VTT SYMPOSIUM 263

2009 Wood and Fiber Product Seminar

VTT and USDA Joint Activity

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Preface

Professor Kari Larjava, Executive Vice President, R&D
VTT

The development of high-value wood and fiber products is one of the most important challenges currently facing the forest industry. Traditional pulp and paper products are on a critical path in developed countries with prices and markets decreasing. Finland and the USA have faced the same problem, which is a fundamental reason for Industrial Biomaterials being one of VTT's four spearhead programmes. The programme focus is precisely on the development of sustainable fiber-based products which generate added value for wood. Forestcluster Ltd works in the same directions and collects all the Finnish forest research and actors in one cluster.

It was a great pleasure to have experts from VTT, Forestcluster Ltd and USDA at a common seminar in Espoo. This publication includes a collection of papers from all the sessions: Consumer Products, Passive Building, Fiber Processing and Wood Durability. Management issues are also introduced.

I would like to express my greatest thanks to all the scientists and experts who made their contributions to this seminar.

Contents

Joint research into forest-based biomaterials – Industrial Biomaterials Spearhead Programme

Ali Harlin
VTT Technical Research Centre of Finland

VTT's Industrial Biomaterials Spearhead Programme 2009–2013 develops technologies and competencies utilising basic skills in chemistry, biotechnology, process technology, material science, modelling and analytics.

The technologies and competencies developed in the Spearhead Programme are steered to generate value chains that start from forest biomass and end up in selected high-volume consumer products. In such development, it is key not to disturb the fragile value chains of the food sector.

The Spearhead Programme focuses on the development of materials and production technologies based on fibers and nanocellulose, as well as biomass-based monomers and polymers. The aim is to integrate these new value chains into existing biorefineries. The annual volume of the Spearhead Programme is 12–14 M€ p.a.

The results will be exploited by actors in the chemical, process technology and material sectors, both domestic and global. Target sectors of particular interest are the plastics, process, forest and energy industries, as well as packaging and building. The Spearhead Programme will co-operate closely with the Finnish strategic centres for science, technology and innovation, in particular, Forest-cluster Ltd, in forest products, in its biorefine project Fubio.

General agenda

Since the Brundtland Commission, formally the World Commission on Environment and Development (WCED) (1983 General Assembly), the environmental perspective has been addressed, and the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development, and long-term environmental strategies have been emphasized for achieving sustainable development in co-operation between developing countries and between countries at different stages of economic and social development, and led to the achievement of common and mutually supportive objectives.

Climate change has recently become a dominant issue. The focus is in preventing the greenhouse effect through evaluation and limiting the carbon. The agenda is well addressed and motivated, especially in the field of fuels. The potential for influencing climate change through greenhouse gas reduction in materials is weak however. In biomaterial development we have to consider the wider scope of sustainable development, which is a pattern of resource use that aims to meet human needs while preserving the environment to meet not only the present needs, but also those of future generations. (UCN 2006, United Nations 1987)

Sustainable development ties together concern for the carrying capacity of natural systems with the social challenges facing humanity. As early as the 1970s, “sustainability” was employed to describe an economy in equilibrium with basic ecological support systems. (Smith and Rees 1998) Ecologists have pointed to the limits of growth (Stivers 1976) in their environmental concerns. The field of sustainable development can be conceptually broken down into three constituent parts: environmental sustainability, economic sustainability and socio-political sustainability.

The Industrial Biomaterials Programme aims to develop new sustainable materials for selected application areas with the objective of developing new sustainable value chains.

Open innovation

The forest industry, polymer and plastic manufacturers have reached a champion position in their markets. Meanwhile the costs of making market-renewing innovations have grown markedly high. Further growth will require cross-border collaboration. A world of widely distributed knowledge through licensing and joint ventures between companies that extends to spin-offs from research institutes and universities is becoming attractive. (Chesbrough 2003a) The boundaries between firms and their environments could become more permeable, leading to easily transferable innovations.

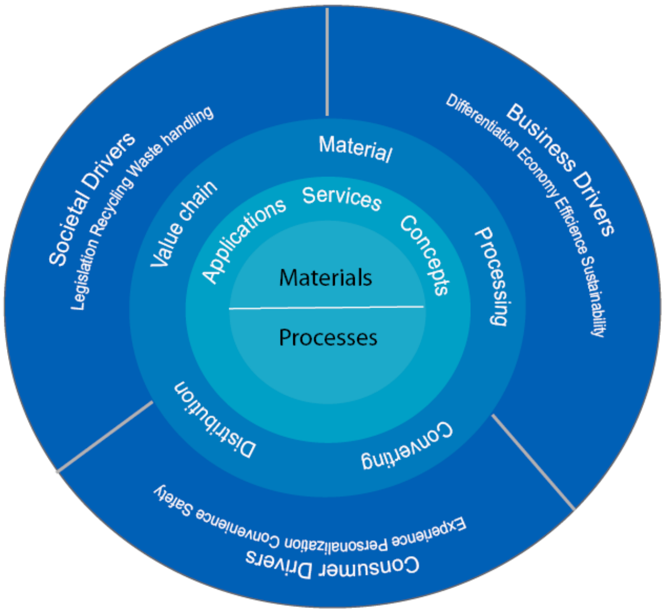
Open Innovation is a concept related to user innovation, cumulative innovation and distributed innovation. In the field of biomaterials, the use of external as well as internal ideas, and internal and external paths to market, looks attractive. (Chesbrough 2003b) Several companies currently operate as open innovation intermediaries using multiple instruments to open up their innovation system, such as corporate venture capital funds, foresight workshops, executive forums and spin-outs. (Rohrbeck et al. 2009) These are the forums in which institutes that develop biomaterial should also be involved.

In the Industrial Biomaterials Spearhead Programme, VTT is actively looking forward to the commercialization of technologies and materials in close co-operation with its industrial customers and international research partners.

Importance of wood biomass

Wood and agrobiomass are the most important raw materials of the European biorefining industries. The annual wood production in Europe is approximately 450 million m^3 (approximately 265 Mt). The European kraft pulping industry is the main actor separating cellulosic paper-making fibers from wood chips with a 23% share of the world production of kraft pulp. Of the wood side-streams, which represent over 50% (w/w) of the initial wood biomass, only about 0.5 Mt/year are valorised to various by-products, while the rest, approximately 31.5 Mt/year of the kraft pulping side-streams and 6–8 Mt/year of bark, is mainly burned for steam and power generation or used for land construction.

The research approach of the Spearhead Programme is application driven. Material applications include packages, building and consumer products. Several industries, e.g., packaging, construction, vehicle, furniture, electronics, food product and cosmetics industries, can create added value for their products by using bio-based materials. Sustainability of the novel material solutions will be evaluated at product and society levels.



Target-driven approach

Packaging, especially food and consumer goods packaging, will be a globally growing product area in the future. Sustainability, quality and functionality will influence consumer purchase decisions, and tailored packaging concepts will set new demands for the packaging industry. Fiber-based packaging materials have good potential to replace glass and metal in some contexts. Fiber-based packaging is lighter to transport and can be reused as an energy source in the end-use phase.

Energy-efficient houses wooden frames still dominate small residential house building. The upcoming energy efficiency regulations, however, can strengthen the role of other competing materials, such as concrete, light concrete blocks and bricks. The demand for better U-values clearly leads to more airtight and thicker wall structures, especially when ordinary glass/rock wool insulation materials are used. These demands can be better fulfilled by using polyfoam insulators like polyurethane, which could also be partially or fully bio-based.

Emerging biopolymers – all the side-streams and waste fractions are undergoing intensive research into biofuel components. Side-streams and residuals of biofuel production are increasing. Just as oil refining has resulted in the petrochemical industry, the emerging biofuel industry will analogically lead to the creation of bio-based chemical industries.

New development is leading towards synthetic polymers, which are increasingly produced from bio-based raw materials. The bio-replaced polymers have high performance, which is combined with renewable raw materials. In well-optimized conditions, it is possible to produce plastic products with an excellent life-cycle analysis.

Developments at VTT

In these activities, VTT is willing to co-operate with leading international partners, targeting economic impact and sustainability in the field of wood and fiber-based material applications including packages, building and consumer products. The seminar with USDA is one example of this endeavour.

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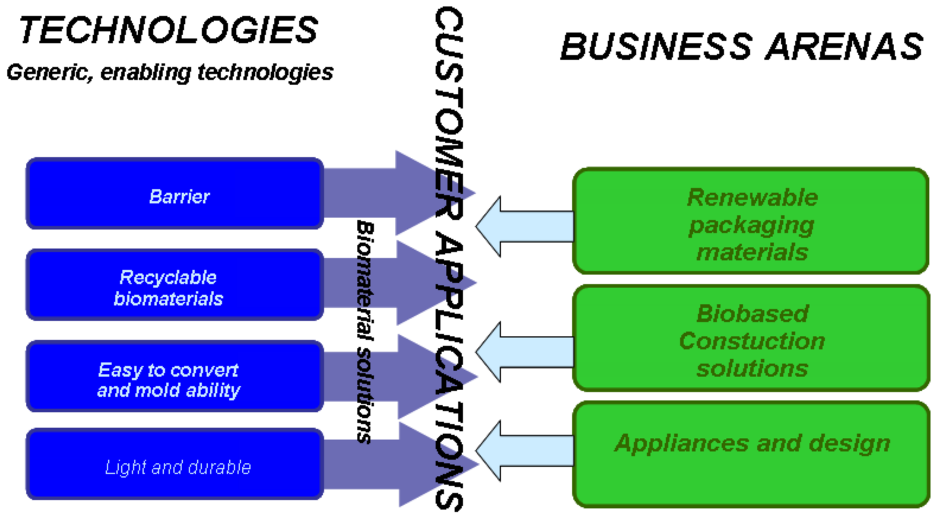
Industrial Biomaterials, VTT Spearhead Programme

Prof., Vice President Anne-Christine Ritschkoff, Dr. Mr. Tuomas Mustonen, and numerous other VTT colleagues active in printed intelligence and packaging-related developments.



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Forest cluster research in Finland

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Forestcluster Ltd (Metsäklusteri Oy) is an innovation company established to network top level research and innovation in the Finnish forest cluster.

Major companies in the Finnish forest cluster together with the Technical Research Centre of Finland, the Finnish Forest Research Institute and four Finnish universities have established Forestcluster Ltd. The forest sector's centre of excellence - led by the Forest Cluster Ltd - intends to become the strongest innovation environment of the branch globally.

The innovation focused company is responsible for the operation of the cluster's strategic centre of excellence. Its task is to initiate research and innovation programmes and to channel research funds to selected focus areas which are presented and defined in the Finnish national strategic research agenda, SRA.

The research strategy for the Finnish forest cluster was published in October 2006. It defines key focuses of research activities in the forest cluster and its customer sector. Meeting the objectives in the research strategy means that Finland will continue in future to have a successful, world's most profitable and sustainable forest cluster whose products and services are the most desired in the world.

The objective is to double the value of the forest cluster's products and services by 2030. Half of this value would come from new products. Domestic use of wood should be increased by one-fourth. The cluster's investments in research and development should also be doubled.

Forestcluster Ltd will be responsible for initiating and resource allocation of the centre of excellence's research programmes by channeling private and public research funds to programmes. In addition to companies, the sources of finance are Tekes, the Finnish Funding Agency for Technology and Innovation, the Academy of Finland and bodies in the EU's Seventh Framework Programme.

Two major programs EffTech (Energy- and Resource-Efficient Production Technologies) and FuBio (Future Biorefinery) are fully operative and the third program, FoCuS Forward Customer Solutions, has been well been initiated.

The main targets of the EffTech program are:

- Develop radically different new manufacturing technologies that are energy-efficient and use resources sparingly
- Develop new kinds of integrated solutions for the production and utilization of bioenergy
- Reduce the capital intensiveness of the cluster
- Improve the efficiency, flexibility and sustainability of the cluster's value chains (print communications, packaging, construction and others)
- Demonstration of new, factory-scale technologies.

The objective of Future Biorefinery, the second research program of Forestcluster Ltd., is to develop new methods enabling fractionation of wood into cellulose, hemicelluloses, lignin and extractives in their native-like form and further, to upgrade these fractions into chemicals and materials.

The structure of the program is designed in manner that facilitates integration of the new value chains also to current pulp mills as well as to emerging biorefineries producing transport biofuels as a by-product. The program consists of different themes. The focus of Theme 1 is fractionation of wood and separation of black liquor hydroxy acids. In Themes 2 and 3, cellulose and hemicelluloses, respectively, are up-graded into value-added chemicals and materials. In Theme 4, a desk top study on the possibilities of black liquor gasification and pyrolysis is performed. Theme 5 is focusing on extraction and up-grading of extracted components. Finally, in addition to administrative tasks the sixth theme (Theme 0) will also include generation of a modeling platform for evaluation of the new value chains.

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Wood products research in the USA

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Forest biomass conversion to biofuels and other value-added co-products; hyper-performance advanced composites custom tailored to end use requirements; advanced high performance wood-based structures; and nanomaterials and nano-enable high performance products from wood represent important research and development investment areas for the successful transformation of the forest products industry into a reinvented and reinvigorated growth industry in the 21st Century. Research and development investments in the preceding areas will help make wood the sustainable, renewable, and recyclable material of choice in the 21st Century.

Introduction

The United States (US) has been the world's largest producer of wood-based products and ranks third of all countries in volume of standing forest biomass. As a result, forest products are an important part of the US economy accounting for about 6.2% of the total US manufacturing Gross Domestic Product (GDP). Forest products contribute over $240 billion to GDP and account for approximately 1.1 million American jobs. The US Department of Agriculture Forest Service (USDA- FS) Forest Products Laboratory (FPL) – cooperating with industry, universities, and others – has been instrumental in advancing the U.S. forest products industry over the past 100 years. Current FPL research areas include the following:

- Developing new technologies for converting forest biomass for energy
- Sustainable chemical feedstock from wood
- Life-cycle analysis assessments of wood products

- Integrated building components for structures
- Engineering and construction standards
- Improving the performance of wood in use
- Environmentally acceptable wood preservatives
- High-performance composites and related adhesives technology
- Environmentally preferable pulping processes
- Economic utilization options for small-diameter timber
- Reduced environmental impacts at conversion facilities
- Improved efficiencies in hardwood processing
- Evaluation of the economic feasibility of new technologies and markets
- Nanoscience and technology of wood-based materials.

While the US forest products industry has had success in the past, its success in the 21st century is not assured as there are significant drivers of change affecting the Wood Products Industry sector world-wide. Drivers of change include:

- Integration of the World economy and subsequent escalation of industrial quality and cost competitiveness
- Growing population, affluence and changing demographics
- Accelerating pace of science and technology
- Mitigating the impacts of climate change through reduced use of fossil fuels
- Quests for individual nations to achieve energy security using biofuels
- Reducing the environmental footprint of human activities
- Reducing the carbon footprint of products and manufacturing processes
- Increasing efficiency of energy and materials use
- Emergence of the concepts of Sustainability, Green Buildings, Green chemistry, and Green Engineering and making life cycle comparisons among competing products and materials via use of life cycle assessment.

While the US forest products industry has become somewhat less fragmented through consolidation of companies through mergers, acquisitions, and shut-downs and closures of older and less efficient production lines, forest products companies generally have limited resources for research and development (R&D) and are increasingly dependent on government and government-sponsored entities for research. Because companies – whether large, medium or small – are facing increasing competitive market pressures, research is even more important to maintaining the positive economic, social and ecological contributions of businesses and production facilities. Universities and government laboratories such as FPL play a critically important role in conducting innovative research. FPL research priorities are advanced structures, advanced composites, nanotechnology, and forest biomass to biofuels and value-added co-products.

Advanced structures

As we move further into the 21^{st} century, the demands and complexity of structures are ever increasing. In the past, structures were designed based solely on life safety issues. That is no longer the case. Today, structures are designed considering life safety along with functionality, environmental impact (e.g. Green building, energy efficiency, etc.) and economics. As a result, structural wood design is moving toward a performance-based design methodology that encompasses the entire life cycle of a structural system. Performance-based design procedures rely upon data that must have a strong scientific foundation. Technical data on the interactions between various exposure scenarios (e.g. mechanical loads, biological agents of deterioration, moisture exposure, fire performance, etc.) form the basis for performance-based wood design. Performance-based design will initially have its greatest impact on nonresidential wood structures where owner-users can realize its long-term benefits. Innovations and knowledge from development of a performance-based design approach also provides the framework for evaluating and minimizing the environmental footprint of wood-based structures.

Adoption of performance-based engineering concepts represents a major change in the thinking, practice, and education of designers. Perhaps most important is a shift away from dependence on empirical and experience-based conventions towards a design and assessment process more firmly rooted in realistic prediction of structural behavior under a spectrum of loading environments that the structure will experience. This requires a shift towards a more scientifically oriented approach with an emphasis on accurate characterization and prediction of structural performance. A second but equally important change in this approach is an emphasis on health monitoring of the structural system, which evaluates performance characteristics and identifies the need for renovation or new construction. These also form the foundation of strategies for revitalizing decaying infrastructure. A performance-based approach provides the appropriate framework for integration of sensing, monitoring, and control systems to monitor and maintain the health of structures. As a result of this, FPL structural research programs are in the general areas of: 1) structural systems, structural analysis and modeling; 2) durability and resistance to natural disasters (e.g. floods, hurricanes, tornadoes, earthquakes, etc.) to include performance and modeling; and 3) health monitoring (e.g. remote monitoring systems that utilize sensors to indicate degradation of wood structure).

Advanced composites

The next generation of advanced wood and biocomposites must both meet the diverse needs of users for high-performance construction and specialty products while simultaneously promoting sustainability of forest and other natural resources. Advanced engineered wood and biocomposites must also provide advanced performance, durability, value, service-life, and utility. Next generation advanced composites must provide construction materials and building products that far exceed current expectations (e.g., lower cost, more adaptable, more reliable, lower maintenance, smarter, etc.) while opening new markets (e.g., commercial construction, automotive, aerospace, etc.) and reducing effects on the environment (e.g., energy, air, water, and waste). FPL research program activities are focused on hyper performance advanced engineered wood and biocomposites that:

- Combine wood, and natural biofibers, and non-biomaterials to create synergistic hybrid materials that far exceed the performance capabilities of current biocomposites
- Are renewable, recyclable, and totally sustainable
- Provide hyper-performance and superior serviceability that again far exceeds the performance capabilities of current biocomposites
- Are more durable, dimensionally stable, moisture-proof, and fire-resistant

- Possess integrated hyper-performance capabilities such as warning users when problems are imminent and/or possess multifunctional capabilities
- Have both materials and processes engineered to customize and optimize performance
- Are sustainably produced, be environmentally beneficial and be less expensive to produce and use (over the life cycle of use) than materials they replace.

Nanotechnology

Nanotechnology has enormous promise to bring about fundamental changes and significant benefit to the forest products industry. By becoming a user of nanotechnology materials and components in its products and processes, industry can upgrade its processes and produce new high performance consumer products from lignocellulosic-based materials in a safe and sustainable manner. The industry also can become a producer and developer of novel, sustainable nanomaterials to replace non-sustainable materials such as those from fossil-fuels. Use of nano-dimensional cellulose in nanocomposites will allow the production of much lighter weight materials to replace metals and plastics with widespread application to the forest products and other industries. Investments in nanotechnology for the forest products industry sector will have substantive, measurable, and pervasive beneficial effects for society such as increased Gross Domestic Product (GDP), increased employment, and creation of high paying, skilled jobs. It will also usher in cost effective and affordable production of sustainable materials and products close to markets where they are used thus greatly reducing transportation costs and energy consumption producing and transporting materials great distances as is the practice now. It will also greatly reduce the waste of materials and energy due to unnecessary over-construction of products and structures arising from our current lack of knowledge of nanoscale structures and interfaces. In the US, a nanotechnology-revitalized forest products industry will also enhance forest health and condition; retard the current accelerating trends of forest fragmentation, parcelization, clearing, and conversion of forest lands to non-forest uses; increase recharge of water to aquifers as 90 per cent of the precipitation that falls on a forest is retained; and provide the full array of other forest ecosystem services to include animal habitat, clean water, clean air, carbon sequestration, recreation, etc.

Nanotechnology is the scientific study and applications of materials that have at least one dimension smaller than 100 nm. The wood cell wall is composed of 3 to 10 nanometer elementary nanofibrils and how they assemble into the cell wall and how they associate with the hemicellulose and lignin in the cell wall are all nanoscale architectural concerns. The crystalline cellulose in wood can be isolated as a particle of up to 300 nm length and 3 nm width. These cellulose nanocrystals have useful properties for reinforcing polymers and should be available at a fraction of the cost of other nano-fibers such as carbon nanotubes. The forest products industry has a role to play in supplying the cost-effective nano-dimensional materials to make a commercial reality of nano-reinforced composites.

The FPL Nanotechnology research program includes the following:

- Characterize the novel nanoscale and nano-structured properties and architectures occurring in wood cell walls
- Develop cost effective technologies for isolating nanocrystalline cellulose from wood
- Characterize cellulose nanocrystal morphology, physical, mechanical, piezoelectric and chemical properties
- Relate the mechanical and chemical properties of nanocrystalline cellulose to its nanoscale surface chemistry and morphology
- Understand the science and technology of water cellulose interactions at the nanoscale
- Understand and learn how to manipulate the photonic, piezoelectric, and electronic properties of lignocellulosic nanomaterials and nanostructures
- Develop the science and technology needed to modify the functionality of nanoscale lignocellulosic architectures present in wood cell walls
- Develop the science and technology needed for using the novel nanoscale and nano-structured properties and architectures occurring in wood cell walls to produce new hyper-performance, nano-enabled products
- Develop the nanomanufacturing science and technology needed to incorporate nanomaterials into macroscopic organic and inorganic composites of interest to the forest products industry

- Develop the science and technology needed to incorporate nanomaterials with a variety of functionalities to enhance the end use performance of wood-based materials to increase durability, strength, adhesion, increase strength to weight, etc.
- Work cooperatively with the forest products industry to help create the precompetitive science and technology needed to achieve its six priorities for nanotechnology – (1) creating higher strength and lighter weight materials and their products, (2) developing forest nanomaterials (e.g. cellulose nanocrystals), (3) controlling the interactions between water and lignocellulosic material, (4) producing hyper-performance nano-composites, (5) capturing and enhancing the photonic and electronic properties, and (6) reducing energy usage and capital costs in processing
- Develop and incorporate unique nanoscale sensors into wood-based products for processing and end use applications.

The forest biorefinery – forest biomass to biofuels and co-products

Forests can sustainably provide substantial renewable sources for biobased products and bioenergy critical to maintaining and enhancing US environmental quality and economic and energy security. The production, handling, and use of woody biomass for energy production and lignocellulosic products – as would be required for a forest biorefinery – are not new for the forestry sector. About 50% of the U.S. current renewable energy comes from wood-fed hog boilers and spent pulping liquor recovery boilers at forest product industry's manufacturing facilities. The breakdown of forest biomass feedstock into basic wood components – as would be required in the forest biorefinery – is also not new to the forest products industry. For example, on the order of 115 million (oven dry) tons of wood are processed annually in the US to extract cellulose for pulp and paper. The forest industry already has significant infrastructure for the production, harvest, and transport of wood – but not primarily for energy, liquid fuels, and chemical feedstock production as would likely be the focus of a forest biorefinery.

A number of important factors influence and contribute to the commercialization and expanded use of wood in forest biorefineries to make biofuels and other value-added co-products. These factors include 1) feedstock sources, feedstock production technologies, and other costs to supply wood feedstock; 2) harvesting and forest operations technologies, transportation, in forest pre-processing technologies; 3) types of conversion technologies including their feedstock needs, conversion efficiencies and costs; 4) connections to forest restoration treatments; and 5) development and deployment of biomass to energy facilities. The economics for producing advanced biofuels from forest biomass are tenuous as witnessed by the need for public funding to reduce risks for commercial efforts. A number of factors must come together with the aid of a focused research and development program to improve conversion technologies and reduce feedstock costs to enable advanced biofuels to be commercially viable without public subsidies.

FPL is developing technologies that permit forest biorefineries to produce bio-based products, bioenergy, and other value-added co-products. For example, FPL is working with a variety of partners to develop the integrated forest products biorefinery where wood-derived hemicellulose sugars are efficiently and effectively removed and fermented to ethanol prior to either being pulped for papermaking or processed into panel products. FPL is also developing new and improved separation technologies to produce chemical constitutive materials from wood at high yield. These constitutive materials will then provide biochemical substitutes for a variety of non-renewable feedstock. Other work includes developing technologies to simultaneously co-ferment C-5 and C-6 sugars to ethanol; developing wood pretreatment processes to allow recalcitrant cellulose to be more easily converted to monomeric sugars; nanocatalysis to produce polyols; developing new and novel high temperature liquid metals based pyrolysis and gasification conversion technologies; and conducting life cycle assessment and carbon foot print evaluations of biorefineries and their products.

Conclusion

The areas of forest biomass to biofuels and value-added co-products; hyper-performance advanced composites; advanced high performance wood-based structures; and nanotechnology and nanomaterials from wood represent important areas for the successful transformation of the forest products industry from the low profit, commodity-based industry of the late 20th Century to a reinvented and reinvigorated growth industry in the 21st Century. New technologies in these areas will help make wood the sustainable, renewable, and recyclable material of choice in the 21st Century replacing fossil fuel derived materials and other less desirable materials. FPL research is focused on developing the underlying enabling science and technology to achieve a renewed use of wood that serves to improve the health and condition of forestlands as well as help prevent privately held forestlands from being converted to non-forest uses by providing sufficient economic returns to cover sustainable forest management costs and provided adequate rates of return to forestland managers and owners.

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Fiber product session I – Consumer products

Chair: Tomi Erho
Senior Research Scientist, Team Leader
VTT

Opportunities for forest-based materials in consumer packaging – Case: Printed intelligence

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VTT Technical Research Centre of Finland

The evolving business needs of consumer-packaged goods companies are opening up new opportunities for forest-based materials and printed intelligence in consumer packaging.

The rapid evolution of information technology and resulting changes in media consumption and communication habits have led the forest industry value chain to place greater focus on seeking new value-added uses for fiber/forest-based products to drive industry growth. This article discusses evolving needs within one major end-application area of paper and board, namely, consumer goods packaging. Combined with new emerging technologies from industrial biomaterials and printed intelligence, these needs can present new and significant business opportunities for the forest value chain.

VTT is a multi-disciplinary, applied research institute, which actively works within and across various value chains. In addition to working with companies in the packaging and printing industries, VTT is actively involved in the research and development of ingredients and technologies used in consumer-packaged goods (CPGs). Based on these collaborations and active participation in CPG industrial networks, VTT closely monitors market trends and development needs, which potentially also impact the packaging and communications industries.

Needs and opportunities in sustainability

A main driver of developments in CPG companies and consumer packaging today is sustainability. This is in part driven by global concerns regarding human impact on the environment, availability of natural resources, and the well-being of a growing global population. As a carrier of products, packaging is increasingly expected to provide better performance through less waste of product and with less burden on the environment from the packages themselves. These requirements are opening up demands, which could be met in part by new advanced bio-based materials in packaging. Furthermore, the projected growth in crude oil prices and the already strong fluctuations in oil spot prices over recent years have the potential to improve the economic attractiveness of new forest-based materials.

While the technical properties of forest-based materials in packaging continue to develop and their supply is established as an environmentally and economically sustainable source, many further value-added possibilities in packaging are also rapidly emerging in the area of smart and interactive packaging. These relate to the communications value and added functionality of packaging.

Consumer packaging as a communications platform

Packaging as a communications platform and source of brand differentiation has been a requirement and driver of packaging developments throughout the evolution of branded product marketing. This need is being further highlighted in today's information-heavy and interaction-rich world. While many new forms of media have captured the time and attention of consumers, and their suppliers have built business models based in part on advertising revenues, there continues to be a disconnect between the physical (branded) product experience and the digital content and services offered by the brand owners.

At the same time, consumers are offered more choice and competitive offerings within and across product categories. As products within the package continue to develop, so too do the brand promises. All this is potentially impacting the way consumers choose products and the types of information and added services they value and are expecting with them. There is an increasing need for packaging to keep up with these promises and, with added functionalities, to take a more active value-creation role in the whole product throughout its life cycle.

These evolving performance and communications requirements for packaging are opening up a market for what is commonly known as smart and intelligent packaging. When in use by consumers, this may also one day be more commonly known as interactive packaging.

While the markets for smart & intelligent packaging are still small and in their very early market stage – due in part to the limited commercial availability of intelligent packaging solution supply and proof of value to the entire CPG value chain – they are expected to significantly impact the > 500 billion USD packaging industry and redefine what we as consumers expect from packaging.

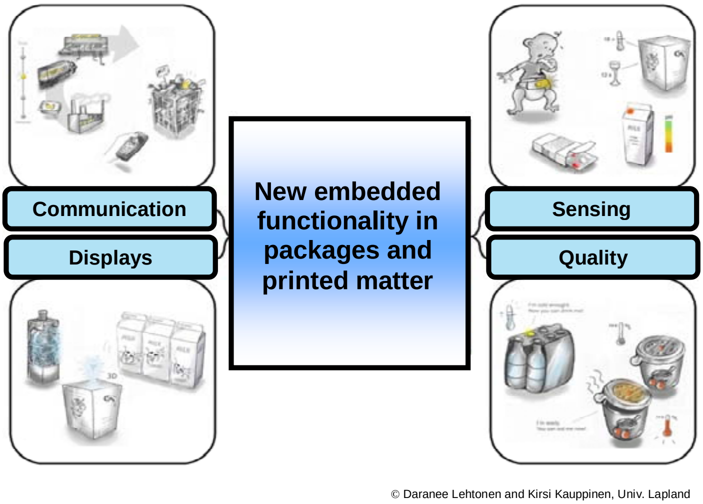

Figure 1. Examples of enhanced and new functionalities in packaging with increasing demand also in consumer packaging. Image © University of Lapland.

Printed intelligence

So what are the technical enablers for smart and intelligent packaging and for increasing the value of consumer packaging? Today, such added functionalities are largely based on labels (e.g. RFID tags, indicators for packaging) and laminated solutions. This will also be the case in most commercial executions in the near future.

However, the emergence of printed intelligence plus functional and bioactive papers will introduce new possibilities for cost-effective in-line integration of intelligence to packaging. This should, in turn, enable significant expansion of the smart packaging markets.

Printed intelligence consists of components and systems which:

- extend the functions of printed matter beyond traditional, visually interpreted text and graphics

- perform actions as a part of functional products or wider information systems.

Printed intelligence is based on:

- processes: large area, high-volume printing like mass-manufacturing methods (examples include high throughput printing such as roll-to-roll, digital printing, hot embossing, lacquering, coating, laser processing, electric sintering, etc.)
- materials: novel uses for advanced materials, new uses for existing materials, new advanced materials in liquid phase (such as conductive polymers, organic semiconductors, nano-particulate materials, bioactive materials) to produce new inks and coatings
- substrates: these are applied to, for example, fiber and are biopolymer based (e.g. functional papers, nano-cellulosic fibers, non-mineral-based filers and pigments)
- components: designed and realized with the above process/material combinations, and include, for example, indicators, sensors, holograms, organic LEDs, power sources, codes, tags and memories, etc.
- plus the possible interconnections of printed systems to wider IS/IT systems (e.g., external readout devices).

Toward smart and interactive packaging

Currently, there are only a few printed intelligence products on the market, but with over a decade of R&D by companies (particularly within the chemicals industry) and research institutes (like VTT), many components are becoming "ready-in-lab". The industry is now starting to address the needs more actively within end solutions and to invest in supply.

Furthermore, today we see less hype around individual components (e.g., printed RFID), and market predictions within industry are becoming more realistic, though the potential impacts and value targets of new printed functionalities remain high. More focus is now being placed on realizing products with existing capabilities rather than rapidly achieving the more futuristic visions of "printed electronics" and replacing traditional electronic components with fully printed ones.

However, the usability of printed intelligence technologies, from both a production and a consumer perspective, still requires further advances before there are real market breakthroughs. Furthermore, the materials used must not interfere with the disposal and recycling of the package. This is a potential showstopper for many efforts aimed at high-volume consumer packaging, but also a major opportunity for forest-based materials.

Developments at VTT

VTT is actively leading developments aimed at bringing new value to CPG packaging and utilizing forest-based materials and printed intelligence technologies as key enablers for this. With over 100 person years of R&D per year, printed intelligence has been a VTT spearhead strategic research programme since 2006. Industrial Biomaterials was lifted to this same status in 2009. With the merger of KCL into VTT, and the programme Re-inventing Paper, VTT continues to invest significant resources toward these goals in consumer packaging – and for the benefit of the forest industry in general.

Forest-based materials have many more value-added opportunities in consumer applications: smart and intelligent packaging is covered as one example area. New businesses and collaboration between different stakeholders in forest industry are required to realize these opportunities. In part to promote such collaboration, VTT is expanding its products and services beyond contract research, laboratory services and IPR licensing. VTT now also provides customer-specific foresights and roadmapping services, and services to application/concept development. VTT actively networks with research institutions and companies across value chains in international joint research projects, joint development projects and application-driven affiliate programme(s).

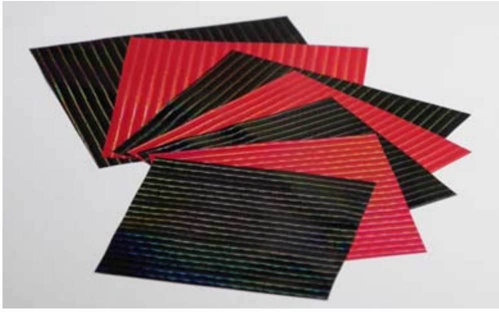

Figure 2. Holographic effects produced directly into printed paper without added foils, labels or laminations. Beyond visually appealing images, these structures can also act as, for example, optical memories or micro-fluidics channels.

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Challenges in the packaging market

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Global packaging development trends address sustainability, ease of use, convenience, differentiation – and cost-efficiency. Advanced fiber-based materials and packaging solutions offer new attempts at possibilities for future markets, for both consumer-packed goods and for secondary/retail packages. Challenges in this area include how to implement high-value functionalities into fiber-based materials and processes for consumer-packed goods. Ever more business-oriented collaboration and development are required within and across the industry value chain – existing and emerging – to realize major new business opportunities. VTT has taken an active role in developing advanced biomass-based material solutions for packaging applications – replacing the non-renewable counterparts in terms of performance, product life cycle and recyclability, without competing with food production.

Introduction

The packaging industry has seen a growing trend in recent years towards the use of plastics, and this has affected sales of metals, glass, and paper and board packaging. More recently, a growing concern for the environment has presented opportunities and challenges to all parts of the industry. Paper and board packaging is well positioned to withstand these pressures, and indeed benefit from them (Pira 2009).

Today's companies in the packaging supply chain are faced with acknowledging, understanding, addressing and managing a range of issues affecting the sustainable use of packaging. Issues include the use of renewable and non-renewable resources, recyclability, regulations, and material and transport costs.

Ongoing demographic and life-style changes, technology changes, environmental issues (in particular as recognised by legislation and/or voluntary agreements in numerous countries), consumer dynamics, and supply chain demands are important factors influencing the packaging supply chain. For fast-moving consumer goods, particularly such as food products, packaging is one of the key product components that can provide a commercial advantage over competing products. Hence, packaging is of significant commercial importance for the economical sustainability and growth of businesses. Key challenges for future business growth and development are:

- The ability to meet supply chain and market requirements in terms of distribution efficiency, marketing power, consumer safety and convenience, and environmental performance;
- To maintain high levels of flexibility for creating a commercial advantage through value-added packaging systems;
- To maximise triple bottom-line performance (economic, social, ecological) in order to satisfy both commercial stakeholders (shareholders, customers) and community stakeholders (government, consumers, non-governmental organizations).

These challenges cannot be successfully tackled with the traditional 4R approach (Reduce, Re-use, Recycle, Recover, Dispose). A holistic, integrated and collaborative initiative involving the entire supply chain is essential to be able to create step change improvements. The focus should not be on how the supply chain can reduce the amount and increase the recycling of packaging used, but on how it can sustainably satisfy the economic, social and environmental requirements for packaging related to the production, distribution and consumption of products in order to further enhance the well-being of our society (IAPRI 2009).

VTT's approach to novel fiber-based packages

VTT has extensive expertise in packaging technologies, including engineering of novel fiber-based and other biomaterials. Research is targeted at competitive products and solutions for the paper, chemical and packaging industries. Special emphasis is placed on combining developed functional systems with novel printing and coating technologies. New solutions for consumer-packed goods are developed through a thorough understanding of product behaviour during storage and distribution. The understanding of end-user benefits and requirements of the packaging value chain is the basis for successful developments. VTT has taken an active role in the applied research and development of new technologies and in the development of applications and markets.

VTT's special expertise lies in using biopolymers in the coating of fiber-based materials. Various intelligent (electrical, chemical or biosensing) functionalities can also be incorporated into the print substrate or the paper structure by means of printing or coating methods. VTT is at the forefront of research into these technologies and is very experienced in developing various low-cost indicator technologies for consumer packages. Recently, the focus has been on the combination of biotechnologies, printing technologies and information technologies. The industrial application of materials produced using renewable raw materials generates new, sustainable value chains and reduces our dependency on oil and the carbon footprint of consumption.

VTT's Industrial Biomaterials Spearhead Programme, headed by Professor Ali Harlin, develops technologies and competencies utilising skills in chemistry, process technology, material science, modelling and analytics. The technologies and competencies developed in the Spearhead Programme are steered towards generating value chains that start from forest biomass and end up in selected high-volume consumer products. In such development, the key is not to disturb the fragile value chains of the food sector. The Spearhead Programme focuses on the development of materials and production technologies based on fibers and nanocellulose, as well as biomass-based monomers and polymers. The aim is to integrate these new value chains into existing biorefineries. The results will be exploited by actors in the chemical, process technology and material sectors, domestic as well as global. Target sectors of particular interest are the plastics, process, forest and energy industries, as well as packaging and building. The Spearhead Programme will cooperate closely with the Finnish strategic centres for science, technology and innovation, namely Forestcluster Ltd., Cleen Ltd. and Fimecc Ltd.

VTT, Helsinki University of Technology, and UPM established an internationally unique Finnish Centre for Nanocellulosic Technologies in 2008. This aims to create new applications for cellulose as a raw material, substance and end product. Cellulose-based nanofibers can be used to alter the structure of the material and create products that better correspond to future market needs.

Towards new materials

Some general development directions towards advanced biomaterials include:

- Improvement of PLA as a packaging material: increased temperature resistance, impact strength and barrier properties, nucleation, impact modifiers, reinforcements, comonomers, etc.
- Biobased high-performance polymers from renewable raw materials, but often non-biodegradable
- Paper products, 100% from renewable raw materials: biobased adhesives, coatings, pigment binders, paper chemicals, etc.
- Organic fillers and pigments
- Polymers from lignin and hemicelluloses.

Potential application areas of nanotechnology, especially in food packaging include:

- Nanocomposites (esp. nanoclay-based) and nanostructured coatings for materials with improved barrier properties against oxygen and light, mechanical strength and flexibility, temperature and moisture stability, durability
- Biopolymers with improved performance through, for example, fiber modification, modification of biopolymer nanostructures, bionanocomposites
- Active materials: antimicrobial materials, oxygen scavenging materials, UV-absorbing materials
- Intelligent packaging: printed indicators based on intelligent inks, active tags, disposable power sources (logistics), product identification and anti-counterfeiting (nano barcodes, nano taggants).

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Product safety of packaging materials

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In general, product safety issues are related to food contact materials. However, safety demands do not only concern food packages. Other packages, e.g., for pharmaceuticals, medical ware, toys and electronics, also need to be safe. In Europe, the General Product Safety Directive regulates all consumer products by stating that "only safe products can be placed on the market". It covers any products intended for and likely to be used by consumers, including the products' packaging.

Requirements behind the product safety

Food packaging is part of the food production chain. The safety of food packages is therefore as important as the safety of food. For this reason, many regulations and recommendations point to food package materials and other materials intended for food contact.

In Europe, all food contact materials are regulated by Framework Regulation (1935/2004/EC) and by the GMP Regulation on good manufacturing practice (2023/2006/EC). The Framework Regulation states that food contact materials shall be manufactured so that under normal or foreseeable conditions of use, they do not transfer substances to food in concentrations that could endanger human health or change the characteristics of packaged food in terms of taste, odour or composition. The Framework Regulation only gives the principle; it does not lay down how to prove safety.

Last year, a new regulation on active and intelligent materials (Regulation 450/2009/EC) was adopted in Europe. It contains specific requirements for active and intelligent food contact materials. Intelligent materials are those that monitor the condition of the packaged food or the environment surrounding the food. Active materials are intended to extend shelf life or improve the condition of packaged food. They are designed to release or absorb substances into or from the packaged food or the environment surrounding the packaged food.

Plastic food contact materials and articles are regulated by directive 2002/72/EC and its five amendments (the next amendment is under preparation). In Europe, no specific legislation exists for food contact paper and board. However, a recommendation on food contact paper and board, called Paper Resolution (ResAP(2002)1), and a recommendation on packaging inks applied to the non-food contact surface, called Packaging Ink Resolution (ResAP(2005)2), have been laid down.

National regulations and recommendations concerning food contact materials are also very widely quoted all over the world. The following are the most important:

- FDA, CFR 21 (USA)
- LFGB (Germany)
- BfR recommendation (Germany).

How to test safety

As mentioned earlier, the Framework Regulation states that food contact materials shall not transfer substances to food in concentrations that could endanger human health or change the characteristics of packaged food in terms of taste, odour or composition. Product safety is therefore often divided into three aspects:

1. Chemical safety
2. Microbiological safety
3. Odour and off-flavour issues.

Many of the food contact regulations and recommendations contain a list of toxicologically evaluated substances that can be used in the manufacturing of the food contact materials (a positive list). The list may contain restrictions, e.g., maximum dosage in the process during manufacturing, specific migration limit (SML), maximum extractable amount of substance in the food contact material. Chemical tests are needed to ensure the material studied meets the requirements.

The transfer of harmful substances from the packaging material to the food can be analyzed via migration tests. Food simulants are commonly used in place of real foodstuffs. Food simulants and migration test conditions (contact time and temperature) shall simulate the real use of the package as accurately as possible. Detailed guidelines for selecting the migration test conditions are given in the directives. After the contact time, the food stimulant is analyzed with a gas chromatograph with mass-spectrometry detection (GC/MS), and the transferred substances are compared with the restrictions.

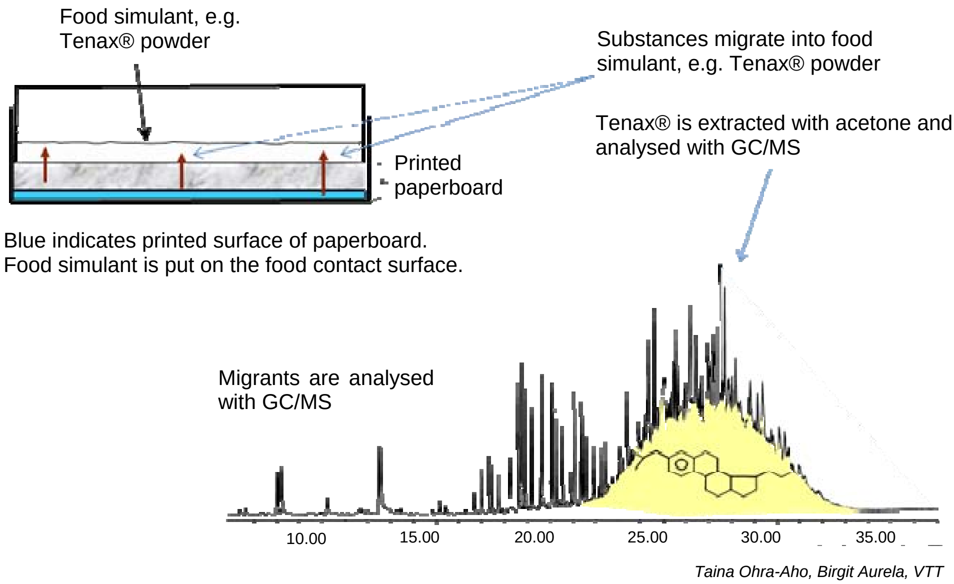

Figure 1. Migration tests are applied to assess transfer of substances to food.

A new approach for ensuring the safety of food contact materials is toxicological testing (biotests). Biotests assess the biological activity of a substance by testing its effect on an organism and comparing the result with some agreed standard. Biotests can be used to determine possible toxicity of packaging material or a certain chemical compound.

Packaging material shall be of suitable microbiological quality, taking into account the intended end use of the material. However, there is no legislative limit for food packaging materials. The most commonly quoted is the Dairyman standard for liquid packages (FDA, USA), maximum 250 cfu/g. The Paper Resolution is a reminder that special attention shall be paid to pathogens when the material is intended to come into contact with aqueous and fatty foods.

The transfer of odour and off-flavour from the food contact material to the food is forbidden according to Framework Regulation 1935/2004/EC. If the packaging material smells strongly, e.g., like engineering works, it is also unacceptable for customers and consumers. Odour from the packaging material and off-flavour transferred from the packaging materials to the packaged food can be evaluated by a sensory panel. Reliable results are provided by a sensory panel with 10 to 12 trained and tested panellists, and relevant methods and adequate quality control means.

Suitability assessment for food contact

Before the packaging material is given a statement of suitability for food contact, it is subjected to detailed examination. In general, the study is based on existing regulations and recommendations in Europe and the USA. The procedure to ensure the safety of food contact material typically contains three parts:

1. Suitability of the raw materials and chemicals used in the manufacturing
2. Chemical and microbiological analysis of the material studied
3. Off-flavour and odour tests.

The need for tests depends on the raw materials, e.g., the use of recycled fibers, and chemicals used in the manufacturing of the food contact material. The end-use conditions of packaging material, e.g., contact with dry, non-fatty foods or fatty foods, or use at high temperatures (conventional or microwave oven), also affect the number and quality of tests needed, as does the regulation that is applied.

Analyses are carried out using international or European standard methods, e.g., ISO and EN, using accredited test methods when possible. Accreditation is a procedure by which an authoritative body gives a formal recognition to a testing laboratory and recognizes that the laboratory is competent to carry out specific tasks. Accreditation is a measure to create confidence, and it reduces re-testing: once tested – accepted everywhere.

Biotests can be used to determine possible toxicity of packaging material or certain chemical compounds. The biotests can be applied to materials that are not regulated by existing legislation or recommendations or cannot be examined using existing means, for example, nanomaterials.

Summary

Product safety concerns all packaging materials, not only food packages. Food packages, as part of the food production chain, have the most detailed regulations. Some other packaging materials have their own recommendations, however, e.g., packaging materials for sterilization. Product safety comprises three parts: chemical safety, microbiological safety, and odour and off-flavour issues. Biotest have recently been applied to paper and board packaging materials, and can also be applied to materials that are not regulated. The General Product Safety Directive states that “only safe products can be placed to the market”.

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Opportunities of using bio-based materials for value-added composites

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Our forests are a naturally renewable resource that has been used as a principal source of bio-energy and building materials for centuries. The growth of world population and affluence has resulted in substantial increases in demand and in consumption for all raw materials. Resulting increases in demand for wood products provides a unique opportunity for developing new generations of renewal, sustainable and materials efficient bio-based composites. The 100-year history of the softwood plywood industry provides a good example of a successful development of an idea, a process, and eventually marketable product. The key to effectively developing marketable bio-based composites for use as building products that can be used for construction of safe and affordable structures is to identify the research and development and market needs for such products. This includes understanding the requirements for product performance, engineering processes, and product implementation.

Introduction

According to the United States (US) Census Bureau, the population of the world is 6.7 billion people today and will reach 7 billion in 2012 as the global community struggles to satisfy its needs for products produced from natural resources. The 2012 world population is over a threefold increase from two billion world population of about 50 years before. The rapid growth of world population has resulted in substantial increases in demand and consumption of raw materials. From 1970 to 2007, the world population increased about 86% and coupled with growing affluence the growth in the use of gross world products (GWP) increased about 446% which is much faster than the growth rate of world population (http://www.worldbank.org/). Responding to the needs of the rapidly growing population and affluence can present many problems and challenges to a country's ability to manage its natural resources (Bowyer et al. 2003).

Opportunity

Our forests are a naturally renewable resource that has historically been a principal souse of energy and building materials. According to the Food and Agriculture Organization (FAO) of the United Nations, the global forest harvest increased substantially from 1950 to 1990. Because of the environmental concerns and government imposed restrictions on deforestation, the global forest harvest reached its highest level at about 3.4 x 10^9 m^3 in 1990. As the world population's need for safe, affordable, environmentally-friendly shelter is expected to increase substantially, it requires seeking some new alternatives for building materials. As a direct result, this provides an opportunity to develop new bio-based composites and utilize the low-value forest resources. A good example is recently-developed straw board which is made with synthetic polymer resins. Its performance is equal or better than traditional wood particleboard and it contains no formaldehyde – a key benefit to people who are concerned about indoor air quality. This new straw board converts a bio-residue that was formerly burned – – causing air-pollution problems – into a profitable product for the furniture and cabinet industry.

Bamboo, another of our important renewable bio-based materials, is a fast growing fibrous grass that has been used mainly for furniture and flooring. Compared with wood, bamboo has higher strength, better ductility and longer durability. However, superior properties alone have not been enough to successfully turn bamboo into a series of marketable products with many diverse structural applications as compared to wood. To maximize the utilization of bamboo, much research has been conducted to understand its fundamental physical and mechanical properties and to develop bamboo composites (Lee et al. 1994, Bai 1996, Chen and Wang 2005, and Jiang et al. 2005). The construction of Pinbian Primary School in China was completed in 2004 and was the first to use bamboo plywood panels and laminated beams for structural applications, i.e., roof truss and sheathing (Chen and Wang 2005).

A good example of utilizing low-value curved (bowed) and cull small diameter trees is to add value to them such as by developing new processes to make them into laminated structural lumber. During normal logging or thinning operations, many low-value curved and cull trees are encountered and these trees present major handling problems as they proceed through the sawing and drying processes in a sawmill. Researchers at FPL initiated a project involving the straightening of small-diameter, bowed lumber for laminated structural timber by developing advanced sawing, drying, straightening, and laminating processes (Hunt and Winandy 2003). In cooperation with the Bighorn National Forest and Wyoming State Forest system, curved and cull small-diameter trees (diameters ranged from 10 to 23 cm) were used in this study. A new alternative method to reduce curvature from the cut boards through the use of microwaves and clamping during drying was developed (Hunt et al. 2005). A prototype microwave press-drier with integrated controlled restraint and heating was developed and used to straighten the curved sawn lumber during the drying process.

In a series of microwave drying and straightening tests, two parameters – initial heating temperature and pressing time were examined (Hunt et al. 2005). It was found that both heating temperature and pressing time had significant effects on straightening of the curved lumber. Higher initial heating temperature and longer pressing times resulted in better straightening. After drying, the lumber was next processed through a planer. The finished 2 by 4 stud lumber was graded using transverse vibration, a nondestructive stress grading method used to determine dynamic modulus of elasticity (DMOE). After nondestructive testing, the 2 by 4 studs were sorted and grouped according to DMOE values as follows: 25% low, 50% medium, and 25% high. Phenol-resorcinol adhesive was used to bond the 2 by 4 studs together according to their DMOE performance.

The finished laminated member was 8.9 cm (3.5 in.) by 22.6 cm (9 in.) by standard 2.4 m (nominal 8 ft) long. If a product made from small-diameter material is used primarily in a bending application, maximum properties would be obtained if the 2 by 4 studs were arranged with higher DMOE material placed on the outside. Selective placement of small-diameter 2 by 4 studs led to a range of performance options. Thus, a low- or no-value material can be engineered to produce a structurally strong and value-added product from virtually valueless small-diameter, curved timber. Parts of this process have recently been commercialized by our industrial cooperator, Wyoming Sawmill in Sheridan, Wyoming.

Development of softwood plywood

To successfully develop a marketable bio-based composite as a building product that can be used for constructing safe and affordable homes, detailed planning is necessary to identify research and development (R&D) and market needs; understand the requirements of product performance; engineer the processing; and implement production of the final product. Softwood plywood provides a classic example of successful product R&D and marketing for new bio-based composites. The history of the plywood industry is one of dramatic rise, of continual process adjustment in the face of changing resource supplies and ever-increasing marketplace competition (APA 2005a).

The idea of using wood veneers to achieve special appearance and decoration and to increase wood's natural strength and stiffness is almost as old as civilization (APA 2005a). Ancient Chinese and Egyptian furniture, built with wood veneers thousands years ago, is displayed in museums. Early plywood was typically made from decorative hardwoods and was most commonly used in the manufacture of household items. Construction plywood made from softwood species first appeared in the later 19^{th} century. On December 26, 1865, John K. Mayo of New York City was issued a patent for what could be called plywood today; additional patents were issued three times in August 1868 (Perry 1942). In the original patent, it stated "The invention consists in cementing or otherwise fastening together a number of these scales or sheets, with the grain of the successive pieces, or some of them, running crosswise or diversely from that of the others. The crossing or diversification of the direction of the grain is of great importance to impart strength and tenacity to the material, protect it against splitting, and at the same time preserve it from liability to expansion or contraction" (Mayo 1865). Mayo envisioned that his invention of softwood plywood could be used for roof, tubing, and other structures. Unfortunately, due to apparent lack of successful advertising and business sense, Mayo was unable to turn his invention into a profitable product.

In 1905, the World's Fair held in Portland, Oregon was actively seeking new product exhibits. The Portland Manufacturing Co., a small wooden box company, decided to produce what it called "3-ply veneer work" made of Pacific Northwest Douglas-fir (Plywood Pioneer Association 1967). The first plywood panel manufactured with softwood species was developed and sent to the 1905 World Fair. During the exhibition, the plywood created considerable interests among the more than a half million visitors, including door and cabinet manufacturers. Tom Autzen, the first Douglas-fir plywood salesman of record, convinced some door manufacturers that the plywood provided cost-savings and was a better performing material to use in their products. Using all of his sales skills, Autzen secured the first order for plywood from a door company.

Technology invention and continual process improvement were critical to the early success of plywood. The first softwood plywood was developed by spreading animal protein-based glue with paint brushes and pressing the veneers together with house jacks. Production was slow and only one set of panels could be made a day. By 1907, Portland Manufacturing Co. installed an automatic glue spreader and a sectional hand press. Plywood product increased to 420 panels a day. Convinced of the promising future of plywood, the Portland Manufacturing Co. built its own door manufacturing plant to promote the use of plywood. Soon other plants began making the product and the young plywood industry spread out all along the Pacific-coasts of the Western US.

Market development and product promotion made the plywood industry grow quickly. During its first 15 years, the softwood plywood industry relied primarily on the single market for door panels. In 1920 automobile manufacturers began using plywood for running boards and trunk stock. The plywood market took off and the sales increased steadily. By 1929, there were 17 plywood mills in the Pacific Northwest and production reached a record 0.32 million square meters.

The formation of a national plywood association helped energize the plywood industry and promoted new markets for plywood. For the first two or three decades after its initiation in 1905, the plywood industry remained fragmented. Each mill had its own product quality and grading system. None had the technical capability and marketing resources to conduct research and develop and promote new uses for plywood (APA 2005a). It wasn't until 1933 that the Douglas Fir Plywood Association (the future APA – The Engineering Wood Association) formed, allowing the industry to organize, promote itself, and create standards.

Standardization, new grading systems, and improved quality enabled promotion of plywood as a standardized commodity building and construction product. Thanks to the development of water-proof adhesives, plywood soon became accepted as a common construction material, recognized as having acceptable levels of both interior and exterior performance. In 1940, the Plywood Association initiated "The House in the Sun", the first plywood demonstration house. This demonstration project along with many others successfully promoted softwood plywood to the construction industry as subflooring, roof sheathing, ceilings, and wall sheathing products (APA 2005b).

The economic boom after World War II resulted in a growing demand for houses and provided an excellent business opportunity for the plywood industry to expand. "The single biggest thing that the industry can be proudest of is that it really helped to house America after World War II.... It probably helped house a whole generation of people," says Dennis Hardman, vice president of marketing for the APA." (Tomasulo 2005). Plywood significantly reduced labor costs to construct new homes because it revolutionized the way homes were constructed, by eliminating the tedious nailing required to fasten hundreds of tongue-and-groove boards that had been traditionally used as flooring, sheathing and roofing material. By 1979, plywood production reached about 18 million m^3.

New technology development continues the evolution of wood panel products. The technological revolution that began with plywood has reached new heights. The structural panel markets, originally pioneered by softwood plywood, have themselves evolved with the development of a number of different types of structural wood panel products that have been now emerged onto the market. Oriented strand board (OSB) manufactured from lower-grade forest resources shares many characteristics with plywood. OSB was first introduced in the late 1970s. Thanks to its efficient resource-utilization potential and low production costs, OSB has been gaining recognition in the world-wide building and construction market as a durable and strong construction material. After competing with plywood for about 10 years in the construction industry, OSB was finally certified to perform as well as structural plywood in 1992. This certification made OSB an economical alternative to structural plywood and caused further market growth (Bowyer et al. 2003). Today, OSB has more than 60% of structural panel market and continues to take more of the structural-panel market.

Summaries

The 100 year-history of plywood provides a good example and guidance in developing new bio-based composites. The future challenge to sufficiently utilize the forest resources is how to deal with the variety of mixed bio-mass materials to develop market acceptable products with uniform and durable performances. To summarize, the following considerations are necessary:

(1) Economic considerations

- Target market
- Competition and opportunity
- Weakness and strengths
- Raw material supply

- Long term profitability
- Investment return and risk

(2) Environmental considerations

- Natural resource impacts
- Chemical emissions & toxic materials
- Recyclability

(3) Research and Development

- Raw material preparation
- Processing
- Performance, standard, and specification
  - ✓ Mechanical and physical
  - ✓ Fire- and water-resistance
  - ✓ Durability (decay and insect)
  - ✓ Chemical emission and toxicity
- Process optimization
- Recommendations

(4) Manufacturing

- Management
- Safety
- Process improvement

(5) Advertisement and sales

- Model/demonstration house
- Sales distribution
- Customer service and education.

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Composites from wood and plastics

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Composites made from thermoplastics and fillers or reinforcements derived from wood or other natural fibers are a dynamic research area encompassing a wide variety of composite materials. For example, as the use of biopolymers grows, wood and other natural fiber sources are being investigated as renewable sources of fillers and reinforcements to modify performance. Nanocellulose, whether cellulose nanocrystals or fibrillated cellulose, have interesting characteristics and offer new composite opportunities if efficient, economical, and scalable methods of producing both the reinforcements and the composites are developed. Experimental and analytical tools are being developed to evaluate the intrinsic material properties of the interphase or to examine the highly nonlinear behavior of large-scale, structural components, for example. This research will result in improved understanding of material behavior and identify new opportunities for composites that may be quite different from those currently produced.

Background

Wood and other natural fibers have been used in composites for many years. However, interest in their use as fillers and reinforcements waned with the development of synthetic fibers such as glass and carbon fibers. Recently there has been a resurgence of interest, largely because of environmental considerations, legislative directives, and technological advances. It was estimated that 900,000 tonnes of thermoplastic composites were produced in 2007 containing wood or other natural fibers.

These composites have been used in applications such as automotive paneling, signs, and consumer products. However, the largest use in the United States is in the construction industry. Over one-half of the composites produced from thermoplastics and wood and other natural fibers in North America are used in decking applications, and the great majority is in exterior building products such as deck boards, railings, and window and door profiles. There has been considerable interest lately in other applications such as furniture, siding, and roofing as well as a variety of marine and construction applications requiring greater structural performance than in current applications.

As several of the large markets for these materials begin to mature, manufacturers seeking to differentiate themselves are driving the next generation of these composites. For example, some manufacturers are using new co-extrusion technologies to apply a durable, scratch and stain resistant layer to wood-plastic composites. Of particular interest are economically improving durability, improving structural performance, and reducing weight. Foaming continues to be of interest as manufacturers seek to balance cost, weight, and performance.

There are many reasons that wood or other natural fibers are used as filler and reinforcements. Customer and builders have a certain familiarity with wood in applications such as decking and railings and often desire an alternative that may have similar attributes. Mixing wood flour with plastic is seen as a way to use wood in these applications yet improve its durability without chemical treatment or the need for painting or staining.

Environmental considerations are also driving increased use of wood and other natural fibers since they are derived from renewable resources, do not have a large energy requirement to process, and are biodegradable. They are lighter than inorganic reinforcements, which can lead to benefits such as fuel savings when their composites are used in transportation and packaging applications. In the U.S., wood-plastic composites represent one of the largest domestic outlets for recycled film. With changing consumer perceptions, some manufacturers use the natural look of these composites as a marketing tool. Others have added wood or other natural fibers to increase bio-based material content.

As part of the Forest Service, FPL also views such composites as potential outlets for wood-based materials from manufacturing residues, recovered post-consumer wood-based materials, and other recycled and underutilized forest-based resources in cost effective, durable products. Use of these wood-based resources as well as natural fibers other than wood offer an opportunity to provide an effective way of meeting the needs of people in the global community while helping to promote a sustainable natural fiber resource base.

Research

Perhaps not surprisingly, some research trends in the wood-derived filler and reinforcement technology parallel those of other fillers and reinforcements. For example, methods for maintaining fiber length for better reinforcement and improved impact performance, the use of biopolymers as matrices, or the application of nanotechnology may result in very different types of composites in the future.

As the use of biopolymers grows, wood and other natural fiber sources are logical, renewable sources of fillers and reinforcements to modify performance. In many instances, their biodegradability can be an attribute rather than the detriment it is sometimes considered in some current applications (e.g., exterior building applications) where considerable durability is required.

Nanocellulose, whether cellulose nanocrystals or fibrillated cellulose, have interesting characteristics (e.g., very large surface areas, low percolation thresholds) and offer new composite opportunities if efficient, economical, and scalable methods of producing both the reinforcements and the composites are developed. Our research focuses on developing a variety of technologies (metrology, production, composite processing, chemical modification, etc) to facilitate and expand the use of cellulose in high-performance products.

Nano-scale additives and reinforcements are also being explored for use with macro-scale composites to affect a wide range of performance criteria and to explore new opportunities. For example, nano-scale additives for controlled-release of moldicides or improved resistance to UV degradation are being investigated.

From a processing standpoint, more advanced technologies are being applied to these composites to overcome current limitations or explore new opportunities. Reactive extrusion offers the opportunity to significantly improve material behavior. Multi-material processing options such as co-extrusion or co-injection molding are other methods to engineer performance, avoiding the detrimental effects that sometimes occur when simply blending the materials or perhaps localizing expensive or more structural components in a surface layer, for example.

Considerable effort is still underway in evaluating the performance necessary for various applications. For example, durability is still a key area of research as exterior applications are still their largest outlet and extending service life is a major goal. New or modified methodologies are being developed that more appropriately measure the moisture sorption, UV or biological degradation, and creep and the relationships between them.

As these materials are used in more applications where greater structural performance is required and the materials are more heavily engineered, experimental and analytical tools are necessary to develop or validate required structural performance. Because of the complexity of these materials, more sophisticated approaches are necessary. For example, FPL researchers and collaborators are using data-driven methodologies and multi-degree of freedom mechatronic loading to examine the highly nonlinear behavior associated with strain-induced micro-cracking and to predict the response of the structural components.

At the other end of the spectrum, new technologies examine material performance and structure at the micro- and nano-scale. For example, nano-indentation methods that separate the intrinsic material properties of the interphase from the effects of the neighboring bulk polymer matrix and wood cell wall are being developed and verified so that the size and properties of the interphase can be more accurately established.

Conclusions

Although not large compared to more traditional wood composites, composites made from thermoplastics and fillers or reinforcements derived from wood or other natural fibers are a varied and dynamic area of research. From cellulose nanocomposites to large structural wood-members, current research is leading to new materials and application areas, greater structural performance, and a better understanding of material behavior.

Acknowledgements

Since this is a broad area of research, there are too many funding sources and collaborators both within and outside of the U.S. Forest Products Laboratory than are practical to list here. Further information on specific areas of research can be provided by the investigators primarily responsible for them.

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Fiber product session II – Fiber processing

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The nanocellulose challenge

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Introduction

The forest industry is seeking new technological solutions and products. One very interesting possibility is the production and utilisation of cellulose nanofibers for new types of materials and novel applications. These new opportunities are being developed at the Finnish Centre of Nanosellulosic Technologies launched in spring 2008 by VTT, Helsinki University of Technology (TKK) and the UPM-Kymmene Corporation. The centre employs about 40 persons, and the project portfolio, which addresses production technology, physical and chemical modification, characterization and novel applications, is financed by public and private investments.

Nanocellulosic materials are expected to have their first application areas within paper industry products. One of the aims is also to create new application and product openings outside the paper sector, which requires the creation of novel cross-disciplinary scientific knowledge of the fundamental material characteristics as well as of chemical and biotechnical modification of nanocellulose fibers. These are the main aims of a public cross-disciplinarily project at the centre called Tailoring of the Nanocellulosic Materials for Industrial Applications and is jointly run by TKK, VTT and ten industrial partners.

Methods for nanocellulose modifications

The work can be divided into three main areas: a) to modify the surface of nanocellulose by different means with the goal of enhancing the applicability of nanocellulose materials in selected products, b) to understand the interactions between modified nanocellulose and other substances on a molecular level and c) to evaluate the suitability of the modified nanocellulose in various applications such as composites, nanomaterial additives and porous materials.

The main scope for modifying the nanocellulosic materials is modification of the hydrophobicity, the introduction of surface charges and the addition of specific functional groups. These goals are achieved by a combination of approaches involving chemistry, physics, and biochemistry that will systematically develop methods to achieve the different types of modifications. For example, nanofibrillated cellulose (NFC) materials can be modified with polymers, chemistry at the fibril surfaces, functionalisation using nanoparticles, and biochemical modifications utilizing cellulose-binding proteins and enzymes. An important field of research is to develop methods to produce water-free NFC material for applications in which water-based NFC formulations cannot be used.

In-depth characterization of these novel nanocellulosic materials, as unmodified and modified, is essential. Properties, such as structure, surface adsorption, self-assembly, rheology, solubility, interfacial activity and adhesion, and phase behaviour, will give direct indications of their suitability for different applications. In addition, these novel nanoscale materials offer new challenges for characterization, and novel or adapted analysis methods have to be developed. The chapter below describes some examples related to NFC characterisation.

Examples on the characterisation of the cellulose nanofibrils

Due to the strong self-association tendency and high swelling ability of nanocellulosic material, the reliable characterization of the nanoscale fine structure is challenging. Retaining the nanoscale fine structure upon drying in particular is quite demanding as film formation easily destroys the structural details. In addition, subsequent to solvent exchanges and chemical modifications, the NFC easily agglomerates and the fine structure is thereby destructed. Thus, the importance of rather routinely conducted microscopic characterization is justified and the proper sample preparation methods are needed. Several techniques have been developed to prepare the NFC samples, and techniques have been tested using the very same highly refined nanocellulose sample. The following conclusions can be drawn:

- Freeze-drying is a quick method for routine analysis of NFC, but the NFC fine structure is hampered by the film formation, perhaps partly due to the high hemicellulose content and water removal that is too slow upon drying, see Figure 1.
- Critical point drying is a method in which the nanofibrils are first solvent exchanged ($H_2O \rightarrow EtOH$) and then dried with supercritical fluid (CO_2, 208 bar and 48°C). As shown in Figure 2, the fibrillous structure of the finest nanocellulosic network is successfully maintained.
- The spin-coating technique is a fast and simple method to prepare fibril samples, and it provides conductive and stable support for SEM imaging also at high magnifications. During high shear spin-coating, the water is quickly removed and the undesirable NFC film formation is effectively avoided. As a result, the individual nanocellulosic fibers are deposited on the flat surface, see Figure 3. An advantage of the spin-coating method is that the same sample can also be characterized by other microscopic methods such as AFM. In addition, the NFC size distribution can be further estimated using image analysis.

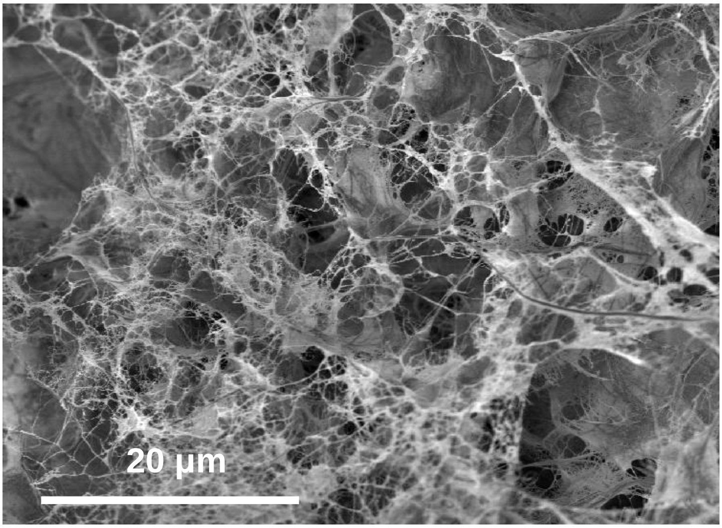

Figure 1. SEM image of a freeze-dried cellulose nanofibril network.

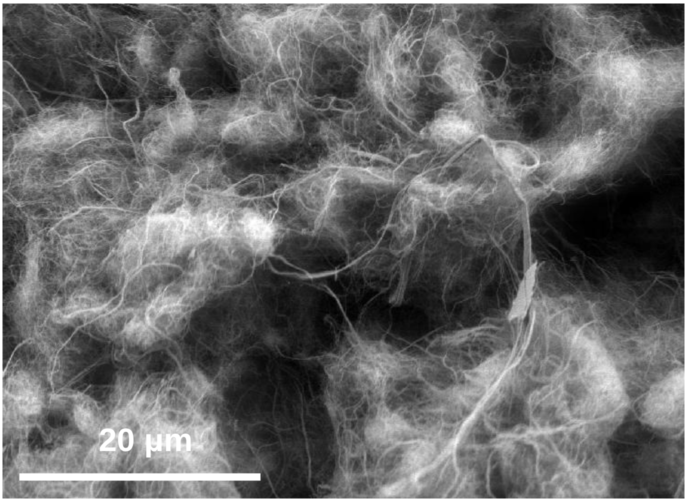

Figure 2. SEM image of a critical point dried cellulose nanofibril network.

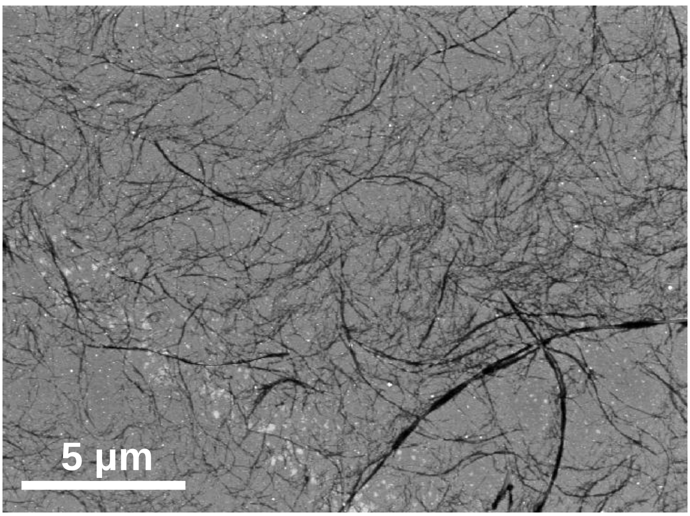

Figure 3. SEM image of spin-coated individual cellulose nanofibrils on a flat surface.

Rheology is a powerful tool for NFC-material characterisation. For example, the gel strength of NFC-water dispersions gives important information on the degree and type of nanomaterial achieved when produced by advanced grinding methods. The storage modulus (G') in the linear viscoelastic region measured with an oscillatory stress sweep gives information on the strength and number of bonds in the nanofibrillar cellulose network (Figure 4). The analysis shows that the results of these rheological methods are dependent on the measuring geometry used, especially when the measured material contains large particles. These results demonstrate the importance of comparing rheological results with visual inspection and microscopy.

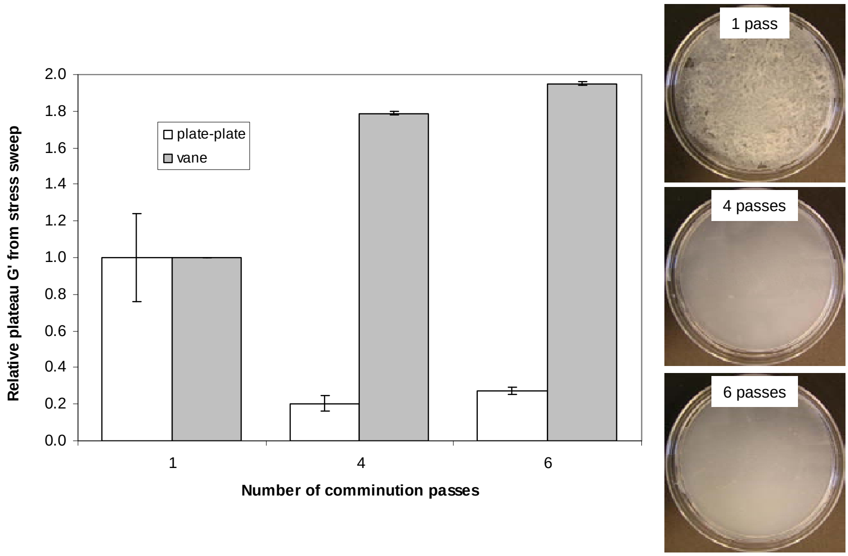

Figure 4. The relative storage modulus (G') of nanofirillated cellulose gels as a function of comminution passes. The G' in the linear viscoelastic region was measured with oscillatory stress sweeps using two different geometries (plate-plate vs. vane). The G' value of the 1-pass sample was taken as 1.

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Enzymatically modified wood fibers

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Wood fibers are currently mainly exploited in forest industries, but their availability and sustainability also make them an interesting raw material option for other material applications. The properties of wood fibers are often not suited, as such, for use in target applications, however, and there is therefore a continuous search for novel methods to modify fiber properties. The chemo-enzymatic functionalisation method developed at VTT is a versatile modification method suitable for various lignin-containing fiber materials including wood fibers. The method developed by VTT appears to offer new opportunities for extending the application of wood fibers outside traditional wood-processing products.

Introduction

Wood fibers are natural composites with unique properties exploited mainly in paper and paperboard manufacture. There is a constant need in the forest industry, however, to improve fiber properties to enhance process efficiency and product properties. Furthermore, the modification of inherent fiber properties could open up new application areas for wood fibers in, for example, natural fiber composites. In addition to traditional chemical and physical modification methods, enzymatic and chemo-enzymatic methods have been shown to have the potential to modify wood fiber properties (Viikari et al., 2007; Grönqvist et al., 2006).

VTT's chemo-enzymatic functionalisation method

A chemo-enzymatic method for functionalisation of lignin-containing fiber materials has been developed at VTT. Compared with traditional chemical fiber engineering methods, enzyme-aided fiber functionalisation has the benefit of accuracy: it is possible to focus the engineering on only the targeted surface components. The gentle process also allows the fiber to retain its best properties, such as strength.

The chemo-enzymatic functionalisation method consists of two main stages: the activation of fiber material and the bonding of a functional chemical component to activated fibers (Fig. 1). Oxidative enzymes, especially laccases, can be used as catalysts in one or both stages. The selection of functional chemicals for use in bonding is dependent on the fiber property at which the functionalisation is aimed. The flexible application process (treatment in water suspension, coating, spraying) is an advantage of this enzyme-based functionalisation method.

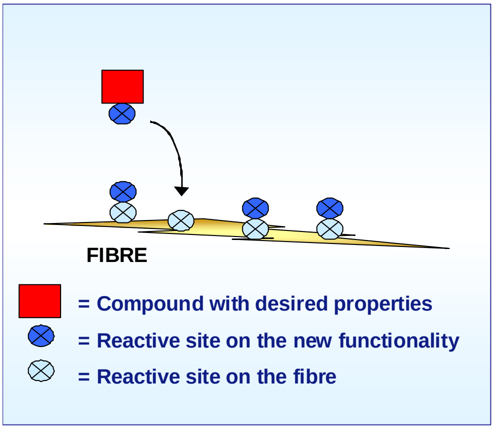

Figure 1. Concept of VTT's chemo-enzymatic functionalisation method.

Chemo-enzymatic functionalisation can be used in the strengthening of the inherent fiber properties or even in the design of completely new properties of fiber materials. The target application determines the functional chemical(s) used in bonding. Charge, hydrophobicity and conductivity are examples of properties that can be brought to fiber materials by functionalisation. The functionalised fibers can find uses in various applications, including paper and board manufacture, food and non-food packages, natural fiber composites and solid wood applications.

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Fibre-based biocomposites

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Fibre-based biocomposites are sustainable materials from a renewable source and are an alternative to fossil-based plastic materials. One of the main drivers of the development efforts in this field is the trend towards greater environmental awareness. VTT has more than a decade of experience, on national and international projects, within the field of fibre-based biocomposites. This paper looks at the possibilities offered by and some of VTT's experience in material research and processing of fibre-based composites, with the focus on thermoplastic materials.

Introduction

The growing global trend in material research towards sustainability and materials from renewable sources has also increased research efforts into and the search for applications for alternative plastic materials and composites. Biopolymers and fibre-based biocomposites are one focus area of these new plastic materials. The main drivers leading the research towards these are:

– Research efforts are leading to the creation of more polymers from renewable resources. Together with **increased production capacity**, there will be more competition, which will lead to a **price decrease**.

– **Growing consumer interest** in sustainable materials.

– **Advertising and environment friendliness** (good image) increase interest and demand.

– New environmental **laws and regulations** provide a stable basis for development.

- **New polymer grades** with tailored and enhanced properties towards engineering plastics enable new applications for biopolymers.
- In some respects, **biodegradability** is a desirable property (e.g., disposable tableware, golf tees).
- **Non-biodegradable** products from renewable raw materials also exist.
- **Closed CO_2-cycle**.
- **Greater industrial help and interest**, e.g., the New Bioplastics Recycling Consortium has been established in the USA to develop an economical and efficient recycling system for biopolymers and markets for recycled biopolymers in addition to making them into economical and sustainable packaging materials. (Press release from Primowater corp 2008)
- Depending on the amount of oil-based additives, the **energy saving** of, for example, starch-based plastics, is 12–40 GJ/t of plastics and the saving in emissions is 0.8–3.2 t CO_2 compared with PE. (Patel 2002)

There are already some commercial applications for biopolymers and biocomposites in areas such as packaging, biomedical applications, hygiene products, agro- and horticulture, transportation, and items that will be left in nature or the ground (e.g., burial items, excavating mats, golf tees). With the help of intensive research and improved material properties, there will also be potential in application areas such as construction, electronics, toys and personal health care as well as new applications for transportation. Fibre-based biocomposites already have the advantage of coming from a renewable source, having the feel and image of 'natural material' and, in some cases, being light in weight due to the lightweight fibre content.

Today, the worldwide production of polymers from fossil sources is approximately 150 ML ton/year with a growth factor of 4–5%/year. Polypropylene and polyethylene have the biggest share with approximately 62% of total production (Bastioli 2005). The production capacity estimate for bioplastics in 2010 is 1,400,000 t with an annual increase of approximately 20%. (Endres et al. 2007) The high increase in production capacity is also an indication of the growing demand for these sustainable materials. There are still relatively few commercially available biopolymers, but the selection of materials with new properties is growing. Large-scale industrial plants exist for biopolymers and biodegradable polymers such as cellulose derivatives (CA, CAB, cellulose regenerates), polycaprolactone and polyvinyl alcohol, polylactide, starch blends and degradable polyesters. There are polymers on a commercially available pilot scale, e.g., polyhydroxyalkanoates, bio-polyamide, polybutylene succinates and adiapates, bio-polyurethanes. The naturally based raw materials bio-ethylen and bio-propanediol also make certain polymers available in a bio-based form. At the R&D stage there will be even more polymers, e.g., in lignin and furfural base (Commercial info 2010). These new polymers will widen the property selection, hopefully also towards existing high-performance engineering polymers.

This paper explains some of the efforts that have already been made as well as VTT's potential in basic and application research in the field of biopolymers and fibre-based biocomposites.

Materials and processes

In the research of fibre-based biocomposite materials, VTT has an opportunity to carry out research into all the parts, from material production to processing and final application. VTT carries out biopolymer research and has its own patented technology based on starch-based polymers. VTT carries out research concerning additives and coupling agents based on renewable raw materials, natural fibre research concerning lignocellulosic fibre modifications and their use in different applications, and research into different processing methods from a small laboratory scale up to pilot scale.

Biopolymer research

At VTT, biopolymer research is quite a wide area and is connected to a number of different applications, not only composites. The biopolymers used may be polymers from biomass such as cellulose, starch, hemicellulose, lignin, protein or chitosan derivatives. They can be synthesized from biobased monomers, e.g., tall oil or different vegetable oils or lactic acid as a polylactide. VTT also carries out research with bio- or biodegradable polymers from oil-based monomers such as polyesters of lactones or adiapates. Some application study is also conducted for polyhydroxyalkanoates, which are biopolymers made by microorganisms.

Fibre research

In composite research, we use quite a versatile selection of natural fibres such as wood cellulose from different sources, cutter chips, sawdust, flax, hemp, straw, reed canary grass and peat fibre. The source of the fibre, lignin and hemicellulose content, fibre aspect ratio, fibrillation, surface modification type and degree all have an effect on composite properties. We use different modification methods with the aim of improving compatibility through covalent and electrostatic interactions between fibre and matrix polymers and thereby for high-performance composites.

Modification methods for fibres can be physical, chemical, enzymatic or different combinations of these. Physical modification can be different grinding methods, fibrillation, fibre classification, plasma treatment or heat treatment. Fibrillation and monomer grafting can be carried out using different enzymatic treatments. Chemical modification can be fibre surface modification, polymer or oligomer grafting to a fibre surface, supercritical liquid treatment or nanomaterial coupling.

Processing

For the processing of fibre-based composites, VTT can perform polymerization reactions and different chemical treatments, batch mixing, compounding, pelletizing, extrusion, injection moulding, thermal moulding, surface treatments with plasma, corona or sol-gel coatings as well as joining products using laser welding.

Physical modification methods available for the manipulation of natural materials:

- **Milling**: disc refiner (Andritz), jet/hammer mill with classifier (Hosokawa Alpine), fluidisators, several other wet milling and dry milling options (e.g., different size ball mills and hammer/blade mills)
- **Fibre sorter** (Metso)
- **Pelletizers**, e.g., disc press (Kahl)
- **Plasma and corona treatment** enables hydrophilisation and hydrophobisation of textiles and fibres, de-oxidation, activation of surfaces for gluing and coating.

For chemical and enzymatic processing, VTT provides **expert services within the fields of fibrous material processing, organic and polymer synthesis, scale-up and piloting**. The systems are operated from laboratory scale up to 1800 l reactor scale with both EX- facilities and some ceramic-plated reactors. The pilot plant has eight reactors from 1.5 l to 1800 l and a wide range of downstream process equipment for product manufacturing, separation, purification and drying.

For thermoplastic **composite processing**, VTT has expertise in processing research as well as equipment to perform compounding, injection, extrusion and thermal moulding from a 6 g scale up to a scale of pilot production of a few hundred. For **compounding** research, Micro Compounder, three different size twin-screw extruders and different batch mixers (Brabender, Two-roll mill, Banbury mixer, Papenmeier, different size ball mill and Forberg mixer) offer a good processing environment. For **injection, extrusion and thermal moulding**, VTT has equipments such as a MiniJet Injection Moulding machine, two production-scale injection moulding machines (Engel ES 200/50 HL with 25 mm screw and Demag Ergotech 100/420-120 with 22 mm screw), two different extruders (Dolci for 300 mm sheet and three layers, Brabender for 100–120 mm sheet and clean room possibility) and a Collins laboratory/pilot-scale blow moulding extruder as well as a press for thermal moulding.

Projects

VTT has carried out research for more than 10 years in the field of fibre-based biocomposites. We have completed two large-scale national and two international, jointly funded projects. We are involved in three European-funded EC FP7 projects and several national projects. The main research targets for fibre-based composites are the replacement of existing products with renewable materials without compromising performance, a price decrease and the use of side-stream-based fillers. Properties such us decreased biodegradability, antimicrobial properties and better reinforcement are also being developed. One challenge is to develop biocomposites that are more hydrophobic and that last longer.

In future activities, the focus will be more on new biopolymers, additives and coupling agents for biopolymers and fibre interaction, fibre modifications towards more compatible and hydrophobic fibres and processing technology. The focus will also be on nanoadditives and their processing. In addition, more attention will be paid to business activities such as closer relations with customers, understanding their needs and requirements and clarifying market potential, opportunities and the risks of new materials for different applications.

With fibre-based biocomposites and bionanocomposites from renewable raw materials, we aim for lightweight, natural-feeling, high-performance materials, which can even be transparent.

Figure 1 presents one typical product chain for fibre-based biocomposites. This is one result of an EU project, BioComp, in which VTT's own starch-based polymer technology was utilised.

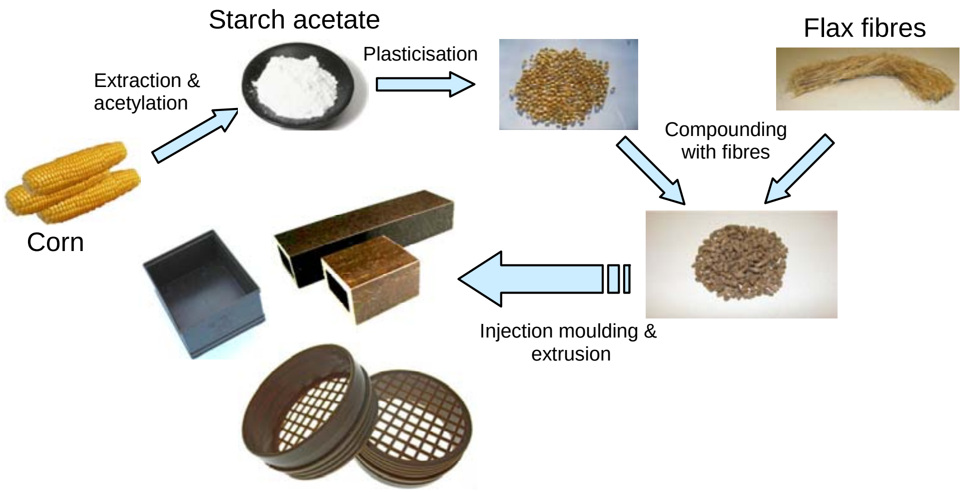

Figure 1. One product development chain in the EU project BioComp (ref. Kalle Nättinen).

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Improved methods for analyzing (bio)chemical interactions with wood

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The chemical and structural complexity of wood has made it difficult to understand the details of wood structure, its alteration when modified by chemical, biochemical, or genetic means, and its interaction with adhesives and coatings. This limitation has led us to the develop tools that can better measure nanoscale properties. These tools include methods for two dimensional solution NMR, advanced nanoindentation analysis, and quantization of reactive oxygen species. These tools have been used to evaluate chemical and biochemical processes with wood.

Introduction

Understanding the chemical and biochemical processes taking place with wood are often limited by the available analytical tools. Thus, we have placed emphasis on developing tools to better understand the chemical and mechanical changes taking place in some specific processes, such as wood adhesion and biologically modified wood. Many of the tools are useful for studies beyond these initial program areas.

For most wood products, strength is an important property measurement, but we need to know both the chemical structure and mechanical properties for doing structure-property relationships. The cell walls are a nano-composite structure made up of three polymer groupings. Of these groups, the cellulose fibrils are the best characterized and understood. Wood also contains cross-linked lignin polymers made from aromatic monomers. The remaining cellulosics are classified as hemicellulose and contain a variety of sugars that are assembled into different polymeric structures and contain some crosslinks to the lignin network. The nano-composite nature of the wood cells makes separation of these polymer classes difficult without degradation of the polymers. Thus, properties of isolated components are often different than those in the native cell walls. Improved in-situ analysis of both the wood chemical structure and mechanical properties is vital to improve our knowledge of wood and wood products.

Methods

To better understand the chemistry, we have developed, in cooperation with the University of Wisconsin, a way to prepare wood so that the entire cell wall can be used to obtain high resolution two-dimensional solution nuclear magnetic resonance (NMR) spectroscopy. First, wood shavings are ground to a small size using ball mills made with non-paramagnetic metals and then dissolved in a special solvent mixture. Then the correlations between proton and natural carbon-13 (^{13}C) atoms are measured. The resulting spectra allow separation of signals from lignin aromatic, lignin side chains, lignin methoxy, anomeric carbon, and remaining carbohydrate carbons. Thus, we have the ability to examine many of the polymer structures in wood without separation or modification of these polymers.

Nanoindentation measures mechanical properties of small domains of materials, making the method suitable for measuring wood cell wall properties. However, the cellular properties of wood complicate the data analysis. Joint studies with the University of Wisconsin has led to advanced nanoindentation methods that are suitable for all materials and are very useful in the analysis of wood. These methods allow removal of wood structural compliances from flexing and edge effects, and measurement of broadband creep and broadband elasticity in addition to hardness and elastic modulus.

To address the difficulty of sorting possible reactions during biological decay of wood, we have developed microbeads that provide micron scale maps of reactive oxygen species activity in decaying wood. These fluorescent beads have provided semi-quantitative measurements of oxidative gradients around decay fungi, giving us a better understanding of the mechanisms used by wood decay fungi during early decay.

Experimental

The chemical analysis via the solution-state 2D NMR and other methods allows the determination of how the adhesives, coatings, and modification chemicals interact with wood. Norimoto separated wood modification into cases of lumen filling and cell wall infiltration. He further separated the cell wall infiltration into simple bulking of the cell wall, reaction with the hydroxyl groups on the polymer chains, and cross linking these chains. Microscopy methods provide information on lumen filling and cell wall infiltration by the added chemicals. This new NMR method provides a measure of whether or not the chemical is reacting with the cell wall polymers. As an example, diisocyanate adhesives provide durable bonds for wood composites, but there has been a debate whether or not the isocyanate actually reacted with the cellulosic and lignin hydroxyls. This NMR analysis allowed us to determine that a small isocyanate molecule reacts with wood only under extremely dry conditions, and that a larger isocyanate molecule reacts even less. Because wood with typical moisture content does not react much with the isocyanate, covalent bonds between the isocyanate adhesive and wood are rare. Therefore, wood-isocyanate covalent bonds do not contribute to adhesive bond durability under normal bonding conditions. Ruling out these options means that the adhesive either simply bulks the cell wall or self-polymerizes to form an interpenetratfing polymer network.

The question of bulking versus self-polymerization can be addressed by measuring the cell wall and middle lamella mechanical properties. Nanoindentation has been used to measure the hardness and elastic modulus on embedded wood specimens. First, we developed a way to make unembedded samples suitable for nanoindentation to eliminate complications from the embedding process. Then, methods were developed to measure the structural compliance effect of wood. The cellular structure can flex, but more critically, the empty lumens create an edge effect, as do the layers in the cell wall. The original materials evaluated using nanoindentation was more uniform than wood and were less sensitive to these effects. Consequently, we developed a way to measure these structural compliances and to correct the measured modulus and hardness values. Having developed ways to determine the structural compliance, we moved on to developing methods for measuring broadband creep and elasticity. These methods were applied to study the isocyanate reactions with wood. From our NMR work, we know that the isocyanate adhesive either simply bulked the cell wall or self-polymerized in the cell wall. The first case would tend to soften the wall while the second would reinforce the cell wall. We found that a monofunctional isocyanate that could only bulk the cell wall did soften it, while the multifunctional isocyanate that could self-polymerize reinforced the cell wall.

The combination of the NMR and nanoindentation methods provides a good route to analyze wood modification processes. Although the methods were developed for and used to understand adhesive interaction with wood, the methods are applicable to many studies on wood and other materials. For example, these methods can be used to study chemical, biological, or genetic modification wood. In fact, the NMR method showed that some the proposed modifications of lignin by a brown rot fungus did not occur, while other, previously unproposed modifications did occur. The nanoindentation methods were first validated on better characterized ceramics, metals, and plastics; thus the methods are applicable to study of most materials.

Another tool to measure processes with wood involves developing a better understanding wood decay. It has been proposed that early stages of wood decay are especially dependent upon the use of reactive oxygen species (ROS). Determining the chemical processes used by fungi during the decay process has been difficult, but we have developed microbead sensors to help understand this. Because these fluorescent beads change color upon ROS exposure, this method allows not only quantization of the ROS, but also the location of the ROS in relation to the structure of the microorganism.

Conclusion

Wood has a very complex chemical composition and morphology that has made it difficult to analyze changes in wood by chemical, biochemical, or genetic processes. This has led us to developing more sophisticated analytical tools for evaluating these processes. The solution state two-dimensional nuclear magnetic resonance method allows the ability to quantify changes in structure of the cell wall polymers. The nanoindentation provides measures of the mechanical properties of the cell walls and middle lamella. These methods have been used to understand the structure–property relationships of wood and wood modified by reaction with an isocyanate adhesive. The NMR method is useful for most wood modification studies, and the nanoindentation methods can be applied to study many materials.

Another tool allows us to measure the reactive oxygen species around fungi during early wood decay. These microsensor beads measure the quantity of oxidant at each location, which we use to create maps of chemical gradients. These gradients are helping us to understand the chemistry of early wood decay.

Acknowledgements

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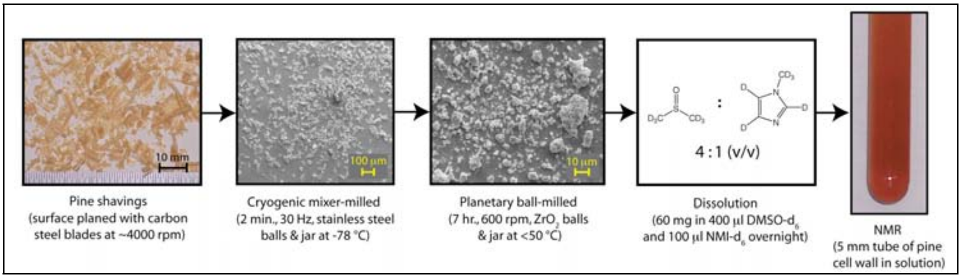

Figure 1. Process for going from wood shavings to a solution for the NMR analysis.

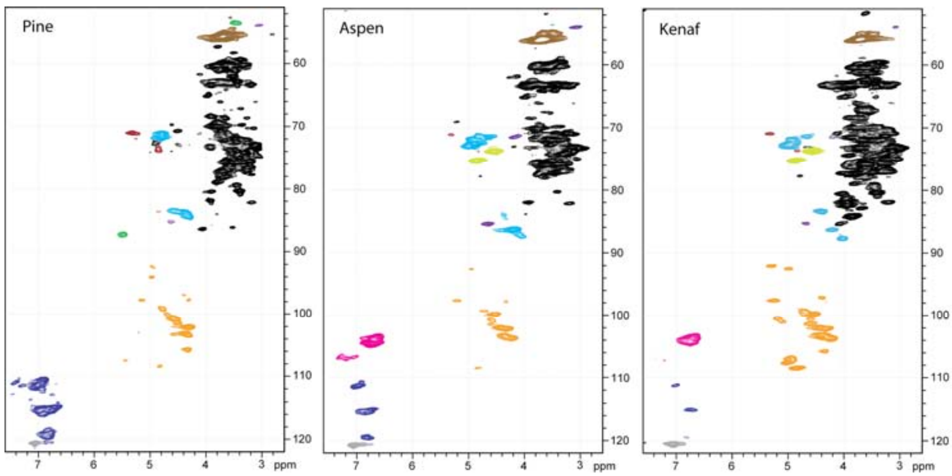

Figure 2. NMR spectra showing differences in spectra between the softwood pine, the hardwood aspen, and the grass kenaf.

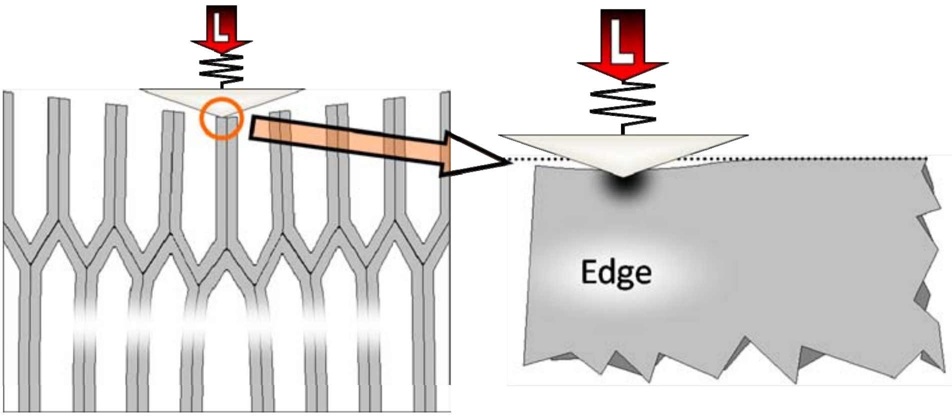

Figure 3. Schematic illustrating the structural flexing on the left and edge effect on the right for the cellular wood structure. (edge picture would be better if left edge was bowed to accentuate deformation.

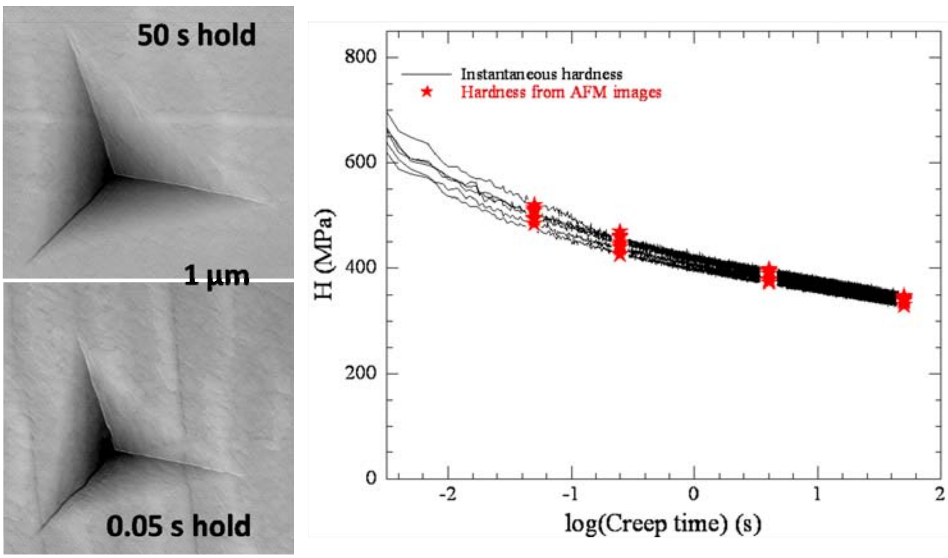

Figure 4. Creep experiments with nanoindenter showing the larger indent on the left for a longer hold time and the creep curve for wood cell wall of pine latewood.

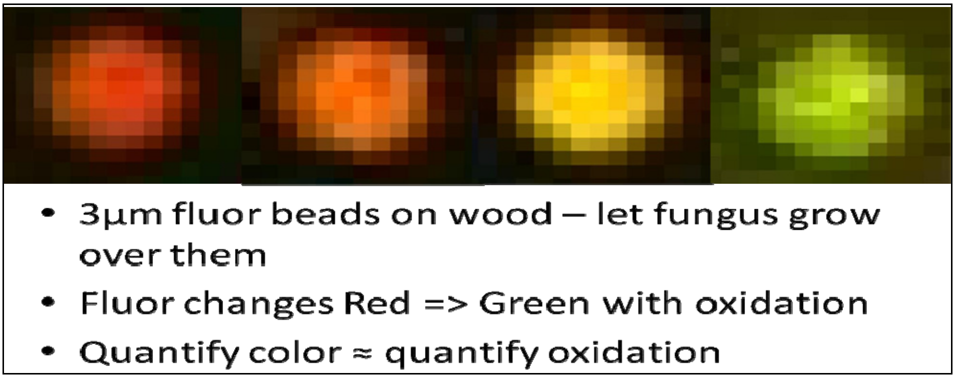

Figure 5. Figure showing the color change from red to green in the microbeads upon exposure to reactive oxygen species.

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New technology for wood adhesives and coatings

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Solving problems and developing new materials for wood adhesives and coatings requires moving beyond the traditional empirical approaches to performance models and design properties. New approaches should provide more efficient and effective research and development programs. One such approach is to develop performance models based on the literature and a full understanding of the root causes of failure, derived from careful failure analysis. This has been done for wood adhesives and provides new insight into the role of adhesive morphology and adhesive-wood interactions for making durable wood bonds.

Introduction

Expanding beyond traditional testing procedures and standard chemistries for performance evaluation can lead to important improvements in wood products. Wood has long been the standard building material for homes, but advancements in other materials have led to the displacement of wood products. Asphalt and metal have replaced wood for roofing, aluminum, vinyl and composites have replaced wood for siding, plastics have replaced wood for decking and fencing, and aluminum and steel have replaced wood for structural members. Improvements in wood products are needed to retain and regain market share.

Performance testing has provided important advancements in the commercially available wood products, but is unlikely to provide basic understanding necessary for breakthrough technologies. Thus, we need to better understand the fundamentals of adhesion and durability of wood adhesives and coatings. The study of wood adhesives is more than breaking sticks! The study of coatings is more than fence studies!

To understand the fundamentals, we need tools that can help us understand wood interfaces and adhesion. In comparison to studies on other materials, the complexity of the wood chemistry and morphology makes interface and adhesion studies more difficult. For example, characterization of the metal surfaces prior to adhesive bonding or coating and after product failure is aided by the many spectroscopy tools available to characterize the metal surface and to distinguish between metals and organic adhesives. Plastics have flat, non-porous surfaces that allow a number of spectroscopy and microscopy tools for analysis. On the other hand, wood is an extremely rough surface with many different chemical groups and extractives that makes it difficult to analyze with many tools.

As with tools, proper models can help to understand product performance. Advances have been made in aluminum bonding by understanding aluminum oxide surface layers for airplanes, and by understanding electrochemistry of corrosion for corrosion resistant finishes for cars. For plastics, understanding their surface chemistry has led to success in automotive coatings of plastic parts. On the other hand, the bonding of adhesives and finishes to wood has not been as well understood. We have placed emphasis on understanding wood adhesion using the following steps:

- Failure analysis investigations using microscopy and spectroscopy
- Understanding internal and external bondline forces, especially under wet conditions
- Understanding adhesive classes and their response to those forces
- Analysis of bondline mechanics.

One can also think of coatings as one-sided adhesive systems for a better understanding of wood coating performance, although they also need sunlight resistance.

Method and results

Although the literature contains a lot of data on bonded wood performance, the data did not make sense without the proper models. For example, why do normally durable and tough epoxies have poorer water-resistant bonds than do the brittle phenolics? Analysis showed that failure appears to be an adhesion phenomenon by eye, but failure is actually in the epoxy near the wood surface. Further evaluation showed that failure is induced by the adhesive's inability to deal with the wood's swelling during water soaking. This observation lead to the generalized model: wood swelling induces an internal stress between wood and adhesive leading to premature bond failure. If epoxies can not withstand the stress from the swelling strain, how can the more brittle phenolics be so good?

Further analysis led to separation of wood adhesives into two classes. *In situ* polymerized adhesives, the first class, are highly cross-linked, made from rigid monomers. The second class, pre-polymerized adhesives, are lightly cross-linked polymers with a flexible backbone that are too large to enter the cell walls. This led to the theory that the first class, the *in-situ* polymerized adhesives, can form durable bonds if they can stabilize the wood cell walls to distribute the stress as a gradient into the wood. On the other hand, many of those from the second class, the pre-polymerized adhesives are flexible enough to distribute the stress through the adhesive layer. Thus to understand the performance of adhesives, one needs to consider:

- the adhesive's polymer structure
- effect of wood structure and strength on bond forming and breaking
- dimensional changes and the associated forces involved in changing moisture conditions
- energy dissipation locations – wood, interphase, adhesive
- energy dissipation mechanisms – deformation, crazing
- uniformity of adhesive – non-coalescence, nano-domains
- internal stresses – polymerization, loss of solvent.

A similar analysis can also be done for coatings because the dimensional change of the wood relative to the coating is also an issue in that system.

Although traditional, bio-based wood adhesives have been replaced by fossil fuel based adhesives, there is a strong desire to return to improved bio-based adhesives. Because of this desire, tremendous advances have been made in soy-based adhesives. Joint research between the Ashland Chemical, Heartland Resource Technologies, and Forest Products Laboratory has led to improved soy adhesives that have good moisture resistance. This technology is helping the plywood, engineered wood flooring, and particleboard producers meet the new formaldehyde regulations by the California Air Resources Board.

Work is beginning to apply similar methodology to study coating durability to make better coatings. One way is to use nanotechnology for wood coatings. Sol-gel technology has the ability to distribute a fine coating on the wood surface. After 1-

year exposure outdoors, sol-gel modified wood surfaces showed no erosion but only slight microchecks, while the non-modified controls showed severe erosion patterns.

Conclusion

The use of very selective analytical methods and failure analysis can lead to models that describe the performance of adhesives and coatings. This process has been used to develop a durability model that strongly reflects the adhesive's ability to minimize the stress caused by the wood swelling under wet conditions. This model was then used to divide wood adhesives into two classes based upon their ability to distribute this strain. These models can then lead to the use systematic design of new products rather than depending upon empirical methods. The information has been used to develop soy based wood adhesives that have excellent moisture resistance.

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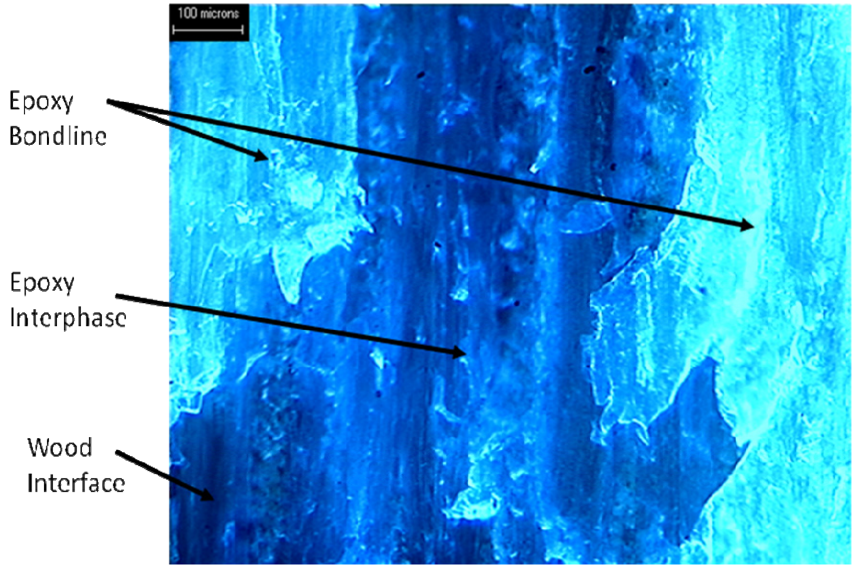

Figure 1. Fluorescence microscopy of failure surface after water exposure for epoxy bonded to wood.

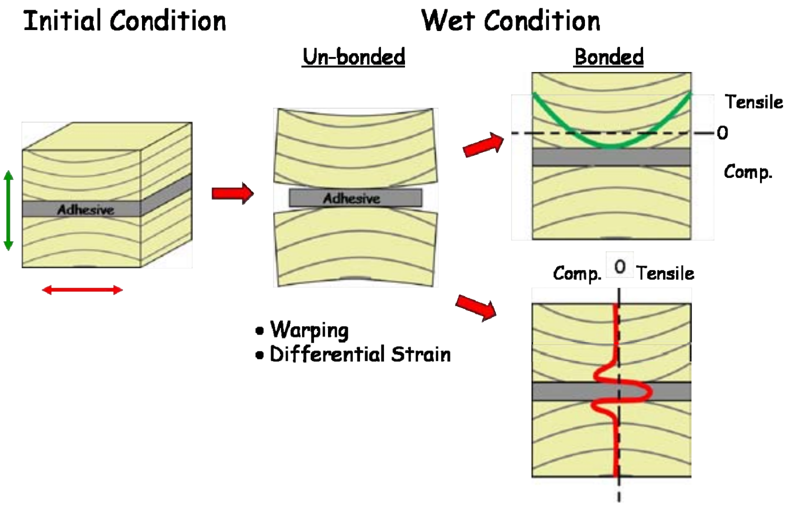

Figure 2. If an adhesive layer is not bonded as in the center drawing the wood expands and warps away from the adhesive layer. These strains impart tensile and compressive forces on the adhesive layer both perpendicular and parallel to the bondline.

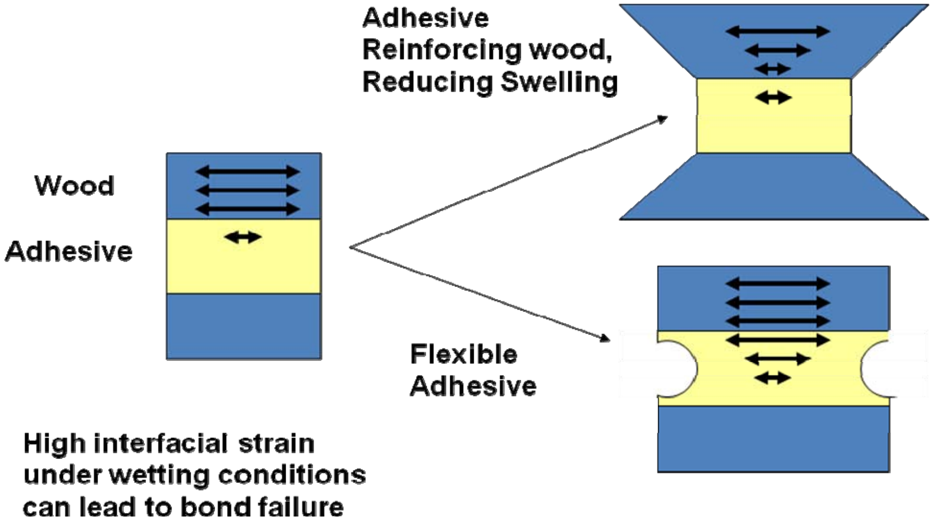

Figure 3. This schematic shows in an exaggerated manner how the two adhesive classes can distribute the strain caused by the wood swelling more than the adhesive under wet conditions.

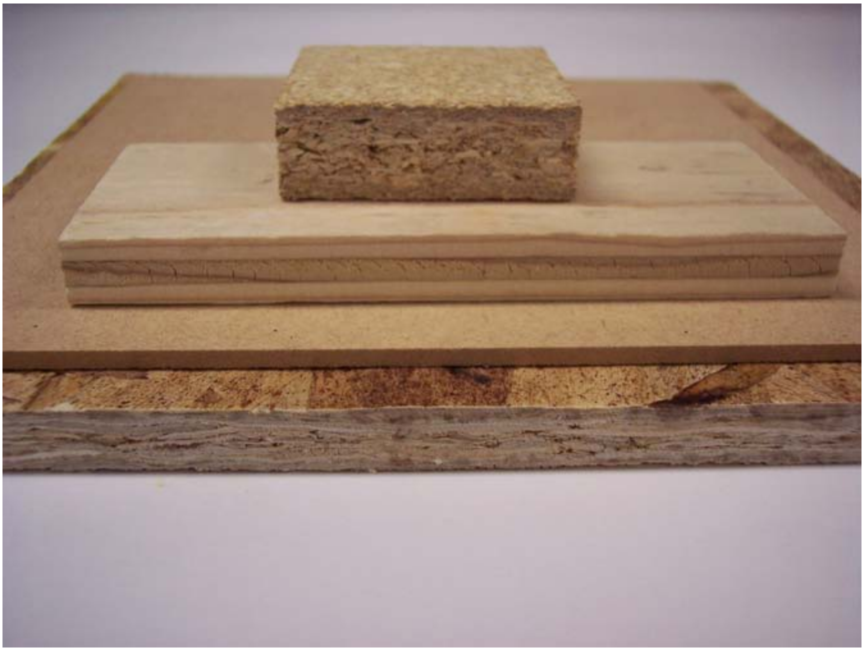

Figure 4. Examples of products made with soy-based adhesives, such as particleboard, plywood, fiberboard, and oriented strandboard (top to bottom).

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New fiber properties through dense media fractionation prior to pulping

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Introduction

Cell wall thickness is an important quality parameter of soft wood pulps. Fibers with a cell wall thickness greater than 4 µm do not collapse in the papermaking process (Forseth 1997). Thick wall fibers will increase the roughness of paper when treated with water (Hallamaa et al. 1998). The tensile index of the long fiber fraction can be increased 100% by reducing the amount of thick wall fibers from 10 to 4%

The cell wall thickness is small in the beginning of the growth season (early wood, EW) and then gradually increases towards the end of the growth season (latewood, LW). Factors affecting growth include soil and climate conditions, and the genetic properties of the tree. Good growth conditions result in large annual growth rings and a large proportion of EW. The cell wall thickness of Norway spruce can vary from 2 to 10 µm.

The important properties that affect pulping properties are basic density, fiber length and moisture content. The average basic density for Scots pine pulp wood chips is 406 kg/m^3, ranging from 390 to 420 kg/m^3 (Lindblad & Verkasalo 2001).

Method

VTT has studied methods that can be used to fractionate wood into low- and high-density fractions. The objective is to separate EW from LW and to direct these into separate fractions. A knife mill has been used to cleave pulp chips into chips thinner than 2 mm in thickness. The cleaving process consists of a feeder pin, belt conveyors, knife mill and Pocket Roll screen, Figure 1.

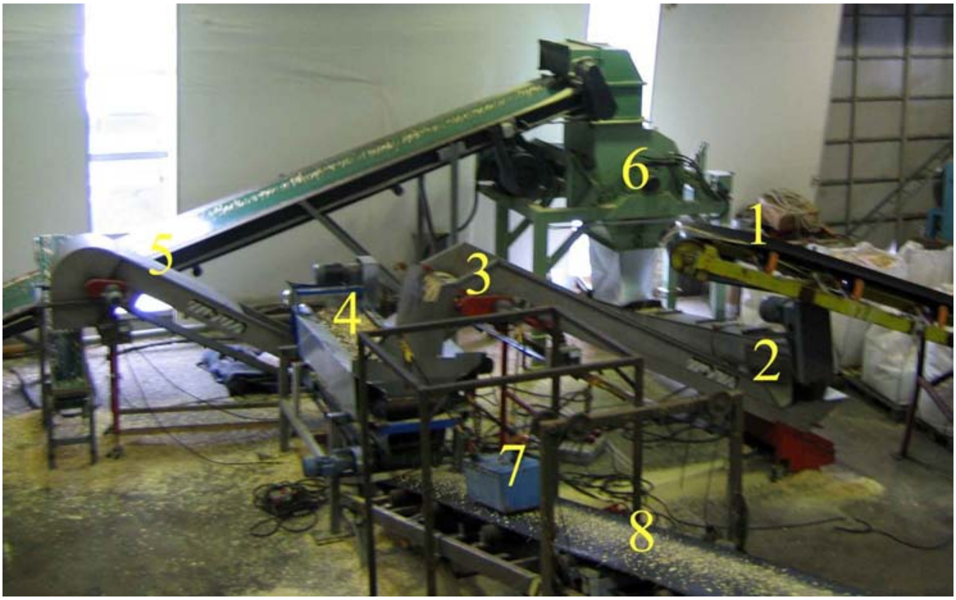

Figure 1. Continuous cleaving and screening process for pulp chips. 1 = feeding of pulp chips, 2 = conveyor of cleaved chips, 3 = feeding pulp chips and cleaved chips on screen, 4 = Pocket Roll screen, 5 = conveyor of oversize chips, 6 = knife mill, 7 = magnet, 8 = conveyor of accepted pin chips

After cleaving, the resulting pin chips were steamed (104 C) to remove air and then impregnated for 15 minutes with warm water (50 C) at a pressure of 0.3 bars to ensure complete impregnation. The chips were then drained and fed into a tubular fractionation device that was operated with a medium of the desired density, Figure 2.

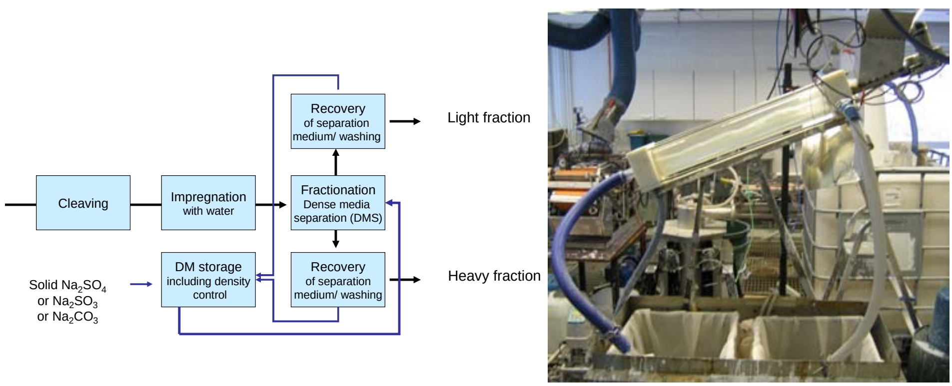

Figure 2. Principle of the dense media (DM) fractionation process and equipment.

After impregnation, the pin chips were stored in plastic bags at 5 C for further use. The impregnated and stored pin chips were laid in water 30 minutes before fractionation if the storage time was longer than 6 hours.

Stationary, preliminary fractionation trials with different dense media were performed in a 1.5 litre static beaker using concentrated Na_2SO_4 solution. The density of the solution was chosen so that the pin chips separated into floating and sinking fractions after the impregnated pin chips were mixed into the medium. After 2 minutes of mixing, a photograph was taken and the fractions were collected and washed with pure water to remove traces of saline solution. They were then weighted with respect to their yields. The yield of the floating fraction was dependent on the density of the medium.

Three different Scots pine samples were used in the study, representing different growth rates. The operation parameters of the DM fractionation equipment were:

- dense media density levels 1075, 1115 and 1160 kg/m^3
- a solution of sodium sulphate was used as the fractionating medium
- slope of fractionator 20°
- velocity of dense media 2.67 litres/s
- temperature of dense media 35–40°C
- fractionation capacity 20 kg (DS)/h.

Figure 3 shows how the proportion of light and heavy fractions is dependent on the medium density. The amount of "light" fraction increased with medium density from 20 to approximately 80%. At the same time, the "heavy" fractions decreased with medium density from 80 to approximately 20%.

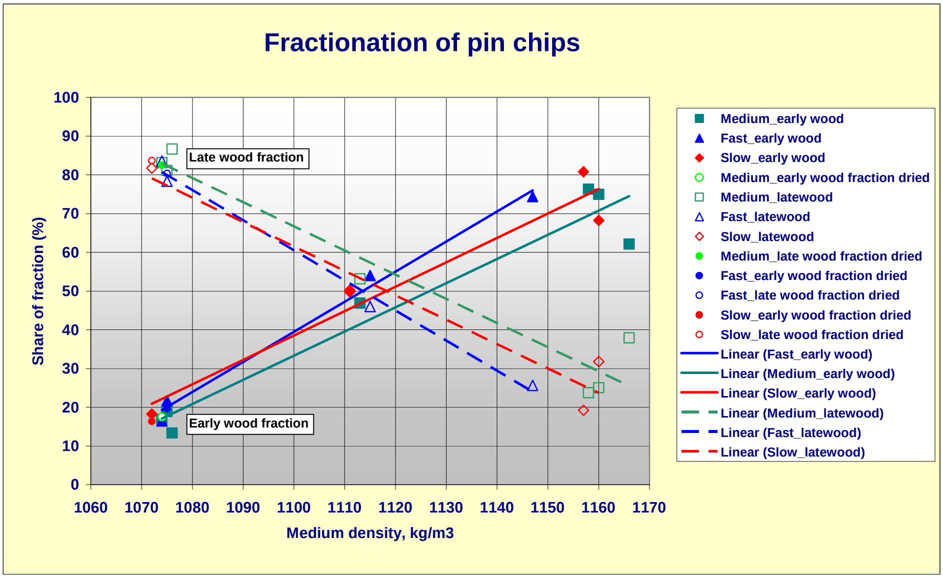

Figure 3. The amount of fractions as a function of medium density.

Results

The fractions were analysed with respect to pin chip dimensions, basic density and fiber properties. In the following, only main results are presented. Figure 4 shows the basic density of fractions. The maximum basic density difference of the fraction was approximately 150 kg/m^3, which is far beyond the density difference of the original trees, which was 33 kg/m^3.

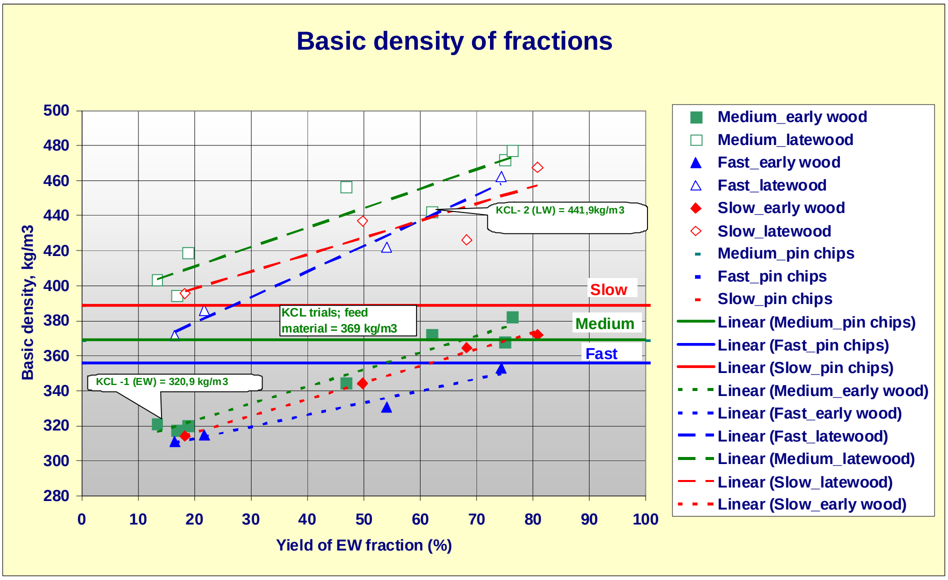

Figure 4. Basic densities of the original trees and their fractions.

The fractionated pin chips were used as raw material in mechanical and chemical pulping studies. According to pulping studies, the light-weight fraction of 320 kg/m^3 consumed approximately 50% more energy than the heavy-weight fraction of 460 kg/m^3. However, the light-weight fraction resulted in lower surface roughness and higher tensile index values than the heavy-weight fractions.

Conclusions

Knife mill cleaving of Scots pine wood chips and DM fractionation can be used in the production of pin chips with widely different basic densities ranging from 320 to 470 kg/m^3. Basic density affects not only the pulping processes, but also the fiber properties. DM fractionation offers new possibilities for improving the efficiency of both mechanical and chemical fiber production methods.

Pilot scale studies are needed, however, to determine the feasibility and attractivity of the fractionation concept. Along with the effects on pulping processes, the product potential of the fractions, in particular, should be explored. It is believed that commercially available equipment can be used for the fractionation.

Acknowledgements

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- The Scots pine wood samples were supplied by the Finnish Forest Research Institute
- The chemical pulping studies were performed by the Finnish Pulp and Paper Research Institute.

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Wood product session I – Passive building

Chair: Markku Leivo
Senior Research Scientist
VTT

Greenhouse gas benefits of wooden building materials

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Wooden building materials have obvious greenhouse benefits when they substitute functionally equivalent but more energy-intensive materials, and these benefits appear to be higher than those of other biomass uses. Wood materials also serve as a temporary biogenic carbon stock which can potentially be recycled for energy after its useful life. Numerical estimates of carbon emission displacement factors for wooden building materials, whole buildings and, for comparison, pure energy end-uses of wood are presented. The carbon balance of the Finnish forest sector and options for efficient wood use are also discussed.

Introduction

At present, the operation of buildings (especially heating and cooling) is the major factor contributing to primary energy use and greenhouse gas emissions in the building sector, while emissions from the production of building materials are of less importance. As a consequence of the tightening climate policy, the energy efficiency of buildings (especially heating and cooling) must be improved substantially over the next decades, which has implications for both new construction and the renovation of old buildings. Along with this development, the relative importance of the manufacturing of building materials as a source of greenhouse gas emissions within the building sector will increase, and its potential for emission reductions should be considered. One option could be the use of wood materials, which generally appear to be less energy and emission intensive than their stone- or steel-based competitors.

Efficient use of wood and its climatic indicators

Increasing wood use is not fully carbon neutral because it has an impact on the biogenic carbon stocks in forests, and this must be taken into account when considering its greenhouse gas impacts.

From the climatic viewpoint, sustainably managed forests function as a store of biogenic carbon and a renewable source of biomass. Forests can be utilised in alternative ways to halt the rising CO_2 concentration of the atmosphere:

- Sequestration: accumulating more carbon (C) in forests, materialized in the net growth of their biomass stocks;
- Substitution: displacing fossil CO_2 emissions using wood as energy or a material source instead of fossil fuels or materials with high-embodied emissions, thereby preventing emissions from permanent tectonic carbon stocks.

These mechanisms can be combined, and there are trade-offs and synergy between them. Here we assume a baseline or reference (e.g., fossil-fuel-based conventional material or energy system) with respect to which we estimate the cumulative carbon sequestration or reduction in emissions. When considering substitution as a mitigation tool, we assume that the biomass use is on a sustainable basis, i.e., harvested biomass is replaced with re-growth of new biomass, which can be rapid or take more than a century, as could be the case in managed boreal forests.

Figure 1 shows a generic example of carbon credits and debits due to substitution. The payback time, i.e., the time to obtain any carbon credits from the use of forest biomass, can be substantially longer compared with the timeframe of emission reductions in case: 1) the carbon stock of forest biomass is high in the initial state, 2) emissions that can be replaced by harvested biomass are relatively low (i.e., substitution is inefficient) and 3) re-growth of forest is slow after a regeneration cut of the stand. From the climate mitigation point, continuing C sequestration into biomass stocks or just conserving them could be defended in this particular case.

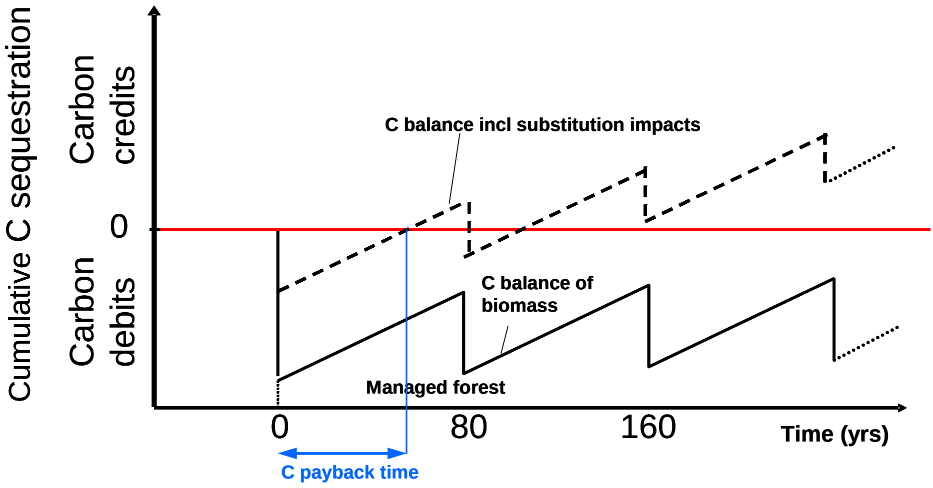

Figure 1. Schematic illustration of carbon debits and credits from the utilisation of an old-grown forest when the substitution benefit is low and re-growth of forest biomass slow.

Fossil C displacement factor DF is an efficiency indicator of substitution. It describes how much greenhouse gas (GHG) emission (e.g., t of $C_{eq.}$) can be displaced through increased use of biomass:

$$DF = (E_{ref} - E_{wood})/(BioC_{wood} - BioC_{ref}) \quad (1)$$

where E_{ref} is the GHG emissions in t of C_{eq} of the (fossil) reference product, E_{wood} is the GHG emissions from the wood product, $BioC_{wood}$ the biogenic C in the wood product in t of C, and $BioC_{ref}$ the biogenic C in the (fossil) reference product (usually = 0). (Thus $BioC_{wood}$ - $BioC_{ref}$ is the additional amount of biomass-based C used in the wood product compared with the reference product.) The total potential of forest biomass in long-term climate change mitigation is delimited by the average substitution efficiency, the available forest area and the forest yield.

The wood biomass cycle for which the displacement factor is estimated could include energy use only, or both material and energy use. In general, it can be said that the displacement factor is potentially higher in the case when the wood can first be used as a material to substitute more energy- and emission-intensive material and then recycled for bioenergy after material use (cascading). Moreover, bioenergy options that require much energy input in the refining process, such as liquid biofuels, are worse than the direct combustion of biomass.

The estimate of the true impacts on GHG emissions from wood materials and their competitors is not straightforward in practice. One issue, for example, is the emissions from purchased energy, especially electricity, required in the processing of the building materials, which could be based on marginal or average energy profiles, leading to very different specific emissions. Furthermore, in the GHG life-cycle analysis, assumptions about future emission displacement are also made, for instance, the proportion of demolished wood that is recycled into bioenergy, increasing the uncertainties. Very diverse assumptions can be defended and this is reflected in the studies, complicating their comparability and increasing uncertainties.

A Finnish study (Pingoud et al. 2009) estimated the displacement factors for harvested raw material: energy wood and saw logs, and covered the whole wood-use cycle, including by-product bionergy from sawmill residues and the recycling of final products into energy (Table 1). The sawlogs were assumed to be used in the construction of multi-storey houses in wood. The calculation of the displacement factors was based on the data collected in the Finnish-Swedish case study (Gustavsson et al. 2006) of the GHG impacts of building two wood houses in Viikki, Finland, and Växjö, Sweden, compared with their functionally equivalent concrete reference houses. (Note also that the displaced emissions due to the wood house cannot be calculated just by multiplying the DF by the total amount of wood-based C used to build the wood house, but by multiplying the DF by the *additional* amount of wood in the wood house with respect to the concrete house.)

Table 1. Displacement factors estimated by Pingoud et al. (2009).

	Displacement factor
Saw logs used for the Swedish wood-frame building***	**1.5**- 2.1*...**
Saw logs used for the Finnish wood-frame building*** (with timber facing)	**0.9**- 1.3***
Energy wood for CHP	**0.5 - 0.9**
*Marginal fuel = Coal, **Marginal fuel = Natural gas ***The displacement factors describe the GHG emission reductions with respect to a functionally equivalent concrete building	

According to the study by Soimakallio et al. (2009), the quantitative estimation of the displacement factor for Fischer-Tropsch (FT) diesel fuel produced from logging residues compared with fossil diesel is very uncertain, especially if the purchased electricity in processing is maximized. This is due to the high uncertainties of the emissions from electricity production. In the case when the use of biomass is maximized and purchased electricity minimized in the FT process, the displacement factor is most likely to be less than 0.4 for the FT biofuel plant integrated into a modern pulp and paper mill and in the order of 0.3 for a stand-alone plant.

Sathre and O'Connor (2008) performed an ambitious review of 48 different studies of greenhouse impacts of wood products and their competitors. The results of 20 studies enabled a meta-analysis to calculate the displacement factor for wood construction materials. The displacement factor was calculated for the *final product*, not for the amount of round wood used to produce the final wood product. This choice is somewhat misleading, because final products with high by-product flows could become high displacement factors. The heterogeneity of study methodologies and assumptions brings advantages and disadvantages to the meta-analysis. Each reviewed study showed a unique result, which varied with physical ("real") factors like the type of forestry and wood product, the type of non-wood material it is compared against, and the post-use fate of the wood. The calculated displacement factors range from a low of -2.3 to a high of 15.0. The average middle estimate, with a value of 2.0, could be viewed as a reasonable estimate of the GHG mitigation efficiency of wood product use over a range of product substitutions and analytical methodologies.

Structural materials can only be produced from a limited proportion of the total harvested wood biomass. However, according to these results, wood construction and the use of wood-based materials in general appear to be a more promising way to decrease the emissions than pure energy use. In addition to the substitution benefit, compared with competing materials, some part of the biogenic carbon is sequestered for a relatively long period into material use. When the displacement factor is higher and some carbon is also sequestered (i.e., the substitution benefits as a whole are high), then the carbon payback time will also be shorter despite long rotation periods (Fig. 1).

Another factor to be considered is the average amount of wood needed to replace other materials. One example is the previous study, which considered the whole new construction sector in Finland in the beginning of the 90s and estimated that on average approximately 3.6 t of stone-based materials could have been substituted by 1 t of construction wood (Pingoud and Perälä 2000).

Estimates of GHG impacts of sequestration and substitution at national level

Depending on the context, a displacement factor can be a measure of *either* the GHG that is avoided because something is made of wood when it could otherwise have been made of non-wood materials, *or* of the potential reduction in GHG emission if something made of non-wood materials was instead made of wood (Sathre and O'Connor 2008).

According to the Finnish national GHG emission inventories (Statistics Finland 2009), carbon sequestration into forest biomass was 32.81 Mt CO_2 in 2007, varying between 25.71 and 40.69 Mt CO_2 in the 2000s. According to the inventories, sequestration into wood products was 1.22 Mt CO_2 in 2007, varying between 0.31 and 1.27 Mt CO_2 in the 2000s.

The above numbers can be compared with the roughly estimated substitution benefits of wood use in Finland. According to the Finnish Forest Research Institute (2008a), the primary energy in waste liquors and other by-products, waste products from forest industries, and the use of solid wood fuels in heating and power plants and small-sized dwellings totalled 295 PJ in 2007. Nearly half of all wood use in Finland is energy use. In terms of biomass, it was approximately 17 Mt of dry matter content and 8.5 Mt of biogenic C. If instead of wood, energy fossil fuels were used, the fossil C emissions would have been approximately 15–30 Mt CO_2 higher (assuming about the same conversion efficiency; in reality it is somewhat lower) depending on the replaced fossil fuel (natural gas, oil, coal, peat). The replacement of *all* wood-based bionergy in Finland with fossil fuels would not be possible in practice, but the above estimate of the rough magnitude of displaced fossil fuel emissions is illustrative.

Domestic consumption of sawn wood in 2006 was about 5.2 Mm^3, and consumption of wood-based panels 1.1 Mm^3. Converting these two into carbon flows equates to roughly 1.5 Mt C. If no wood products had been used, the emissions would have been 4 Mt CO_2 higher applying the low estimate displacement factor (0.7), 11 Mt CO_2 higher applying the middle DF (2.0) and 24 Mt CO_2 higher applying the high DF (4.4). This calculation is of course unrealistic, but it illustrates the order of magnitude of the impact of material substitution.

An increase in the use of wood as a source of energy and material would create additional savings of fossil C emissions, but, on the other hand, the C sequestration into forests would decrease. From the above calculations we can conclude that carbon sequestration into wood products (i.e., excluding sequestration into forest biomass) is quite small compared with the climatic benefits of energy and material substitution. These substitution benefits must be added to the impact of the potentially displaced emissions in the export markets of Finnish wood products. This is not estimated here.

Summary

The climatic benefit of substitution is a product of the wood product flow and the displacement factor. To be significant for national emission reductions, the mass flow of biomass used for displacement must be sufficiently large and, at the same time, the efficiency of wood use should be high, preferably maximizing the displacement per consumed biomass. It is difficult to project if there could be some totally new wood-based products that could essentially increase the climatic benefits of using wood biomass. The re-growth of forest biomass is slow in Finland compared with most forested regions in the world, leading to longer C payback times for biomass use. However, the payback time is shorter the higher the displacement factor (assuming no change in growth rate). Currently most of the residues are left in the forest after final felling. When not utilised for bioenergy, they decay quite rapidly without any benefits in the displacement of fossil fuels. This potential could be used to increase the average displacement factor of harvested wood. From the climatic viewpoint it is justifiable to develop uses for forest biomass to provide maximal emission displacement per harvested biomass while, at the same time, considering the constraints due to biodiversity and other non-GHG issues.

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Comfort and wood interiour

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Summary

The aim of the study was to find out how a hygroscopic material such as wood influences the comfort of indoor conditions (humidity). For the field measurement, 14 single family houses were chosen, representing massive hygroscopic, massive non-hygroscopic, light hygroscopic and light non-hygroscopic structures. According to the measurements, there were no significant differences in behaviour when the monthly values (temperature and relative humidity) were compared. Differences could be found, however, when the daily values were studied. The interior (furnishings, textiles, carpets, etc.) has a high impact on the hygroscopic behaviour of the indoor climate. The non-hygroscopic structures were thus actually somewhat hygroscopic due to the interior.

Introduction

The relative humidity indoors plays a very important role in respect of the indoor air quality, thermal comfort, occupant health, material emissions and energy consumption. If the relative humidity indoors is too low, it may cause respiratory illnesses and asthma. If it is too high, the relative humidity has negative effects such as mould, moisture problems and dust mites, and it may also cause respiratory illnesses. In most of the previous studies, the temperature and air pollutants were well analysed, but the indoor air humidity has received far less attention, even though it can have important consequences.

The humidity of the indoor climate typically changes rapidly due to the behaviour of the inhabitants, for example, cooking, showering, etc. In a northern climate, the relative humidity is at its lowest during the winter months and at its highest during the summer period. In Finland, the main concern is relative humidity that is too low. Studies focusing on high humidity are far less common.

The aim of this study was to find out the influence of hygroscopic properties of wood-based structures on indoor air humidity, temperature and comfort (PPD, predicted percentage of dissatisfied). This paper focuses on results based on field measurements.

Methods

In this study, four different kinds of buildings were selected for measurements: 1) construction with a high thermal but no moisture capacity, 2) construction with a high thermal and moisture capacity, 3) construction with a low thermal but high moisture capacity, 4) construction with a low thermal and moisture capacity. Fourteen buildings were selected for measurements. Six of the buildings had mechanical exhaust ventilation and the rest had mechanical supply and exhaust ventilation.

Measurements of temperature and relative humidity (RH) were taken in the living room, master bedroom and shower room.

The airflow rates and the pressure difference between the indoor and the outdoor air were measured at different stages of the ventilation system. The air tightness of the building was also measured according to standards EN 13829:2000 and ASTM E779-87.

The acceptability of the indoor climate was analyzed according to the ISO 7730 standard by calculating the Predicted Percentage of Dissatisfied (PPD). The PPD values can be calculated from predicted mean values (PMV).

Results

The average air tightness, n_{50}, was 3.7 ach, which is typical for dwellings in Finland. The pressure difference between the indoor and outdoor air with normal use of the ventilation system was small, on average -1.7 Pa, indicating a slight under pressure inside the building. Only one building had a slight over pressure, 1 Pa. The exhaust airflow was on average 0.31 L/s,m^2.

The percentage of predicted dissatisfaction was clearly lowest in the buildings whose temperatures were lowest, Figure 1. In building 3, the recommended value of dissatisfaction of 20% was exceeded only 2% of the time. The construction with a high thermal and low moisture capacity exceeded the value of dissatisfied 20% of the time.

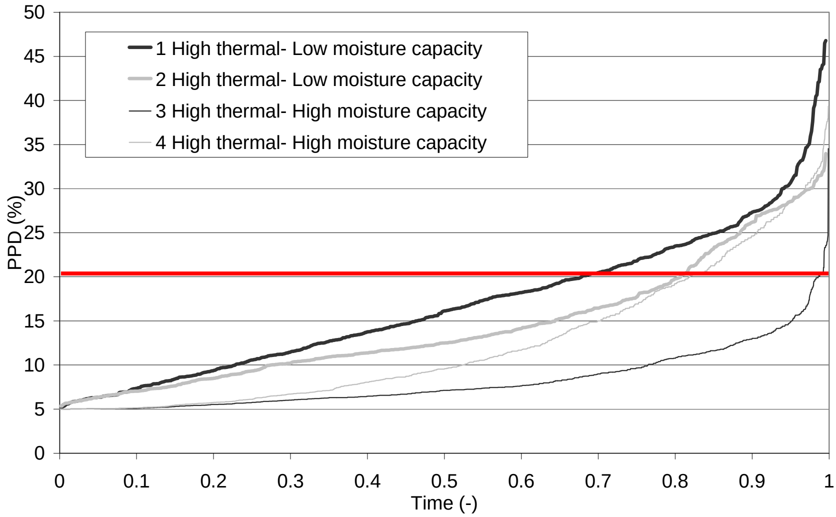

Figure 1. Duration curve of predicted percentage of dissatisfied for constructions with high thermal capacity, in August.

Building 11 had the highest value of dissatisfaction out of the buildings with a low thermal and low moisture capacity, PPD 48%, Figure 2. In that construction, the limit value PPD 20% was exceeded 17% of the time. Buildings 10 and 13, which had the lowest temperatures, also had very low PPD values; their PPD values exceeded the 20% limit value only a few per cent of the time in August. Building 6 with low thermal but high moisture capacity exceeded the limit value 53% of the time in August. This building also had the highest temperatures and the highest peak value of PPD 66%.

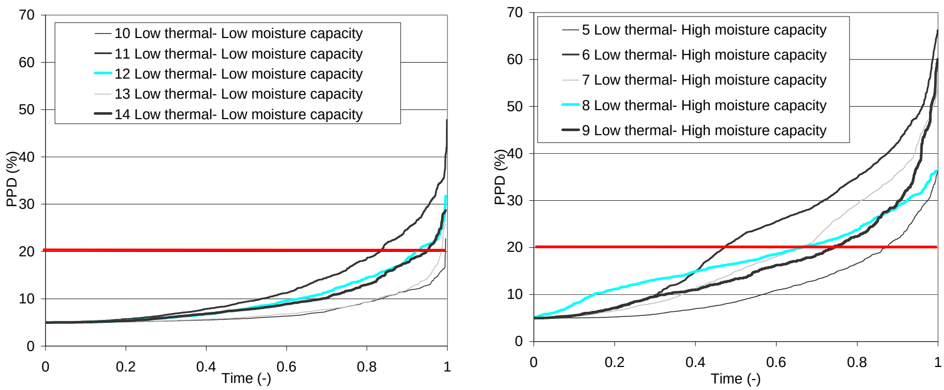

Figure 2. PPD values for constructions with low thermal capacity.

Discussion and conclusions

There was a wide range of variation in relative humidity in the bedrooms. When the levels of absolute humidity were compared, the differences were small however. It seems that the temperature had a stronger effect on humidity in the buildings than the moisture capacity of the construction.

When the values of the predicted percentage of dissatisfied, PPD, were compared, the lowest values were achieved in the buildings with the lowest temperatures in August. The buildings with a high thermal capacity did not always have the lowest temperatures. It appears that the location of the building and the amount of solar radiation probably also had a big effect.

Although there were no significant differences in the duration curves of relative humidity between the studied constructions, the differences were clear when the daily behaviour was studied. A construction with a low moisture capacity could not bind the moisture flow from the inhabitants in the bedroom at night, and the relative humidity was higher at night. In buildings with moisture capacity, the daily difference between the bedroom and the living room was not significant.

Acknowledgements

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VOCs in wood interior

Helena Järnström
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Introduction

Volatile organic compounds, VOCs, are emitted from a number of consumer products used indoors, like building materials, furniture, cleaning agents and fragrances. Building materials are an important source of VOCs especially in newly built buildings. In order to reduce emissions indoors, different construction material labelling systems have evolved. The classification systems use standardized measurement methods for VOCs (ASTM 1997, ISO 2006). The Finnish M1 label has been given to > 1100 building materials (www.rts.fi). The M1 label gives target values for the total VOC emission (TVOC), ammonia and formaldehyde. The M1 label is given to unfinished, domestic wooden materials without testing. However, the TVOC emission from unfinished wood can be higher than the M1 target value of < 200 µg/m^{2}h.

Wood VOCs

Typical VOCs emitted by wooden materials are terpenes, aldehydes, acids and formaldehyde. The emissions from fresh, undried softwood are high. The main components are mono-terpenes like alpha-pinene, carene, terpinolene and limonene. The emissions from fresh hardwood are low compared with softwood. The main components are alcohols, aldehydes and small molecular acids. The drying process decreases emissions significantly. Figure 1 shows the effect of a 6–12 day drying period on pine and spruce to a humidity content < 20% on VOC emissions (Englund 1999). Emissions decreased to ~1/3–1/20 level. In general, VOC emissions are affected by wood species, habitat, drying process (temperature), humidity content, the proportion of heartwood and surface wood, age, storage and packing.

The finishing (e.g., paint, lacquer) of wood products changes the VOC profile markedly. VOCs typical of paints and lacquers like glycols and glycol ethers become dominating compounds.

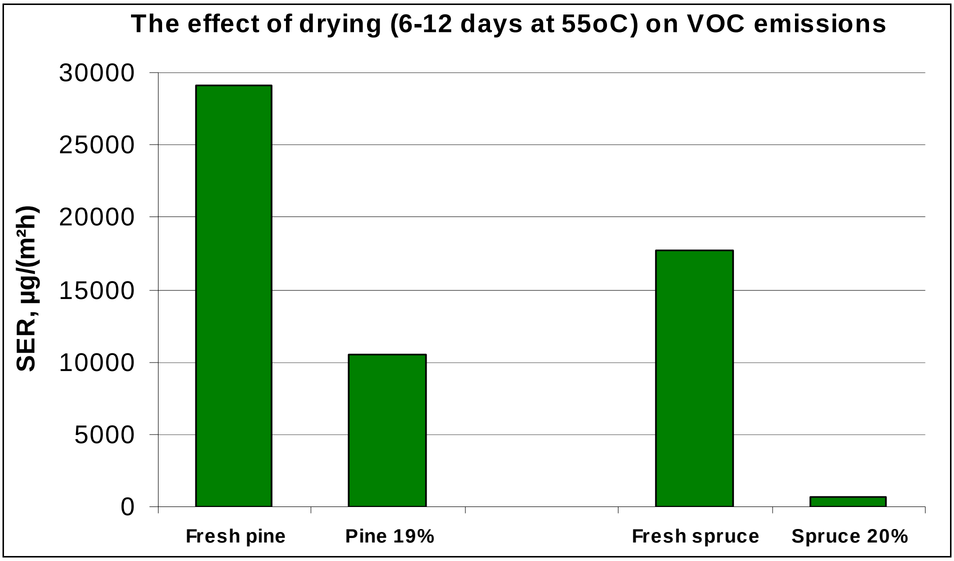

Figure 1. The effect of drying (6–12 days at 55°C) on the VOC-specific emission rate (SER) from pine and spruce (Englund 1999).

Indoor air concentration of VOCs in wooden houses

Indoor air concentrations in wooden houses are typically higher than in concrete houses.

Figure 2 compares indoor air concentrations of TVOCs, the terpene compounds alpha-pinene, carene and limonene as well as the aldehyde compound hexanal, in a log house and in concrete buildings (average in 10 apartment buildings). The buildings were 2–4 weeks old. The TVOC concentration was more than two times higher in the log house compared with the concrete buildings. The terpene compounds were up to 20 times higher in the log house than in the concrete building.

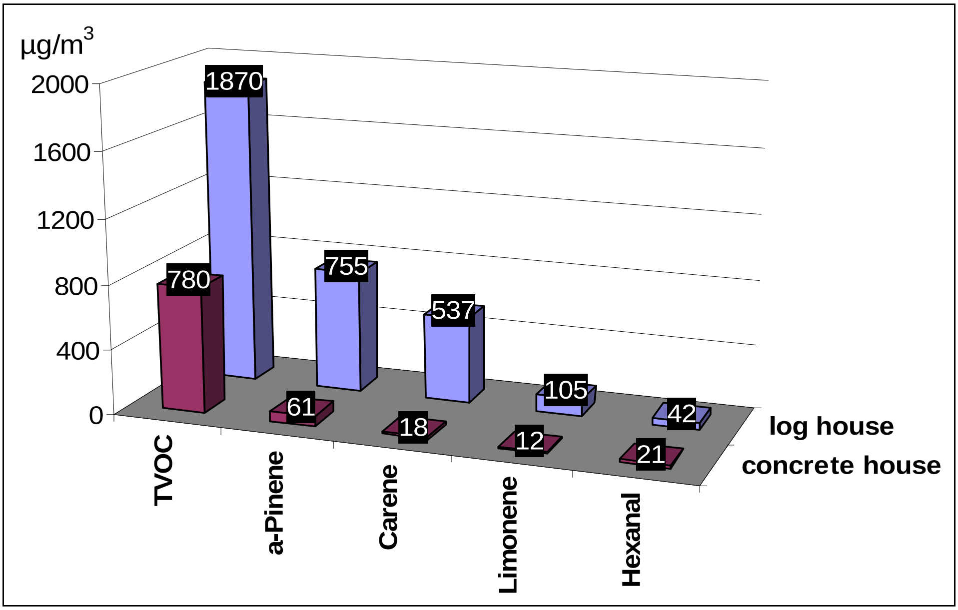

Figure 2. VOC concentrations in a log house and in concrete buildings (average in 10 apartment buildings, VTT 2009)

Discussion and future research needs

The concentration of VOCs in wooden interiors is typically high compared to interiors with a concrete structure. The main compounds are terpenes, which are the most common VOCs measured indoors. Complaints on indoor air quality (IAQ) are rare in wooden houses however. In fact, indoor air measurement results collected during the last decade at VTT indicate that higher terpene concentrations are measured in buildings with no complaints on IAQ. According to VTT's indoor air database, the average concentration of terpenes in "problem" cases is ~50 µg/m^3 whereas the concentration level in "no problem" cases is ~100 µg/m^3 (VTT 2009).

In the future, more research will be needed about VOCs in wooden houses, like concentration levels, trends and the occupants' experiences of perceived air quality. Material labelling actions can be taken to reduce VOC emissions from wooden furniture and materials. The health effects of wood VOCs (terpenes) need to, however, be investigated more thoroughly, in order to reveal the emission target values for wooden products.

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Critical conditions for mould and decay resistance of wood

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Several factors are involved in the biodeterioration of materials and buildings, and mathematical modelling may help us to understand the complicated interaction between many factors. For mould growth, long-lasting humidity exposure above RH 80–90% is critical for wood-based materials, and above RH 90–95% for stone-based materials, depending on the temperature, material properties and exposure time. Mathematical modelling will not give the answers to all the problems, however, and users should be aware of the limitations of providing a true picture of the complicated process of biodeterioration and damage development in buildings and materials.

Introduction

Resistance against biodeterioration, e.g., mould and decay of wood-based materials in buildings, is an important factor, especially for products that will be used in exterior conditions. Moisture exposure exceeding the tolerance of structures is the most common cause of different types of damage to building materials. Mathematical modelling of mould growth has been a research topic at the VTT Technical Research Centre of Finland for many years. The research has included several experimental studies on conditions for mould growth, primarily on wood, but also on other building materials. The present VTT model consists of a mathematical model that also takes into account the delay in the mould growth rate due to unfavourable conditions. The model has also been connected to the building of physics calculation methods. For the durability of wood, decay may be the critical factor, especially for the exterior target of high humidity exposure.

Models of decay development provide a tool to evaluate the effect of moisture exposure conditions on the service life of wood materials.

Results and discussion

A classical way to express suitable exposure conditions is to use so-called isopleth diagrams. Mathematical modelling of mould growth has been developed at VTT, based on large laboratory studies. The evaluation of mould growth on materials is based on a mould index (Table 1), in which several different mould species and growth types are included.

Table 1. Use of the mould index to evaluate the intensity of mould growth on the material samples.

Index	Growth stage
0	No growth
1	Growth found only under microscopy, some hyphae
2	Growth found only under microscopy, several colonies found
3	Visual growth detected (growth area < 10%) and first fruit bodies found or mould growth found only under microscopy (growth area < 50%)
4	Visual growth detected (growth area 10–50%) or mould growth found only under microscopy (growth area > 50%)
5	Plenty of visual growth detected (growth are > 50%)
6	Very heavy mould growth, area around 100%

According to the model, the lowest humidity level for mould growth is around RH 75–80% depending on the temperature and exposure time (Figure 1). The response times proved to be short (from a few days to a few weeks) in pine sapwood in conditions favourable to the growth of microorganisms and long (from a few months to a year) in conditions close to the minimum and maximum moisture or temperature levels. Under fluctuating humidity conditions, the total exposure time for a response of growth of mould fungi is affected by the periods of high and low humidity conditions, as well as the humidity and temperature levels and materials. The final condition of the surface is also dependent on the surface quality, e.g., nutrient contents. The favourable temperature range for growth of mould fungi is 0–50°C, and the critical relative humidity required for the initiation of mould growth is a function of temperature and exposure time.

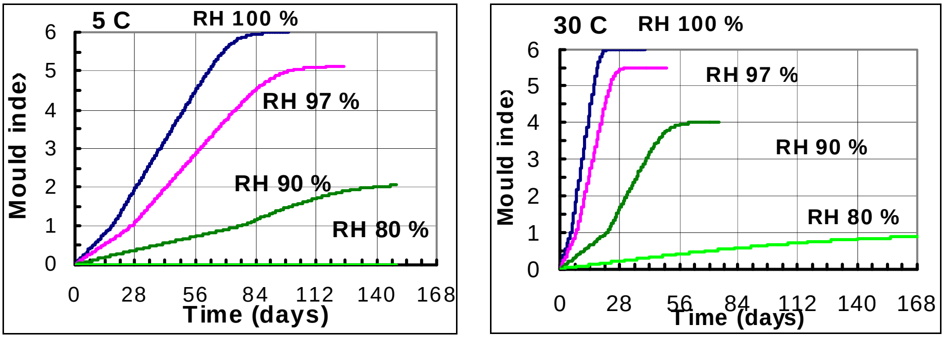
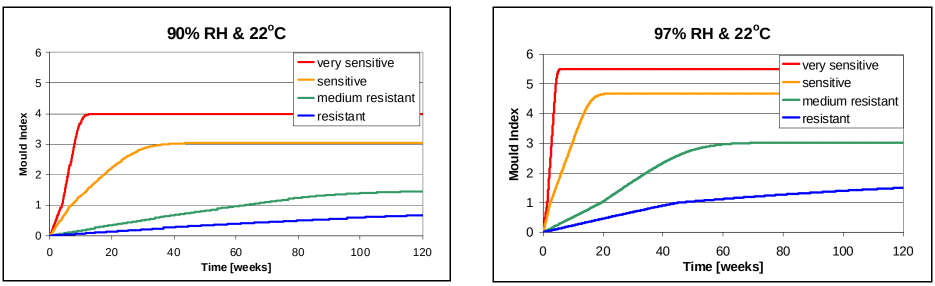


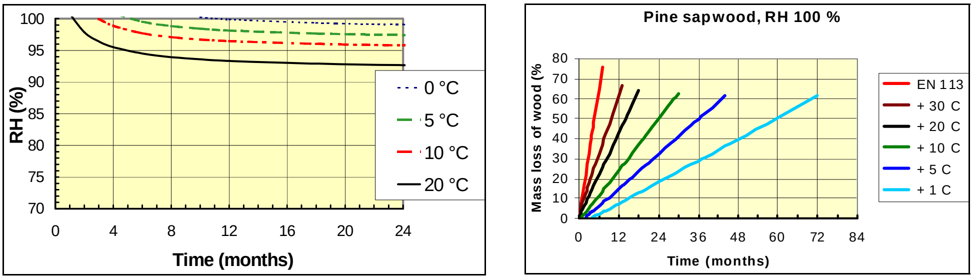
Figure 1 a and b. The response of mould growth (mould index) to the exposure conditions (RH, temperature and exposure time) on untreated pine sapwood.

Different types of materials also have an effect on the time periods needed for spore germination. In Figure 2, a comparison is shown of the critical conditions for mould growth assumed by some of the models proposed. When evaluating the resistance of different materials to mould growth, different types of resistance levels could be found as well as a large variation within one material type. The performance of the final product may be different to that of the raw material used, and the evaluation of the durability of the product should not only be based on the material used.



Figures 2 a and b. Resistance of different building materials to mould at RH 90% / 97% and 22°C. The properties of the surface are important for the resistance to mould fungi.

For the growth of decay fungi and decay development to start, the ambient critical humidity level of the microclimate should be above RH 95–100% and the moisture content of pine sapwood above 25–30%. According to experience, decay will develop when the moisture content of the wood exceeds the fiber saturation point (RH above 99.9% or wood moisture content 30%). Tests in laboratory conditions are most often performed under the worst-case scenario, like EN 113.), in which the conditions for fungal growth are optimal. The mathematical evaluation may provide a tool to evaluate the decay development in actual conditions and thus evaluate the performance of the material in lower exposure conditions (Figure 3 b).



Figures 3 a and b. The critical exposure time for the early stage of decay to develop (left) and the development of decay under the most suitable conditions (EN 113 test) and at a humidity level of RH 100% and in different temperature conditions. The model may give a high mass loss evaluation at low temperature.

Conclusions

Mould fungi are a part of nature: a normal phenomenon in the exterior part of structures or untreated wood objects. Humidity, temperature, exposure time and material properties are critical for protection against mould and decay problems. Modelling is a tool to evaluate the eventual risks and needs for additional protection of wood against mould growth or even against decay development -> several conditions affect it at the same time: wood material, modification, impregnation, surface treatment.

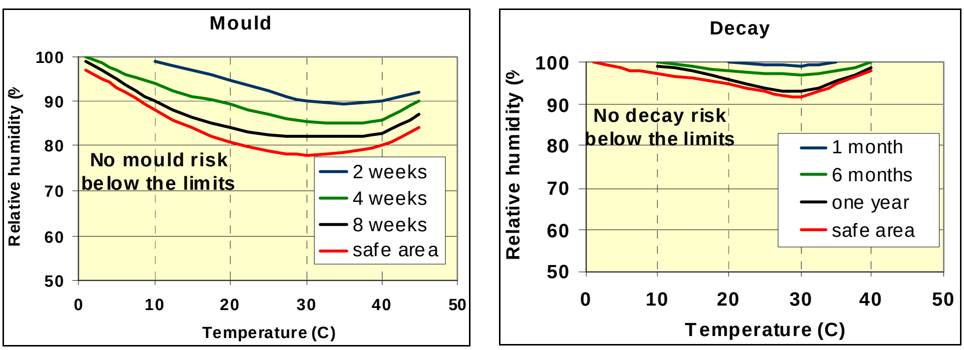


Figure 4 a and b. Humidity and temperature isopleths for mould and decay to develop in untreated pine sapwood.

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Wood product session II – Wood durability

Chair: Hannu Viitanen
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New approaches to wood protection

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Introduction

In the United States, billions of dollars are spent annually to replace wood damaged by decay fungi or infested with termites. Equally costly are the insurance claims for mould clean up in houses. All three wood inhabiting organisms are attracted to excess moisture. Realistically, moisture control is undermined by a combination of factors including architectural style, workmanship, building materials, building practices, weather, energy efficiency, and maintenance. Protection of wood from biological agents is also achieved by preservative treatments with biocides. Since chromated copper arsenate (CCA)-treated wood was restricted from most residential applications in the U.S. the need for new "green" wood protection systems has increased. Several environmentally friendly approaches to heavy metal-free wood protection are being investigated including targeted biocides, synergistic combinations of new and existing biocides, nanotechnology, and naturally durable wood species. Developments in each area will be discussed.

Heavy metal-free technologies

Targeted biocides

Chemicals to protect wood from biodeterioration by fungi and termites have generally been broad-spectrum biocides that are now facing increasing environmental regulatory pressure. A more logical approach to development of selective biocides would be to define a target, characterize that target, and then design inhibitors based on the mechanism of action of the defined target. Targeted biocides may act by sabotaging the mechanism of fungal infection or disguising structural components of wood from fungal recognition. One targeted biocide developed and patented is N, N naphthaolylhydroxyamine (NHA), a low toxicity, water soluble, calcium-precipitating stain typically utilized in electron microscopy. NHA forms a stable calcium precipitate in calcium containing wood cell wall structures such as the bordered pit membrane and compound middle lamella. Fungal infection is halted to two ways; first, by altering the path for hyphal movement from cell to cell and second, by interference with metabolism of decay fungi. NHA is also a direct termiticide and at low concentrations, it acts as a feeding stimulant resulting in termites consuming twice as much of a commercial termiticide, often a chitin synthetase inhibitor, in cellulose termite bait systems.

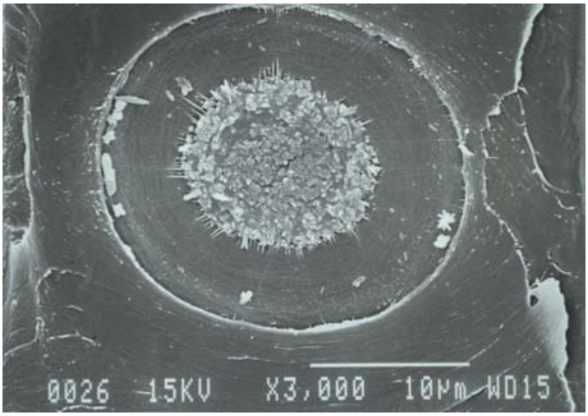

Figure 1. N, N naphthaolylhydroxyamine alters the pathway for fungal infection by forming a stable calcium-precipitate on the bordered pit membrane.

Essential oils

Essential oils from herbaceous plants, used most often in the food industry as flavoring, the cosmetics industry as fragrance, and the pharmaceutical industry for their functional properties, are now being evaluated as fungitoxic and insecticidal wood protectants. Their naturally occurring anti-microbial properties are conferred by monoterpenes, diterpenes and hydrocarbons with various functional groups. Primary chemical constituents of essential oils vary considerably between oils. However, AFNOR (Association French Normalization Organization Regulation) and ISO (International Standards Organization) certification standardizes the chemical profile and principal constituents that differentiate therapeutic grade from lower Grade A essential oils ensuring a minimum levels of activity is present for a specific oil. Selected herbaceous plant essential oils have demonstrated high efficacy towards mould fungi, decay fungi, and termites. Our research has shown that dill weed oil selectively acts as a fumigant to cause 24-hr mortality to subterranean termites. Egyptian geranium and white thyme oils selectively inhibit mould and decay fungi when used as a surface treated for wood suggesting they may be useful for inhibition of mold fungi on wood and wood products in service. The volatile components of dill weed oil are better suited as fumigants for protection of stored building materials, such as framing lumber, millwork, or truss systems.

Fatty acid chemistry

Fatty acids, used successfully as agricultural fungicides, are being evaluated for antifungal activity against the wide variety of ascomycetes, deuteromycetes and basidiomycetes inhabiting wood. Conditions affecting the efficacy of fatty acids on wood products need to be identified. Previous research, though scant, suggests that fatty acids demonstrate a high degree of specificity towards inhibition of spore germination of brown- and white-rot basidiomycetes that is dependant on the fatty acid, concentration tested and the test organism. Fatty acid formulations require an emulsifier to form a miscible dispersion; some emulsifiers possess some degree of antimicrobial activity and can be used to selectively enhance efficacy of a fatty acid formulation. Adjuvants, such as organic acids, may be useful to further enhance the performance of fatty acids. Many organic acids are classified as GRAS (Generally Accepted As Safe) compounds by the U.S. Food and Drug Administration (FDA) and have common acceptance for use in the food industry as acidulants and flavor enhancers. The safety record of these compounds is a positive feature for development of antimicrobial formulations based on “green chemistries”. Adding organic acids, such as L-lactic acid, to the fatty acid emulsifications may increase the proportion of non-ionized fatty acids over ionized species, thereby promoting greater fatty acid penetration through cell membranes. Intracellular proton pump activity is increased and more energy is required by the cell for electrolyte balance, thus placing more stress on the cell. Higher intracellular concentrations of free fatty acids possibly results in damage to organelle membranes and protein structure. Multifactorial fatty acid emulsifications incorporating an appropriate adjuvant are promising for effective protection against numerous fungal species that affect wood products. Using this strategy, new “green” wood protection formulations are being developed and their application is likely to extend to other biodeteriorating agents such as termites and decay fungi.

Synergistic biocide combination

Finding a single, synthetic or natural antimicrobial compound, either newly recognized or already registered, to inhibit the immense variety of fungi capable of colonizing wood and wood products is highly unlikely. Likewise, biocide resistance that occurs frequently and to varying degrees in wood-inhabiting fungi increases the importance of co-biocide interaction for successful wood protection. Synergistic combinations of selected compounds, preferably using those derived from natural sources, is generally recognized as the most promising approach for obtaining successful control of wood inhabiting organisms. A synergistic biocide for interior application, called Durazol, has been developed based on several components that are well known to the wood preservation industry, namely boric acid, propionic acid and quaternary amine compound. While the preservation industry is also familiar with two azoles, propiconazole and tebuconazole, Durazol incorporates thiabendazole as a mould inhibitor. Thiabendazole is an agricultural fungicide that has greater efficacy towards mould fungi than either propiconazole or tebuconazole. The combination of actives in Durazol act synergistically to protect wood from a number of test fungi and termites at lower concentrations than are required for individual active ingredients.

Nanotechnology

Nanotechnology has the potential to greatly impact the wood protection industry through the creation of nanobiocides and nanomaterials with unique properties. Two areas of nanotechnology are currently being investigated, nanometals and nanocarriers.

Nanometals

Nanobiocides may find applications as co-biocides, or may alter treatability properties such as penetration and biocide distribution. Nanometals typically used by the wood preservation industry, namely nanocopper oxide and nanozinc oxide, were evaluated for leachability and efficacy of treated southern pine against mould fungi, decay fungi, and subterranean termites. Nanocopper and nanozinc showed favorable leach resistance compared to their soluble metal oxides. Nanozinc also inhibited termite feeding and caused moderate termite mortality. Both nanozinc and nanocopper inhibited a white-rot test fungus and were approximately as effective as their soluble counterparts at inhibiting brown-rot test fungi. Neither was effective against mould test fungi.

Nanocarriers

Nanotubules made from ceramics, clay, metal or lipids have been used as carriers in various medical and industrial applications. Some properties of nanocarriers that would benefit the field of wood protection include:

- Delivery and placement of biocide
- Slow release of a biocide
- Release of the biocide upon exposure to certain environmental conditions, such as high humidity
- Protection of heat labile organic biocides during treatment processes or panel fabrication.

Nanotubules can be capillary-loaded in a process that is highly dependent on the internal diameter of the nanotubule, chemical viscosity and solubility as well as chemical reactivity to the nanotubule material. Capillary loading may also rely totally on adsorption of the chemical. Resistance of physical forces is not only important to capillary loading of nanotubules, but is also important in the release of the treatment chemical, both intentional slow-release and unintentional leaching.

Loaded nanotubules may be used for surface application, pressure impregnation, or as an additive to engineered products, films, coatings or sealants. Some considerations include how to precisely control release of a biocide, compatibility with resin if used to treat composites, whether the resin itself may be a barrier to release of the biocide, risk of release during finishing, refinishing, or sanding, as well as calculating and regulating actual release rate. Proper design could lead to increased applications for biocides that are otherwise unsuitable for exterior or in ground applications, including but not limited to soluble biocides, heat labile biocides and delivery of targeted nanobiocides.

Figure 2. Painted gypsum board demonstrates effectiveness of controlled release nanocarrier following challenge with *Aspergillus niger*. Untreated control (left); treated with nanotubules loaded with commercial biocide (center); treated with nanotubules loaded with nanosilver (right).

Naturally durable wood species

The current emphasis on green technologies has renewed research interest in utilization of naturally durable wood species. Extractives have long been recognized as key features that impart natural durability in the heartwood of certain wood species. Extractives from some wood species have been evaluated for use as environmentally friendly preservatives or additives to coatings, but little is known about the chemical makeup of the extractives from underutilized wood species. In the U.S. there is also a need to find new uses for invasive and low-value, underutilized wood species in order to reduce the fire fuel load and restore the health of our National forests. Invasive and underutilized wood species selected for their natural durability are being evaluated in aboveground simulated deck tests in different decay hazard zones. Concurrently, bioactive extractives are being characterized in the laboratory. Successional microbial changes are being determined with T-RFLP and successional changes in chemical extractives are being followed during long-term outdoor exposure. Bioactive extractives responsible for imparting durability could provide new environmentally benign wood protection systems for aboveground applications.

Figure 3. Naturally durable underutilized and invasive wood species in aboveground simulated deck test.

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Challenges in accelerated testing of durable wood products

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The types of durable wood products are changing rapidly, but predicting their long term durability with our short term tests remains a serious challenge. Improved understanding and interpretation of our test methods is needed to provide greater confidence in our durability evaluations.

Introduction

As societal expectations and economic conditions change, there is increasing pressure to develop and market new types of durable wood products. The last few years have seen the introduction and rapid acceptance of micronized copper preservative formulations as well as the introduction and commercialization of metal-free organic preservative systems. Preservative retentions have been lowered to lessen environmental concerns and lower cost. Numerous other types of preservative formulations are rumored to be on the near horizon, and there is renewed interest in the use of naturally durable wood species. Non-preservative approaches to durability such as thermal treatments and modified wood have been commercialized in European countries, and their potential is being explored in the United States. The rapid evolution of durable wood products has further highlighted an old problem in wood protection… how do we evaluate long term durability with short term tests? This challenge is further complicated by the wide range of exposure environments, types of structures and service life expectations. There are also vast differences in the consequences of premature failure.

Over the last century numerous laboratory and field test methods have been developed to evaluate durability, and many of these methods have gained broad acceptance in Europe, Australia, Asia and the United States. In the United States the American Wood Protection Association (AWPA) has over 20 preservative evaluation standard methods, and other organizations, such as ASTM International, have applicable methods as well. These methods detail the testing procedures, and in some cases suggest or prescribe the manner of presenting the results. However, the methods generally provide little guidance on how to interpret the results in terms of expected service life or in terms of “pass/fail” criteria. In other words, what is the significance of an average stake rating of 9.0 after 3 years exposure? Does this rating demonstrate efficacy of a preservative in ground-contact? A similar problem in data interpretation exists in European countries, where there is a need for a harmonized system for durability classification.

Figure 1. Soil block (or soil-bottle) decay test.

Accelerated laboratory tests

The most widely used laboratory test in the United States is the soil-block (also called soil bottle) decay test. In this test a cube of the wood product is placed into a bottle that contains moist soil and a feeder-strip that has been pre-inoculated with a specific decay fungus. Sterile technique is used to ensure that only the fungus of interest is present in the bottle. The intent of the method is to provide the fungus with ideal conditions for colonizing the test material, and to evaluate the ability of the wood product to resist colonization. The method can perhaps be best understood as a measure of resistance to fungi that are known to be tolerant of a specific preservative. However, the relationship between the results of the soil-block test and in-service durability are poorly understood. One of the drawbacks of the method is that the fungi evaluated many not be relevant for in-service conditions. The standard fungi have been selected for their known resistance to some of the conventional preservatives, and are not necessarily those found degrading wood products. The vigor of the fungi also varies greatly between laboratories, and the results appear to depend on factors such as the age of the fungal culture, soil properties, and moisture content. Perhaps a larger concern with this method is that the sterilization process eliminates other organisms, such as bacteria, that may play a role in degrading and detoxifying organic preservatives. Thus, although the soil-block test does provide some insight on the ability of a wood product to resist colonization by certain fungi, it does not offer great promise for predicting the service life of a wood product used either in ground contact or above the ground.

Ground contact stake tests

Stake tests continue to be the primary method of evaluating products intended for use in ground contact. However, there are several factors that can interact to affect the results of these tests. Perhaps the most important of these factors are site conditions and duration of the test. It has long been recognized that deterioration is more rapid in warm, moist climates than in cool or dry climates. In the US, the AWPA standards recognize that climate affects the rate of deterioration, stating that while the minimum exposure time is 3 years in high decay hazard areas such as southern Mississippi, longer exposure times are required for lower decay hazard test sites such as Wisconsin. It is left up to the discretion of the subcommittee evaluating the proposal to determine whether the length of the exposure is adequate, but in the past, 3–5 years of data have generally been considered to be sufficient. However, results derived from northern climates are potentially misleading, even with longer exposures. For example, stakes that perform well in Wisconsin for over 5 years can be nearly destroyed in less than three years Mississippi.

Figure 2. Stake test plot in Mississippi, USA.

Similar challenges in interpreting data from different sites are encountered in European countries. It has been proposed that the site differences can be partially accounted for by creating adjustment factors based on the relative performance of reference materials at various sites. While this approach would remove some of the subjectivity in determining the required length of exposure, it is not a perfect solution because the effect of test site on preservative performance is a function of the formulation (or type of product) being evaluated. Thus, one cannot always assume that exposure for a certain number of years in a moderately severe site is equivalent to exposure for a certain number of years in a more severe location. Perhaps the most practical solution is to require data from at least one test site that has demonstrated a severe deterioration hazard.

Length of exposure is also a concern even within high decay hazard areas. It is far from clear that the three years specified in AWPA standards is sufficient. For example, consider the ratings of stakes in one of the USDA, Forest Products Laboratory's plots in southern Mississippi. This plot contains over 100 treatment groups, each of which was replicated with 20 stakes (19 by 19 by 457 mm). The stakes in these plots have been rated for 11 years. The data was analyzed to compare how well a treatment group with a perfect rating (all 20 stakes rated as perfect) at 1 through 9 years faired after 11 years. The analysis revealed that only about half of the groups with a perfect rating after three years performed as well as the reference preservative (average rating of 9.10) after 11 years. Thus, perfect ratings or equivalent performance to a reference preservative after three years does not provide a high degree of confidence that a test system will be performing similarly to the reference preservative over the longer term. These data indicate that when evaluating preservatives intended for use in ground contact in high hazard areas, a minimum of at least 5 years of exposure data is needed, and that the average rating of the test preservative should be at least as high as that of the reference preservative. Even slight evidence of vulnerability after 5 years appeared to be a strong indicator of poor future performance.

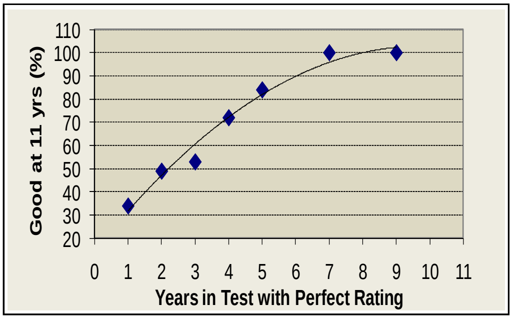

Figure 3. Only about 50% of groups with perfect ratings at three years perform well after 11 years.

The European Standard EN 252 for ground contact exposure does require a minimum of 5 years of testing before results can be interpreted. However, similar concerns have been expressed about the use of 5 year data from Nordic test plots to predict long term performance. Researchers in Norway compared the average ratings of over 700 treatment groups (approximately 10,000 total stakes) at 5 and 10 years to their median life and concluded that even treatment groups with no signs of decay after 5 or even 10 years may have a relatively short median life. One treatment group with no evidence of decay after 10 years had a median life of only 14 years.

Stake size effect

Often stakes with relatively small dimensions are used in tests because they are thought to have accelerated deterioration relative to larger stakes or commodity-size stakes. Small stakes do generally fail more rapidly, and so provide accelerated information on the relative efficacy of a test formulation in comparison to a reference preservative. However, it is unclear how their ratings or durability correspond to the service life of larger commercial members. In a recent study, the years to reach average ratings corresponding to loss of 10% of the cross section or complete failure were compared for 53 sets of matched 19- by 19-mm and 38- by 89-mm stakes exposed in plots in Mississippi. The larger stakes required an average of 2.1 times longer to reach an average rating corresponding to loss of 10% of the cross section, but this ratio ranged from as low as 1.0 to as high as 8.0. It took an average of 2.2 times longer for the larger stakes to fail, with maximum and minimum ratios of 3.5 and 1.4, respectively. Linear regression of average years to loss of 10% of the cross section or failure for the two stake sizes yielded R^2 values of

0.60 and 0.69, respectively. The data indicates substantial uncertainty in using the durability of 19- by 19-mm stakes to predict the durability of 38- by 89-mm stakes, and by extension, the durability of in-service members.

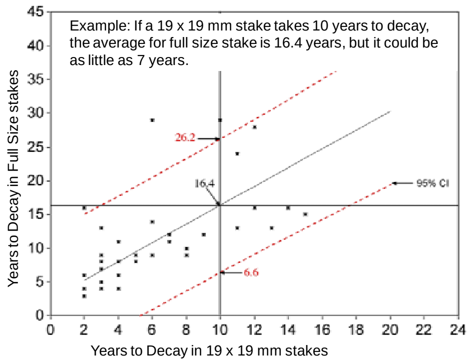

Figure 4. The relationship between the durability of these two stake sizes varies greatly.

Above-ground durability evaluations

Evaluation of wood products intended for use above-ground has proven even more difficult than ground contact evaluations. Although it is recognized that the decay environment presented by stake tests is very severe for products intended for use above-ground, the selection of an appropriate above-ground test method has been problematic. The greatest source of difficulty appears to be the wide variations in severity of exposure for wood used above-ground. The severity of above ground exposure does vary with climate but it also varies greatly with construction practices and localized site conditions that influence moisture, temperature and UV exposure. In areas where organic debris can collect in connections, the above-ground decay hazard may be higher than anticipated.

Figure 5. Current above-ground test methods may not adequately account for the accumulation of organic debris that can occur in-service.

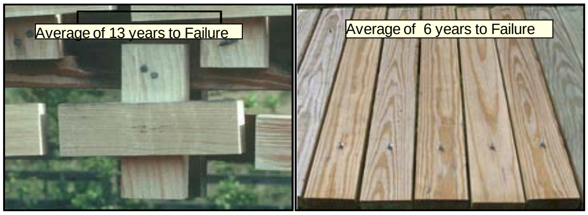

Figure 6. Small specimens used for above-ground testing may not hold sufficient moisture for sustained decay.

Substantial research on above-ground evaluations continues to take place in Europe, where the transition to use of "above-ground only" preservatives has preceded that in the United States. Despite extensive research however, it remains unclear how well above-ground tests characterize the hazard, or if they actually accelerate the rate of decay relative to in-service applications. Much of the difficulty is derived from creating test arrangements that simulate the moisture-trapping conditions present in actual structures. Most methods utilize some type of joint, connection or layering in an effort to trap moisture, but this effect can be undermined by the use of specimens with small dimensions. Although the smaller dimensions do allow more rapid detection of decay once it is present, smaller specimens dry more rapidly than dimension lumber. Smaller specimens also may be less susceptible to the formation of the checks that allow penetration and trapping of moisture in larger material. Thus, although we associate the use of small specimens with accelerated testing for wood placed in ground contact, this assumption may be misleading for above-ground evaluations. Some studies suggest that common test arrangements may actually slow the time needed for decay to develop. In a comparison of tests units of untreated southern pine sapwood exposed above-ground in southern Mississippi, the most rapid visually evident average years to failure (6 years) was achieved by simply using 102 mm thick planks. An earlier study reported that initial decay was not observed in untreated pine cross-brace units (20 x 75 x 15 mm) until after 6 years of exposure in southern Mississippi. In contrast, fruiting bodies of the brown rot fungus *Gloeophyllum sepiarium* can be observed after only three years of exposure of southern pine decking specimens (38 by 140 x 914 mm) in the lower decay hazard climate of Wisconsin. In addition to the effects of specimen dimensions, none of the commonly used test methods simulate the accumulation of decaying organic debris that often occurs in connections of treated wood used above-ground. Specimens are typically exposed in open areas to remove variability associated with natural shading, and when organic debris does accumulate it is removed during periodic inspections. European researchers have also noted that shading alone can promote above-ground decay, possibly because of increased wood moisture content.

Both the United States and European above-ground methods do indicate that meaningful results are not obtained until the untreated specimens reach a certain level of deterioration, but AWPA guidelines for preservative evaluation also state that a minimum of only three years of data may be needed in high hazard climates. This relatively short test duration may be based on the optimistic assumption that the above-ground test arrangements provide for accelerated testing. The standard methods do not provide criteria for ratings that would be considered acceptable or “passing” for the preservative-treated specimens, and given our uncertainty about the relationship between the results of these tests and in-service performance such criteria may be difficult to develop. It is also worth noting that although we may associate above-ground treatments with decking, the same use category also applies to structurally critical support members used above-ground. Given the ramifications of failure in some of these members, such as, third story balcony supports, some consideration should be given to providing more conservative durability estimates.

Conclusions

For evaluation of products intended for use in contact with the ground, it appears that even extended durability tests conducted in less severe (northern) climates may not be adequate for estimation of durability in more severe climates. Even in severe decay hazard climates, excellent performance of stakes after only three years is not a reliable indicator of long term durability. Basing test duration or performance criteria on the durability of untreated controls also does not appear to be sufficient for ground contact evaluations. The approach used in Australia, where test duration is based on the performance of low concentrations of an established reference preservative, does appear to have some merit.

Our current methods of assessing above-ground durability may not accelerate decay in comparison to some conditions encountered for durable wood products in service, suggesting that much longer evaluation periods or more severe tests should be considered. Alternatively, above-ground uses could be further divided, with more stringent test methods utilized for products intended as above-ground structural supports. Ground-contact testing of products used in structurally critical above-ground members may be necessary until the meaning of above-ground test methods is better understood.

Interpretation of test data also remains problematic. A return to more prescriptive data presentation may be warranted, as average ratings do not always adequately characterize the performance of a durable product. In addition, methods should provide more specific guidance on the distribution of ratings that is considered to represent adequate performance.

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A laboratory facility for research on wind-driven rain intrusion in building envelope assemblies

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Moisture management is critical for durable, energy-efficient buildings. To address the need for research on wind-driven rain intrusion in wall assemblies, the U.S. Forest Products Laboratory is developing a new facility. This paper describes the underlying principle of this facility and its capabilities.

Introduction

Increasing concerns about climate change, energy, and other environmental impacts have stimulated a trend toward "sustainable" or "green" construction. Currently the building sector accounts for 40 percent of total U.S. energy consumption; clearly there is a significant potential for reducing energy consumption in this sector. Buildings with highly-insulated envelopes and extremely low energy demand for space heating and cooling are targeted for widespread adoption in the near future. However, improvements in the energy efficiency of new and existing buildings must be accompanied by attention to moisture management. Increasing the level of insulation, for example, can lower the drying potential of building assemblies. Proper design of buildings is critical for preventing moisture accumulation, which can lead to a host of undesirable consequences, among them the possibility of shortening building service lives.

The importance of durability is underscored by the sheer quantity of wood used in buildings. Construction and repair of buildings account for approximately one-half of all lumber and other wood products (excluding paper) consumed annually in the U.S., and further increases in demand for residential and non-residential building products are anticipated. The sustainability and health of America's forests depend on efficient use of timber resources.

Reliable strategies for managing moisture in buildings require a quantitative, performance-based approach. Measurements are necessary to quantify moisture sources, the physics of moisture migration and moisture accumulation over time, the properties of building materials as they relate to transfer of heat, air, and moisture, and criteria for acceptable performance, such as avoidance of mold growth, decay, or corrosion. Quantification is integral to a scientific approach; in contrast, many traditional guidelines are based on experience, opinion, or limited technical information. A significant area in need of experimental research is wind-driven rain penetration through wall assemblies. To address this need, the Forest Products Laboratory is developing a new laboratory facility for evaluating wall systems for hygrothermal performance and durability, both for new construction and for retrofit applications.

Materials and methods

The facility, known as the Chamber for Analytic Research on Wall Assemblies exposed to Simulated weather (CARWASh), provides a realistic laboratory simulation of wind-driven rain impinging on a full-scale (approximately 3-m by 3-m) wall assembly. The method of exposure is unique and is representative of the physical phenomena typical in rainstorms. Spray nozzles direct water droplets downward into a moving stream of air, which imparts a horizontal velocity component to the droplets prior to their colliding with the test specimen. In contrast, typical water spray tests rely on water pressure fed to a rack of spray nozzles for control of the impact force. The CARWASh enables precisely-controlled rain simulation up to 150 mm/h at air speeds up to 11 m/s with variable wind direction. The chamber also maintains control of air temperature and humidity as well as the pressure difference across the wall assembly. Infrared radiation can be directed at the specimen to simulate solar warming. On the indoor side, air temperature and humidity are controlled. Tests can be programmed with weather data and set to run for weeks or months at a time.

A data acquisition system records readings from sensors in numerous locations: exterior environmental conditions, including temperature, humidity, wind-driven rain on the wall assembly, wind speed and direction, and radiation on the wall assembly; interior conditions, including temperature and humidity; and conditions within wall assemblies, including moisture content and temperature in wood framing and sheathing, relative humidity and temperature at select locations, and pressure differentials across components.

The facility will be used in a variety of research areas:

- Investigating wind-driven rain intrusion in walls and drying rates after wetting events
- Investigating the effect of air infiltration and exfiltration on moisture levels in walls
- Providing experimental data for validation of heat, air, and moisture transfer models
- Testing innovative wall assemblies
- Testing window installation details, water management details, and details for enhanced drainage and drying of wall assemblies.

Conclusions

The U.S. Forest Products Laboratory is developing a new laboratory facility for research on wind-driven rain intrusion in wall assemblies. This research will contribute to a quantitative, performance-based approach to moisture management, which is critical for the design of durable, energy-efficient buildings.

Figure 1. Chamber viewed from the exterior.

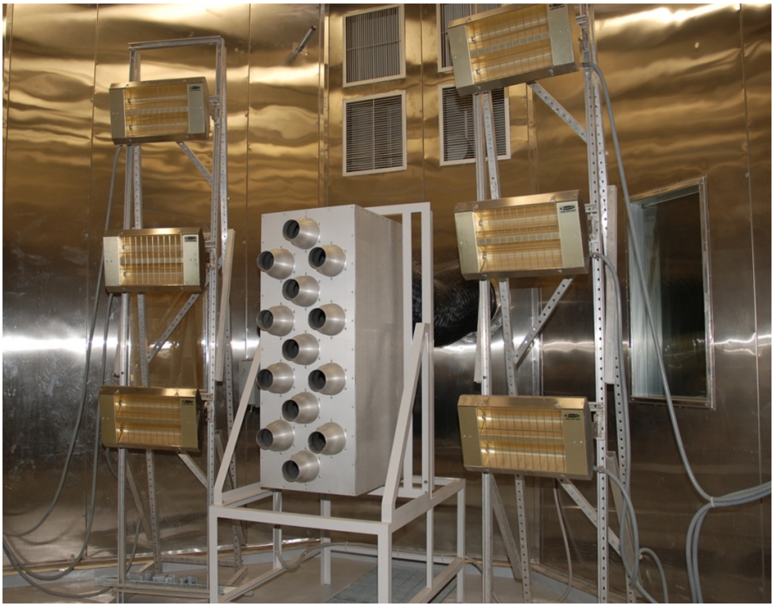

Figure 2. Array of infrared heat lamps and wind nozzle assembly inside the chamber.

Figure 3. One of 16 spray nozzles mounted near the chamber ceiling.

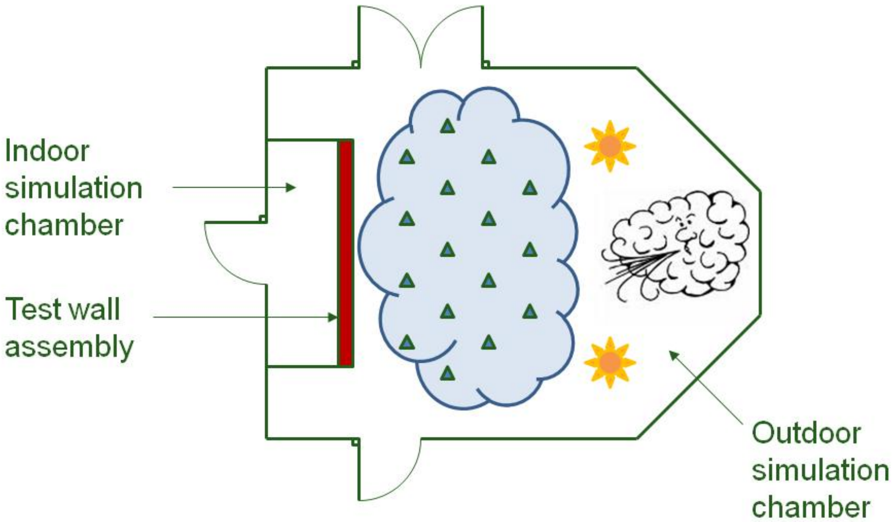

Figure 4. Plan view showing the main components of the facility.

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Moisture durability for wood products

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This paper provides an overview of the various ways in which moisture (meaning the substance H_2O in any of its phases, including that sorbed within wood) can result in performance problems of wood or wood-based products in building structures. Moisture-induced problems of wood and wood products can be categorized as follows:

- *"Delamination" of adhered products*
- *Dimensional change*
- *Creep deflection*
- *Problems with fastened connections*
- *Finish failures*
- *Biological infestation.*

Members of the Building Moisture and Durability Research Team at the U.S. Forest Products Laboratory (USFPL) conduct research activities in three of these areas. Until 2005, the Team consisted of two research scientists and an engineering technician. The Team currently consists of two research scientists, a materials engineer, a general engineer, and an engineering technician.

Delamination of adhered wood products may make itself readily apparent as visible dis-bonding of members as can occur in plywood or glue-laminated members. This type of failure is believed to be considerably less prevalent than it was in past decades. In the mid-1970's, "boil-proof" adhesives largely replaced less durable adhesives in the production of construction plywood. The most recent (2007) revision of the U.S. Dept. of Commerce Product Standard for

Construction and Industrial Plywood[1] no longer recognizes plywood classes with “Interior” or “Intermediate” bonds[2]. Plywood panels classed Interior were commonplace prior to the 1970’s. Likewise, glue-laminated timbers were, before the mid-1960’s, largely adhered with casein glue. Because of this, moisture control in older buildings that were constructed with plywood or glue-laminated members may be of concern from the perspective of avoiding delamination of structural members. In buildings constructed since the 1970’s plywood, glue-laminated members, and structural composite lumber are assumed to be largely resistant to delamination caused by occasional or accidental wetting. In wood composition materials adhered with durable adhesives, (such as hardboard, oriented strandboard, or parallel strand lumber), some degradation of bonds will occur with product exposure to elevated moisture conditions, but the degradation, even when appreciably advanced, is not made apparent by visible disbonding of wood constituents (fibers or stands). The constituents are inter-leaved within the product. Even when product degradation is appreciably advanced, the constituents largely remain in an inter-leaved configuration. These products undergo irreversible thickness swelling when exposed to elevated moisture conditions. They can be made to show limited (and in some cases appreciably limited) irreversible thickness swelling, but all wood composition materials made from interleaved wood constituents will display some irreversible thickness swelling when exposed to soaking conditions. An increase in water absorptivity accompanies irreversible thickness swelling. In hardboard siding, which will be exposed to wetting at some time during its service life, “edge welting” and “surface deconsolidation” have sometimes been problematic performance attributes; these attributes are associated with irreversible thickness swelling. Members of the Building Moisture and Durability Research Team have performed empirical and experimental research concerning the performance of hardboard siding in environments of appreciable moisture exposure. The Team is performing research concerning the performance of strandboard sheathing in response to cyclic seasonal moisture fluctuations.

The anisotropic dimensional change attributes of wood that are associated with changes in moisture content have been well-characterized for slightly less than a century. Before they were well-characterized, they were nonetheless rec-

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[1] This Voluntary Product Standard is designated PS-1.
[2] These classes can be found in the 1995 (and earlier versions) of PS-1.

ognized by woodcrafters. Warp, surface checking, compression-set shrinkage, and buckling of panels are all undesirable performance attributes that are associated with restrained dimensional movement. Irreversible thickness swelling of wood composition materials is associated with moisture-induced dimensional change of their wood constituents, although relaxation of elastic strains induced within the constituents by the pressing operation plays the prominent role. The relaxation of elastic strains within constituents occurs by the phenomenon of mechano-sorption. In recent years, truss arching (in insulated attics) and end-joint opening of wood siding have sometimes become problematic. These result from moisture-induced dimensional change in the longitudinal direction that is not of an insignificant amount. A common assumption is however made that dimensional change in the longitudinal direction is insignificant. When this incorrect assumption is made, the dimensional movement that occurs is not accounted for, and problematic behavior results. In the view of this author, moisture-induced dimensional changes can be effectively dealt with by a combination of component design, building design, and building moisture management. Dimensional movement is not a field in which the Building Moisture and Durability Research Team has conducted experimental research.

Creep deflection will occur in structural members that are heavily loaded. It is well-recognized that changes in moisture content while members are under load exacerbates creep deflection. The term “mechano-sorption” reflects the recognized influence that moisture content changes have on mechanical behavior of members under load. Creep deflection can be noticeable in buildings constructed before the adoption of building codes, and tends to be more prevalent in buildings constructed for persons of modest financial means. These buildings may be framed with under-sized members. An appreciable number of these buildings still exist in the housing stock of the United States (Figure 1). The phenomenon of creep deflection is largely ignored in new construction. The reason for this is not entirely clear, but a plausible explanation is that new buildings are typically framed with members of such size that they are lightly loaded and thus unlikely to undergo noticeable creep deflection. Consideration of creep by the National Design Specification is confined to a deflection allowance for members in bending; it specifies that a higher amount of anticipated creep deflection be calculated for wood beam members installed in a green condition and maintained in a dry environment. The existence of this caution in the National Design Specification (NDS) most likely reflects that in the state of California, residential buildings are typically constructed with green (unseasoned) lumber. The NDS does not address creep deflection under seasonal moisture cycling; it thus apparently assumes that seasonal moisture fluctuations will be modest. Control of creep deflection is not a field in which the Building Moisture and Durability Research Team has conducted experimental research.

Figure 1. Noticeable sag of rafters on a single-story home of modest size, constructed in 1940. At the time of construction, regional building codes had not been developed.

Fastened connections are subject to weakening by three moisture-induced phenomena: loosening of connections with moisture cycling, iron-catalysed degradation of wood substance in the proximity of fasteners, and fastener corrosion. The National Design Specification specifies load adjustment factors for mechanical connections based on wood moisture content at time of joint fabrication and on in-service moisture content. The NDS does not address the effect of repetitive moisture cycling on the load carrying capacity of fastened joints, apparently assuming that significant moisture fluctuations do not occur in service. Likewise, the NDS does not address the effect of fastener corrosion on load capacity of joints. A current member of the Building Moisture and Durability Research Team has expertise in characterizing corrosion parameters of a variety of ferrous metal fasteners. This is an area of research focus for the Team.

The failure of exterior paint on insulated buildings in the 1930's and 1940's led to the development of moisture control theory for buildings. Exterior paint failures can still be observed in cold climates in the United States. They are most prevalent on older buildings, which tend to lack interior vapor retarders and have fairly vapor-permeable sheathings. In contemporary construction, exterior paint failure caused by cold weather moisture accumulation is relatively rare. In contemporary construction seasonal moisture accumulation in strandboard sheathing is typically of greater concern than is failure of exterior finishes. The Building Moisture and Durability Research Team is involved in the issue of limiting seasonal moisture accumulation in exterior building walls in cold climates, but primarily for reasons other than failure of exterior finishes.

The role of moisture in biological infestation is usually considered as more significant than any other role with regard to the performance of wood and wood products. In the case of mold, biological infestation can render the substrate unserviceable without physically destroying it. In the case of carpenter ants, biological infestation will physically damage the substrate, even though the infesting agent does not consume the substrate for nutritional sustenance. In contrast, wood decay fungi and termites destroy wood substrates while consuming them for nutritional sustenance. The Building Moisture and Durability Research Team has expertise in this field, with an emphasis on decay infestation. This is a field of ongoing emphasis within the Team.

Conclusion

The Building Moisture and Durability Research Team at USFPL maintains active research in three of the six general problem areas relating to performance for wood and wood-based products. The number of researchers on the Team has increased over the last five years, as the importance of the Team to the mission of USFPL has gained recognition.

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Modelling durability of wooden structures

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A model of wood decay has been developed that can be incorporated into a hygrothermal model of building physics. This enables the assessment of the effects of the various exposure conditions on the durability and service life of wood. It can also be used for the evaluation of structural choices (e.g., protection from driving rain, coatings, etc.) and other affecting parameters (e.g., geographical location and orientation) on the durability of wooden structures. Here, the wood decay model is used in conjunction with the climatic database ERA-40, which is based on weather observations in Europe. These studies provide new tools to evaluate the durability and service life of wooden parts, and a preliminary European map of wood decay vulnerability is produced. The effects of the projected climate change on wood decay may also be considered by this methodology.

Introduction

The long-term durability of structures typically depends on the effect of excess moisture loads that, in combination with temperature conditions, may cause deterioration of materials and change their performance properties. Long-term, high moisture levels may start biological growth on timber surfaces: first mould or fungi and finally decay. When the durability only comprises the decrease in structural strength, the decay of timber is the main factor to be considered in wooden structures. For decay and serious problems to develop in pine sapwood, the moisture content should stay above RH 95–99% for weeks or months, depending on the temperature (Viitanen 1996). For wood products and other species of wood, the critical factors are different from those for pine sapwood: coatings protect wood against water and high humidity as well as micro-organisms, and the resistance of pine heartwood against decay is high. In cases of water damage, claddings, roofs, floors and lower parts of walls can be exposed to high humidity and attacked by decay and discolouring fungi.

There is always a wide variation in the growth conditions of different fungus species, and we need an overall evaluation of the growth activity and decay development of a "typical" example fungi (mixture of mould/blue-stain fungi) or typical decay fungi (e.g., *Coniophora puteana* or *Gloeophyllum sepiarium*). VTT has conducted comprehensive research into mould and decay growth, and numerical modelling on timber (Viitanen et al. 2003). This paper shows the results on the updated decay model, and an overview of the decay risks of timber structures under different climate zones.

Using the decay model and the climatic exposure, we can obtain information on the hazard zones of Europe. The model is based on pine sapwood, but in future stages, a modification of this model should also be studied for other materials. For other wood products, as well as for coated, treated or modified wood, the critical values may be different. For example, UV light causes the outer surface of the wood to deteriorate, especially when liquid water is present. The greyish colour of the wood surface and aging of coated wood is caused by the go-action of water, UV light and microorganisms (mould and blue-stain fungi).

Results and discussion

Updated decay model

The present model has been developed from the work presented in the references Viitanen and Ritschkoff (1991), Viitanen (1996) and Viitanen (1997). In these references, the decay growth of brown rot in spruce and pine sapwood is studied experimentally in different, constant relative humidity and temperature conditions. In the present model, only the data of pine sapwood are considered. Based on the experimental findings presented in the references, a model for variable conditions is proposed. This model is a time-stepping scheme. The development of decay is modelled with two consecutive processes:

a) Activation process:

This is termed the parameter, which is initially 0 and gradually grows depending on the air conditions to a limit value of 1. This process is able to recover in favourable conditions (dry air) at a given rate (although no experimental evidence of recovery is available).

b) Mass loss process:

This occurs when the activation process has developed fully (α=1) otherwise it does not occur. This process is naturally irrecoverable.

These processes only occur when the temperature is 0–30°C and the relative humidity is 95% or above. Outside these condition bounds, the activation process may recover, but the mass loss process simply stops. The activation process is as given in Equation 2. The recovery time (i.e., α recovers from a value of 1 back to 0) is assumed to be 17520 hours (2 years). Recovery takes place when the conditions are outside the bounds of the decay growth.

$$\begin{aligned}
&\text{Activation process } \alpha=0..1\\
&\alpha(t)=\int_0^t d\alpha=\sum_0^t(\Delta\alpha) \text{ ,where}\\
&\Delta\alpha=\frac{\Delta t}{t_{crit}(RH,T)} \text{ or (in favorable conditions of decay)}\\
&\Delta\alpha=-\frac{\Delta t}{17520} \text{ (in unfavorable conditions of decay)}\\
&t_{crit}(RH,T)=\left[\frac{2.3T+0.035RH-0.024T\times RH}{-42.0+0.14T+0.45RH}\right]\times 30\times 24 \quad [hours]
\end{aligned} \tag{1}$$

The mass loss process proceeds the activation process, when α has reached 1 (Eq. 2).

$$\begin{aligned}
&\text{Mass loss process when } \alpha\geq 1\\
&ML(t')=\int_{t\ at\ \alpha=1}^{t'}\frac{ML(RH,T)}{dt}dt=\sum_{t\ at\ \alpha=1}^{t'}\left(\frac{ML(RH,T)}{dt}\times\Delta t\right)\\
&\frac{ML(RH,T)}{dt}=-5.96\times 10^{-2}+1.96\times 10^{-4}T+6.25\times 10^{-4}RH \ [\%/hour]
\end{aligned} \tag{2}$$

Using the model to evaluate the decay risk

The measured weather conditions in the Helsinki area – temperature and relative humidity – are given. This climate, in hourly values for a one-year period (Fig. 1), is used consecutively for several years.

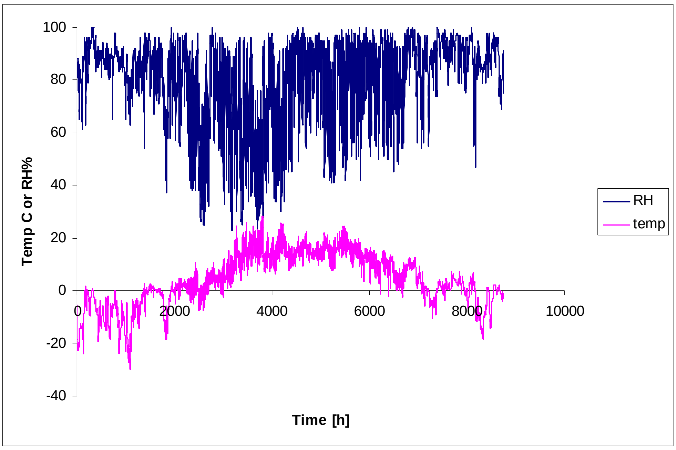

Figure 1. Measured climate (Helsinki) used in the decay model for one year.

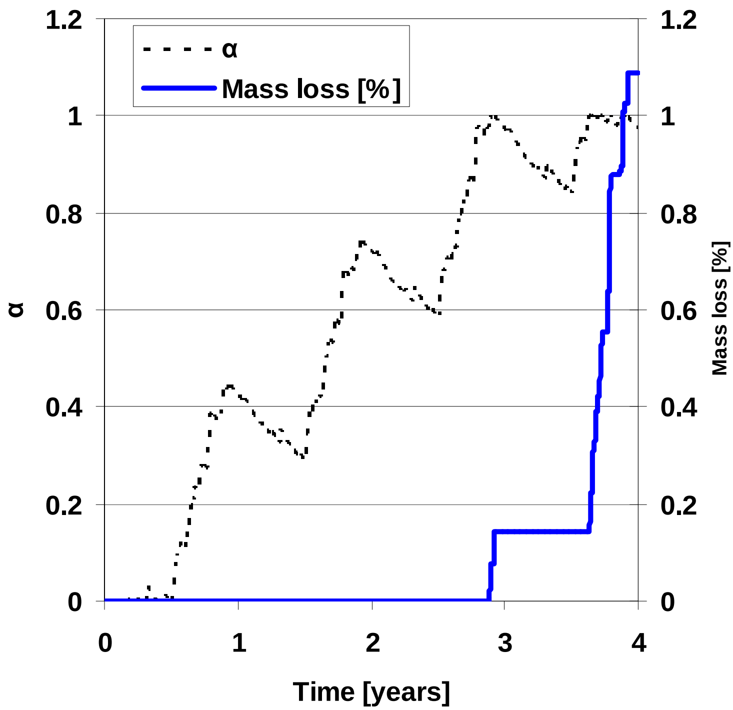

Figure 2. Activation of decay. No decay during the first two years. A slight activation of decay will be expected in the outer surface of pine sapwood after three years in the calculated exposure conditions.

Evaluating a different area of Europe for decay risk

The empirical wood decay model was run using the ERA-40 data for air temperature, humidity and precipitation at 6-hour intervals. ERA-40 is a massive data archive produced by the European Centre of Medium-Range Weather Forecasts (ECMWF). The reanalysis involves a comprehensive use of a wide range of observational systems including, of course, the basic synoptic surface weather measurements. The ERA-40 domain covers all of Europe and has a grid spacing of approximately 270 km. The nature of the data and the reanalysis methods of ERA-40 are described in detail in Uppala et al. (2005).

The resulting modelled mass loss in 1961–1970 at the calculation points of the ERA-40 grid was analyzed by chart production software, which produced a map of wood decay in Europe (Figure 3). A modification to the weather data was made so that the humidity of the air was set to 100% during precipitation (at non-freezing temperatures).

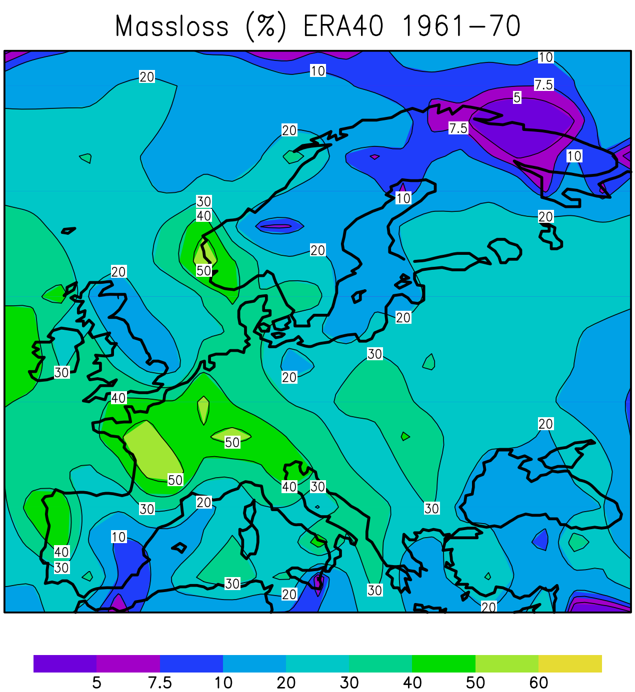

Figure 3. Modelled mass loss (in %) of small pieces of pinewood exposed to rain for 10 years in Europe.

The evaluation of decay development in the model is based on the mass loss caused by the decay fungus. Within specified limitations, the mass loss is an applicable variable for evaluating the decay development in wood. The decay development model will give a general assumption of the effect of humidity, temperature and exposure time on the start and progress of the decay.

Conclusions

The modelled results are at present only preliminary indicators. Tentatively, the modelled wood decay rate perhaps appears too high, suggesting that the α-parameter in the decay model may need to be modified. A further development would be to bring the European map of decay development together with the observed decay in different locations. The developed model is a tool for risk assessment. Uncertainties of the model also have to be evaluated.

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An “Industrialized” methodology for material characterization: Moving away from P/A

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Introduction

My presentation aims to report on how computational technologies, computational modeling, and mechatronic technologies have evolved, especially in recent years, in order to facilitate “Industrialized,” data-driven constitutive characterization of materials subjected to complex loads. The desire to be able to predict the behavior of physical systems under complex generalized loading conditions is primarily driven by the need to design and utilize such systems in various areas of human technological endeavors. The means of predicting the behavior of physical systems since Robert Hooke has been generally encapsulated by an approach that seeks to develop a system model within the context of continuum mechanics using hypothesized constitutive models. While these hypothesized constitutive models are based upon theorized laws of physics, observer invariance for example, they are not always successful in accurately reproducing actual (experimentally established) behavior of existing systems. A data-driven approach forgoes hypothesizing material behavior by relying on a database of sampled behavior.

Rationale

The rationale to develop an “Industrialized” (data-driven methodology in conjunction with an automated mechatronic system) is to provide more reliable and cheaper materials and structural systems faster than the current process for material and structural system certification. A major area where researchers might look for improving the ability to produce more reliable and cheaper materials and structural systems is the enormous potential of the computational technology and other associated (data acquisition for example) technologies. The need and ability to test and analyze complex materials and structural systems are simultaneously being pushed and pulled. The contemporary demands for cost and time reduction, multi-mission design requirements, and increased systemic complexity constitute the technology-push motivators for automation of material characterization. In particular, systemic complexity, resulting from the need for realistic systems predictive simulation, often requires computationally intensive mathematical models. On the other hand, the desire for engineering elegance using simple "unified theories" and need for efficient solutions that solve problems on a societal scale and the evolution of computational and data acquisition technologies are the primary science pull motivators for automating the material characterization process.

Overview

My presentation begins with a brief historical overview of Leonardo da Vinci's first attempt at material characterization Figure 1; pointing out that material characterization has not changed in principle since then. The subsequent section introduces a theoretical view of the general structural and material system with an emphasis on the black box input output relation and its differential equation system specification to set the framework for the data-driven material characterization approach. I also show how this computational modeling works in conjunction with the automated mechatronic test systems. In the sections that follow, I provide two successful examples of data-driven material characterization on wood-plastic composites and structural insulated panels which demonstrate the validity and robustness of the data-driven methodologies. For details and comparison to hypothesized constitutive models see Lockyear[1] and Alwin.[2] The last section describes ongoing collaborative research between myself at the

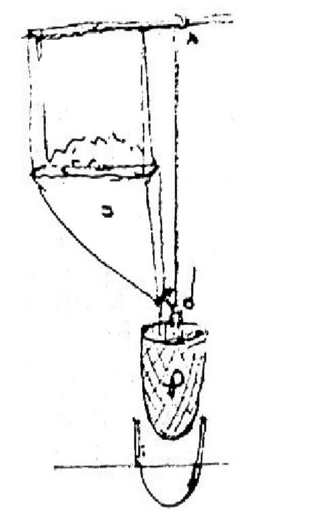

Figure 1. Leonardo da Vinci's first test machine for determining the strength of wire

Forest Products Laboratory and John G. Michopoulos and Athanasios Iliopoulos at the Naval Research Laboratory to develop a mechatronic system for automated material characterization. We have incorporated a Stewart platform to create a six degree of freedom test machine (Figure 2) and the corresponding data acquisition and data-driven modeling. In this work we are using inverse methodologies to develop a fully defined multi-axial constitutive characterization which accurately reproduce behavior of existing systems.

Figure 2. An instantiation at the Forest Products Laboratory of a mechatronic system capable of 6 degree of freedom motion (3 translations and 3 rotations) to test structural materials and systems.

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Research management session

Chair: Anne Ritschkoff, Prof., Vice President
VTT

Pooling together to meet wood composite sustainability requirements

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We are entering a new period in which resources and knowledge need to be combined in new ways to improve control over natural resource use. This offers new potential for the sustainable creation of wealth and well-being globally and nationally, and nations with high forest resources can make a marked contribution to this process. In order for this happen, changes in policy-making, socio-economic behaviour and business models are essential. Sustainable values and concerns about oil dependency are not only political issues, but clearly an increasing megatrend among consumers and brand-owners alike.

National policy in Finland

As a country rich in expertise and relatively abundant in natural resources, Finland has particular strengths and interests in the promotion of sustainable and innovative use of natural resources. The wealth potential offered by our natural resources obliges us to use them intelligently. The Natural Resource Strategy for Finland was drawn up in broad collaboration with policy makers, the government, business and research organizations, and the media. Representatives from different natural resource sectors played a key role in the strategy development work (Sitra 2009).

The Ministry of Agriculture and Forestry coordinates the programme implementation with the help of the Forest Council and its Secretariat and Working Groups. In March 2008, the Government made a decision in principle on the new National Forest Programme, extending it until 2015 together with the Forest Biodiversity Programme for Southern Finland (METSO) 2008–2016. The National Forest Programme policy (Finnish National Forest Programme 2010) aims to secure forest-based employment and livelihoods, forest biodiversity and vitality, and commercial opportunities prepared as an open process between all stakeholders in forest issues.

With Finland's domestic wood consumption currently standing at nearly 60 million cubic metres, the importance of securing future resources and operating conditions for the forest sector is clear. The Finnish forest industry (2010) has recognised the needs for change. In Europe, a common 2030 vision for the forest-based sector has been drawn up by leading stakeholders, and the Forest-Based Sector Technology Platform has defined its strategic research agenda. The objectives are to increase competitiveness and to ensure economic growth while protecting the environment. Innovative products and new markets together with smart applications derived from societal needs are the cornerstones for value creation.

Improved eco-efficiency is a vital prerequisite for development. There is a clear need for new products and technologies that consume less energy, wood and water, that have a lower environmental footprint, and that increase product value. There is a need to transform the forest-based sector to become less resource-based and more expertise-based. In addition, new business concepts must be developed.

The Finnish industrial research and development environment

Forestcluster Ltd is responsible for the operation of the cluster's Strategic Centre for Science, Technology and Innovation. Its task is to initiate research and innovation programmes and to channel research funds to selected focus areas. The goal of the Strategic Centre for the forest sector – led by Forestcluster Ltd – is to become the strongest innovation environment in the industry globally.

Finland's leading wood products corporations – Ekovilla, Metsäliitto Group, Ruukki Group, Stora Enso Timber, Tikkurila and UPM – have established a broad-based research organisation, Finnish Wood Research Ltd, to boost the renewal of the industry (Mikkola 2009). The common research strategy published by the wood products industry in autumn 2008 will serve as a foundation for Finnish Wood Research Ltd's efforts to establish a broader basis of innovative competence that will support the renewal of the wood products cluster and provide support for the generation of new, robust business activities for the industry in Finland (Janatuinen 2003). The organisation is actively seeking new partners both from within the industry and from actors closely associated with the wood products industry.

The wood products cluster has defined the following areas as the focal points of its shared innovation activities and as potential sources of new development opportunities:

1. The environmental performance of wood
2. Wood construction and the energy-efficiency of building
3. The opportunities of bioenergy and bio-based chemicals
4. Business innovations, new products and services
5. Production technologies of the future
6. Research in support of standardisation.

In addition to its domestic research activities, Finnish Wood Research Ltd will pool Finland's shared resources and bring together different views, promoting their realisation through international research cooperation. International cooperation partners include, for example, the European Confederation of Woodworking Industries CEI-Bois, the Forest-Based Sector Technology Platform, and the Building with Wood cooperation programme.

The aim of international cooperation is to boost the position of the Finnish wood products cluster as a pioneer in its field, and to promote the utilisation of wood products. International cooperation in standardisation research will hopefully lead to more widespread bulk production of wooden building components, as well as to improved specialisation and further processing opportunities.

Biorefinery concept

In recent years, Europe has witnessed the transition of pioneering biorefinery concepts from the drawing board to reality. In addition to the many new bioenergy plants already in operation, the most significant of these new concepts is the currently booming production of 1st generation transport biofuels (i.e. bioethanol and bio-components for diesel engines). Multi-product biorefinery concepts have also been gaining ground, such as the high-volume production of by-products such as ethanol and lignosulphonates by sulphite pulp mills. A multitude of by-products is also produced in combination with soy and sugar beet processing. There is, however, potential for much more.

Natural fiber reinforced composites are making inroads in a variety of applications. Combination of wood and other natural fibers with polymers and plastics processing technologies offers exciting new market opportunities for biocomposites as well as wood plastic composites (WPC) based on agrofibers.

In Europe, the majority of naturally-reinforced plastic composite applications are related to the building and automotive sectors. In the market overview, packaging is not mentioned so it is clear that packaging is currently not a leading sector for naturally-reinforced plastic composites. However, the global market volume for foodservice disposable packaging was $ 30 billion in 2006, and is expected to have a compound annual growth rate of around 24 %. If we assume that 30 % of this material will be replaced by WPCs, then by 2014 the potential for WPCs in foodservice disposable packaging will be $ 40 billion worldwide.

Carbon will be sequestered in wood products during the coming decades in Finland. The overall estimate for Finnish wood product based carbon reservoirs in 2004 was 26.6 million carbon tonnes. Projected scenarios indicate that, in the Finnish building construction sector alone, wood product based carbon reservoirs will account for 39.6–64.2 million tonnes of sequestered carbon by the year 2050. When a logistic decay pattern is used, at a price level of EUR 15/CO_2 tonne, the discounted value of the predicted carbon sink of wood products in Finland is between EUR 850 million and EUR 1380 million (Laturi et al. 2008).

VTT activity in naturally reinforced materials

VTT has more than a decade of R&D experience in EC, national and contract research projects concerning the development of WPC and biocomposites for various end–user applications. Biocomposites research at VTT includes material combinations of wood (e.g. sawdust, cellulose) and fibers such as flax and hemp with bio- (and oil based) polymers, as well as different processing technologies. VTT has developed, in cooperation with Conenor, a processing technology for WPC composites with a wood content of up to 80 w-%.

Coarse materials can be processed without downsizing, wet materials without pre-drying and pre-compounding. Grinding, drying and compounding are performed inline with a single extruder. If waste is used as raw material, the manufacturing cost of an extruded product, including depreciation on capital investment, can be as low as EUR 0.3/kg. Attractive product application opportunities include decking, panel board and profiles for the construction and vehicle industries, sound barrier elements, fencing, poles, pallets, cores and tubes.

Novel concepts of ultra-high consistencies of over 20% may provide even more benefits compared to existing extrusion as a process for producing objects of fixed cross-sectional profile. For example, the BIVIS process allows a 10 to 15% reduction in energy consumption in fiber separation, and a 10 to 30% decrease of chemicals in chemical treatment and pulps.

Current research at VTT is focused on second generation biocomposites of different material combinations including bio-based polymers, additives, coupling agents, nanoparticles and multilayer composites. The analytical and testing capabilities at VTT include a comprehensive set of mechanical, chemical, morphological, biological and construction related methods and equipment offered by the largest contract research organisation in northern Europe.

Wood products

Thermally treated wood products, such as the trademark product ThermoWood (Stora Enso 2010), embody all the valuable properties and attributes of wood, including functionality, cost-effectiveness and eco-friendliness. The first extensive research into the heat-treatment of wood was conducted in the early 1930s in Germany. Further leading research has since been carried out in Europe and the United States, but the most intensive and comprehensive work has been conducted by the Technical Research Centre of Finland (VTT). VTT developed and patented the heat treatment process which Stora Enso Timber uses at its Kotka Mill today.

Biopolymers

Renewable bio-based materials offer viable material options for a wide variety of applications. Biopolymers can be formulated into glues, coatings, pigments and extruded into injection moulded materials. VTT has strong know-how in the modification and functionalising of natural polymers (e.g. starch, cellulose and wood fibers). Our product group contains starch derivatives for tailoring the surface properties of paper; starch-based pigments; water-based and hot-melt glues; injection-moulding materials; dispersion formulations for coatings; adhesives; and coatings and matrix materials for the controlled release of active ingredients.

Tailored fibers

The application of novel enzymes with improved properties in harsh pulp and paper mill conditions has led to commercialised innovations. Fiber functionalisation has proved to be a great opportunity for new innovative products giving properties such as charge, hydrophobicity or conductivity.

Major research project environments

The **Wood Wisdom** programme serves to improve the competitiveness of the forest cluster by strengthening the knowledge base of the cluster and promoting the transfer of knowledge and technology across national borders. The first ERA-NET on wood material science and engineering, **WoodWisdom-Net**, started in 2004 with 12 partners from 5 countries, and later expanded in 2006 by a further 6 new partners (3 countries). The project was initiated as a part of the European Commission's Framework Programme 6 ERA-NET scheme (European Comission Research 2010), which aims to support the cooperation and coordination of research activities carried out at national or regional level. As a result of the scheme, the first **Joint Transnational WoodWisdom-Net Research Programme** (2006-11) was launched, with 17 projects and a total budget of over EUR 20 million. The first phase of the WoodWisdom-Net ERA-NET project came to its end on Dec 21, 2008.

The follow-up ERA-NET project **WoodWisdom-Net 2** – "Networking and Integration of National Programmes in the Area of Wood Material Science and Engineering in the Forest-Based Value Chains" was started in March 2009 (duration 36 months) and is run under the European Commission's FP7 ERA-NET scheme[3]. The consortium currently includes 19 partners from 12 countries and is tasked with further extending the co-ordination and integration of a common European research and funding platform within wood material science and engineering and setting the basis for long-lasting cooperation in the field.

Besides other activities, one of the main goals during 2009–2012 is the launch of two new projects under the WoodWisdom-Net Research Programme: the first of these (2009) is an applied research and industrial development project focussing on wood and fiber-based products; the second (2010) focuses on consortia combining basic and applied research, with a broad scope covering new and innovative production in forest-based value chains and promoting the participation of researchers outside the EU (Wood-Wisdom-Net 2010).

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[3] www.cordis.europe.eu

Tekes – the Finnish Funding Agency for Technology and Innovation is the main public funding organisation for research, development and innovation in Finland. The Tekes BioRefine programme (Tekes 2010) for 2007–2012 will generate new and unique expertise in the processing of biomass and apply it to the creation of processes, products and services related to biorefineries. The programme budget totals EUR 137 million.

The programme aims to develop innovative technologies, products and services based on national strengths related to biorefinery and biomass processing for the international market, and to generate necessary new expertise. A further objective is to promote the development and use of second-generation production technology in biofuels for transport, which is also a major goal set out in Finland's energy policies.

Another key objective is to increase national and international cooperation and networking between sectors and businesses in order to achieve further innovations.

The objective **for Finnish forest cluster research** is to double the value of the forest cluster's products and services by 2030. Half of this value will come from new products. Domestic use of wood will be increased by one-fourth. The cluster's investments in research and development will also be doubled. In 2005, the total value of production in the Finnish forest cluster was approximately EUR 40 billion. The value of exports was about EUR 15 billion, or nearly 30 percent of Finland's total exports. In addition to the forest industries, the cluster includes forestry, engineering and maintenance for the pulp, paper and sawmilling industries, the forest sector chemical industry, wood furniture and wood and fiber packaging, and the graphic publishing and printing industry. Last year, the cluster's R&D investments totalled roughly EUR 350 million.

The focuses of research in the forest cluster are:

- **Intelligent and resource-efficient production technologies**: The goal is to develop radically new production systems that make the best use of resources and are energy-efficient, so as to reduce capital intensiveness and improve the efficiency and flexibility of the cluster as a whole.
- **Future Biorefinery**: The goal is to develop new ways to fractionate wood and thereby, enable the generation of new wood-based value chains.

FPL Research Emphasis on Advanced Composites

The USDA Forest Product Laboratory has long experience in wood composite technologies (e.g. plywood, particleboard, flakeboard, hardboard), which have for decades been used to create value-added commodity building and home furnishing products. More recently, new innovative bio-based composite products based on natural fibers, such as agricultural fibers, oils, or residues, or on wood–natural fiber hybrids have also come on the market. New hybrid products, such as wood- or natural fiber–plastic composites, have recently become popular for decking, siding, roofing, and millwork. Each of these wood- and/or bio-fiber-composite technologies allows user/producers to add considerable value to diverse wood- and bio-fiber feedstocks, including small-diameter timber, fast plantation-grown timber, agricultural fiber and biofiber residues, non-desirable exotic–invasive species, and timber removals required to reduce hazardous forest fuel loadings.

Recent advances within the wood and biocomposites research community have led to the beginnings of a fundamental understanding as to the relationships between materials, process, and composite performance properties. Another major advance in engineered wood and biocomposites is in product and performance enhancement. Advanced engineered biocomposites are currently being developed that will simultaneously meet the diverse needs of users for high-performance and economical commodity products. VTT and USDA have shared interests in bio-composites in the following areas:

- wood and natural biofiber combinations to produce synergistic hybrid materials,
- renewable, recyclable, and wholly sustainable bio-composites,
- hyper-performance and superior serviceability bio-composites,
- durable, dimensionally stable, moisture proof, and fire resistant bio-composites,
- bio-composites with advanced sensory capabilities,
- material and process engineering for customized and optimized performance.

Development of advanced engineered biocomposites will require significant scientific advances. Researchers will need to initiate and follow an integrated and multi-disciplinary approach to advanced biocomposite research. To this end, joint projects between FPL and VTT offer natural synergy benefits and high research and development potential.

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Opportunities for joint FPL and VTT research

Theodore H. Wegner
US Forest Service

Openness, collaboration and sharing of information in developing the basic underlying, precompetitive science and technology for areas of emerging importance to the forest products sectors of the US and Finland are expected to provide synergistic benefits and allow for more creative problem solving. There appear to be a number of common interests with respect to developing the underlying science and technology needed to reinvent and reinvigorate the Finnish and US forest products industry in the 21st Century.

Introduction

Openness and free information sharing through scientific discussion; presentations at scientific symposia conference and workshops; publications in the open literature; and scientific exchanges of researchers amongst laboratories have long been the hallmarks for advancing science and technology. In addition, the disclosure of problem information to a larger and diverse group of researchers is an effective means of solving scientific problems as problem-solving success has been found to be associated with the ability to attract specialized solvers with a range of diverse scientific interests and expertise. Interactive clusters of researchers with diverse specialties have been able to solve problems at the boundary or outside of their fields of expertise, indicating a transfer of knowledge from one field to others. However, global market place competition has intensified among companies, nations and trading blocs of nations. As a result, openness and free information exchange has oftentimes fallen victim to the desire to gain a proprietary advantage – even in emerging areas where the underlying science and technology based upon first principles has not been established.

Such lack of openness and transparency oftentimes means that scientific problem solving is constrained to fewer numbers of scientists working in isolation and who fail to leverage the entire accumulation of scientific knowledge available thus impeding progress.

Government industry-university cooperation in the US

Across all industry sectors in the US, the Federal government and private industry are by far the two largest contributors of research (basic and applied) and development funding. The Federal government provides approximately 28% of all US research and development funding while industry provides 65%. US expenditures with respect to total funding for basic research, applied research and development are 18%, 23% and 57% respectively. The US Federal government focuses its funding most toward fundamental, underlying science and technology in new and emerging higher-risk, high pay-off areas. Industry tends to focus most of its funding toward applications and developments where risks are lower and the path forward is more clearly defined. Industry expends approximately 80% of its funds on development and the Federal government spends approximately 50% of its funds on basic research. Universities conduct over 60% of the basic research while industry carries out about 90% of all development. Federal funding for research primarily goes to universities and federal laboratories. However, Federal government and industry interests oftentimes come together. For example, Federal government public interests are linked to private industry success by such things as the need for job retention and creation, implementing strategies for sustainable use of forest-based materials, offsetting the costs of forest management on public lands, maintaining privately owned forest lands as forests versus conversion to non-forest uses, meeting national goals for biofuels and energy independence, etc. On the other hand, to industry success means being able to maintain profitability, compete in the market place domestically and internationally and to cost effectively produce new and improved goods and services that consumers want. While industry and the Federal government often work together, the reasons each side uses for doing so are usually quite different.

Proposed areas of mutual cooperation

While market place competitiveness is essential to cost effectiveness and efficiency of production of products for consumers, it makes sense to work openly and freely share information in emerging areas where the underlying science and technology has not yet been developed sufficiently to allow for competitive applications. For the USDA Forest Service, Forest Products Laboratory (FPL), such emerging areas where cooperation and openness with VTT are desirable include:

- The forest biorefinery for producing advanced biofuels and other value-added co-products without the need for massive government subsidies
- Nanotechnology involving wood-based materials and nanomaterials derived from wood
- Next generation advanced wood-based composites where hyper-performance is desired
- Advanced wood-based structures that are more energy efficient, environmentally preferable; and functional – as our current wood frame construction concept for housing dates back to the 1830's
- Understanding, isolating and cost effectively using for industrial purposes the components of living cells within trees that transport oxygen, carbon dioxide, and water as well as separate water from waste products and perform other functions.

Reasons and benefits for FPL to work with VTT

Forestry and forest products are important industry sectors in both the US and Finland with both countries being in the top ten producers forest-based materials world-wide. In addition, Finland expends about 3.5% of its GDP on research and development and ranks first among nations with respect to numbers of scientists and engineers per capita. The US is the world's largest producer of forest products but its forest products industry is only ninth with respect to size as compared to other industrial sectors in the US. Several multinational forest products companies operate substantive production facilities both within Finland and the US. Both VTT and FPL are substantively government funded and operated as national laboratories which are tasked with developing new science and technology.

There appear to be a number of common FPL/VTT interests with respect to developing the underlying science and technology to reinvent and reinvigorate each country's forest products industry in the 21st Century. In particular there appears to be a mutual interest in creating the underlying pre-competitive science and technology needed by which commercially important novel and innovative applications for wood and wood-based materials and from which industry in both countries would benefit. By focusing on pre-competitive science and technology the mutual perceived benefits from the FPL perspective are:

- Allowing for higher risk/higher reward research to be undertaken by both institutions
- Creating the underlying science and technology for new and emerging innovations
- Allowing industry within each nation to use the research for competitive purposes
- Side stepping/avoiding issues of intellectual property
- Permitting research findings to be freely shared via open communication and publications
- Achieving critical scientist mass and speeding up research progress
- Reducing cost and unnecessary duplication of effort
- Helping create the forest products industry of the 21st Century within each country
- Allowing for future expanded partnerships with others within and external to Finland and the US

Mutually identifying underlying science needs

For each area of cooperation, precompetitive science needs – mutually acceptable to both FPL and VTT – would need to be developed. For example in nanotechnology related to wood and wood-based materials, the following have been identified by FPL as potential precompetitive science and technology needs:

- Determining the range of nanomaterials obtainable from wood (cellulose nanocrystals and nanofibrillar cellulose)

- Developing energy-efficient liberation and fractionation of cellulose nanocrystals and nanofibrillar cellulose from wood
- Achieving reproducible and artifact-free characterization of nanomaterials from wood
- Functionalization and chemical modification of surfaces of cellulosic nanomaterials
- Determining the photonic effects achievable from wood-derived nanomaterials for light scattering, light absorption, light transmission, wavelength shifting, etc.
- Developing processes for preparing, stabilizing, and utilizing wood-based nanomaterials in manufacture of composites
- Developing biomimicry – using nanomaterials for ultra high strength and particular effects by imitating natural structures
- Developing nanomaterials that react to ambient stimuli optically, electronically, or mechanically
- Developing protocols and methodologies for imaging and holography with wood-derived nanoparticles
- Developing standard nomenclature for wood-derived nanomaterials and getting this adopted with ISO.

As mentioned above, for each area of cooperation, priority activities would need to be mutually developed.

Conclusions

FPL and VTT have a number of mutual research interests and common objectives as government funded national laboratories. To move the US and Finnish forest products industries forward, we need to create the new science and technology needed to move into new product areas and enable creation of new and improved valued-added products, co-products and materials. With fewer professional staff available within companies, research on new technologies and innovative materials is falling more and more to not only industry suppliers but also governmental laboratories and academic research institutions. Instead of being at odds with one another over trade and other issues and with the concurrence of their respective industry groups and partners, the US and Finland would be best served by taking advantage of cooperative working relationships and commonalities with each other's economic systems that has been developed over many decades.

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11:00–11:20	Opportunities for Advanced Bio-based Fiber Products ***Zhiyong Cai**, USFS Forest Products Laboratory*	VOC in Wood Interior ***Helena Järnström**, VTT*
11:20–11:40	Composites from Wood and Thermoplastics ***Zhiyong Cai**, USFS Forest Products Laboratory*	Critical Conditions for Mould and Decay Resistance of Wood ***Hannu Viitanen**, VTT*
11:40–12:20	Luncheon [Canteen, Vuorimiehentie 5]	
	FIBER PRODUCT SESSION Vuorimiehentie 5, auditorium **Fiber Processing** – Session Chair: ***Niklas von Weymarn**, VTT*	**WOOD PRODUCT SESSION** Vuorimiehentie 5, 1227 **Wood Durability** – Session Chair: ***HannuViitanen**, VTT*
12:20–12:40	Nano-cellulose Challenge ***Mika Härkönen**, VTT*	Wood Protection Systems ***Carol Clausen,** USFS Forest Products Laboratory*
12:40–13:00	Enzymatically Modified Wood Fiber ***Eero Hurme**, VTT*	Accelerated Tests of Building Materials ***Carol Clausen**, USFS Forest Products Laboratory*
13:00–13:20	Fiber-based biocomposites ***Kirsi Immonen***, VTT	Characterization of Moisture Loads ***Samuel Glass**,USFS Forest Products Laboratory*
13:20–13:40	Improved Nanoindentation and NMR Methods for Analyzing Wood and Wood Products ***Charles Frihart**, USFS Forest Products Laboratory*	Moisture Durability of Wood Products ***Samuel Glass**, USFS Forest Products Laboratory*
13:40–14:00	New Technology for Wood Adhesives and Coatings ***Charles Frihart**, USFS Forest Products Laboratory*	Modeling of Wood Durability and Service Life ***Tomi Toratti**, VTT*
14:00–14:20	Mechanical Fiber Processing ***Kari Edelmann**, VTT*	Mechanical Material Characterization ***John Hermanson**, USFS Forest Products Laboratory (recorded)*

14:20–14:40	Break/Refreshments, Vuorimiehentie 5
	RESEARCH MANAGEMENT WORKSHOP Vuorimiehentie 5, auditorium Session Chair: ***Anne Richsckoff***, *VTT*
14:40–15:00	Strategic objectives in VTT forest sector research ***Anne Ritschkoff***, *VTT*
15:00–15:20	Joint Research of Biobased Composites ***Ali Harlin***, *VTT*
15:20–15:40	Joint Research Programs USA and Finland ***Ted Wegner***, *USFS Forest Products Laboratory*
15:40–16:00	Fiber Processes ***Janne Poranen***, *VTT*
16:00–17:00	Reception, Vuorimiehentie 5
18:00–20:00	Dinner

Wednesday, September 23 ***Ted Wegner, Carol Clausen, Samuel Glass, Zhiyong Cai, Charles Frihart*** *USFS Forest Products Laboratory*	
09:00–11:40	**Re-inventing paper**, Tour at laboratories and discussions, Tekniikantie 2 (KCL, meeting room ISO3) Host: Sanna Tuominen, Raimo Pollari and Eva Sandås
11:15–12:00	Lunch, Tekniikantie 2
12:00–15:00	**Functional paper products**, Tour at laboratories and discussions (BIC7, meeting room ISO) Host: Tomi Erho
16:00–18:00	**Reception at US Embassy**

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VTT and USDA Joint Activity

Abstract
The *2009 Wood and Fiber Product Seminar* was held on 22–23 September at VTT in Finland. The seminar was organized by VTT's Industrial Biomaterials spearhead programme together with the United States Department of Agriculture (USDA). Experts from VTT, Forest Product Service-laboratory belonging in USDA and Forestcluster Ltd participated in the event. The aim of the seminar was to present the current research activities of VTT and USDA in the field of wood- and fiber-based materials, and to evaluate possible joint research cooperation between the two organizations. This publication presents a collection of papers representing the following focus areas of wood- and fiber-based product research: consumer products, passive building, fiber processing, and wood durability.

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