Durability of Wood-Plastic Composites

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Abstract

Until recently, markets for wood-plastic composites (WPCs) have grown at an astounding rate, despite their higher overall costs compared to naturally durable or treated wood (Smith and Wolcott 2006). Surveys suggest that these products have excellent reputations for durability and environmental friendliness and there is an overall perception that WPCs are maintenance-free.

When they first emerged on the market, wood plastic composites (WPCs) were touted as impervious to biological attack because the plastic was presumed to completely encapsulate the wood particles, thereby protecting them from both moisture and fungal attack. However, WPC decks in Florida showed evidence of fungal fruiting bodies on the surfaces within a few years after installation, illustrating that the wood in these materials was still susceptible to biodeterioration (Morris and Cooper 1998). An array of subsequent studies have clearly illustrated that the wood in many WPCs remains susceptible to degradation (Khavkine et al. 2000, Laks et al. 2000, Mankowski and Morrell 2000, Silva et al. 2001, Verhey et al. 2001, Ibach and Clemons 2002, Pendleton et al. 2002, Silva Guzman 2003, Lopez et al. 2005, Schirp and Wolcott 2005, Schauwecker et al. 2006, McDonald et al. 2009).

While great improvements have been made in product formulations designed to increase durability, it is clear that these materials are not completely immune to deterioration, but how susceptible are they?

Deterioration is broadly defined as any negative effect on the properties of a material (Zabel and Morrell 1992). The effects can be due to biological attack or to various non-living agents (sunlight, moisture, temperature), but often deterioration results from a combination of factors. Nowhere is this more evident than with WPCs, owing to the marriage of dissimilar materials.

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Biological Agents of Damage

A variety of biological agents can attack wood and plastic, either as a food source (primarily the wood) or as shelter (both wood and plastic). For practical purposes, the agents most commonly associated with WPC applications include fungi, insects, and marine borers, although other organisms that colonize the surface, but do not necessarily degrade the material, such as lichens and algae might also be considered because of the exceptionally high dependence on surface appearance for product quality.

Fungal Decay

The first reports of biological attack on WPCs involved a white rot fungus, clearly showing that wood particles in this material remained susceptible to fungal attack. These observations led to a number of laboratory studies showing that various decay fungi could cause substantial weight loss under the proper conditions. Fruiting bodies, however, do not always correlate with substantial losses in material properties. One observation from laboratory trials has been that brown rot fungi appear to be more capable of attacking these materials, even in WPCs composed of hardwood particles (McDonald et al. 2009). However, white rot fruiting bodies appear to be more

prevalent in field trials. This may reflect a tendency to test these materials under sub-tropical or tropical conditions where white rot fungi tend to be more dominant.

Laboratory decay-tests in North America have typically been performed using the American Wood Preservers' Association Standard E10 (AWPA 2004), ASTM Standard D1413 or D 2017 soil block tests (ASTM 2004a, 2004b), although agar tests are also used. In general, the primary difficulty in assessing WPC durability has been wetting the blocks. The inherent resistance of WPCs to moisture uptake can sharply limit fungal attack for much of the period traditionally used in these tests (Schmidt 1993, Naghipour 1996, Ibach et al. 2005). Once wetted, however, wood in the WPCs will degrade. The degradation rate then becomes a function of the wood:plastic ratio, the use of additives, the particle size of the wood, and the wood species (Chow et al. 2002, Verhey and Laks 2002, Silva Guzman 2003, McDonald et al. 2009). All of these factors indirectly relate to moisture uptake and accessibility of the wood to the fungus.

While fungal attack clearly affects the wood in a WPC, the effects on overall WPC properties are less clear-cut. A number of studies have shown substantial losses in bending properties after relatively short fungal exposures under controlled conditions (Silva et al. 2001, Stark 2001, Ibach et al. 2005, Schirp and Wolcott 2005); however, microscopic examination of specimens exposed to wetting, drying, and fungal attack revealed the presence of relatively few fungal hyphae. The absence of substantial fungal attack suggests that the damage was more likely caused by disruption of the wood/plastic matrix by wetting and drying. This suggestion is further supported by studies involving long-term wet/dry cycling (Wang and Morrell 2004). This effect appears to be associated with the first few moisture cycles. The effects of water disruption of the limited wood/plastic interactions in a WPC are, in many ways, analogous to those observed with wood-based composites such as oriented strandboard when subjected to wetting and drying. In both cases, there is a substantial, non-recoverable loss in properties associated with wetting and subsequent drying.

Insect Resistance

Plastic is largely resistant to insect attack except as it might be mined or grazed to create galleries for rearing by social insects such as carpenter ants or termites, or inadvertently by adult beetles and wasps as they emerge from adjacent wood. While insects might be capable of obtaining some nutrition from the wood particles, substantial insect attack of WPCs is unlikely. Given the density of most WPCs, it is also not likely that social insects, such as carpenter ants, would mine galleries, since they tend to seek softer materials (Hansen and Klotz 2005).

Marine Borer Resistance

Plastic is largely immune to marine borer attack. Studies have shown that Limnorans and shipworms, which obtain at least part of their nutrition from wood, do not directly attack either plastic or WPCs (Schirp et al. 2008). Small, inadvertent damage to the plastic or WPC by shipworms has been observed when WPC or plastic is placed adjacent to wood attacked by these organisms. Rock-boring clams, such as pholads, are capable of inhabiting materials softer than their shells but damage to wood or plastics in the ocean by these organisms is rare.

Physical Agents of Deterioration

Although we most often think of biological damage when considering material deterioration, physical and chemical agents can have a substantial impact on the properties of a WPC and they can render the wood components more susceptible to biological attack. These effects on WPCs are primarily surface-related but the damage is particularly critical because these products are sold for a premium on the premise that their surfaces will resist such changes.

Chemical Discoloration

Many wood species are susceptible to a variety of chemical stains and this susceptibility does not appear to diminish in a WPC. These stains can result from reactions of extractives with metals, by thermal degradation, or they can be mediated by bacterial enzymes. Often, the discolorations are dark and appear to be of a biological origin, but the rapidity with which they form and the lack of associated microbial growth suggest otherwise. These stains have little impact on darker colored WPCs, since the background masks any discoloration, but they are particularly damaging in materials produced to look like wood. Numerous dark blotches can develop shortly after installation and, because the stain is often beneath the surface, it is difficult to remove. Careful selection of wood species may help reduce the potential for stain; however, this can be difficult and it may be more practical to add oxidative inhibitors to the mixture prior to extrusion. These materials must also be capable of withstanding the elevated temperatures associated with blending and extrusion.

Moisture Cycling

Early in the history of WPC lumber it was often suggested that WPCs were resistant to moisture because the wood was completely encapsulated by the plastic. Plastic does impart resistance to moisture uptake, but once the moisture enters the matrix, the damage begins.

WPC moisture absorption can lead to a degradation of mechanical properties since the wood particles swell as they absorb moisture. As the wood particle swells, three things happen to the composite, 1) the interface breaks down due to repeated wood swelling and shrinking, 2) microcracks in the plastic are created, and 3) the wood particles fracture internally due restrained swelling. For example, a 9% moisture increase was associated with flexural modulus and strength reductions of 39 and 22%,

respectively, when an injection-molded WPC containing 40% wood flour was soaked for 2000 h (Stark 2001).

Manufacturing method can have a tremendous influence on surface quality of the WPC, thereby influencing moisture absorption. Extruded WPCs absorbed roughly four times as much moisture as injection-molded composites in a two-week water soak (Clemons and Ibach 2004). Injection-molded surfaces were smoother than extruded materials, and had a plastic-rich layer that inhibited moisture penetration. Manufacturing stresses may also play a factor in moisture uptake. For example, uneven stresses produced during manufacturing may result in crack development near the WPC surface that accelerates moisture uptake (M. Gnatowski, personal communication, 2008).

Freeze-Thaw

There have been suggestions that the limited degree of bonding between the hydrophilic "water loving" wood and the hydrophobic "water hating" plastics can also be disrupted by physical activities such as freezing and thawing. This would be a critical performance issue in many northern temperate exposures. Testing of small samples showed some loss in properties after freeze-thaw cycling; however, there were no significant effects on the flexural properties of freeze-thawed cycled commercial samples (Wang and Morrell 2004). Others have shown losses in flexural strength and modulus of 5 and 15%, respectively, after exposure to five water-soak freeze-thaw cycles. A large portion of the mechanical property loss was associated with moisture absorption rather than the freeze-thaw cycle (Pilarski and Matuana 2006).

UV Degradation

Both major components of WPCs undergo photodegradation upon exposure to UV light. While all components of wood are susceptible to photodegradation, lignin absorbs 80 to 95% of the total amount of UV light absorbed by wood and only constitutes 25 to 30% of wood (Fengel and Wegener 1983). As lignin oxidizes, the lignin (and wood) content at the surface decreases (Fabiyi, et al. 2008, 2009). As a result, the surface of degraded wood is typically hairy and cellulose-rich. The plastic matrix theoretically should not undergo photodegradation. Unfortunately, residual solvent in PVC, other impurities in polyolefins, and photo-oxidized wood can sensitize the matrix to photodegradation. The degradation reaction propagates via free-radical mechanisms, and can lead to oxidation of the polymer chain, chain scission, and/or crosslinking. The result is a loss of surface quality, increase in UV-absorbing characteristics, and a decrease of mechanical properties.

Ultimately, WPC photodegradation results in changes in color, surface composition, and small changes in mechanical properties. Weathering is a combination of photodegradation in the presence of water/moisture and heat. Extruded WPCs exposed to UV radiation for 2000 hours in an accelerated test lightened 13%, while flexural modulus of elasticity (MOE) decreased 12% and no significant change in strength occurred. In contrast, exposing similar samples to 2000 hours of UV radiation with a water-spray cycle produced 46% lightening and flexural MOE and strength decreases of 52 and 34%, respectively (Stark 2006). UV exposure in conjunction with water exposure is deleterious because oxidation reactions are accelerated in the presence of water, swelled wood particles facilitate UV light penetration into the WPC, and the degraded wood (loss of lignin) becomes more water absorbent. These actions exacerbate the degradation. Clearly, UV light penetrates only a short distance into the material and its effect on overall properties would be small. However, the effects on surface characteristics cannot be ignored, particularly for a product that is marketed on an appearance basis.

Methods for Improving Resistance to Biotic Degradation

As it became evident that the wood in WPCs was susceptible to degradation, some manufacturers began to add zinc borates to the mixture (Verhey and Laks 2001, Simonsen et al. 2004). Borates are excellent fungicides and insecticides and zinc borate is especially attractive because it has very low water-solubility and does not appear to affect or be affected by the manufacturing process. One disadvantage of borates is their inability to protect against many mold fungi, a particularly important characteristic given the appearance issues inherent in the products. There is a continuing search for other compounds that might be suitable mold inhibitors; however, the search is hampered by the lack of heat stability in many of the common mold inhibitors used to protect solid wood.

Methods for Improving Resistance to Abiotic Degradation

A variety of technologies are available for protecting WPC against photodegradation. Adding photostabilizers to the plastic is the most common strategy for protecting WPCs. Common types of photostabilizers include ultraviolet absorbers (UVAs) that protect the matrix by preferentially absorbing UV light, and hindered amine light stabilizers (HALS) that protect the matrix by interfering with the free-radical degradation mechanism. Both materials have been shown to offer some protection to WPCs (Stark and Matuana 2003, Muasher and Sain 2006). Pigments in WPCs can also act as light-blockers, limiting the penetration of UV light into the matrix.

There is little information available regarding protecting the wood component in WPCs from photodegradation independently. However, UVAs and pigments in the matrix should offer some protection, and pigments would also mask some discoloration of the wood component.

Perhaps the most important issue for improving WPC durability is moisture. Moisture uptake can be limited by either altering the hygoscopicity of the wood particles or by changing the structure of the final composite. Wood particles can be protected by the addition of coupling agents, such as maleic anhydride-grafted polyolefins that react/interact with the hydroxyl groups present on the wood surface to improve plastic and wood-particle interactions. Other approaches involve wood-surface chemical modification, such as acetylation to reduce hygoscopicity of the particles (Mahlberg et al. 2001). The resultant WPC has very low water-absorption characteristics; however, the process adds additional costs. Changes in the processing variables can also alter WPC surface quality and directly affect the composite's moisture resistance. For example, altering process conditions (heat, line rate) may produce smoother surfaces that reduce moisture uptake, thereby delaying surface degradation. Other methods for reducing moisture sorption include coating the WPC and co-extrusion with an unfilled thermoplastic cap.

Accelerated Testing

One of the issues that has arisen with WPCs in the marketplace is the lack of long-term field data on durability. Instead, manufacturers have depended upon limited laboratory testing using artificial weathering, wet/dry cycles, and decay tests. The methodologies employed in these tests have largely derived from wood-based materials. Given the moisture sorption characteristics of WPCs, there is every reason to believe that these methodologies, while useful for comparative studies, are largely inadequate to predict service life because they fail to provide a sufficient exposure period.

There is a continuing need to develop realistic methods for assessing the many aspects of WPC-durability and these methods will continue to evolve as material scientists refine these composites to improve properties. For example, Silva et al. (2007) clearly showed the need for very thin materials for accelerated testing owing to the limited moisture uptake. However, this approach creates an extremely artificial environment that may not accurately reflect field exposure. Similarly, the fungi used for accelerated testing are largely those used to assess preservative performance of solid wood. These fungi were selected for preservative evaluations because they have tolerances to specific classes of fungicides. None of these fungi have been observed in field inspections of fungal-colonized WPCs. These observations suggest that the current test methodologies may be using the wrong fungi. At the very least, they suggest the need for further investigations of the fungi colonizing WPCs. The final component of accelerated testing has been a limited use of mixed physical/biological exposure. Most materials are tested in weatherometers to assess physical resistance to UV light and wet/dry cycles and then other materials are subjected to biological testing. These materials are subjected to multiple deterioration agents in the field and our tests should reflect that risk. Further development of test methodologies that incorporate some short-term weathering, mold exposure and, finally, exposure to appropriate decay fungi may provide more realistic, but accelerated performance data. These methods need not be extremely long—but they need to more closely replicate the actual exposure risk.

Conclusion

It is clear that the wood in WPCs must be protected from both biotic and abiotic damage; however, it is equally apparent that technologies are available to achieve this goal. As these products continue to evolve, we should expect to see increasingly durable materials that overcome the biological, moisture, and UV factors to produce materials that retain their appearance.

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