Protection of Wood: A Global Perspective on the Future

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Abstract The current state of wood protection is briefly reviewed, and then the issues that are currently affecting preservative treatments are summarized. The strategies for addressing these issues are discussed in relation to the role of wood as a renewable building material. The potential for addressing biological attack, ultraviolet light degradation and dimensional stability in a single product are discussed in relation to the need to produce a longer-lasting material that retains the environmental attributes of wood.

Keywords Wood deterioration · Wood protection · Preservatives · Barriers · Wood modification

Introduction

Wood and wood-based materials are among our most important renewable materials with many desirable properties, but susceptibility to damage by combinations of sunlight exposure (primarily ultraviolet light), repeated wetting/drying and biological degradation remains as major negative attribute. The agents of deterioration can combine to markedly shorten the useful lives of many wood-based products. Shorter service lives diminish the value of wood as a renewable resource while placing additional pressure on our forests.

While estimates of total global losses to degradation are scarce, Boyce (1961) long ago suggested that 10% of the timber harvested in the USA was used to replace wood that had failed prematurely in service due to biodeterioration. Extended globally, the UN Food and Agricultural Organization (FAO 2006) estimated global timber harvests to be 3 billion m^3 per year, with 60% of this production being used for products and the remainder for fuel. The 10% of harvest

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K.K. Pandey et al. (eds.), *Wood is Good*,
DOI 10.1007/978-981-10-3115-1_20

figure would translate into 180 million m^3 of wood that could be conserved by controlling degradation losses. This does not account for other squandered resources associated with energy consumption during harvesting and processing as well as installation, environmental impacts, and economic effects of the added harvesting. Clearly, limiting degradation can have sizable impacts on both economies and quality of life. While it would be virtually impossible to completely eliminate this loss, it is readily apparent that wood must be used more efficiently and protected more fully if it is to reassume a leading role as a critical structural material. Preservative treatments already contribute to improved wood conservation through extended service life, but there are opportunities for improvement. An important aspect of this effort must be the continued development of effective strategies for protecting wood against physical agents such as UV light, wetting as well as biological attack.

Protecting wood from all of these agents is certainly not new, but the methods used for protection have come under increasing scrutiny from a skeptical public that questions the use of chemicals for all purposes. For almost two centuries, we have depended on heavy-duty preservatives such as creosote, pentachlorophenol or heavy metal combinations for wood protection, but public pressures have encouraged substitutions in many applications. Changes have not been uniform globally, and examining the various strategies and patterns of change may help us to take a more holistic approach to wood protection. In this paper, we will review the general trends in wood protection in North America with references to activities taking place elsewhere. For the purposes of this review, we will concentrate on long-term protection of exterior exposed solid wood products, thereby avoiding the limited market for whole-structure treatments and treated composites. While we recognize that naturally durable wood species have a role to play, they will not be discussed here and we will restrict ourselves to initial wood treatments excluding those used strictly to limit fungal mold and stain attack.

Current State of Affairs

Although wood protection is a global need, the vast majority of treated wood is used in temperate climates and the bulk is used in North America (Vlosky and Shupe 2006). This market constitutes approximately 60% of the total global market for treated wood. It is unfortunate that the areas with the most critical needs for wood protection tend to employ these technologies, but the higher costs of treatment largely limit their use to developed nations. There remains a critical need for low-cost wood protection for developing countries in tropical regions where deterioration rates are more severe.

The North American markets have long been dominated by the so-called heavy-duty wood preservatives. Industrially, creosote, pentachlorophenol and heavy metal-based systems remain the dominant preservatives for industrial applications. While there have been challenges to the continued use of these chemicals, the producers have generated the required data to demonstrate that these systems can be safely used with minimal environmental impacts. The US Environmental Protection Agency and Canada's Pesticide Management Regulatory Agency have both reviewed chemicals under their jurisdictions and continue to allow industrial uses (note: there are some differences in chemicals allowed between the two countries). In general, industrial uses of chemicals have been judged on their technical merits and very few chemicals are banned outright, although they may be restricted to specific uses. At the same time, some alternatives for industrial wood protection have emerged, including copper naphthenate and alkaline copper compounds. However, users, who are, by nature, conservative in adopting new systems without long-term data, have been slow to adopt these systems.

On the residential side, the market was long dominated by chromated copper arsenate (CCA), but the 2004 decision by the manufacturers to withdraw the use of CCA for residential applications created opportunities for new systems. Much has happened in the intervening decade. The first CCA alternative was alkaline copper quaternary, closely followed by alkaline copper azole. These systems both depend upon copper as the primary biocide with smaller amounts of a carbon-based biocide to protect against copper-tolerant organisms. Alkaline copper systems have been touted as more environmentally friendly because they lack arsenic or hexavalent chromium. However, they also contain much higher levels of copper than CCA and this can pose issues with regard to metal migration from the treated product. The high pH of these systems also creates the potential for corrosion of unprotected steel connections, necessitating the requirement for either hot-dip galvanized or stainless steel hardware. Despite their different handling characteristics, the use of these systems rapidly grew and they dominated the residential markets until the recent introduction of micronized copper systems. Micronized systems use finely ground copper suspensions in place of solubilized copper, along with either a triazole or quaternary ammonium co-biocide (McIntyre and Freeman 2008). Micronized systems are widely used to treat southern pine, which is highly permeable and easily treated; however, these systems are not suitable for more difficult to impregnate species, making them less suitable for treatment of most Canadian wood species as well as woods from the western USA. The shift to micronized systems has not been without debate because of concerns about the lack of long-term performance data and the lack of standardization by the American Wood Protection Association (AWPA); however, they appear to be performing well when properly applied.

The primary suppliers of wood preservative systems have also been working to develop metal-free alternatives (Morris 2002). These systems can incorporate mixtures of triazoles, carbamates, quaternary ammonium compounds and various insecticides. While they appear to be working well for non-soil contact applications, they are not yet suitable for direct ground contact. As we will discuss later, the potential for replacing metal-based preservative with these organics has largely been muted by their inability to perform well in soil contact. Interestingly, some producers of these colorless products have had to add colorants including small amounts of copper because the public expects treated wood to be colored.

At the same time, the North American market has seen the emergence of alternative systems including various wood extracts, silanes, and a host of other systems that claim to provide non-biocidal protection. Unfortunately, there are very little publically available data to support these claims. There have also been attempts to introduce acetylated wood and heat-treated wood into the market, but these products have not achieved substantial market acceptance, primarily because of higher cost.

Europe has seen the emergence of a host of alternative protection methods including acetylation, thermal modification and furfurylation. Ironically, both acetylation and thermal modification have roots in North American research dating back to the 1950s. The situation in Europe is a bit different owing to a very different regulatory structure and a public willingness to pay more for wood products coupled with a lower risk of decay in many parts of the continent. This has fostered a willingness to look more closely at alternatives and a seeming willingness to accept some level of reduced performance. This has allowed the development of products with shorter expected service lives. This approach recognizes the tendency of wood users to more often remove wood products from service for changes in appearance rather than any loss in biological performance. However, this approach does have a negative side in that shorter service lives mean that wood products will not perform as well in life cycle analyses. The outcome of shorter service life can be negative when the tree required to replace the product takes longer to grow than the resulting product service life.

Europe has been the center of developments in dimensional stabilization, heat treatment, silanes, and barriers or coatings (Hill 2006). All of these processes invariably produce materials that are more costly, but these costs do not appear to be a barrier to market entry, perhaps because alternative (non-wood) materials also have higher costs.

Future Concerns

In order to more fully understand where the use of treated wood is headed, we need to understand why changes are necessary.

There is no doubt that society has a strong desire for the use of less toxic chemicals for all purposes and wood protection is no exception. At the same time, there is increasing public concern about the potential for migration of preservatives into the surrounding environment. Virtually all of the currently used wood preservatives have some degree of water solubility. In addition, these molecules tend to have a much greater effect in aquatic environments because nontarget organisms are literally bathed in the chemical. Concerns about preservative migration have led some regulatory bodies to severely restrict the use of treated wood (Brooks 2011a, b; WWPI 2012).

Another factor affecting the use of treated wood is disposal. The rules regarding disposal vary widely across the globe. In the USA, the first recommendation for treated wood that has reached the end of its useful life is to reuse it in a similar application. For example, a utility pole might become a parking barrier or a railway sleeper might become a landscape timber. Ultimately, the wood will no longer be useful in any application. In most of North America, treated wood can be disposed of in lined municipal solid waste facilities (landfills) provided that it meets certain criteria. Virtually all wood treated with oil-borne preservatives meets these requirements, and there is an exemption for water-based systems such as CCA. There is no shortage of landfill capacity in many parts of North America, and this has made it difficult to develop alternative disposal options. Most industrial-treated wood is given away or reused, while most residential-treated wood appears to be placed into landfills.

Despite the lack of a major incentive to avoid landfilling, some options are emerging. Wood treated with oil-based materials contains almost 20% by weight of oil and represents a valuable energy source. At present, creosoted railway sleepers are burned for energy production, but poles and other products are more difficult to process because of the presence of penta, which has more restrictive combustion permitting requirements. As a result, little penta-treated wood is currently burned, but could be a useful bioenergy resource. The other issue related to disposal is the presence of heavy metal-treated wood in waste streams that are destined for combustion. The final hurdle to developing alternative methods for resulting or recycling treated wood is the cost of collecting a widely dispersed material with differing degrees of treatment (Smith et al. 2002). Given the current costs of collecting a widely dispersed material, landfilling seems the most viable option in North America, but disposal represents a key lingering issue among wood users.

New Approaches

As with any industry, technologies related to preservative-treated wood must continue to advance or alternative materials will be substituted. There are a number of opportunities involving new chemistries, treatment methods, non-biocidal treatments and coatings.

New Chemistries: The process of developing a new wood preservative can vary from as little as 5–10 or more years. This includes developing toxicological as well as performance data. In general, it is not economical to develop a chemical solely for wood protection. Many agricultural pesticides have been adapted for wood use as evidenced by the use of triazoles for wood protection. While chemicals are often developed without close public scrutiny until they are released, the time periods required for establishing efficacy of wood protectants generally result in gradual emergence of chemicals for increasingly more aggressive environments (Cabrera and Morrell 2012; Pernak et al. 2004; Schultz and Nicholas 2006; Schultz et al. 2004; Zabielska-Metjuk et al. 2004). One disconcerting observation for the development of new wood preservatives is the relative paucity of new chemicals entering major markets over the past few years. The exception has been micronized copper, which has only been commercially available for a few years but now dominates the residential market in the eastern USA (Preston et al. 2008; Cookson et al. 2008; McIntyre and Freeman 2008; Larkin et al. 2008). This system, however, is still dependent on heavy metals and could be viewed as a modification more than a completely new development. The lack of a pool of readily available alternative treatments suggests the need for further development of new chemicals and could be an opportunity for the company that can create the ideal system.

The other area that continues to receive research interest is the potential for using natural products extracts for wood protection (Kawamura et al. 2011; Kondo and Imamura 1986; Li et al. 2008; Schultz and Nicholas 2000). Researchers have long sought to use heartwood extractives as potential wood preservatives; however, the approach has two problems. Extractives removed from highly durable woods are rarely effective when introduced into less durable species. This may reflect that inability to achieve the same microdistribution that was present in the original wood, as well as the tendency for these chemicals to be water soluble and therefore susceptible to leaching. A more important problem is that many naturally durable species are already in short supply, making it difficult to justify cutting more wood for production of natural preservatives. Extraction of by-products such as sawdust may be possible, but this material contains a mixture of non-durable sapwood and heartwood and may therefore produce lower yields. It may be more useful to employ these by-products for the production of durable composites, provided that the materials are compatible with resins.

An alternative to the use of heartwood extracts might be the use of foliar extracts or materials from other organisms (Li et al. 2008). Many plants have evolved to produce foliage that contains an array of compounds designed to discourage attack by bacteria, fungi and insects. Foliage may be an especially attractive source of biologically active compounds because it can be repeatedly harvested without cutting the tree, or alternatively, it could be collected at the same time the tree is harvested for wood. A number of recent studies suggest that foliage extracts exhibited activity against a variety of fungi and insects, although none of the extracts appears to have the broad-spectrum toxicity necessary to function in a natural environment. It may be possible to combine extracts to produce a more effective cocktail of natural products. At the same time, it is important to remember that natural products extracts are, potentially, just as toxic to nontarget organisms as synthetic pesticides. As these compounds are explored, it will be essential that they be tested accordingly to ensure that we do not inadvertently introduce more toxic molecules into the system.

Another interesting natural products approach has been the use of chitosans for wood protection (Maoz and Morrell 2004; Eikenes et al. 2005). These compounds are derived from shrimp-farming operations and are available in large quantities. Modified chitosans have been shown to be effective against a variety of fungi, although their effectiveness against insects remains untested. Nevertheless, they offer the potential for producing antimicrobial compounds from what is largely a waste product. These examples highlight the potential for developing alternative systems from waste streams produced by other processes.

The search for lower toxicity systems for protecting wood against the diverse array of wood-degrading agents will be essential for retaining the viability of wood as renewable construction material in adverse environments.

Non-biocidal Treatments: The protection of wood without biocides has long been a goal of many wood users. The use of glycol to bulk wood and the development of dimensional stabilizers such as acetic anhydride show that wood can be made less susceptible to the water uptake that creates conditions conducive to biological attack (Hill 2006). However, these approaches have drawbacks that include the need to impregnate with large volumes of expensive reactants, lingering odors and textural changes. These systems also appear to be limited to use on a restricted number of highly permeable wood species. Alternatively, heat treatments can be used to modify the hemicelluloses in the wood to render the wood less susceptible to fungal attack (Esteves et al. 2007, 2011; Jamsa and Viitaniemi 1998; Kamdem et al. 2002; Tjeerdsma et al. 1998; Vidrine et al. 2007). However, this process is not completely protective and can reduce wood properties.

Despite their limitations, dimensional stabilization strategies do have some applications. Wood modification clearly limits water uptake, and this reduces the risk of fungal decay; however, the process does not appear to alter susceptibility to surface molds or UV degradation (DeVetter et al. 2010a, b; Donath et al. 2004; Dubey et al. 2012; Lande et al. 2004; Mai and Militz 2004; Metsa-Kartelainen and Viitanen 2012; Pfeffer et al. 2012; Weigel et al. 2012). Thus, there remains a need for non-biocidal treatments that are more broadly effective against abiotic and biotic agents of deterioration.

New Treatment Practices: The wood treatment processes employed to impregnate the majority of treated wood used globally date to the middle part of the nineteenth century. The seeming lack of progress in this aspect of wood protection stems, in part, from the limited ability to overcome the inherent impermeability of heartwood and the overall effectiveness of existing treatment processes. In essence, good performance of properly treated materials has limited interest in investing in entirely new treatment technologies. Despite the overall acceptance of existing processes, there is considerable opportunity for both improving the quality of treatment and placing the chemical in the wood in such a way that it is less likely to migrate outward once in service.

Reducing the risk of preservative migration has become a major concern in some regions, notably where treated wood is used in close proximity to riparian zones. While there is no doubt that some chemical will migrate from treated wood, the goal is to ensure that the levels remain below those capable of inducing a negative environmental effect. Models have been developed that use migration rates for a given volume of treated wood coupled with information about specific waterway conditions such as pH or water current speed to predict total releases over time (Brooks 2011b). These predictions can then be compared to known minimum effects levels for various organisms. At the same time, treatment practices have been modified to reduce the risk of over-treatment, remove surface deposits of chemical, reduce the risk of bleeding in service and, where ever possible, ensure that preservatives have been immobilized or reacted with the wood. These best management practices are required in many localities across North America (WWPI 2012).

At the same time, there is still a need for new treatment processes that result in more effective preservative penetration. While much of the coniferous wood treated globally has thick bands of easily treated sapwood, there are many species that resist impregnation. Developing methods for effectively treating these woods would help improve performance, thereby reducing the need to harvest additional trees. Modifications to existing liquid treatments, with the possible exception of dual treatments involving an initial boron treatment with a diffusion period, following by subsequent over-treatment with a heavy-duty wood preservative are limited by the inherent impermeability of the resource. The further development of supercritical fluid treatment processes offers the potential for overcoming the inherent refractory nature of many major wood species (Kjellow and Hendriksen 2009; Morrell et al. 1997). This process is currently commercially used in Denmark and has been explored elsewhere, but the high costs of entry in terms of equipment have largely limited development. Ultimately, SCF impregnation will emerge as a viable technology as we move to carbon-based systems and employ more wood-based composites.

There is a need for continued development of other novel systems for impregnating wood and for limiting the ability of the treatment to migrate outward once installed.

Coatings: While we have developed preservative systems capable of protecting wood against biological degradation for 50 years or more, most treated wood ultimately fails because its appearance declines to the point where the user will no longer accept it. This remains a major problem for wood in exterior applications.

Coatings can reduce damage caused by ultraviolet light as it strikes the wood and also reduce the ability of the wood to sorb water, thereby reducing the wetting and drying that leads to warping, twisting and checking.

UV degradation of lignin on the wood surface, coupled with subsequent removal of other wood components, markedly reduces wood appearance (Feist 1990; Hon and Chang 1984; Schauwecker et al. 2009). While opaque coatings can reduce this damage, most wood users want to see the natural grain and color of the wood. Transparent or semi-transparent coatings can provide some protection, but this protection generally declines within 1–2 years of exposure. Developing effective treatments that can be impregnated into wood to provide long-term UV protection remains a major challenge. Iron oxide pigments, titanium dioxide or hindered amine light stabilizers are just a few of the many possible surface protectants that have shown some promise, but most are rapidly inactivated by sunlight (Schauwecker et al. 2009; Schmalzl and Evans 2003; Rowell and Banks 1985). Water repellency is often produced through the inclusion of various waxes or silicates in the treating solution (Levi et al. 1970; Lesar and Humar 2011; Sun et al. 2010). These treatments can reduce the rate of water uptake, but add cost to the system and only slow water uptake.

Ultimately, however, wood protection must be considered in a more holistic fashion. Biological performance is important, but so is resistance to water and UV light. The material must not only remain structurally sound, it must look sound as well. If it does not, the wood is replaced prematurely. It is also important to alter the premise that wood has to be the less expensive alternative. Homeowners have shown a willingness to pay 2–3 times more for wood/plastic composites that promise infinite service life with no maintenance. These materials have their own issues, but they highlight the potential for upgrading wood materials to reach a higher market.

Material specifiers are increasingly comparing the environmental attributes of materials to make specifying decisions. One of the most important emerging tools for these comparisons is life cycle analysis (LCA). The LCA examines all of the inputs required to produce a product including energy and water along with the environmental impacts. There is no correct answer regarding a given material. LCAs allow users to compare the impacts of different materials that can be used for the same application. Wood, by virtue of its renewability, low manufacturing impacts and ability to sequester carbon, should have a major advantage in these comparisons. However, service life plays an important role in these comparisons. Premature removal of wood sharply increases the overall life cycle impact. Thus, factors such as weathering and wood instability must be considered in performance because they often lead to premature wood replacement.

As a result, biological protectants, water repellents and coatings must all be considered as an integral part of a wood protection system that ensures long-term performance. Another performance component is the original wood. Some species are inherently prone to warping and checking. While it is unlikely that species will be replaced, it may be possible to selectively sort lumber for treatment. For example, dimensional changes tend to be greatest in the tangential direction in most wood species (flat-sawn wood). Selecting materials that are vertically sawn would result in a lower tendency to shrink and swell. Careful material selection would reduce the tendency of treated wood to check and deform in service.

None of these approaches is without some cost; however, it is also important to avoid the view of wood as the cheapest material. In North America, treated wood is typically the least expensive decking material, followed by naturally durable heartwoods and finally by wood/plastic composites (WPCs). Surveys show that consumers perceive these products in terms of increasing quality in the same order. Purchasers have clearly shown a willingness to pay a premium for products that they perceive to be more durable and less maintenance intensive. At the same time, extensive advertising has convinced them that WPCs are greener. Wood-based materials, however, should have more favorable LCAs provided that they are properly treated, and consumers have demonstrated their willingness to pay for materials they perceive to combine greenness, durability and low maintenance. There appears to be niche for the development of a durable, more dimensionally stable wood product.

Barriers: Preservative treatment is ultimately a barrier that precludes entry by wood-degrading organisms, but there have been recent efforts to develop physical barriers to protect wood. The first successful products originated in South Africa in response to early failures of creosoted utility poles, and these products have spread across the globe (Baecker and Behr 1995; Behr and Baecker 1994; Behr et al. 1997). In some cases, they encapsulate untreated wood, but generally, they involve coating of preservative-treated wood. Barriers reduce contact between soil and wood, thereby diminishing the risk of fungal decay and insect attack. They also reduce the potential for preservative migration from wood into the surrounding environment. Barriers clearly reduce the risk of environmental contamination, but they may also have a side benefit. Since less chemical will migrate from the wood and soil is not in direct contact, the barrier may allow the use of lower preservative loadings to produce equivalent protection. Barriers can be simple polyethylene barriers or heavy plastic sleeves applied by shrink wrapping. Other systems spray polyurea on the wood surface to provide a flexible coating whose thickness is based upon the environment to which the wood is exposed. Several barriers systems are currently standardized by the American Wood Protection Association (AWPA 2012). These systems add cost, and users must clearly determine if the added expense is worthwhile, but they help address the issues related to biocide mobility.

New Opportunities

Wood has a long history of use in a variety of applications, and preservative treatments have played a major role in the extension of useful life, but there are still other opportunities for growth in the use of treated wood. Among these applications are wood used as solid packing material in global trade, wood used in mass timber structures and a higher-end decking product.

Wood pallets seem to be everywhere, and most people assume that they have always been used, but palletized shipping only dates back to the Second World War. Pallets make shipping easier and fast, but the lower-quality wood used in these pallets and other solid wood packing materials can harbor insects and fungi (Morrell 1995). These organisms can be inadvertently introduced into new environments during shipping. Nearly all countries require that solid wood packing materials used in global trade be subjected to some type of mitigation treatment. The two most commonly applied treatments are heating to 56 °C for 30 min or fumigation with methyl bromide (FAO 2002). These treatments are not verifiable, nor do they prevent reinvasion. Preservative treatment may provide a more verifiable method for limiting the risk of pest introduction that also provides long-term protection against reinvasion. Preliminary tests of solid wood packing material infested with the new house borer (*Arhopalus productus*) suggested that beetles were not killed by treatment with ACQ, borates or an organic preservative mixture, but also never completed their life cycle (Schauwecker and Morrell 2008). Clearly, much additional work needs to be completed before preservative treatment is approved as a mitigation tool, but the volumes of wood used in this area are well worth the effort.

Mass timber structures are seeing increasing use in more temperate climates as a part of efforts to compete with concrete and steel in the high-rise building market. Cross-laminated timber is one of the primary products used in this area. While this material has a number of advantages over alternative materials, it will ultimately need some types of protection against biological degradation. This protection need not entail heavy-duty wood preservation, but the fact that all buildings eventually leak means that these structures will experience water intrusion that creates conditions suitable for fungal attack. Some types of treatment will be needed to ensure performance. These appears to be a hesitancy to use traditional wood preservatives in this application, but alternatives such as thermal modification may find some use creating new markets for durable wood.

The most promising potential new market for treated wood is decking. Treated wood long dominated this market; however, wood/plastic composites (WPCs) have continued to erode market share. Declining market share has been less noticeable because the overall decking market has also grown, masking the change. Wood decks have generally been perceived as of lower quality than either WPC or naturally durable decks; however, there is also a general desire to use wood in decks. There is an opportunity to create wood decking products that are both durable and able to remain visually attractive for a longer period of time. Consumers have already shown their willingness to pay more than two times the cost of a treated wood deck for a WPC deck. There is clearly an opportunity to create a better decking product that is cost competitive with WPC products but incorporates features that make it more durable. These features might include a carbon-based wood preservative, selection of materials that are more stable (i.e., vertical grain), and application of UV stabilizers to the wood. The resulting product would not compete with traditional lower cost wood decking, but rather with the higher-end products.

Conclusions

Wood remains one of our most important renewable building materials. Continued use of this material under adverse conditions will require renewed interest in developing technologies that resist biological and physical damage. Some of these technologies are already available, but remain too costly. Other approaches are under exploration. Effectively protecting wood against biological and physical damage without depending on broad-spectrum pesticides must remain a goal if wood is to retain its rightful place in a green society.

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