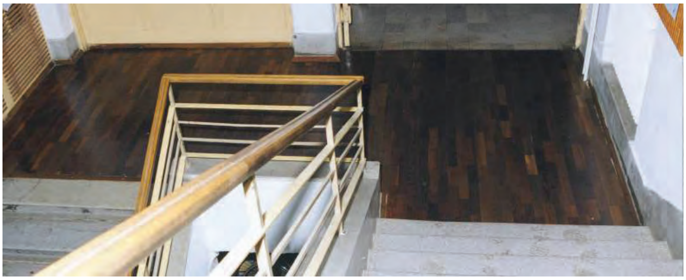

Figure 1: The appearance of the floor after installation.

Regarding dimensional changes and deformation, tests yielded similar results for oak and natural black locust, whereas light steamed black locust performed even better, and dark steamed black locust proved to be inferior to all other observed materials. Both the in-service and the laboratory tests indicated that wood density, grain orientation and element structure (three-layered-plywood) appeared to affect the performance of the floor to a much higher degree than the different structure and treatments of the materials used. Black locust wood proved to be suitable for indoor flooring applications.

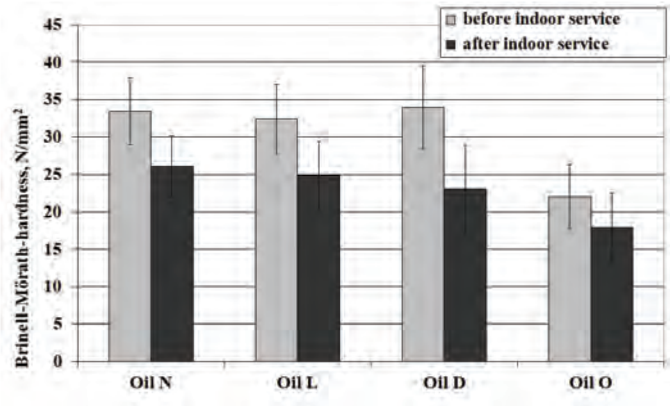

Figure 2: Brinell-Mörath hardness values before and after indoor service. (Legend: Oil - surfaces coated with transparent oil, O - oak, N -natural (unsteamed) black locust, L- light steamed black locust, D - dark steamed black locust).

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Thermo-hydro mechanical densification process of *Nothofagus pumilio* and *Nothofagus antarctica* and the effect of annual width ring on modulus of hardness, and dynamical mechanical properties

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Keywords: beech, densification, densification rate, hardwood, modification

Nothofagus pumilio is the most important native timber species from the southern Patagonia region of Argentina and Chile (Martínez Pastur *et al*. 2000). Since 1990, foresters are managing forests of *N. pumilio* to increase their economic value. To increase growth potential in the forests one of the strategies is to sustain even-aged forests, which can lead to better growing conditions (Martínez Pastur *et al*. 2009). However, fast-growing conditions affect the physical/mechanical properties of wood, sometimes negatively. *N. pumilio* (lenga) and *N. antarctica* (ñire) both belong to a group of trees collectively referred to as southern beech. These species typically have an intense red color that is attractive for use in furniture. To expand the range of applications beyond furniture, methods to improve the physical/mechanical properties of southern beech have been investigated. One such method is a densification process that uses a combination of heat and pressure. This technique has been successfully applied to other fast-growing tree species, increasing their mechanical properties (Kutnar *et al*. 2008; Kutnar *et al*. 2015). Schwarzkopf *et al*. (2017) used a similar process to design 3-layer composites from lenga and ñire wood. They evaluated mechanical properties and showed that densification increased modulus of elasticity (MOE), modulus of rupture (MOR), and modulus of hardness (MOH). Based on these results, this study will further investigate and optimize the use of densification with lenga and ñire for in-depth understanding of modification in wood structure. The objective of this study is to apply densification treatments to lenga and ñire assessing key mechanical properties correlated with annual growth ring width.

The approach taken in this study is to apply two densification treatments developed in previous studies and assess: MOH, set-recovery (SR) after submerging and drying cycles and dynamic mechanical properties. These results will then be analyzed with respect to annual growth ring width to assess the effect that the forest management regime had on them.

Samples of lenga and ñire originating from Tierra del Fuego, Argentina were provided by foresters in that region. A total of ninety-six specimens were manufactured with dimensions of 46 mm x 5 mm x 300 mm (width x thickness x length). Before densification, specimens were conditioned at 20°C and 65% relative humidity (RH), weighed, and measured at three locations for the width and thickness. Sections for ring width measurement were cut and measured. The remaining parts of the specimens were densified with a hot-press using two temperatures (160 °C and 170 °C). Thin steel plates (2 mm) were used as hard stops to achieve a target thickness. Immediately after the densification process was completed, measurements were taken to assess the densification. Additionally, after one week of conditioning, specimens were measured for the last time to assess the spring-back effect. Due to the low thickness of densified specimens, standardized hardness testing is not ideal and MOH will be measured. To achieve this, specimens for MOH will be prepared from four square parts of each board and glued together into 4-layer composites. A Janka imprint ball will then be used to assess MOH. Two specimens from each board were cut for dynamic mechanical analysis with two orientations. Specimens for set recovery test will be used to assess the set-recovery over time exposed to water.

Average annual ring width for ñire and lenga was 2.315 mm and 1.135 mm respectively. On average, specimens from ñire had initial density of 646 kg/m^3 and specimens from lenga 548 kg/m^3. After the densification a density ratio of 1.85 for ñire and 2.12 for lenga was calculated. In general both wood species exhibited higher spring back for densification process using 160 °C as compared to 170 °C.

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Enhancing outdoor durability of heat treated wood surface by photo-stabilization with waterborne acrylic coating using bark extract

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Keywords: acrylic coating, bark extract, heat treatment, UV absorbance, weathering

High temperature heat treatment is an effective technique which improves wood properties such as biological stability, dimensional stability and heat insulation. It also turns the natural color of wood into a dark brown color (Hakkou *et al*. 2006). Heat treated wood is especially used for decorative purposes in construction materials. However, color of heat treated wood is not stabile, as the surface color turns gray or white in outdoor conditions if left unprotected (Kandem *et al*. 2002). To overcome this problem, an environmentally friendly and transparent coating needs to be applied to protect the heat treated wood surface against outdoor conditions without altering its appearance and texture. Acrylic-based coatings containing natural antioxidant (bark extract), UV absorber and lignin stabilizer have been found to be very effective in protecting heat treated wood in outdoor conditions (Saha *et al*. 2011, Kocaefe and Saha 2012).

In this study, the durability of two wood species (oriental beech and Scots pine) treated with heat treatment are compared under accelerated weathering conditions (672 h). Both the color change data and macroscopic evaluation indicate improvement in protective characteristic of waterborne acrylic coating when bark extracts are used in place of commercially available UV stabilizer (Fig.1). The artificial weathering test was used to compare the durability of acrylic coatings containing bark extract (test) and without any bark extract (control) in outdoor conditions. Four different tree bark species (black pine, calabrian pine, alder and oak) were used for the test group. The UV absorbability and physical properties (viscosity, solid content and pH) of waterborne acrylic test and control coatings were investigated. The adhesion strength and dry film thickness of the control and test coatings were determined on the heat treated and untreated wood surfaces. The results showed that although acrylic coating with bark extracts were more efficient compared to acrylic coating without any bark extract in color stabilization of heat treated wood, it failed to protect untreated wood effectively after 672 h of accelerated aging. Furthermore, UV-VIS spectroscopy analysis showed that the UV absorption effect of acrylic coatings containing bark extracts was higher than the control coating. Compared to untreated wood surfaces, coating adhesion strength and dry film thickness values on heat treated surfaces were found to be quite high. This degradation was not due to the coating adhesion loss or coating degradation during accelerated aging; rather, it was due to the significant color change of acrylic coating with bark extract.

Figure 1: Macroscopic evulation of waterborne acrylic coating systems applied to beech and pine wood before and after artifical weathering test (A: black pine; B: calabrian pine; D: alder; M: oak; K: control).

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Changes in wood surface properties caused by aging techniques

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Keywords: aging, structuration, ammonia fuming, potassium permanganate dye

Wood aging techniques have been used for a long time in the history of furniture and flooring making (Rodel 1999) and are still popular nowadays (Weigl *et al.* 2009, Miklecic *et al.* 2012). Modification methods help to achieve a unique colour of wood, comparable with antique timber (Matsuo *et al.* 2011) or exclusive species (Weigl *et al.* 2012). The aim of this work is to determine the impact of traditional wood aging techniques such as: surface structuration, ammonia fuming and potassium permanganate dye on the wood colour, gloss, resistance to scratches (scratch width with the accuracy of 0,01 µm) and abrasion (mass loss with the accuracy of 0,001 g). The species chosen for this study are the ones most frequently subjected to wood aging treatment: oak (*Quercus* Sp. L.) and Scots pine (*Pinus silvestris* L.) - wood with high and medium durability.

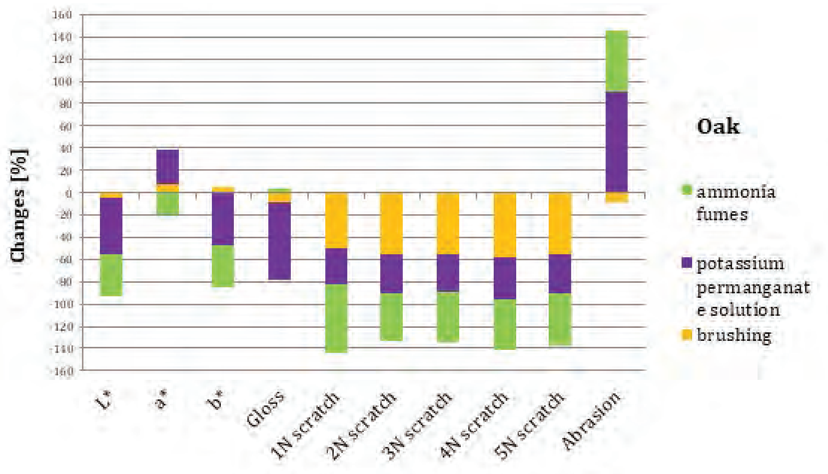

Figure 1: Impact of treatment methods on the change in oak wood properties.

In case of oak wood (Fig.1), the most significant changes in the tested parameters took place as a result of potassium permanganate treatment in measurement of abrasion (decrease by 91%). Ammonia dyeing also caused significant changes in abrasion (decrease by 54%), as well as brushing (increase from 50% to 58%). In addition, treatment with ammonia improved the resistance to scratches (increase from 44% to 61%). The smallest changes in the tested surface parameters were caused by brushing, in case of the colour parameters (change from 4% to 9%). All the modification methods increased the resistance of wood surface to scratches, while brushing had no significant influence on colour or abrasion changes.

In measurement of abrasion, pine wood (Fig.2) was most significantly affected by dyeing with potassium permanganate (decrease by 140%). The smallest change for the b* colour parameter (no change) was observed for brushing treatment of samples. In case of pine wood, contrary to oak, ammonia fuming did not affect the L* parameter values. The influence of modifications for oak and pine wood is similar in case of resistance to scratches (the smallest impact of potassium permanganate), but for oak wood this influence was much higher. Differences between wood species were observed in the colour parameters (for oak, the smallest influence was observed for the a* parameter, while for pine in case of L* and b* parameters). Dyeing with a solution of potassium permanganate resulted in total change of wood colour (ΔE=37 for oak, ΔE=49,5 for pine), as well as with ammonia fuming in case of oak (ΔE=27,8). Ammonia fuming caused darkening of pine wood colour significantly (ΔE=4,1).

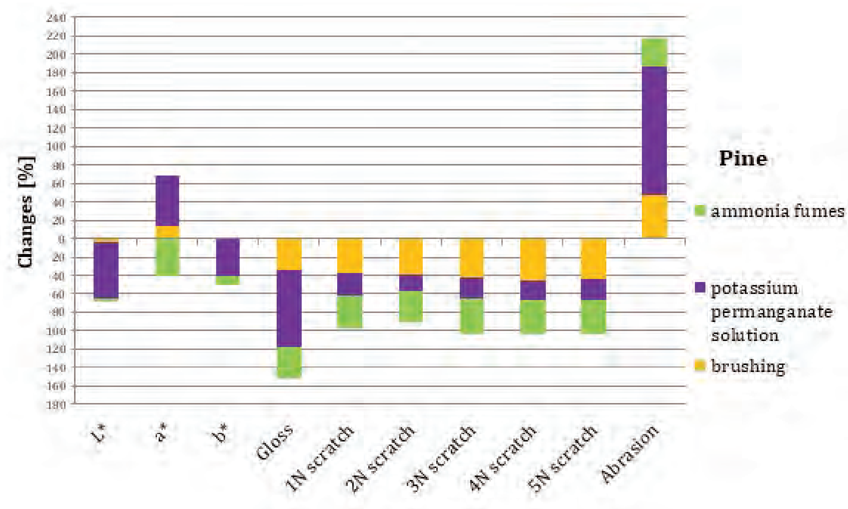

Figure 2: Impact of treatment methods on the change in pine wood properties.

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Photostability of thermally modified poplar wood coated with alkoxysilanes

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Keywords: thermal modification, poplar wood, photostability

The colour change after UV radiation is mainly caused by solar radiation and refers to both natural and thermally modified wood. Ayadi *at al.* (2003) showed that the characteristics of both materials are quite different. The surface of thermally modified wood changes its colour more rapidly than in the case of natural wood. Despite the different characteristics of materials, the mechanism of colour changes is related to lignin reactions, in both cases. The literature shows few methods of wood protection against UV light and, corresponding with this process, the colour changes. One of them involves the stabilization of lignin. Norrstrom (1969) presented that lignin contributes 80–95%, carbohydrates 5–20%, and extractives about 2% to the total UV absorption coefficient of wood. Another way to reduce photodegradation of wood is to reduce the penetration of UV radiation through the use of filters and absorbers of radiation. Usually, filters and absorbers form a transparent coating (Hill 2006). Furthermore, it is also possible to coat the surface of the wood with nanoparticles and silicones (Donath 2007, Kaboorania 2016).

The aim of the study was to determine the effectiveness of selected wood protectants against photodegradation.

The study was performed on heat-treated poplar wood (*Populus nigra*). The following protecting agents were used for the wood treatment: UV filter (Tinuvin® 5050), and lignin stabilizer (Lignostab) as a reference protectants, and a model preservative based on methyltrimethoxysilane (MTMOS) or [3-(2-aminoethylamino)propyl]trimethoxysilane (AATMOS) and two types of nanocellulose (cellulose nanocrystal-CNC and cellulose nanofibril-CNF) (Table 1). The protected wood samples were submitted to an accelerated aging procedure simulating the natural weather conditions according to the following conditions: relative humidity of air 65%; temperature of wood surface 65°C; irradiance 550 W/m^2, time exposure of 20, 50 and 100 hours. The colour change was examined with the use of DataColor 600® system CIELab.

Table 1. Characteristics of photostability agents within samples (type and its retention) and colour changes of treated wood (after impregnation and after 50 hours of UV radiation)

Sample ID	Silane		Acetic acid	Ingredient		ΔE after impregnation [-]	ΔE after 50 hours of aging [-]
	ID	Absorption [g/m²]		ID	Absorption [g/m²]		
A	AATMOS	9,25	-	-	-	4,4	9,5
B	AATMOS	8,90	-	CNC	0,97	5,3	8,1
C	AATMOS	10,30	-	CNF	0,92	2,5	10,1
D	AATMOS	9,75	+	-	-	3,5	9,4
E	AATMOS	9,50	+	CNC	1,06	4,1	9,2
F	AATMOS	8,95	+	CNF	1,03	3,3	9,0
G	MTMOS	9,90	-	-	-	3,8	11,5
H	MTMOS	10,45	-	CNC	1,02	2,3	11,2
I	MTMOS	10,40	-	CNF	0,92	1,4	10,9
J	MTMOS	9,70	+	-	-	3,3	11,6
K	MTMOS	10,65	+	CNC	0,97	2,0	14,3
L	MTMOS	11,25	+	CNF	0,88	1,3	13,5
M	Tinuvin® 5050	-	-	Tinuvin® 5050	7,2	6,9	12,4
N	Lignostab	-	-	Lignostab	7,1	7,3	10,8

Impregnation of wood with MTMOS did not result in visible changes of the wood color. This preservatives proved to be ineffective in protecting wood color against UV radiation as evidenced by the ΔE value (exceeding 11). Wood protecting products containing a UV filter or lignin stabilizer resulted in a clear color change immediately after impregnation (ΔE approx. 7). Its protective properties occurred to be insufficient after long-term exposure to UV radiation (ΔE exceeded 10). The coating with AATMOS demonstrated the best results in the protection of wood color against UV radiation (ΔE was lower than 9).

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Wood properties and extractive exploitation from thermally modified chestnut wood

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Keywords: thermo vacuum, extractives, wood properties, antioxidant activity, surface degradation

In the last years, there has been growing interest from researchers and industries to generate diversified, innovative and renewable products using on site bio-resources such as wood and tree residues (Todaro *et al*. 2017). In this respect, chestnut (*Castanea sativa* Mill.) wood has been chosen and used as a source of plant material. Chestnut wood was thermally treated (TMT) and compared to native wood by investigation of four main aspects: 1) changes of the physical and mechanical wood properties; 2) improvement of the extractive yield through the combination of thermal modification process and highly efficient extraction techniques; 3) evaluation of the antioxidant activity of extractives; 4) potential application of TMT extractives as protective means against weathering of black poplar and Norway spruce wood.

Chestnut wood was thermally modified at 180 °C for 3 hours and the effects of TMT treatment were evaluated by characterization of wood properties such as the mass loss, colour change and Modulus of Elasticity (MOE). For the preparation of extractives, chestnut wood was subjected to solid-liquid extraction by using three extraction techniques, namely maceration (ME), ultrasound assisted extraction (UAE) and accelerated solvent extraction (ASE). Then, the extraction yield, the content of secondary metabolites (polyphenols, flavonoids and tannins) and the antioxidant activity of extractives were determined. In particular, the radical scavenging activity by 2,2-diphenyl-1-picrylhydrazyl (DPPH), the reducing power (FRAP) and the inhibition of lipid peroxidation (BCB) were evaluated. Additionally, chemical characterization by Gas Chromatography-Mass Spectrometry (GC-MS) was also performed on obtained extractives. Finally, the possible efficacy of extractives in their radical-scavenging role was tested on UV-irradiated poplar and Norway spruce wood surfaces. For this purpose, the extractives from chestnut wood derived by ASE technique were used and the colour fastness and contact angle variation after artificial weathering were measured. Additionally, a FT-IR analysis on the photo-degraded surfaces was executed (Fig. 1). The findings acquired in this work provide some useful physical and mechanical information for future research and application of the thermal vacuum modification on chestnut wood. The detailed knowledge about the extractives (Fig. 2) from chestnut wood can contribute to better understand the effect of temperature during thermal treatment on the chemical composition and antioxidant activity of the extractives. Chestnut wood could be applied as a potential source of bioactive compounds for nutraceutical or pharmaceutical applications by selection of appropriate extraction techniques or as starting material to use in the wood industry.

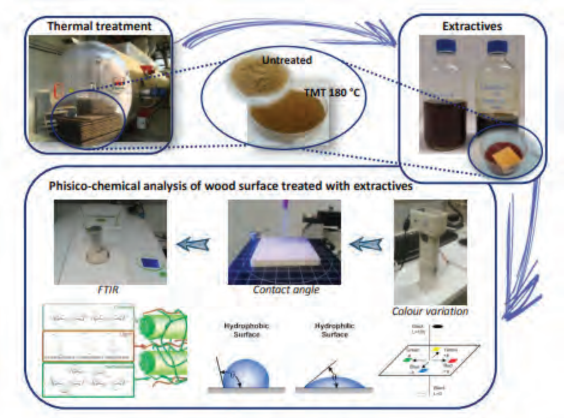

Figure 1: Experimental design of wood extractives used on poplar and Norway spruce wood surfaces.

Extractives	Treatment	DPPH (mg TE/g)			FRAP (mg TE/g)			β-Carotene (%AA1mg/mL)		
		ME	UAE	ASE	ME	UAE	ASE	ME	UAE	ASE
Chestnut	Ctrl TH 180 °C	✓	✓	✓	✓	✓	✓	✓	✓	✓

Extractives	Treatment	Yield (%)			TPC (mg GAE/g)			TFC (mg QE/g)			TTC (mg TAE/g)		
		ME	UAE	ASE	ME	UAE	ASE	ME	UAE	ASE	ME	UAE	ASE
Chestnut	Ctrl TH 180 °C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

LEGEND	
✓	Positive effect *(significant statistical difference)*
✓	Moderate influence *(no significant statistical difference)*

DPPH and FRAP expressed as mg of Trolox Equivalent per g of dry extract (mgTE/g); β-Carotene expressed as % of antioxidant activity (%A.A.) at 1 mg/mL; total phenol content (TPC) expressed as mg of Gallic acid Equivalent per g of dry extract (mgGAE/g); total flavonoid content (TFC) expressed as mg of Quercetin Equivalent per g of dry extract (mgQE/g); total tannins content (TTC) expressed as mg of Tannic acid Equivalent per g of dry extract (mgTAE/g).

Figure 2: Behaviour of extractives derived from untreated and thermally treated chestnut wood.

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Antimicrobial particleboards – part 1: preparation and strength

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Keywords: particleboards, nano-ZnO, internal bond strength, bending strength

When applying special additives to particleboards (PBs) with the aim to increase their antibacterial properties, a change in their mechanical properties may occur.

This paper gives information about the preparation, density and selected mechanical properties (internal bond strength according to EN 319 and bending strength according to EN 310) of one layer PBs modified with zinc oxide nanoparticles (nano-ZnO). The absolute dry mass of PBs consisted of 10 parts of wooden particles (9.5 parts of coniferous and 0.5 part of hardwoods) and of 1 to 1.24 parts of melamine urea formaldehyde (MUF) glue containing hardener, paraffin and 0, 2, 6, 12 or 24% wt. of nano-ZnO. The PBs were hot pressed at t = 210 °C, $p_{s\ max.}$ = 5.33 MPa, and with the pressing factor of 14 s/mm of thickness. The anti-bacterial and anti-fungal resistance of prepared PBs were also determined (Reinprecht and Vidholdová 2018).

The density of the nano-ZnO-treated-PBs (629 - 653 kg.m^{-3}) was very similar to the density of the control PB (644 kg m^{-3}) (Fig. 1).

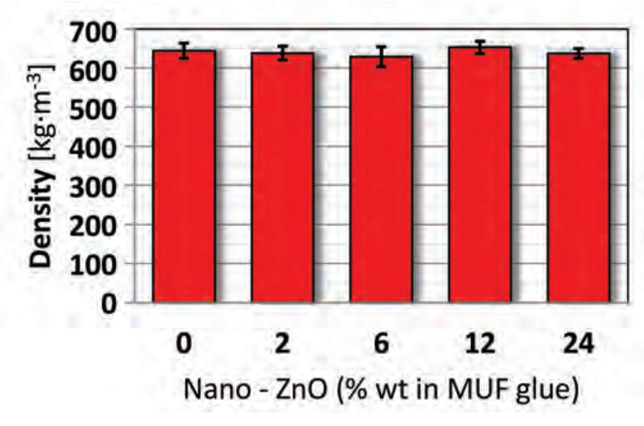

Figure 1: Density of particleboards treated with nano-ZnO.

Internal bond strength (IB): The increase of nano-ZnO addition in MUF gluecaused a continual decrease of the IB of PBs, from 0.49 MPa maximally to 0.30 MPa, i.e. about 38.7% (Fig. 2).

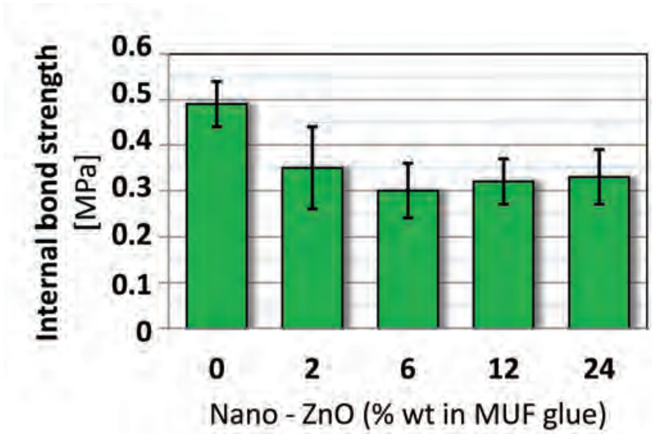

Figure 2: Internal bond strength of particleboards treated with nano-ZnO.

Bending strength (BS): The bending strength of nano-ZnO-treated-PBs decreased from 9.8 MPa maximally to 7.8 MPa, i.e. about 20.4% (Fig. 3). Decrease of BS was a smaller as of the IB, and simultaneously it was not apparently affected by the amount of nano-ZnO in PBs (Fig. 3).

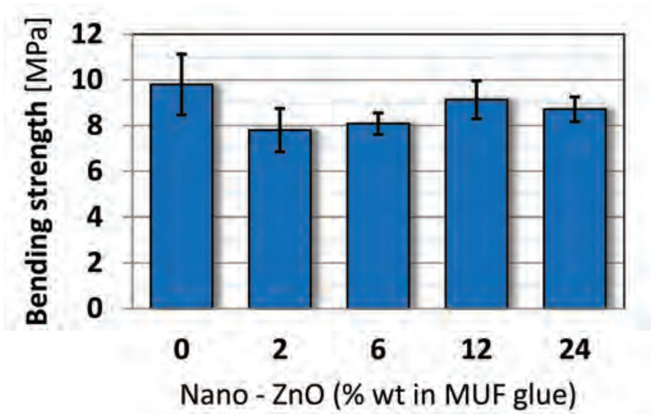

Figure 3: Bending strength of particleboards treated with nano-ZnO.

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Antimicrobial particleboards – part 2: resistance to bacteria and fungi

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Keywords: particleboards, nano-ZnO, bacteria, molds, decaying fungi

Particleboards (PBs) with improved antimicrobial properties are recommended for indoor occasionally moistened expositions, e.g. for kitchens, bathrooms or hospitals.

This paper gives information about the anti-bacterial and anti-fungal resistance of one layer PBs prepared by a traditional pressing process (Iždinský and Reinprecht 2018) from wood particles, paraffin and melamine urea formaldehyde (MUF) glue modified with zinc oxide nanoparticles (nano-ZnO) in the amounts of 0, 2, 6, 12 and 24% wt. (weight of solid nano-ZnO per solid weight of catalysed MUF glue).

Bacterial activity: The activity of bacteria on the top surfaces of the nano-ZnO-treated-PBs was measured using 1.0 McFarland scale of bacterial inoculum, when incubation lasted 48 h at temperature of 37°C. The activity of the Gram-positive bacterium *Staphylococcus aureus* has decreased maximally about 70% (i.e. from 0.40 up to 0.12 $\times 10^8$ CFU/ml) and of the Gram-negative bacterium *Escherichia coli* maximally about 50%(i.e. from 0.38 up to 0.19 $\times 10^8$ CFU/ml) (Fig. 1).

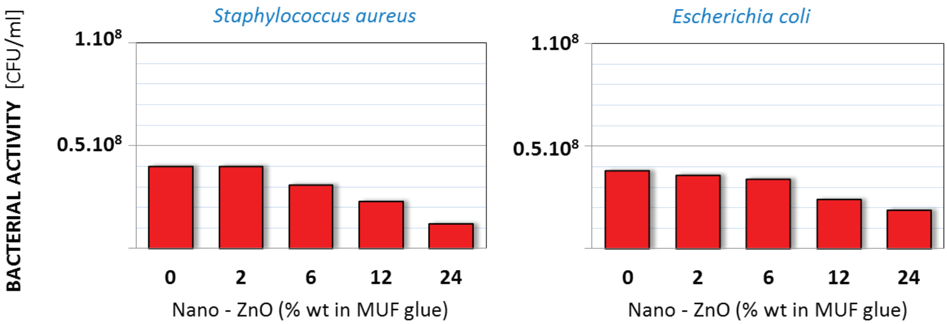

Figure 1: Activity of bacteria on the top surfaces of particleboards treated with nano-ZnO.

Growth of molds: The growth intensity of two microscopic fungi *Penicillium brevicompactum* and *Aspergillus niger* (according to partly modified EN 15457) on the top surfaces of the nano-ZnO-treated-PBs has decreased maximally about 49.8% and 62.6% on the final 21st day (Fig. 2).

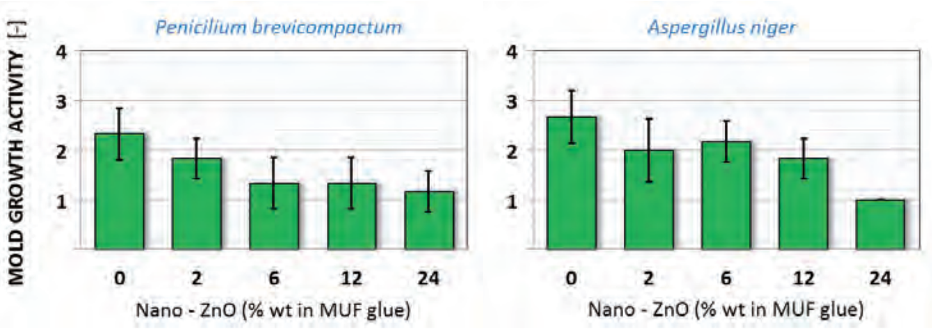

Figure 2: Growth intensity of molds on the top surfaces of particleboards treated with nano-ZnO.

Decay: The nano-ZnO-treated-PBs had an apparently improved resistance against the brown-rot fungus *Coniophora puteana* (according to partly modified ENV 12038), since their weight losses at a 6-week fungal attack exponentially decreased up to 85.7%, i.e. from 17.4% to 2.5% (Fig. 3). Similarly, Marzbani *et al.* (2015) determined for PBs bonded with nano-ZnO-modified-urea formaldehyde glues an exponential decrease of their weight losses at action of *C. puteana*, and also at action of the white-rot fungus *Trametes versicolor*.

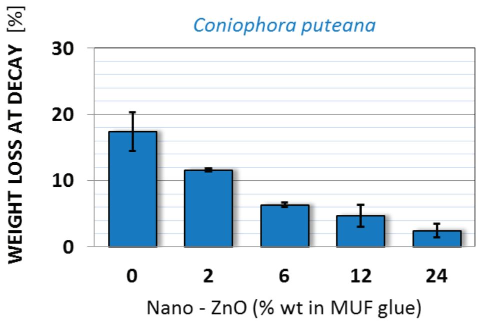

Figure 3: Weight losses of particleboards treated with nano-ZnO at action of *C. puteana*.

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Selected mechanical properties of lignocellulosic layered composites produced in various temperature conditions

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Keywords: plywood, resin, glue, composite, temperature

The state-of-art of wood-based composites research show, that in case of layered materials – like plywood – the significant factors, which determine the durability, the application ways, as well as the conditions of use, are the composite usage environment parameters (Frihart 2014, Gillespie and River 1976, Vasileiou *et al*. 2011). The aim of this study was to examine the influence of bonding line temperature in layered wood composites on the selected mechanical properties of pine plywood produced with different adhesives: phenol – formaldehyde (PF), melamine – urea – formaldehyde (MUF), urea – formaldehyde (UF), polyvinyl acetate (PVAC) and polyurethane (PUR). In the scope of research the examinations of modulus of rupture during static bending (Fig. 1), modulus of elasticity (Fig. 2), as well as density profile (Fig. 3) were conducted.

On the basis of the results it was noticed that plywood, which was bonded with PUR and PF resin showed the highest values of mentioned mechanical properties. As the bonding line temperature ranged from 20˚C to 100˚C, the modulus of rupture decreased from 27% for UF, MUF, PF and PUR adhesives up to 37% for PVAC adhesive with respect to the initial strength value at 20˚C. In the same temperature range, the modulus of elasticity decreased from 21% for UF, MUF, PF and PUR adhesives up to 52% for PVAC adhesive.

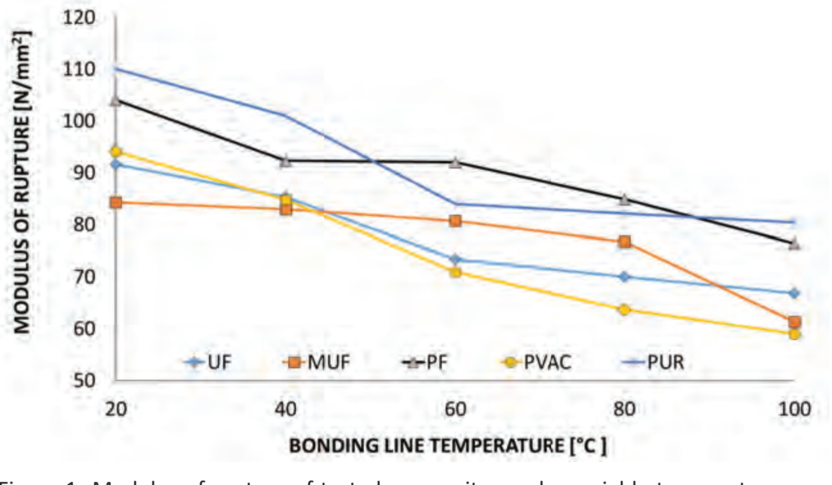

Figure 1: Modulus of rupture of tested composites under variable temperature.

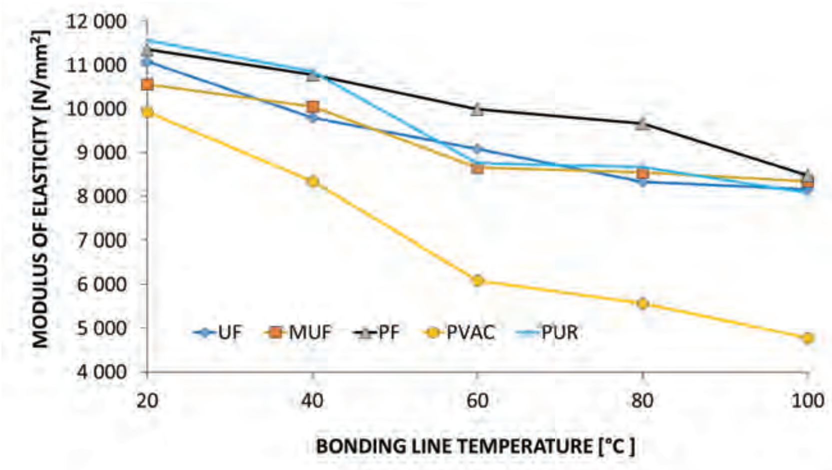

Figure 2: Modulus of elasticity of tested composites under variable temperature.

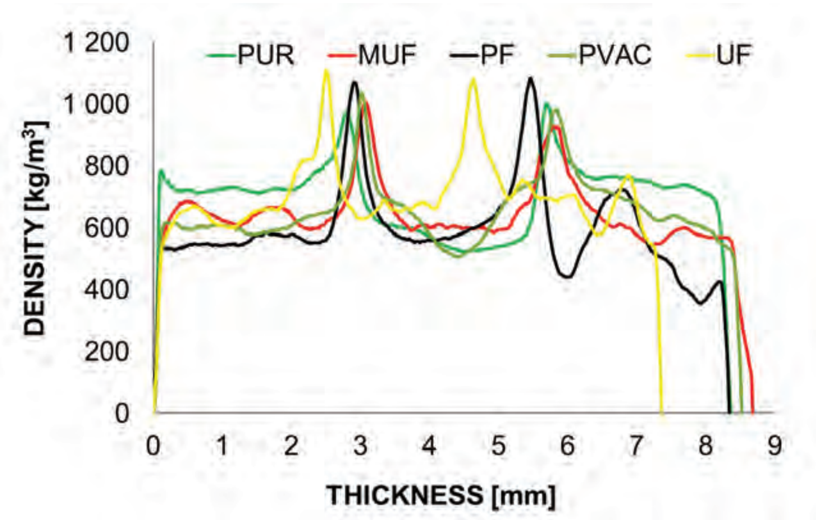

Figure 3: Density profiles of tested composites.

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Assessment of lignocellulosic-substrate fungi-based materials

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Keywords: fungi, wood, hemp, lignocellulosic

Introduction

Nowadays the population is facing the effects of an excessive and reckless consumption of limited resources and energies. Global warming, the Great Pacific Garbage Patch, and air pollution are critical warning indicators for the need to develop more sustainable alternatives to our current lifestyle. Using renewable resources to produce materials is a partial solution to lower our impact on the environment. The specificity of the fungi mechanisms of growth makes them attractive as bioconversion agents (Dashtban *et al*. 2009) and potential advanced materials (Haneef *et al*. 2017). The present study investigates the properties of lignocellulosic-substrate fungi-based materials. Fungi secrete enzymes that decay lignocellulosic materials to convert them into glucose, which will provide the energy for the fungi to grow. Fungi grow by creating a net of hyphae (Fig. 1a) as they decompose organic substances. If stopped before the complete degradation of the substrate, these intra lignocellulosic hyphae threads form an interesting composite structure (Fig. 1b).

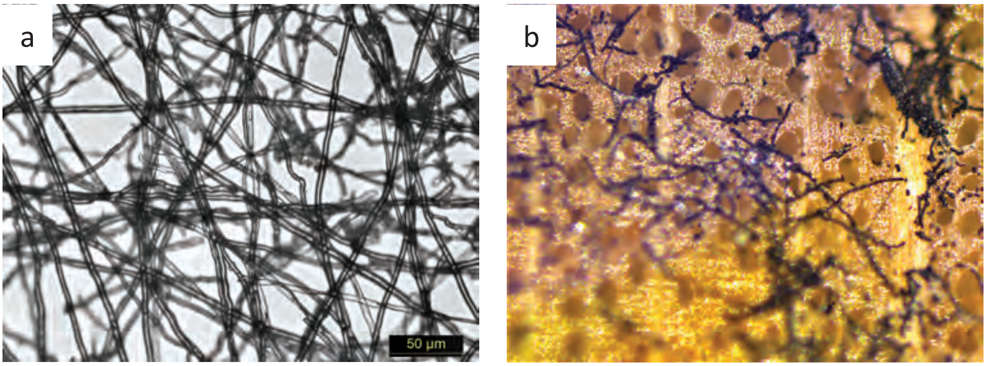

Figure 1: Microscopical observation of a) Net of hyphae, b) Hyphae on a wood substrate.

Materials

Ganoderma Lucidum fungi was inoculated in four different substrates (Table 1). Beech wood and hemp were milled at a particle size ranging between 5 and 15 mm. The composition and particle size of the substrate, and the amount of water, are crucial parameters for the growth of the fungi.

Table 1: Description of the substrates

Specimen	Substrate Composition	Water intake [%m]
1	100% Beech wood	70
2[a]	100% Beech wood	126
3[b]	50% Beech wood + 50% Beech dust	70
4	100% Hemp (shivs + fibres)	68

[a] *Influence of the water content (x2 vs specimen 1),* [b]*Influence of the particle size vs specimen 1*

The resulting lignocellulosic-substrate fungi-based materials are presented in Fig.2.

Figure 2: Lignocellulosic-substrate fungi-based materials.

Results and perspectives

The characteristics of the lignocellulosic-substrate fungi-based materials will be assessed. The physical and mechanical properties (density, thermal conductivity, moisture absorption, UV resistance, mechanical strength), the environmental and health impact, and the safety of use will be considered. Based on the results of the analysis, the most suitable applications (insulation, packaging, building, substitute for single use plastic materials) will be defined for every formulation (substrate/fungi couple).

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The compressive resistance of low density mycelium boards

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Keywords: mycelium boards, particleboards, compressive resistance

About 30 million tons of wood waste is generated each year in the countries of the European Union. The large volume of wood waste has new business opportunities and new markets. In recent decades, new ecological and environmentally suitable materials made from wood or other organic substrates colonized by mycelium have been developed as novel bio-based materials. Mycelium boards are made by inoculating an individual strain of fungi (hyphae) in a substrate of organic substances (Bayer *et al*. 2008, Holt *et al*. 2012). Hyphal network (mycelium) colonizes the substrate, and, like a self-assembling biological binder, glues the used substrate giving it strength and integrity. A bio-composite consisting of mycelium-plant material can be applied as a biodegradable alternative for a wide range of industrial materials replacing non-renewable resource materials such as polystyrene, Styrofoam and poly-urethane foams (Attias *et al*. 2017).

Two sets of samples were made. The first set was made as low density mycelium boards (MBs) consisting of mycelium of fungus *Trametes versicolor*. A second set was made as low density particleboards (PBs). Applied substrates consisted mostly of spruce wood particles obtained from PB factory. The portion and size distribution of particles in substrates can be found in Table 1. Further, the MBs substrate contained wheat flour in the amount of 4 % wt. (weight of flour per weight of wood particles), mycelium of *Trametes versicolor* on malt agar plates (170 cm^2 for 100 g substrate) and demineralized water (30 ml for 100 g substrate). The special PBs with low density were prepared from the same particles with average moisture content 3.7 ± 0.17%, urea-formaldehyde glue, hardener - ammonium nitrate in amount of 7% wt (weight of solid hardener per solid weight of glue) and paraffin emulsion in amount of 22% wt (weight of solid paraffin emulsion per solid weight of glue).

Table 1: Overview of wood substrate – the size and portion distribution of wood particles

Spruce wood particles	The portion of particles fractions in substrate [%]								
Size [mm]	**20**	**11.2**	**4**	**1.6**	**1.25**	**0.8**	**0.5**	**0.25**	**finesse**
Low density MB	6.03	13.59	40.68	24.95	4.84	6.11	2.84	0.60	0.36
Low density PB	0.94	10.50	54.70	24.42	3.72	3.84	1.32	0.40	0.16

Note: Substrate weight = 100 g.

Fabrication of the MBs - The substrate was sterilized by placing it in an autoclave at a temperature of 121 °C and pressure of 1.25 kPa for 60 minutes. After cooling, the substrate was mixed with flour, water and fungal mycelium. The substrate was then placed into Petri dishes with a diameter 120 mm and the nominal thickness of 30 mm. The Petri dishes were closed and then placed in a climatic chamber. The samples were allowed to grow in dark conditions, during 21 days, at a constant temperature of 30 ± 2 °C. After the growth period, the samples were placed inside the room and subsequently in an oven at 60 ˚C and dried for 8 hours.

Fabrication of the PBs – The 1-layer PBs with the area size of 250 mm × 180 mm and the nominal thickness of 25.0 mm were prepared in laboratory conditions. Application of a mixture of urea-formaldehyde glue, hardener and paraffin emulsion on wood chipped particles was performed in a laboratory rotary mixing device. Wood particles coated with glues were then loaded into a pre-pressing form and finally pressed in a laboratory press. Pressing process was performed according to the three stage pressing diagram at a maximum temperature of 210 °C, maximum specific pressure of 15 MPa, and pressing factor of 12 s.

Measuring compressive properties of prepared board was done according the standard test ASTM C 165-07. Strength was defined as stress at 20% deformation.

The results are shown in Table 2. The stiffness increases exponentially with stress. The average compressive strength of MBs samples at 20% deformation is 23.95 kPa. Though the observed strength is comparatively low, it should be noted that MBs are fully bio-based and fully degradable whereas the other materials in table 2 are not.

Table 2: Comparison of low density structural materials

Material	**Density [kg/m^3]**	**Compressive strength at 20% deformation [kPa]**
Low density MBs	103.0 (0.01)	23.95 (6.79)
Low density PBs	189.2 (3.68)	199.0 (73.98)
Expanded polystyrene	13.50 – 18.00	96.90 (Vnuk 2017)

Note: In parentheses is value of Standard deviation.

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Variability of hemp concrete material performance: a focus to modulus and their calculation methods

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Keywords: hemp concrete, modulus, variability, cyclic loading, compression test

In the process of eco-design/construction of buildings, bio-sourced and recyclable materials are experiencing considerable success. They include, amongst others, wood, bamboo and innovative concrete in which aggregates of plant origins are used like coconut, sunflower or hemp shiv. The later is being used increasingly, thanks to its environmental benefits of positive CO_2 balance and easy life cycle management. In construction, it also offers other advantages such as good thermal and acoustic insulation properties. Its major drawback, however, is poor mechanical performance. In a previous study (Niyigena *et al.* 2016), parameters influencing mechanical properties have been investigated, and it has been concluded that the method used may significantly impact the modulus results. This, combined with the lack of a standard method, may be a barrier to the further development and use of hemp concrete.

This study focuses on the variability of the modulus properties and the methods of calculating them. For a stress–strain curve with 3 loading/reloading cycles, two main types of modulus, apparent and elastic, were determined using different calculation methods: floating, tangential and cyclic. According to the literature, apparent modulus is calculated in the linear phase by applying Hooke’s law, while elastic modulus corresponds to the reversible modulus in reloading/loading cycles. Within this study three formulations were used (Table 1). “A” corresponds to the wall and flooring applications while formulations “B” and “C” are for flooring and coating applications, respectively. 45 cylindrical specimens 11x22 cm^2 were manufactured using one kind of hemp shiv and one kind of commercial hydraulic binder (binder C). Compression test with cyclic loading has been conducted on 5 samples per formulation at different ages (60, 90 and 180 days).

Table 1: Tested formulations for wall, coating and flooring applications per 100-litre batch

Formulations	Shiv(kg)	binder C (kg)	Water (Litres)	Water/binder ratio	Shiv/binder ratio
A (250kg/m^3)	9.5	25	31	1.24	0.38
B (187.5kg/m^3)	9.5	18.75	26	1.387	0.507
C (500kg/m^3)	9.5	50	50	1	0.19

Their stress–strain curves at 180 days are presented in Fig. 1. The higher the binder content, the greater is the maximum compressive strength. In contrast, the strain level decreases when binder content increases. Using curves of formulation A, floating and tangential methods were used to calculate both the apparent and elastic modulus, while the cyclic method was used to calculate only the elastic modulus.

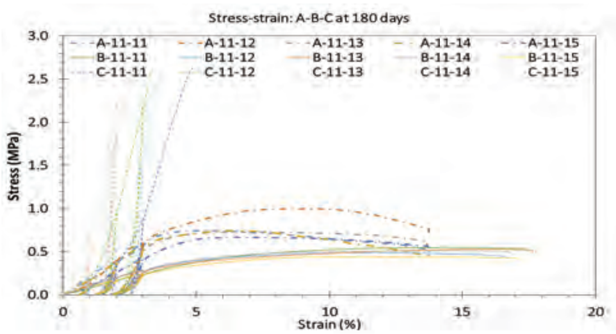

Figure 1: Stress–strain curves for formulations A, B and C at 180 days.

The results obtained at 60, 90 and 180 days are presented in Fig. 2. The apparent modulus obtained by the floating and tangential methods are different, with higher values in the case of the floating modulus. On the other hand, the elastic modulus values are also different. As the floating modulus is calculated as the maximum at each loading stage of the curve, their values are rather high, whereas the cyclic ones are low. Their confidence intervals (CI) are almost the same but with slight differences; in general, the higher the modulus values, the larger the CI is.

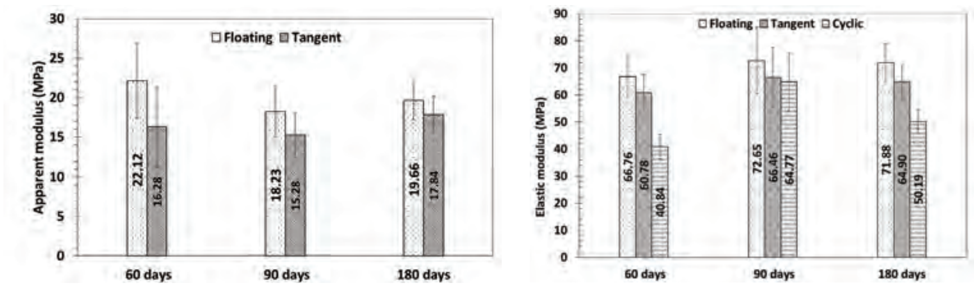

Figure 2: Apparent and elastic modulus by floating, tangential and cyclic methods at 60, 90 and 180 days.

The study highlights differences between methods used to calculate the various moduli. Thanks to its low dispersion and variation over time, the floating method seems to be better suited than tangential or cyclic methods. Its tendency to overestimate the modulus values has been highlighted. In addition, it has been evidenced that the tangential method is a particular instance of the floating method. It has also been demonstrated that the cyclic method tends to underestimate modulus results with low values.

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Characterization of two liquefied agricultural wastes

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Keywords: liquefaction, polyol, polyhydric alcohols, renewable resources

In recent decades, due to concerns about global warming and the environment, researchers have been studying different renewable resources as an alternative for replacing petrochemical compounds in formulations (e.g. phenolic resins).

Agricultural waste causes a disposal problem due to the quantity that is generated and/or its proper use. This lignocellulosic material can be converted, however, by liquefaction technique, into polyol with high added value (Hassan 2008, Jo *et al.* 2015). In this sense, almond and walnut shells were liquefied using polyhydric alcohols such as polyethylene glycol (PEG) and glycerol (G) as solvent and sulphuric acid (SA) as catalyst. The mixture of solvents of PEG:G in a weight ratio of 80:20 and 4.5 wt% of SA were charged inside of a glass reactor and stirred under controlled temperature. Afterwards, when the reaction reached 135 ^{o}C, 15 wt% of the feedstock was added and the process was kept for 1 h. The percentage of SA and feedstock were in respect to mixture of solvents.

The aim of this study was to evaluate the influence of two different agricultural wastes on the liquefaction yield. The properties of the polyols such as hydroxyl and acid number and viscosity were investigated. In addition, molecular distribution and structural composition of obtained polyols were determined.

Preliminary results showed that the highest liquefaction yield was obtained with almond shells (93.46%) which had less acid substances than liquefied walnut shells (36.72 and 42.06 mg $KOH.g^{-1}$, respectively). Both polyols showed hydroxyl number around 245 mg $KOH.g^{-1}$ and similar functional groups (Fig. 1).

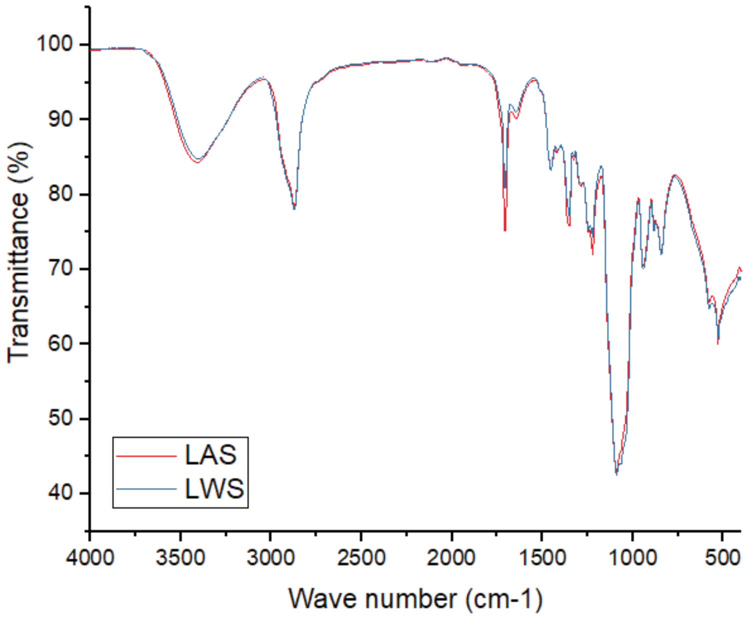

Figure 1: FTIR spectrum of the polyols (LAS- liquefied almond shells, LWS – liquefied walnut shells).

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Influence of hydrothermal modification on the properties of cellulose and lignin after-service-life valorisation of wood

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Keywords: radiate pine, heat-treatment, lignin, cellulose, wood products cascading

The use of wood-based products in Europe is projected to increase threefold between 2010 and 2050. The need for innovative products from fewer resources to help reduce pressure on forests is attracting the attention of the scientific community to provide a value-added use of wood-based products after their traditional service life. In this sense, cascading of wood is an efficient use of these resources from the point of view of natural resource higher value uses that allow the reuse and recycling of products and raw materials. There are tree definitions of cascading processes: cascading-in-time, cascading-in-value and cascading-in-function, which is the most prominent definition. Cascading in function has been described as a process through which different products can be produced simultaneously to maximize the value of the original biomass, resembling the functionality of a biorefinery. Basque Forestry Inventory has reported as of 2017 a total wood existence of 27 688 992 m^3 of radiate pine and an average of 221.13 m^3 ha^{-1} being radiate pine in the main forest plantation in the Basque Country (HAZI Fundazioa, 2017, AIEF, 2017) .

For this work, radiata pine (*Pinus radiata* D. Don) was harvested from the forest area of the Basque Country (Spain) after which it was debarked, sawed, stored and conditioned before the heat-treatment at Torresar® Company in fulfilment of the chain of custody according to the PEFC certification. Pine boards were thermally modified according to industrial production standards at 212 °C (Termogenik®, Spain) in a heat-treatment chamber with steam presence and under inert N_2 atmosphere. Afterwards, the samples were aged naturally as reported previously (Herrera *et al* 2014).

After weathering, samples were milled and fractioned into cellulose and lignin through environmentally friendly methods (Robles *et al.* 2018). An organosolv treatment (65/35 v/v, 90 min, 200 °C, 9% consistency and 0.05 M $MgSO_4$ as catalyst) was used as first treatment, followed by a totally chlorine-free bleaching sequence consisting of two alkaline oxygen stages (E_O), one peroxide stage (P) with secondary chelating reaction (P_{OQ}) and an alkaline peroxide stage under oxygen atmosphere (P_O). Oxygen-alkaline stages were done with 1.5 wt% NaOH, and the reactions were performed during 60 min at 98 °C under a 6 bar O_2 atmosphere. Black liquors from the two oxygen-alkali stages were collected. The first peroxy stage was done using 3M H_2O_2, with pH stabilized at ~11 with a mixture of

NaOH and $Mg(OH)_2$ (3:1 wt%). The use of Mg(OH)2 as a partial substituent of NaOH was done as it has been reported its efficiency as alkaline agent for peroxide bleaching with a 30 % substitution being the optimal. The reaction was performed during 120 min at 105 °C with N,Nbis(carboxymethyl)glutamic acid (GLDA) as chelant. The second peroxy stage was performed at 105 °C during 150 min under 6 bar O_2 atmosphere. In this stage the pH was stabilized at ~11 by using NaOH only and with no further addition of chelant. For all the reactions pulp consistency was kept at 9%. To evaluate the influence of hydrothermal modification of wood, a control was used in both before and after weathering fractioning.

Lignin was precipitated from black liquor of the organosolv treatment (L1) by adding 2 volumes of water at pH 2. A second lignin (L2) was precipitated from the spent liquor of the alkaline extraction by acidifying the liquor until pH~2. The efficiency of the fractioning was calculated by comparing the total obtained lignin and cellulose yields with the lignin and cellulose content of the raw material as calculated by standard methods.

Scanning electron microscopy (SEM) images were recorded before and after fractioning. The obtained celluloses were characterized by the means of purity (cellulose Iα content), crystallinity (x-ray powder diffraction) and structure (nuclear magnetic resonance). Lignin fractions were characterized by the means of purity (Klason lignin content), molecular weight average (M_w), polydispersity index (M_w M_n^{-1}), inorganic content (thermal degradation) and structure (nuclear magnetic resonance).

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Improving hydrophobicity and thermal stability of wood through esterification with fatty acids

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Keywords: wood modification, wettability, thermal degradation, radiata pine

The properties of wood as a material are primarily influenced by the chemistry of its cell wall components (cellulose, hemicelluloses and lignin). The modification technologies are based on this principle (Hon 2017), in which the main target is to replace accessible hydroxyl groups of cell wall components with other functional groups with lesser affinity to water, and, if possible, to improve properties. The substitution of these groups with long chain acid chlorides can provide a hydrophobic effect, as well as an improvement of some properties (Prakash and Mahadevan 2008). In this study, samples of pinewood (*Pinus radiata*) were modified with acid chlorides with 6, 12 and 18 carbons (C6, C12, C18) at a concentration of 1M. The procedure started with isolating of the wood extractives (toluene: ethanol (2:1)), and successively, the wood samples (without extractives) were oven-dried (103±2 ^{o}C) and kept under vacuum atmosphere to facilitate the product uptake. The reaction was conducted in DMF for 3h at 100 ^{o}C (for C6) and at 80 ^{o}C (for C12 and C18) using pyridine (10%) as catalyst. Finally, dietylether and ethanol were used to remove any residual from samples. After the modification process, the density and moisture content (MC) of samples were compared to untreated wood, and weight percentage gain (WPG) and leaching rate of the applied products were measured (Table 1).

Table 1: Physical properties and product uptake

Sample	Pine contol	Pine-C6	Pine-C12	Pine-C18
MC [%]	7.31	6.99	6.51	7.23
Density [kg/m^3]	440.42	436.95.	468.30	441.94
WPG [%]	-	4.44	6.19	2.38
Leaching rate [%]	-	50.10	39.60	39.00

The changes in the surface wettability were measured by means of a sessile drop technique on the goniometer OCA20 (DataPhysics), at the state of equilibrium contact angle and recording the contour of the sessile drop in function of time (Fig.1, left). Finally, the thermal resistance of samples before and after modification were performed by dynamic thermo-gravimetric measurements (TA instruments TGA Q5000 IR equipment), under O_2 atmosphere in the range of temperature from 30 to 600 °C at a constant heating rate of 20 °C/min (Fig. 1, right).

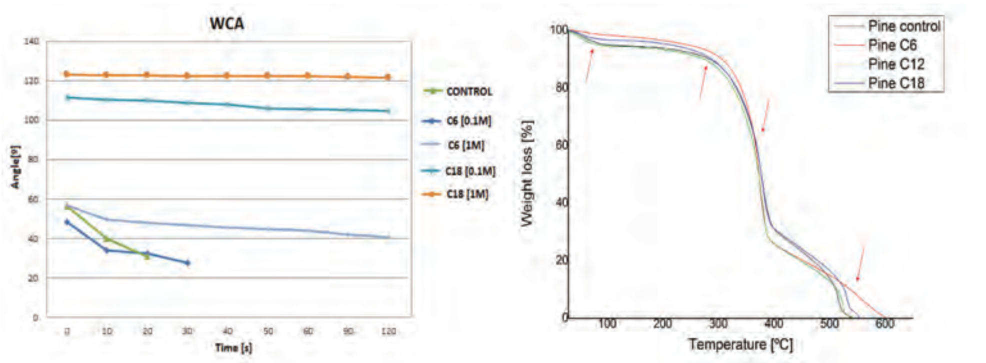

Figure 1: Wetting contact angle (WCA) (left) and Thermo-gravimetric analysis (right) of pine and esterified wood.

According to the preliminary results, the acidic by-products generated during the process did not degrade the modified wood, obtaining physical values in the range of the control samples. In addition, the esterification process decreased the availability of hydroxyl groups, changing the hydrophilic character of pinewood. The thermal behaviour of the samples modified with C6 and C18 suggest that these treatments could be explored as fire retardant (Gérardin 2016).

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Preservation of wood structures in non-controllable environment by the example of pre-stressed laminated timber bridge deck with two curved geometry

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Keywords: bridge deck, two curved geometry, pre-stressed lamellae

The concept of the paper belongs to the topic of integration, dissemination and exploitation.

Main features

Changing MC lead to expansion or shrinkage of timber members and to generating extra inside forces what are very difficult to take into consideration if the structure itself is not very simple. Especially it applies to the structures standing in open space as long span timber bridges, towers, tall timber buildings etc. The treating can`t guarantee the exact MC always. Because of that the initially projected geometry start to change what can lead to breaking the nodes until collapse of structure. The correct geometry for timber structures is the key to avoid such cases. By the example of two curved laminated timber bridge deck of pre-stressed lamellae will be shown how such type of structure react to the outside loads. The purpose of this experiment was to design bridge deck models what are capable to use outdoors. To control their behaviour under the loads and to study their deflections and permanent deformations, depending on the applied load the cyclic bending tests were carried on.

Bridge deck structure

The Nordic spruce was used to produce special shape of lamellae. The starting workpiece was always 32x90x900mm. Lamellae of the structure of exact specimen were equal. Longitudinally shape of them was the same, where the middle part of lamella was narrower than the ends. Cross-section was wedge-shaped and the angle of it depended of requested elevation angle of the whole structure.

The lamellae were mounted to each other one by one in pre-stressed way on radial direction with help of screws so that every screw had to undergo at least three lamella. Depending on the thickness of lamellae the screws of different length was used. By the result and because of shape of lamellae the timber bridge deck was formed with two-curved geometry.

Cyclic loading test for analysing deflections and permanent deformations

Cyclic loading tests were carried on to analyse deflections and permanent deformations of bridge deck models/specimen (Fig. 1). Specimen were rested to the jig only by 4 corners.

a) b) c)

Figure 1: Pre-stressed laminated timber bridge deck (Specimen 05):
a) before loading, b) max loading/deflection, c) after loading

Six series of test specimen (3 in each) were mounted with different evaluation angle. Test series from 01 to 05 were with increasing pre-ascent. To compare them with ordinary laminated slab the test series 06 was made too. All specimen were loaded three times. The first specimen of each series was loaded with one additional cycle, until maximum possible load was applied. Results of loading tests of different specimen are shown in Fig. 2 (Kullamaa *et al*. 2018).

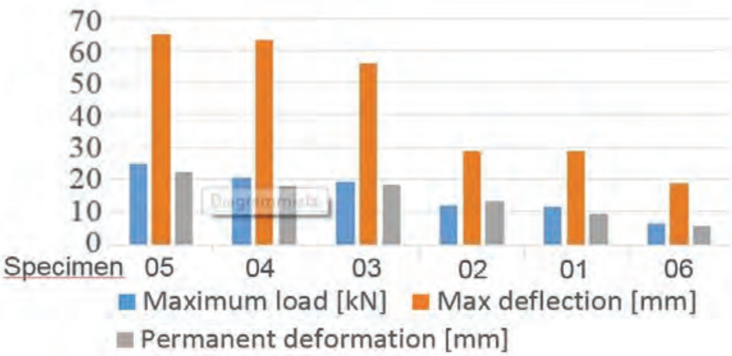

Figure 2: Test results (mean) of loading tests.

Results and Conclusions

Pre-stressed two-curved bridge deck acted under the load as spring. Permanent deformation was not remarkable comparing with maximum deflection. Under the maximum load all test specimen had a negative Gauss curvature, but after releasing the load, it almost completely restored its original shape. It happened because of distribution of the redundant load at first tangentially, then radially and at least longitudinally along the lamellae to the supports. Specimen series 05 were loaded at 24,91 kN.

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Sensitivity and reliable design of a timber beam considering crack growth and environmental effects

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Keywords: sensitivity analysis, reliability based optimization, finite element analysis, fracture mechanics, crack growth

The use of bio materials in sustainable construction aims to reduce the environmental impact of buildings. However, wood materials suffer from several drawbacks like uncertainties of timber mechanical properties, knots in the material and the appearance of cracks. Timber elements exhibit micro-cracks, which can propagate due to fatigue, overload or creep loading. Thus, crack initiation is one of the most important factors involved in the collapse of timber components in building structures. To predict the crack initiation, many numerical methods have already been developed to characterize the mechanical fields in the crack tip vicinity (Dubois *et al.* 2005). In this work, an energy method based on invariant integrals is used to estimate the fracture parameters such as energy release rate and stress intensity factors (Moutou Pitti *et al*. 2010). The analytical formulation of the T-integral to viscoelastic materials is extended to A-integral in order to take into account the effect of thermal loading and the effect of moisture variation (Riahi *et al.* 2016). In fact, the study of the crack growth initiation and crack propagation in timber structures may consider the effect of temperature and the moisture content on the mechanical field distribution in the crack tip vicinity. Moreover, in the context of wood timber structures the calculation procedure must be performed in an orthotropic material. In this study, the A-integral is implemented in the finite element software CASTEM. Thus, several parameters are involved in the numerical model: geometry, material, loading and environmental parameters (temperature and moisture content). The first step of this work was to quantify the effects of uncertain parameters on the crack growth of a timber beam. The Morris method (Morris 1991) was used to identify the most significant uncertain parameters of the variability of the crack growth. Fig. 1 shows the most important parameters on the energy release rate. In fact, this approach lead to a reduction of the stochastic dimension of the reliability analysis in the second step of this study. The most uncertain parameters were modelled as random variables and considered in the Kriging metamodel and the remaining parameters were fixed to their respective mean values.

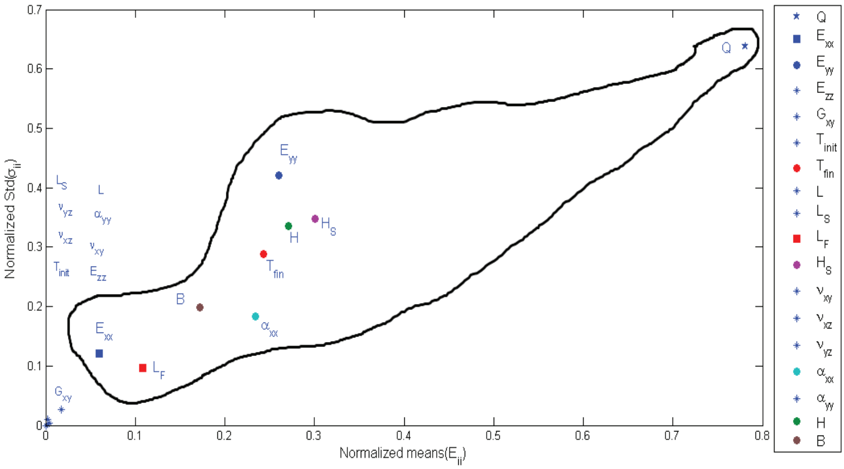

Figure 1: Important parameters of the variability of the energy release rate in timber beam.

The second step of this work was to find the optimal and the reliable design of a timber beam for several crack sizes. The Reliability-Based Design Optimization (RBDO) is developed to balance cost and reliability, where it offers a means to quantify uncertainty propagation and determine the most reliable design that meets the performance criteria (Aoues *et al*. 2011). However, the RBDO implies the evaluation of probabilistic constraints, leading to expensive computation cost due to the numerical fracture mechanical model. In this study, the Kriging metamodel is adopted in order to surrogate the performance functions (the release energy rate). The RBDO approach combines updating of Kriging approximation by using the technique of constraint boundary sampling to enhance the prediction of the Kriging metamodel. The kriging based RBDO of a timber beam considering several crack sizes was then performed, and AK-MCS method based on Monte-Carlo simulations and Kriging metamodel were used to validate the optimal reliable design of the timber beam.

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Creep response of European species under environmental and mechanical loadings in outdoor conditions

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Keywords: creep, environmental impact, thermo-hydro-mechanical, *Pseudotsuga Mennziesii*, *Abies Alba mil*

Wood material and timber structures play an important role in the limitation of greenhouse effects (Pambou Nziengui et al. 2017). But in service, their modification and durability are affected by mechanical loadings and environmental conditions (Angellier et al. 2017). Hence, the damage of two European beam species of Pseudotsuga Mennziesii (Douglas fir – DF) and Abies Alba mill (white fir – WF) under mechanical (creep) and environmental (temperature, relative humidity, moisture content-MC) loadings have been investigated. The beams have been loaded for 2 years but, in this work, only the effects during ten (10) days were exploited. The two beams (WF and DF) were loaded in 4-point bending tests (Fig. 1a) in outdoor conditions as shown in Fig. 1b.

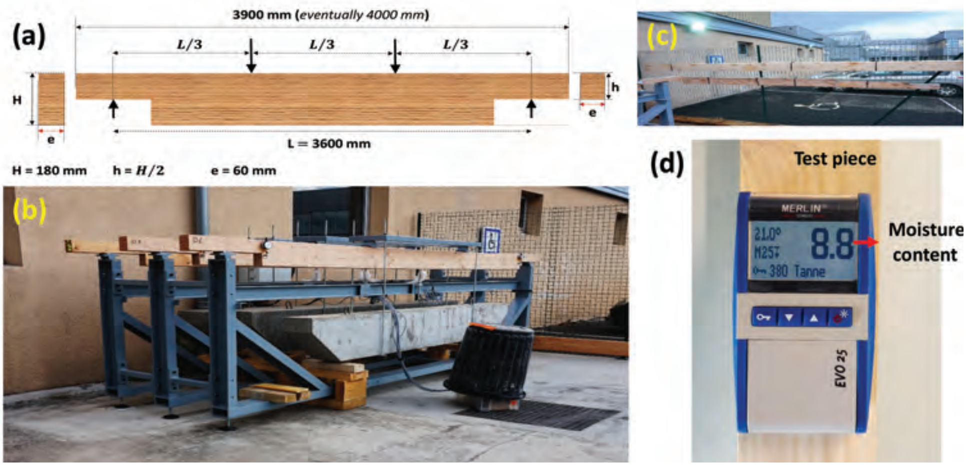

Figure 1: Experimental setup of test; (a) type of specimen used; (b) Testing apparatus; (c) matched beams used for the following of MC; (d) merlin-non-destructive moisture meter.

The evolutions of the deflections are continually following by LVDT sensors and the MC are following on two matched beams (Fig. 1c) with a moisture meter (Fig. 1d) during the creep test. The creep loading is applied thanks to a concrete beam and the deflexion is automatically recorded each 5 min by the LVDT sensors. The MC was obtained with a Merlin non-destructive moisture meter (Fig. 1c and 1d).

A typical study has been done during 10 days as presented in Fig. 2. Especially the evolutions of the deflections of the beams DF6 and WF12 in the time versus the moisture content MC taken from the matched beams during this period. For the two observed beams, Fig. 2 shows that there is a correlation between the variation of MC and the relative deflection of the beams studied.

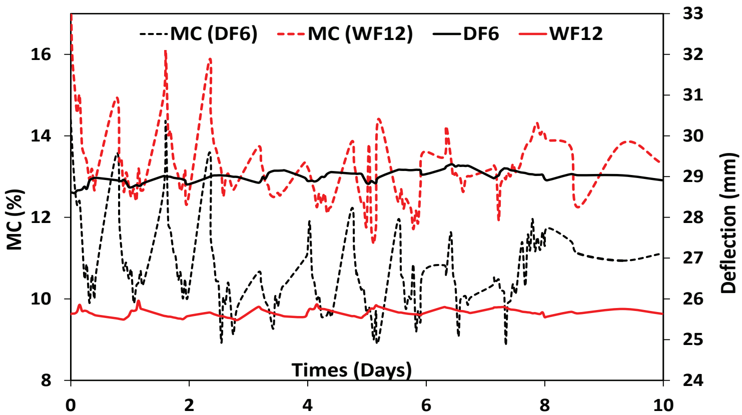

Figure 2: Evolutions of deflections of the beams versus moisture content during the testing period.

Lastly, the impact of climatic parameters, coupled with fracture processes, on the deflection will be analysed during this laps time. For future work, an analytical model including mechanical and environmental parameters will be proposed.

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Understanding shrinkage and fracture process of green wood using X-ray microtomography

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Keywords: green wood, X-ray microtomography, fracture, environmental impact, image analysis

The behaviour of wood material under mechanical and environmental changes is very significant. In this case, the modifications due to these impacts can also compromise the durability of timber structures. The subject of this paper is to investigate the damage of green wood tropical Gabonese (Miliciaexcelsa- Iroko, Aucoumeaklaineana – Okoume, and Pterocarpussoyauxii- Padouk) and European tempered (Abies alba, Populusnigra) species, in order to improve their sustainability. The experimental setup is composed of an electronic testing machine, camera (Fig. 1a), wooden specimen (Fig. 1b), with an Arcan steel system that constitutes the Mixed-Mode Crack Growth or MMCG (Moutou Pitti et al. 2011). Only the results for tropical species are presented.

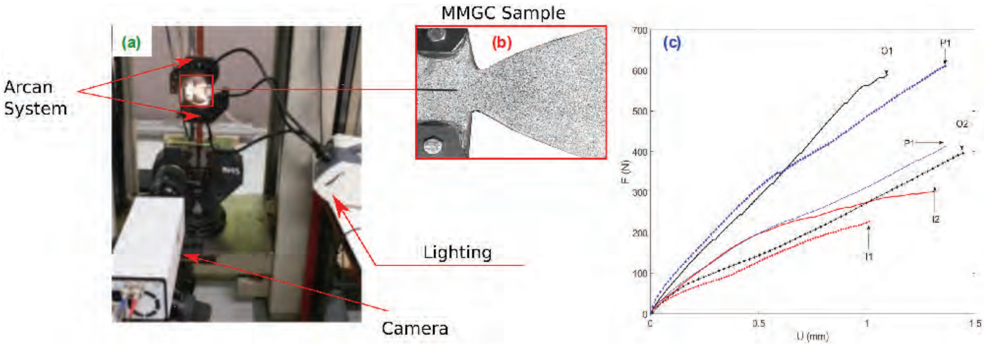

Figure 1: Experimental setup (a); Hydro-thermally densified pine wood (b); Displacement fields (c).

The displacement fields (Fig. 1c) and deformation were measured by the Digital Image Correlation (DIC) technique. The advance of the crack tip at different loading stages has been recorded. These results were obtained from the displacement and strain maps given by the camera (Fig. 1a). Hence, for the three species, the surface critical energy release rate was obtained by using the compliance method (Moutou Pitti et al. 2011). In 2D image, preliminary results showed detailed information about the fracture toughness of these tropical woods in constant and variable environmental conditions.

Simultaneously, in order to track the three-dimensional crack growth process of these tropical species, the X-ray microtomography (XMT) method was performed (Mayo et al. 2009). Fig. 2 shows the 3D image acquisition protocol by XMT. The tested specimen (Fig. 2a) was cut according to the initiated crack path with a pre-cut of 22 mm (Fig. 2b). The wood sample to be scanned was then introduced into the microtomograph chamber (Fig. 2c). After reconstruction, a 3D volume (Fig. 2d) was obtained from several 2D scans at 7µm resolution.

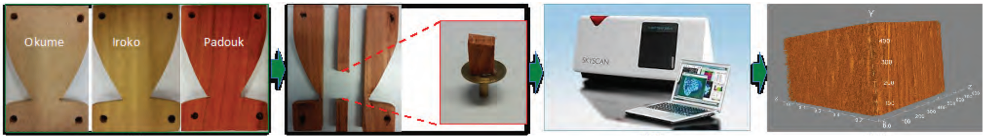

Figure 2: Wood specimens (a); Extracting cracked specimen – Padouk (b); X-ray microtomograph (c); 3D volume of cracked specimen – Padouk (d).

Fig. 3 shows the images for the three species, of healthy and cracked samples which were taken under dry/green wood non-cracked (Fig. 3a-c), and dry/green wood cracked (Fig. 3b-d) conditions, respectively. Coupled with the density of each species, the ability of the XMT to detect and track internal crack growth in tropical species under environmental changing conditions has been shown.

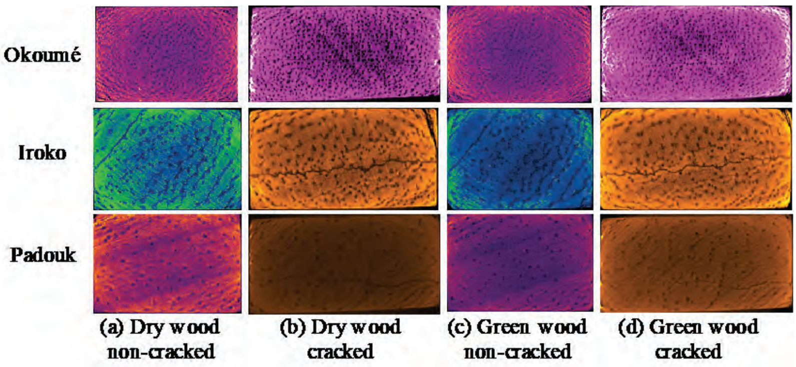

Figure 3: 3D cross sectional images of cracked and non-cracked specimens vs. moisture content.

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Modified wood – research on selected physical and mechanical properties

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Keywords: flooring material, THM treatment, fire parameters

Currently, there are many methods to improve the properties of wood. The newer ones are the thermal and thermo-mechanical treatments. It is an environmental friendly process due to the lack of chemicals used, only water vapor and high temperature are the factors for the reaction (Hill 2006; Laine *et al*. 2016.)

The scope of research sought to determine whether it is possible to increase the technical and utility parameters of layered floor boards by THM treatment, as depicted by greater hardness (resistance to scratches, abrasion and indentations), higher thermal conductivity, higher resistance for contact with liquid water and increased temperature in combination with high relative humidity. Additionally, the aim of the study was to achieve higher wood flammability parameters than commonly available on the market. For selected variety of thermally and thermo-mechanically modified samples the following parameters were determined:

- fire characteristics (including flammability test, determination of combustion heat parameters and heat release intensity) for control and modified material,
- recommended preservatives that slow down the flammability process, and
- range of thermal and thermo-mechanical impact on wood for the purpose of upgrading its utility parameters.

Research material was industrially-prepared, 3-layer composite flooring. It consisted of several variants differing by:

- material of the surface layer: beech/oak,
- material of the core layer: pine/birch,
- surface layer finishing: varnish/oil, and
- surface layer modification: unmodified/thermomodifed/densified/thermomodified and then densified.

Recommended density of oak and beech wood after densification is 900-1000 kg/m³, which is equivalent to increase in density at around 140%, corresponding to two-fold increase in hardness of wood. The tests showed an increase in hardness due to densification of beech wood at the level of 152% and oak wood at 201% in relation to natural wood. As a result of thermomodification, oak and beech wood show hardness reduced by around 70% and 84%, respectively, in comparison to natural wood. Secondary densification of thermomodified wood leads to re-increase in material hardness at a value equal or even greater than natural wood.

Densification of beech and oak wood has a positive effect on the thermal properties of wood in the aspect of using it for underfloor heating. Densification makes wood conduct heat better. Beech and oak wood show higher values of heat conduction coefficients by around 105% and 122%, respectively. Alternatively, thermomodification causes further increase in heat reduction coefficient by around 135% and 118%, respectively.

Comparison of termomodified oak wood with natural wood within fire characteristics (using cone calorimeter) found that in both the initial and advanced stages of the fire, time needed to ignition, intensity of heat release, value of heat released and rate of mass loss is higher.

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Paper tissue reinforcement – coating with nanocellulose and silanes

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Keywords: nanocellulose, alkoxysilanes, strength property, tissue

Nanocellulose (NC) is one of the most promising bio-based material. Its main advantages are: reversibility, biodegradability, nontoxicity, outstanding mechanical properties, high aspect ratio, low density and accessible intervention by chemicals (Moon *et al.* 2016). Attaining homogenous dispersion of NC is a key in maximizing effectiveness of NC. It mainly limits the processing with water or polar liquid medium in which the NC is dispersed without any surface functionalization. Thus, NC functionalization has gained a significant attention in materials community. For NC functionalization, silane is a valuable option used to achieve different requirements. For instance, the NC films modified with amino silanes showed improvement of adhesion, hydrophobicity, optical properties and scratch resistance. Furthermore, the NC films modified with methacryloxy silanes showed improvement of plastic deformation and crack resistance. And the NC films modified with epoxy silanes showed improvement of elasticity (Pacaphol and Aht-Ong 2017).

The aim of this study was to improve strength properties of paper tissue coated with NC modified with alkoxysilanes. The idea for the future work is to implement this coating on the surface of wooden historical objects as a part of its conservation process.

A paper tissue as a model base material and two types of NC (cellulose nanocrystal-CNC and cellulose nanofibril-CNF) were used in this study. NC was modified with three types of alkoxysilanes: methyltrimethoxysilane (MTMOS), [3-(2-aminoethylamino) propyl] trimethoxysilane (AATMOS) and fluorosilane (PROTECTOSIL S.C. CONCENTRATE ®). The silanization reaction was catalyzed by acetic acid. Paper tissue was treated through soaking method. Mechanical properties (tensile strength and elongation) and moisture content of paper tissues were determined.

The results of the tensile strength of coated paper tissue are shown in Fig. 1a. b. Tissue coated with CNC exhibited higher tensile strength (4.17 N) in comparison to tissue coated with CNF (3.84 N). Tissue coated with NC modified by AATMOS had better strength properties compare to tissues coated with NC-MTMOS and NC-fluorosilane. In addition, tissue coated with NC modified with fluorosilane had lower tensile strength compared to tissue coated with CNF. However, the use of NC and silanes reduced elongation of coated tissues. The uncoated tissue had the highest value of elongation in comparison to coated ones (2.74%). According to Fig.1c, tissue coated with NC-AATMOS showed a significant increase of moisture content. Theoretically, moisture content and strength properties of paper tissue have negative correlation. In addition, tissue coated with AATMOS showed best tensile strength as well. The lowest moisture content was observed for tissue coated with CNF-MTMOS (1.33%). The moisture content of tissues coated with CNC-MTMOS (1.46%) and CNF-MTMOS (1.33%) were similar. Modification of NC with fluorosilane was not able to reduce moisture content of tissue coated with these agents.

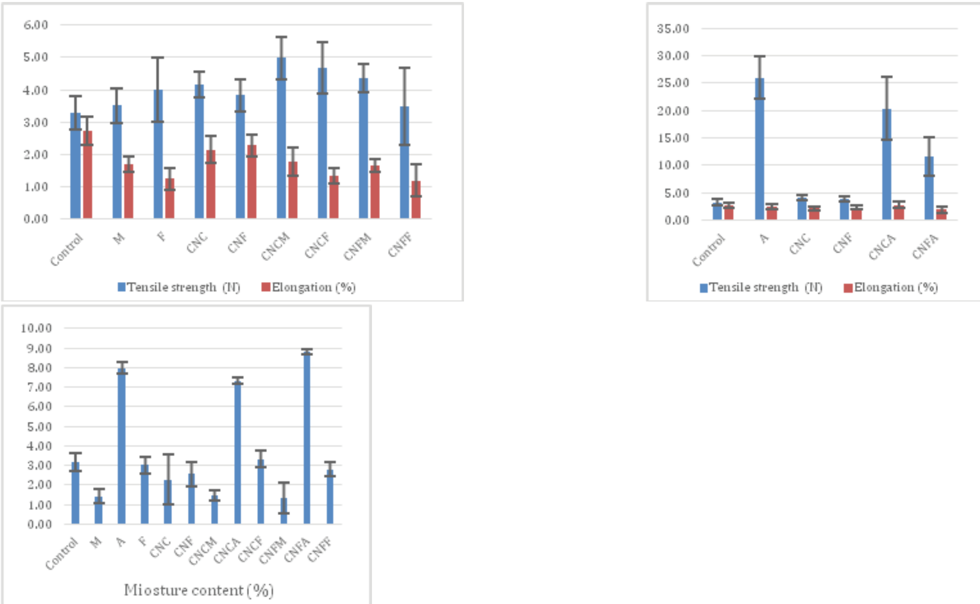

Figure 1: Properties of tissues coated with modified nanocellulose: tensile strength and elongation (a and b) and moisture content (c). (M: MTMOS, A: AATMOS, F: fluorosilane).

The results from this study indicates that strength properties of paper tissue coated with NC modified with alkoxysilanes were improved. CNC was more effective than CNF in improvement of tensile strength of paper tissue. AATMOS was suggested to be used for improving tensile strength and MTMOS was suggested to be used for reducing moisture content of paper tissue. The use of NC and silanes reduced elongation of coated tissues. Further experiments will be designed to improve elasticity of coating made of nanocellulose and silanes.

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Preliminary analysis of bio-sourced hybrid resins as coatings for wood protection

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Keywords: tannin, lignin, hybrid, wood coating

Solid wood and wood-based products are an active part of our lives and play a significant role in buildings and interior fittings due to their structural, mechanical and environmental properties. Nevertheless, they present some disadvantages such as the hygroscopicity and the vulnerability against biological (fungi, bacteria and insects) and non-biological (sun, wind, water and fire) agents. For this reason, wood protection via modification has become a major issue. Currently, phenolic resins have a main role in the chemical industry. They are commonly used in the production of wood-based panels as adhesives (Yang *et al*. 2009). However, the current environmental concerns regarding the depletion of fossil fuels have led to the introduction of natural and environmentally friendly products in these types of resins. Lignin and tannins are two kinds of phenolic compounds, which are abundantly present in various vegetal biomass sources. Their utilization in phenolic resins has been extensively studied as a substituent of phenol, either partially and/or totally (Jahanshaei *et al*. 2012, Zhang *et al*. 2013, Chupin *et al*. 2015). On the other hand, the study of nano-structure hybrid materials derived from natural substances have attracted a great deal of attention lately in several fields, e.g. construction (Saad *et al.* 2018). Among these natural substances, the use of nanoclays and nanosilicates has proved the synergistic effect concerning thermal and mechanical properties. In this work, the synthesis of bio-sourced phenolic hybrid resins was carried out, aiming to their application as coatings for wood protection. In the formulation of the resins, lignin and tannins were used as natural phenol substituents and two different inorganic compounds, a nanoclay and a nanosilicate were employed.

The resins were elaborated using lignin previously modified with glyoxal and two different inorganic compounds, namely an organically modified montmorillonite (nanoclay) and a polyoligomeric silsesquioxane (nanosilicate). After that, the modified lignins were mixed with a tannin solution and a reticulating agent. The different formulations are displayed in Table 1.

Table1: Composition of the different formulations of the resins synthetized

Resins	Components [w/w]		
	Lignin [%]	Tannins [%]	Inorganic phase [%]
R10	50	50	0
R10A	48.78	48.78	2.44 (nanoclay)
R10B	48.78	48.78	2.44 (nanosilicate)

The resins were applied on two different wood species, maritime pine and beech. Prior to coating application, the wood surfaces were refreshed and the samples were conditioned (25 ºC and 65% RH). Moreover, the resins were characterized physico-chemically to elucidate different properties and the results are shown in Table 2.

Table 2: Results of physicochemical analysis of the different resins

Resins	pH	Density [g/cm^3]	Non volatile content [w/w][a]
R10	8.920±0.014	1.169±0.003	36.811±0.035
R10A	9.015±0.035	1.173±0.015	37.416±0.073
R10B	8.990±0.028	1.177±0.006	37.412±00028

[a]Determined according to the EN ISO3251 standard

The resins were applied onto the wood surface and cured at 60 °C during several hours. After the curing process, different analysis were performed to evaluate the coating performance concerning various properties such as leaching, colour, fire and impact resistance.

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Nano-modified adhesives for composite wood panels manufacturing

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Keywords: nanobioadhesives, nanocellulose, silanes, rheological properties, wood-based panels

Taking into consideration more and more stringent requirements concerning assurance of safety for human health and the environment, it is reasonable to conduct research on bioadhesives for the wood industry. Among the most promising biomaterial with wide variety of properties and functionalities is nanoscale cellulose (Habibi *et al.* 2010, Isogai 2013). Due to high mechanical strength modulus and high tensile strength, nanocellulose can be utilized as a reinforcing agent for development of new adhesives for wood-based panels (Hubbe *et al.* 2008, Veigel *et al.* 2012, Mahrdt *et al.* 2016, Amini *et al.* 2017). The combination of the properties of nanocellulose and silanes as modifiers, leads to obtaining an ecological binder, characterized by the desired technological properties.

The goal of the study was to develop a new type of biopolymer adhesives modified with silanes intended for use in wood-based materials technology, as well as to optimize the method of application of these adhesives into lignocellulosic material. The main focus is to create an adhesive binding mass with the desired physicochemical parameters which allow the use of the adhesive as a binding agent in the production of wood-based panels. The result of the project will be an adhesive that presents an ecological alternative to currently used adhesive with amino resins, which are source of harmful formaldehyde emissions. A key factor when determining the technological usefulness of the adhesive, in respect to its use in panel manufacturing, is identifying the stability and rheological properties of the adhesive. Moreover, interaction of silane-modified cellulose films with water are also crucial to evidence the chemical modification efficiency. In this work, the viscosity and flow curves were evaluated before and after 4 weeks of storage in the atmosphere of (23±2)°C and (50±5)% relative humidity using Brookfield Rheometer LV DV2T EXTRA equipped with the SSA SC4-31 spindle, in an increasing shear rate mode. The contact angle tests were performed on thin cellulose films formed on glass, which were obtained from an aqueous suspension of nanocellulose. The initial contact angle and the change of contact angle during time (30 s) were determined using optical tensiometer Attension Theta.

The preliminary results demonstrated that resins modified with nanocrystalline (NCC) cellulose kept their rheological behaviour and the proper viscosity after 4-week storage. In addition, the percentage of viscosity retention of the nanocellulose-reinforced resins was lowered by around 1.5 times in comparison to the industrial used resins. Moreover, NCC might be used as a stabilizer in adhesive compositions during the long-term storage. The study showed also improvement in the hydrophobicity of nanocellulose films as a result of their modification with silanes.

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Session 5: *Thermally modified wood – properties*

Influence of heating rate during thermal modification on some properties of maple wood

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Keywords: thermal modification, heating rate, maple timber, colour, wood properties

Although extensively researched over the past few decades, thermal modification remains a highly empirical process in the wood industry due to uncontrolled variables, different systems and equipment, various treatment schedules, etc. (Torniainen *et al.* 2016). On an industrial scale, one of the main difficulties is to produce the product with constant and controlled quality (durability, dimensional stability, colour). Due to a lack of knowledge, operators in the industry often do not change modification schedules obtained from the equipment manufacturer. It is well known that decisive influences on wood properties are peak temperature and time, but the influence of heating rate (time to reach maximum temperature) is less researched. This heating time is considerably longer than the highest temperature period. Also, effective heat power exchanged during the treatment process influences wood mass loss (Candelier *et al*. 2015); an important part of this energy is exchanged during heating time.

The aim of this work was to investigate the possibilities for shortening duration of thermal modification under industrial conditions, in comparison to duration prescribed by the equipment manufacturer. In addition to the shortened time which brings organizational flexibility and lowers energy consumption, the goal was to keep the high quality (lack of cracks and deformation) and a similar color as with previously used modification schedule.

Research was done on maple (*Acer pseudoplatanus* L.) timber, 25 mm thick. Timber was previously conventionally dried to a moisture content of 8%. Thermal modification was carried out in the industrial chamber in a steam atmosphere which was reached by using a spraying of water (high and low pressure). The first test run was performed under regular schedule (“Slow”) that lasted for about 6 days, and the second one under a new schedule (“Fast”) in which the heating phases (temperature rise from 105 °C to 200 °C) were shortened (Table 1). The phase of the maximum temperature (200 °C, 3h), as well as the cooling phases, remained unchanged. In this way, the total duration of the modification was reduced to about 4 days (2 days shorter).

Moisture content, colour (measured on planed surfaces), density, modulus of elasticity (MoE), bending strength and Brinell hardness were determined before and after thermal modifications.

Table 1: Phases of thermal modification (Slow and Fast Schedule)

Phase		1	2	3	4	5	6	7	8	9	10	11	12
Temperature at the end of phase[°C]		85	105	120	130	140	150	200	200	140	85	85	80
Duration [h]	Slow	19	8	8	9	9	9	50	3	11	11	5	1
	Fast	19	8	6	4	4	4	20	3	11	11	5	1

The visual examination after thermal modification did not reveal differences in quality between timber from the slow and fast test run. Amount of cracks and deformations in both test runs was low.

It was shown (Table 2) that heating rate, i.e. the total duration of thermal modification, affected the moisture content and properties of timber after treatment. Higher temperature increasing rate (°C/h) resulted in lower oven-dry density. This can be explained by the fact that faster heating possibly means a small presence of water in the wood at the moment when chemical transformation begins. Water catalyses the chain splitting by acidic hydrolysis and thus promotes the degradation of wood polymers (Poncsák *et al*. 2006). As expected, after both treatments wood had reduced lightness (-L^*) and became redder (+a^*) and less yellow (+b^*). However, no visual difference was found between colour of wood after two different treatments.

Table 2: Moisture content, oven-dry density and colour parameters of untreated and thermally modified maple wood

	MC [%]	ρ_0 [kg/m^3]	L^*	a^*	b^*
Untreated	7.6 (0.3)	587 (30)	74.5 (2.8)	5.0 (0.8)	14.5 (0.9)
Slow treatment	4.1 (0.4)	556 (31)	44.1 (2.2)	9.3 (0.3)	18.7 (1.7)
Fast treatment	5.8 (1.1)	534 (50)	41.0 (1.0)	10.8 (0.4)	22.4 (0.8)

Standard deviation in brackets

Brinell hardness of wood after fast treatment was lower as compared to hardness after slow treatment, while no clear conclusion of how the heating rate influenced other mechanical properties (MoE, bending strength) can be made.

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The evaluation of the quality control methods for thermally modified wood

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Thermal modification is commercially the most important wood modification process. Thermally modified wood has been accepted as well performing material by architects and the building sector. There are several thermal modification processes developed. All processes are based on the fact that wood is heated at elevated temperatures in the atmosphere with reduced oxygen concentration. In general, the quality of the modified wood is the function of modification temperature and the duration of modification. One of the most important measures of modification quality is mass loss. Mass loss is rather easy to determine in a laboratory, or directly after modification, but is not suitable as the quality control measure in case of users complaints or warranty issues. In order to increase the importance of wood modification on the market, independent, fast and reliable methods for quality control of thermally modified wood have to be developed. The aim of the presented paper was to screen suitable methods and to select the most appropriate methods for quality control of modified wood. The research was performed on Norway spruce wood, as one of the most frequently used species in a thermal modification.

Samples were made of dry, defect-free Norway spruce wood. Any signs of decay, blues staining or insect decay was not permitted. Samples were modified according to three different laboratory processes: unwrapped (1) and wrapped wood in aluminium foil in an laboratory oven at normal atmospheric conditions (2) and modified according to the vacuum-based Silvapro® procedure (3), at four temperatures (200 °C, 210 °C, 220 °C and 230 °C). Control specimens were left non-modified. After modification, mass loss of the samples was determined gravimetrically, based on absolutely dry mass before and after modification. After three weeks of conditioning, samples were cut to smaller specimens for further analysis, namely: colour measurements (CIEL*a*b*), envelope density (GeoPyc 1365, Micromeritics), true density (AccuPyc II 1340, Micromeritics), compression strength (Zwick Z100), pH value of wood extract, contact angle (Theta optical tensiometer, Biolin

Scientific), short-term water uptake (Krüss K100 MK2), long-term water uptake, adsorption above saturated salt solutions and dynamic vapour sorption (DVS Intrinsic, Surface Measurement Systems). Results were calculated and correlated to the mass loss of the samples after the modification procedure (Table 1).

Mass loss of the samples increases with increasing modification temperature. The highest mass loss was found at unwrapped samples modified at the normal ambient atmosphere in the oven and the lowest one at samples wrapped in foil. Colour changes increased with modification temperature and respective to mass loss. However, we believe that colour change is not the best indicator, as the colour of modified wood changes during weathering, this quality control measure is not applicable to weathered wood. A similar effect of weathering was found for contact angle and short-term water uptake. On the other hand, sorption properties were found more reliable. Unfortunately, assessment of sorption properties above saturated salt solutions was found rather time-consuming. However, among all methods tested, the most indicative method for determining the degree of modification has proven to be DVS (dynamic vapour sorption). Also there is no need to run the whole sorption and desorption cycle. Conditioning to reach equilibrium moisture content in one target climate is sufficient. The method was tested on blind samples from industry and was validated as 95% accurate. This method is fast, cheap and easy to perform. DVS is becoming standard equipment in several material-science laboratories. Promising results were also obtained using thermogravimetry, where the mass loss in the temperature range from 130 to 300 °C corresponds well with the mass loss during previous thermal treatment (R^2 = 0.99).

Table 1: Pierson's correlation factors between mass loss after thermal modification and respective quality control measure.

Method	**Correlation**	**Method**	**Correlation**
Immersion 1 h [g]	-0.8495	L*	-0.8760
Immersion 24 h [g]	-0.8510	a*	-0.6817
Contact angle 1 s [°]	0.8228	b*	-0.7741
Contact angle 5 s [°]	0.8261	ΔE	0.8753
Contact angle 60 s [°]	0.6958	pH	0.3136
Short-term water uptake [g/cm^2]	-0.1883	Compression strength E [GPa]	-0.2763
RH = 100 % - 24 h [g]	-0.8374	Envelope density [g/cm^3]	-0.4397
RH = 100 % - 1 w [g]	-0.8667	True density He [g/cm^3]	0.2574
RH = 100 % - 3 w [g]	-0.8718	DVS Time - EMC [min]	-0.6477
RH = 100 % - 4 w [g]	-0.8712	DVS Time - EMC/2 [min]	-0.8014
RH = 100 % - 5 w [g]	-0.8723	DVS Time - 5 % EMC [min]	0.5368
RH = 100 % - 6 w [g]	-0.8727	DVS Time - 10 % EMC [min]	0.8501
RH = 100 % - 7 w [g]	-0.8697	**DVS Time - 15 % EMC [min]**	0.9636

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Physical and elastomechanical properties of full-size fir (*Abies alba*) sawnwood after heat treatment with different intensities

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Keywords: thermally treated wood, weight loss, colour, dynamic modulus of elasticity

Thermal treatment of wood at high temperature (160 °C to 260 °C) is one of the modification methods used to enhance the dimensional stability and bio-durability of timber and wood-based composites (Bekhta and Niemz, 2003). However, the important negative aspects of thermally treated wood are strength reduction and stiffness alteration, which vary with the anatomical direction of the wood, and between wood species. Nevertheless, the use of thermally modified timber for structural purposes is of increasing interest, where the preservation of mechanical properties of wood is preferable (Widman *et al*. 2012).

The main goal of the study was to use non-destructive mechanical and physical test methods to investigate possible internal structural changes of fir (*Abies alba* Mill.) full-size sawnwood (45 x 120 x 4000 mm) after vacuum industrial heat treatment (SilvaproTM, SI-Ljubljana), having varying treatment temperature between 170 °C and 230 °C. The machine stress grading by the flexural vibration response of sawnwood before and after the heat treatment using Euler-Bernoulli theory (Roohnia and Tajdini, 2014) was analysed and compared with the weight loss of boards and their CIE*Lab* colour parameters.

Heat treatment by rising the temperature induced a significant increase in the weight loss of wood and caused a drop in the wood mean density of 2.5% at a temperature of 170 °C (ρ_{170} = 415 kg/m^3) and up to 10.3% at the treatment temperature of 230 °C (ρ_{230} = 392 kg/m^3). Even after the lightest thermal modification (T = 170 °C), the equilibrium moisture content of the wood in the normal climate (20°C / 65% RH) dropped to 8.0% and stabilized between 6.9% and 7.6% in stronger thermally modified wood. By increasing the intensity of the heat treatment, the colour lightness L* of wood was significantly reduced, however changes in a* and b* colour parameters were insignificant (Table 1).

The modulus of elasticity in the test specimens increased initially by the intensity of thermal modification (≤ 190 °C), however at higher temperatures, particularly at 230 °C, it dropped below the values of control samples (Table 2). This trend followed the mean strength class of sawn timber and was present in all five tested vibration modes. The theoretical linear decreasing slope of the flexural moduli of elasticity with increasing vibration mode number was confirmed only at control specimens. Major changes between the sequencing moduli with regard to vibrational mode (q), especially for higher modal numbers, occurred at higher heat treatment temperatures (≥ 210 °C).

Table 1: Mean wood density (ρ), weight loss (WT_{loss}), equilibrium moisture content (EMC) and colour parameters (L* - lightness, a*, b* - chromaticity on green-red and blue-yellow axis; (2nd rows present Coef. of variation (%)).

Heat treatment [°C]	ρ [kg/m³]	WT_{loss} [%]	EMC [%]	L^*	a^*	b^*
Control	425		12.4	74.9	6.1	25.1
	6.4		*4.1*	*2.8*	*10.5*	*5.7*
170	415	2.5	8.0	57.8	13.0	31.5
	6.7	*36.6*	*12.7*	*6.2*	*9.2*	*4.8*
190	415	3.1	7.5	47.6	11.7	24.8
	7.3	*26.8*	*11.9*	*7.1*	*6.5*	*10.9*
210	397	5.9	6.9	44.2	11.6	23.5
	6.5	*24.9*	*8.1*	*6.0*	*5.8*	*4.9*
230	392	10.3	7.6	37.6	10.3	18.8
	6.7	*15.9*	*13.9*	*4.4*	*8.5*	*9.9*

Table 2: Mean moduli of elasticity of heat treated structural timber determined by flexural vibration at individual vibration mode (1 ≤ n ≤ 5), the moduli variation (q) and the mean bending strength according to EN 338 (2nd rows present Coef. of variation (%)).

Heat treatment [°C]	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	E_4 [GPa]	E_5 [GPa]	q [%]	Mean strength class
Control	12.74	13.01	12.38	11.83	11.45	149.5	31.6
	12.18	*12.56*	*12.85*	*12.66*	*12.43*		21.1
170	13.58	13.48	12.96	12.47	12.06	131.4	34.1
	9.55	*11.12*	*10.65*	*10.17*	*10.32*		17.6
190	13.59	13.73	12.96	12.50	12.12	178.8	34.9
	12.47	*10.55*	*10.34*	*10.20*	*10.12*		20.3
210	12.94	12.81	12.12	11.71	11.40	231.5	29.4
	14.48	*10.81*	*11.66*	*11.81*	*11.42*		20.9
230	11.58	12.45	11.69	11.21	10.92	270.4	26.8
	23.39	*17.81*	*18.86*	*18.16*	*18.27*		36.6

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