NANOTECHNOLOGY OPPORTUNITIES IN RESIDENTIAL AND NON-RESIDENTIAL CONSTRUCTION

Theodore H. Wegner, Jerrold E. Winandy and Michael A. Ritter
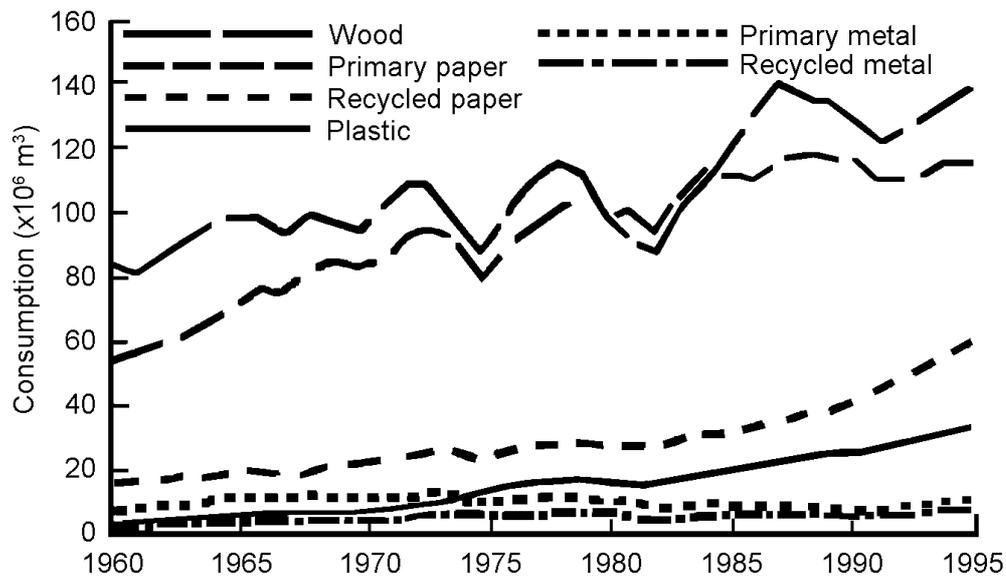
USDA Forest Service, Forest Products Laboratory, USA

Abstract

Over 1.9×10^6 housing units are constructed in the United States in 2004. On a volume basis, wood products comprise almost 80% of all materials used in residential housing. It is estimated that over 7×10^9 m^3 of lumber have gone into structures in the United States over the last century. Half of the wood products now used in construction are engineered wood composites. Employing nanotechnology within the forest products industry could result in previously undreamed of growth opportunities for bio-based products. Nanotechnology will result in a unique next generation of wood-based products that have hyper-performance and superior serviceability when used in severe environments. They will have strength properties now only seen with carbon-based composites materials, and they will be both durable while in service and biodegradable after their useable service-life. Other potential benefits will be improved traditional wood- and bio-composite products similar to those now used in construction, but with significantly improved performance or economy. Nanotechnology will also promote the development of intelligent wood- and biocomposite products with an array of nanosensors built in. Building functionality onto lignocellulosic surfaces at the nanoscale could open new opportunities for such things as self-sterilizing surfaces, internal self-repair, and electronic lignocellulosic devices. The high strength of nanofibrillar cellulose together with its potential economic advantages will offer the opportunity to make lighter weight, strong materials with greater durability.

Key Words

Construction, nanotechnology, wood, biocomposites

1. INTRODUCTION

Large forest resources combined with prudent forest management and a good system of roadways and railways has allowed the United States to develop and maintain the world's largest forest products industry. As shown in Figure 1, the United States is the largest producer of industrial roundwood—wood used to produce forest products [1]. At the current rate of timber consumption (400 $\times 10^6$ m^3 per year), the United States is still far short of depleting the almost 31×10^9 m^3 of standing timber in America's forests, which currently grow at a rate of over 850×10^6 m^3 per year. With this quantity of resources available, not only could more wood be obtained from United States forestlands without detriment to the environment, but a variety of positive environmental benefits are also possible.

Figure 1. Industrial Production of Roundwood, Showing the United States as the World's Largest Producer.

On a volume basis, wood is the most-used material in the United States (Figure 2) [2]. Wood is used extensively in housing in the United States. Over 1.9×10^6 housing units were constructed in the United States in 2004 [3]. Wood-frame construction is used in almost 90% of these residential structures for a variety of reasons including cost, ease of fabrication, and the ability to produce a variety of architectural designs. On a volume basis, wood products comprise almost 80% of all materials used in residential housing in America. It is estimated that over 7×10^9 m^3 of lumber was used in structures in the United States over the last century. Half of the wood products now used in housing are engineered wood composites annually comprising over 50×10^6 m^3 of lumber, 1.85×10^9 square meters of panel products, and 195×10^6 lineal meters of I-joists.

Figure 2. The Volume of Materials Consumption in the United States.

However—as in all markets—technology and shifting demographics give rise to changing market demands. Materials and products used in housing construction are not immune to such changes. Because a home or a commercial building is typically the largest purchase a family will make and one of the larger investments a corporation will make, consumers want structures that maintain their value over time and are safe and secure, healthy, comfortable, long-lasting (durable), low maintenance, affordable (lower in cost and providing more value for the dollar), easily adaptable to new and modified architectural designs, and allow for personalized customization, have smart system capabilities, and reduce costs for heating and air conditioning. However, being the material of choice today doesn't ensure that wood will be the construction material of choice in the future. While undergoing many improvements, the basic North American wood frame home construction concept is approaching 200 years old. Further, wood has never achieved a significant position in non-residential construction because of perceived issues related to strength, durability, and fire safety. Thus, significant future opportunities exist for making major improvements to residential and non-residential construction. We believe these changes will occur because residential construction has largely been developed without a systems approach to building envelope construction and because of a growing shortage of skilled labor in residential and non-residential construction. Manifestations of change are being seen already. Wood and wood-based materials are facing increased competition from alternative non-wood materials such as concrete, glass, polyvinyl chloride (PVC), aluminum, and steel as well as composites of various materials. This competition with other materials has been a major driver behind recent developments in wood-based- and wood-plastic-composites.

In addition, governmental concerns for assuring resource sustainability, promoting green technologies, enhancing fire resistance, mitigating effects from natural disaster (e.g., floods, hurricanes, tornados), and other social concerns related to housing and population

demographics also come into consideration. These concerns are often demonstrated in building codes, governmental policies, and research-sponsorship. For example, each year building fires in the United States result in over 3,000 deaths and cause more than $12 billion (USD) in property damage. Losses to natural disasters such as floods, earthquakes, hurricanes, and tornadoes cause loss of life and tens of billions of dollars in property damage each year. Likewise, some wood and wood-based materials already in service must be replaced because of equally costly events such as rot, decay, termites and other insect infestations. These replacements account for approximately 10% of the wood products produced annually. Improving the durability and serviceability of wood will reduce material demand, thereby allowing forests to be managed for other amenities such as watershed flows, recreation, and animal habitat. Nanotechnology represents a major opportunity for the forest products industry to develop new products, substantially reduce processing costs, and open new markets.

2. MATERIALS FOR ADVANCED BUILDING CONSTRUCTION

The U.S. Department of Energy has developed a 20-year plan for advancing building construction by convening representatives of the construction industry, product manufacturers, industry associations, building code officials, design professionals, and academics [4]. The 20-year plan identifies strategies for achieving building envelopes that meet consumer demands (e.g., lower cost, more adaptable, lower maintenance, smarter) while reducing effects on the environment (e.g., energy, air, water, and waste).

Major material needs identified were as follows: (1) Cellular building materials; (2) Disaster resistant materials; (3) Intelligent materials (e.g., self-repairing and adjusting); (4) Superior moisture barrier properties; (5) Non-toxic materials; (6) Resource-efficient materials; (7) Superior insulating ability; (8) Superior weathering resistance and low maintenance; (9) Smart materials with sensors that can detect loads, temperatures, decay, fire, etc., and (10) Sustainably produced and recyclable materials.

Major systems and design needs identified for construction were as follows:
(1) Advanced panel/prefabrication/framing systems; (2) Intelligent building envelope systems; (3) Multi-functional building component systems (e.g., energy-supply heating, cooling, electricity); (4) Building envelope component integration; (5) Rooms that convert easily from one use to another (e.g., bedroom to office); (6) Modular components that allow for movable walls; (7) Systems that easily "grow" as the demographics of the inhabitants change; and (8) Systems and components that are adaptable to future innovative technologies.

3. NANOTECHNOLOGY AND WOOD AS A BUILDING MATERIAL

Technology is the major driving factor for growth at every level of the world's economy. The ability to measure, model, and manipulate matter on the nanoscale is leading to new technologies that will impact virtually every sector of our economy and our daily lives. Nanotechnology is fundamentally changing the way materials are produced in the future. The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then assemble them into larger structures with unique properties and functions will revolutionize the materials-producing industries—especially the forest products industry. Nanotechnology provides the ability to control materials. Determining and altering how materials and their interfaces are constructed at nano- and atomic scales will provide the

opportunity to develop new materials and products. Because of this ability, nanotechnology represents a major opportunity for wood and wood-based materials to improve their performance and functionality, develop new generations of products, and open new market segments in the coming decades.

A nanotechnology roadmap was recently developed by the United States forest products industry sector by bringing international experts together with experts from industry, academia, and government [5]. The roadmap identifies the major areas, needs, and opportunities for nanotechnology in the forest products sector. Attributes of wood that made it a unique and intriguing material for nanotechnology include the following: (1) Wood is one of the most abundant and ubiquitous biological raw materials; (2) Wood has a nanofibrilar cellular architecture based on cellulose nanofibers. (3) Wood is self-assembled through controlled and repeatable biocontrolled synthesis processes from the nanoscale level to the macroscale level; (4) Lignocellulose as a nanomaterial and its interactions with other nanomaterials is largely unexplored; (5) Wood has the capacity to be made multifunctional; and (6) Wood is a cornerstone for advancing the biomass-based renewable and sustainable economy. In addition, wood-based materials can be readily recycled and reused.

Employing nanotechnology with wood and wood-based materials could result in previously undreamed of growth opportunities for bio-based products. Nanotechnology will result in a unique next generation of bio-products that have hyper-performance and superior serviceability. These products will have strength properties now only seen with carbon-based composites materials. These new hyper-performance bioproducts will be capable of longer service lives in severe moisture environments. Enhancements to existing uses will include development of resin-free biocomposites or wood-plastic composites having enhanced strength and serviceability because of nanoenhanced and nanomanipulated fiber-to-fiber and fiber-to-plastic bonding. Nanotechnology will allow the development of intelligent wood- and biocomposite products with an array of nanosensors to measure forces, loads, moisture levels, temperature, pressure, and chemical emissions. Nanotechnology can also be developed to detect and warn us of attack by wood-destroying fungi and termites. Building multi-functionality onto lignocellulosic surfaces at the nanoscale could open new opportunities for such things as self-sterilizing surfaces, electricity generation, and electronic lignocellulosic devices. The high strength of nanofibrillar cellulose offers the opportunity to make lighter, stronger materials with greater durability. These new materials will have great effects on the use of wood in all phases of construction by helping wood and wood-based materials to overcome current shortcomings.

4.   NANOCOMPOSITE MATERIALS

The definition of nanocomposite materials has significantly broadened in the last few years. This term now encompasses a large variety of systems combining one-, two-, and three-dimensional materials with amorphous materials mixed at the nanometer scale. Recently, it has come to include bio-based nanocomposites. Whereas the general class of inorganic nanocomposites has enjoyed much discussion and is still a fast-growing area of research, exciting new research on bio-based nanocomposites may have even greater potential because the bio-resource can be both sustainable and genetically manipulated.

Significant effort is focused on the ability to obtain control of the nanoscale structures via innovative synthetic approaches. The properties of nanocomposite materials depend not only

on the properties of their individual parents, but also on their morphology and interfacial characteristics. This rapidly expanding field is generating many exciting new inorganic, bio-based and hybrid materials with novel properties. These property enhancements derive by hybridizing properties from the parent constituents into a single material. There is also the possibility of new properties unknown in the parent constituent materials. For example, some recent work has shown that most types and classes of nanocomposite materials lead to new and improved properties when compared to their macrocomposite counterparts. Therefore, nanocomposites promise new applications in many fields, but especially in construction, with the potential for producing mechanically reinforced lightweight components and entire systems.

Lamellar nanocomposites can be divided into two distinct classes, intercalated and exfoliated. In intercalated nanocomposites, the polymer chains alternate with the inorganic layers in a fixed compositional ratio and have defined number(s) of polymer layers in the intralamellar space. In exfoliated nanocomposites, the number of polymer chains between the layers is almost continuously variable and the layers stand >100 Å apart. Our work includes work on both the lamellar classes of intercalated and exfoliated organic–inorganic nanocomposites, but focuses on systems that exhibit the potential to enhance construction technology. This work is now in its infancy, and we propose to carry out extensive investigations.

5.   OPPORTUNITIES FOR NANOTECHNOLOGY IN WOOD-BASED BUILDING MATERIALS

Two basic strategies incorporate nanotechnology into wood and wood-based materials. The first uses nanomaterials and nanosensors developed by efforts in other industry sectors and adapts them to the current array of forest products used in construction. The expected gains will be to improve existing product performance through minor to moderate modifications and additions. Products would range from lumber, sheathing, and siding with barrier coatings for water resistance to high-performance composites of wood, wood fiber, and other materials including plastics, metals, glass, and cement. The second strategy is to exploit the nanoscale properties of wood to develop completely new construction materials and product platforms. Exploiting and using improved knowledge of nanoscale structures and properties of the wood will lead to materials and products that are economical, light weight, multifunctional, biobased, and capable of competing with steel, concrete, and other high performance materials. Wood is composed of cellulose nanofibrils that have approximately 25% the strength of carbon nanotubes. If these cellulose nanofibrils could be mined (i.e., extracted) from sustainable woody biomass at 10 to 100 times less cost than manufacturing carbon nanotubes, then such a development would certainly shift many of the existing paradigms in construction.

Wood-based construction materials function extremely well under a variety of end-use conditions. Under wet conditions, however, they can be prone to decay, mold, mildew, and insect attack. Wood can be protected from biodeterioration by treatments using toxic chemicals or by maintaining low moisture content in wood. Achieving control of moisture is a major opportunity for nanotechnology to aid in preventing biodeterioration of wood and wood-based materials. New non- or low-toxicity nanomaterials such as nanodimensional zinc oxide, silver, titanium dioxide, and even possibly clays might be used as either preservative

treatments or moisture barriers. In addition, resistance to fire might be enhanced by use of nanodimensional materials like titanium dioxide and clays.

Nanodimensional barriers could impart long-term weathering resistance, provide ultraviolet light (UV) protection, and provide aesthetically pleasing finishes that will last decades in exterior applications. They might also be used as barrier films and coatings (e.g., paints, stains, and other finishes) to provide improved dimensional stability, UV protection, and weathering resistance for wood-based materials used in exterior applications such as windows, doors, and siding. Such barrier films and coating could be applied to engineered biocomposites in the manufacturing process or they could be applied in the field. Either way, the result could be wood-based materials that do not need refinishing for decades. Development of nanobased films and coatings represents a reasonable near-term application. More theoretical concepts would include developing nanocomposites that exclude liquid water or rain but breathe to allow controlled moisture–vapor movement. Such coatings and treatments would help mitigate the damage caused to wood-based materials from flooding or faults in design or construction that unintentionally allow water to enter the building envelope.

Producing new generations of structural and nonstructural multifunctional composite materials and products for construction is an extremely promising area. Composites allow an array of disparate materials with greatly differing properties to be engineered into products matched to end-user needs and performance requirements. For example, future nanocomposite construction materials may use combinations of wood, wood fiber, plastics, steel, and concrete. To achieve this, it will be necessary to be able to make hydrophilic materials compatible with hydrophobic materials such as wood and plastics. Shorter term applications include using new nanobased adhesives and resins to achieve enhanced composite materials. For example, super insulating capabilities could be built into wood-based panel products used for sheathing or siding applications in residential construction. In the longer term, multifunctionality can be built into composites. Photovoltaic capabilities can be built into composites to allow wood-based composite siding to produce some or all of the electrical needs of a residential structure. Siding, doors, windows, roofs, and decks could become photovoltaics producing heat and electricity to attain a "Zero Energy-Use House." Nanoscale chromophores could be developed that would allow surfaces to change color as desired to suit the decorative tastes of homeowners. We might also produce biomemetic nanocomposites that possess the ability to repair themselves whenever major damage is sustained or after minor events accumulate. If self-repair can be built into nanocomposite materials, the next level of smart materials will have been achieved.

Incorporation of non-obtrusive active or passive nanoscale sensors will provide feedback on product performance and environmental conditions during end-use service by monitoring structural loads, temperatures, moisture content, decay fungi, heat losses or gains, and loss of conditioned air. Such nanoscale sensors will need to be rugged and robust enough to survive product fabrication processing and building envelope construction. We expect that such sensors will become increasingly available and affordable over the coming decades. These sensors would enable production of so-called smart building products that would signal the building residents of structural defects; insect, decay, or animal-pest infestations; moisture problems related to plumbing leaks and building envelope leaks; and conditioned air losses. In addition, as nanoscale sensors and multifunctionality can be built into materials and products,

self-sterilizing surfaces can be developed to guard against biological agents and improve aseptic conditions in homes from pathogens and other contaminants.

Using wood as a source of nanofibrils has the potential to make wood-based building products not only both stronger and lighter weight, but also far less expensive. Wood cellulose nanofibrils have about 25% of the strength of carbon nanotubes, which are expected to be the strongest fibers that can be produced. Their potential cost, however, might be 10 to 100 times less, giving cellulose nanofibrils a unique economic advantage. Finding ways to liberate these cellulose nanofibrils and use them in the production of composite materials will allow for greater resource efficiency, allow for improved building designs and advanced construction techniques (e.g., panels, framing systems, modular components, etc.),and improve the ability of structures to resist wind loading and damage and lessen energy demands.

Ultimately, building component and building systems, "Nanomaterials by Design," will be achieved [6]. "Nanomaterials by Design" refers to the ability to use scientific principles in deliberately creating materials and products that deliver unique functionality and utility for target applications. Nanomaterials in technically useful forms, such as bulk nanostructured materials, dispersions, composites, and spatially resolved, ordered nanostructures will be created. This will allow nearly limitless flexibility for precisely matching material functions to end-use applications. Such a powerful, function-based design capability holds the potential to solve critical, unmet needs in both residential and non-residential construction. Techniques being developed in the areas of self-assembly and directed self-assembly will allow us to use the building blocks available in wood to manufacture materials with radically different performance properties.

6.   CONCLUSIONS

Nanotechnology presents a tool to extend structural performance and serviceability by orders of magnitude. Nanotechnology will allow engineers and scientists to manipulate and systematically eliminate the formation of random defects that now dictate the properties, performance, and serviceability of biocomposites as we know them today. This new ability to minimize and eliminate naturally occurring and human-made internal defects will allow us to realize the true potential of biomaterials. Nanotechnology will help us greatly expand our ability to manipulate and control fiber-to-fiber bonding at a microscopic level, and it will also offer an opportunity to control nanofibrillar bonding at the nanoscale. Nanocomposites will be the new frontier.

The ability to see materials down to nanoscale dimensions and to control how materials are constructed at the nanoscale is providing the opportunity to develop new materials and products in previously unimagined ways. Nanotechnology will result in unique new generations of wood-based construction products that have hyper-performance and superior serviceability in more severe moisture environments. These products will have strength properties now only seen with carbon-based composite materials. Nanotechnology will also promote the development of intelligent wood composite products with an array of nanosensors built in. Building functionality onto wood-based construction product surfaces at the nanoscale could open new opportunities for such things as self-sterilizing surfaces, electricity generation. and self-repair. The high strength of nanofibrillar cellulose together

with its flexibility offers the opportunity to make lighter weight strong construction materials with greater durability.

REFERENCES

[1] United Nations, Food and Agriculture Organizations. State of the World's Forests–2005. (United Nations, 2005)

[2] Matos, G. and Wagner, L. Consumption of materials in the United States 1900–1995. Annu. Rev. of Energy Environ. **23** (1998) 107–122

[3] U.S. Census Bureau News Joint Release U.S. Department of Housing and Urban Development. http://www.census.gov/indicator/www/newresconst.pdf. Accessed July 12, 2005.

[4] U.S. Department of Energy. Office of Building Technology. Building Envelope Technology Roadmap (2001) p.32.

[5] Jones, P.; Wegner T.; et al. In: Nanotechnology for the Forest Products Industry—Vision and Technology Roadmap, based on the results of the Nanotechnology for the Forest Products Industry Workshop, Landsdowne, Virginia, October 17–19, 2004. Atlanta: Tappi Press (2005). p.92.

[6] Chemical Vision 2020 Technology Partnership. http://www.chemicalvision2020.org/nanotechnology.html. Accessed July 12, 2005.