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FOREWORD-OVERVIEW: WOOD–PLASTIC COMPOSITES

Let us take a look at a generic wood–plastic composite (WPC) deck, preferably of a premium quality. What should be done in order to avoid the deck owner complaints and, god forbid, a lawsuit? Which properties of the deck should we consider, in order to extend its lifetime as much as possible, preferably longer than that of a common pressure-treated lumber deck? In other words, what is required to make a material that is both durable enough to meet the warranty guidelines and at the same time cost-efficitive to be competitive in the marketplace? What can happen to the WPC deck in use, and how to prevent it? Which properties of the composite material should we aim at, what should we study in that regard, what should we test and how, what should we optimize in order to make a premium product, or, at least––for a less ambitious manufacturer—to pass the building code?

These are the questions considered in this book.

Decking is defined as a platform either attached to a building, or unattached, as in the case of boardwalks, walkways, piers, docks, and marinas. The decking market includes deck boards, railing systems (consisting of a top rail, balusters, bottom rail, and posts), and accessories, such as stairs and built-in benches. According to Principia Partners, U.S. demand for decking (wood and WPC) in 2005 reached $5.1 billion, or approximately 4.0 billion board feet, and projected to grow to $5.5 billion and 4.2 billion lineal feet in 2006 [1].

Wood-Plastic Composites, by Anatole A. Klyosov

Now, let us consider a WPC deck. In a simple case, it is assembled with boards, made of a composite material. The boards can be solid or hollow, or of an "opened," engineered design (see Figs. 1.1–1.25), which can be extruded (in a common case) or compression molded. Typically, but not always, WPC boards have a width of 5½ in. (139.7 mm), height (thickness) of 1¼, 1.00, 15/16, or 13/16 in. (31.75–20.64 mm), and—for standard boards—12, 16, or 20 ft. in length. The board's surface can be smooth (unbrushed), brushed, embossed, or having an "exotic" pattern, such as streaks, simulated wood texture, among others.

Percentage of Decking Demand By Material (Sources: [1, 2, 5])

		Share of (%)		
Year	Market ($ billion)	Wood	Neat plastic	WPCs
1992	2.3	97	1	2
2002	3.4	91	2	7
2005	5.1	77	4	19
2006	5.5	73	5	22
2011 (forecast)	6.5	66	4	30

Note: According to The Freedonia Group, composite and plastic lumber decking demand in 1999, 2004, and 2009 (forecast) was/will be (in million) $317, $662, and $1,370, respectively. According to Principia Partners, only composite decking was sold in North America in 2004 for $670 million.

The boards can be made of plastic of any kind. However, the majority (if practically not all) of WPC boards, manufactured and sold today, are based on polyethylene (PE), polypropylene (PP), or polyvinyl chloride (PVC), see

Figure 1.1 Fading of a composite deck. The "Welcome" mat is just removed.

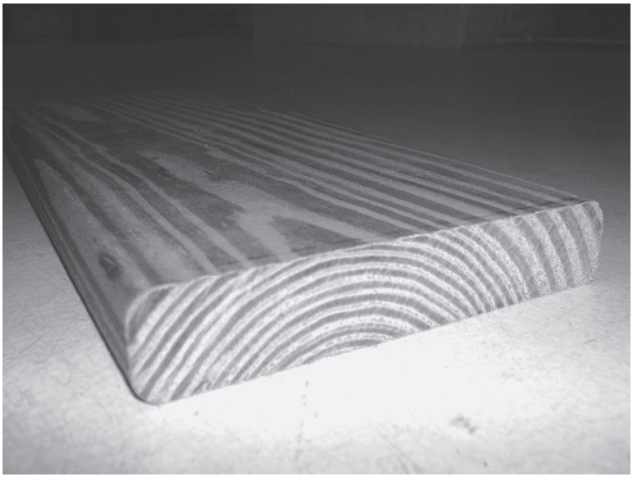

Figure 1.2 Pressure-treated lumber (as a reference deck board).

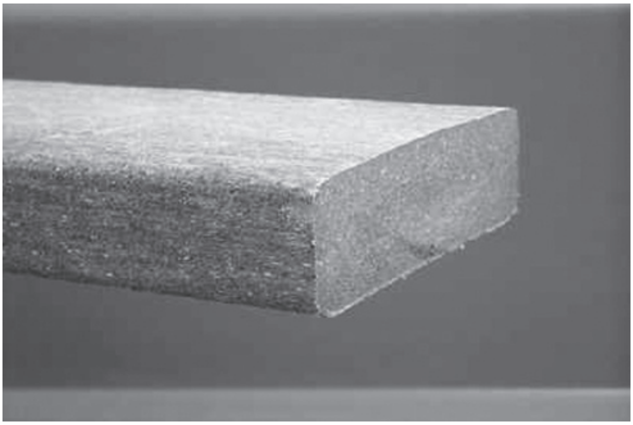

Figure 1.3 Trex.

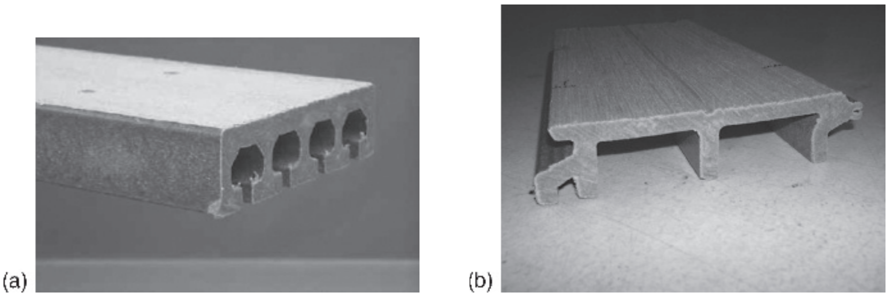

Figure 1.4 TimberTech.

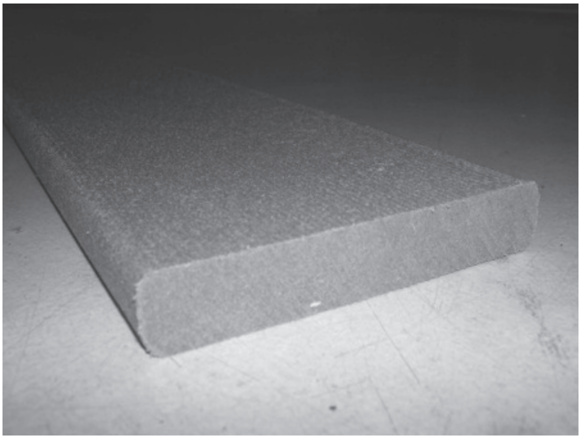

Figure 1.5 Fiberon.

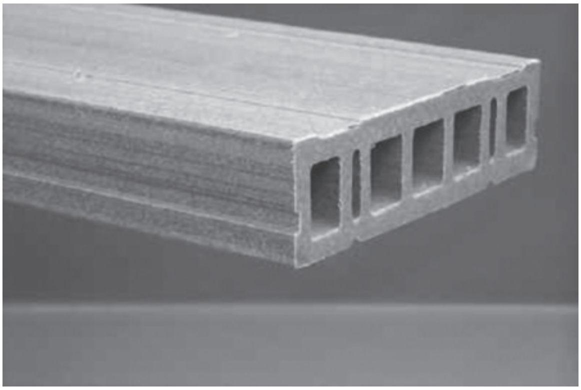

Figure 1.6 WeatherBest^{EHP} (hollow).

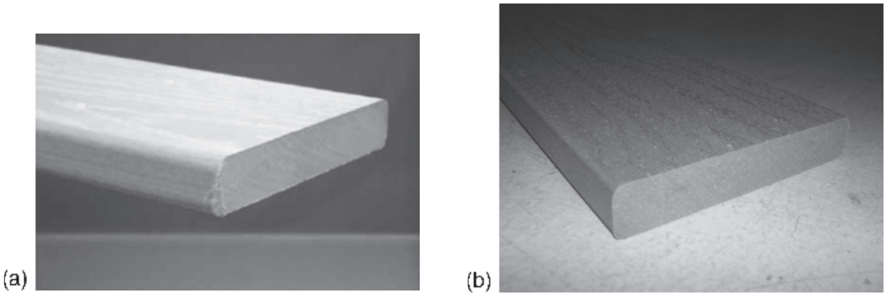

Figure 1.7 WeatherBest^{SP} (solid).

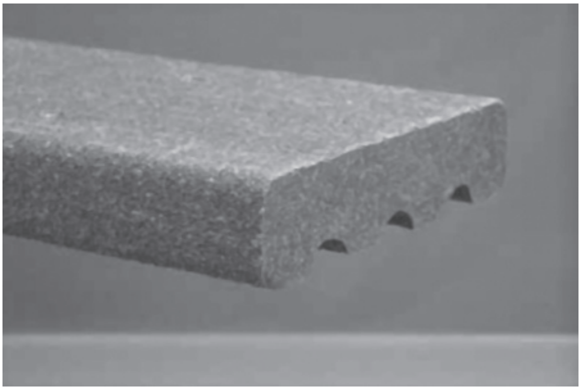

Figure 1.8 ChoiceDek.

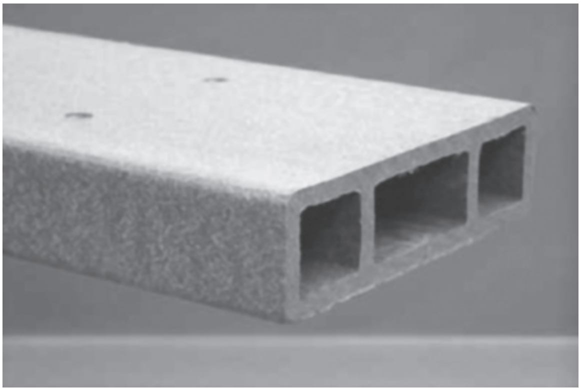

Figure 1.9 Nexwood. See color insert.

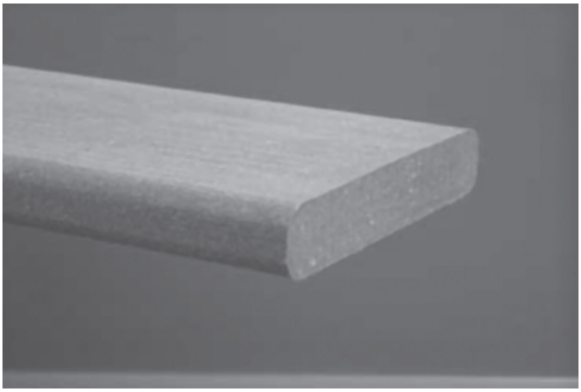

Figure 1.10 Rhino Deck. See color insert.

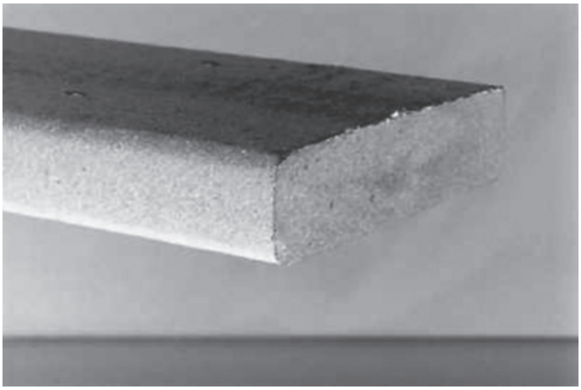

Figure 1.11 SmartDeck. See color insert.

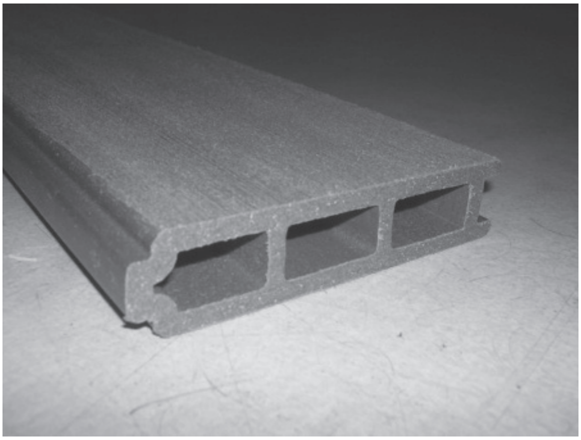

Figure 1.12 Geodeck, Tongue, and Groove.

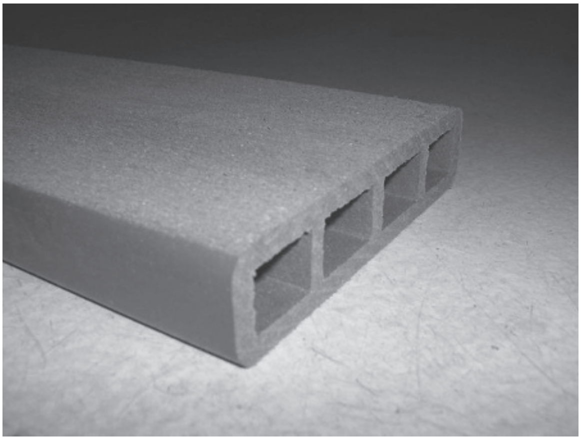

Figure 1.13 Geodeck, Traditional.

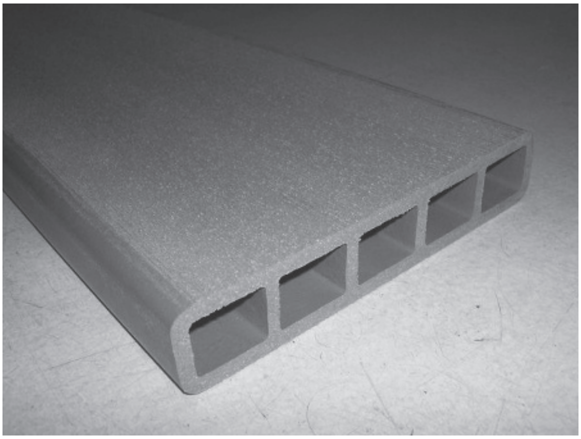

Figure 1.14 Geodeck, Heavy Duty (Commercial).

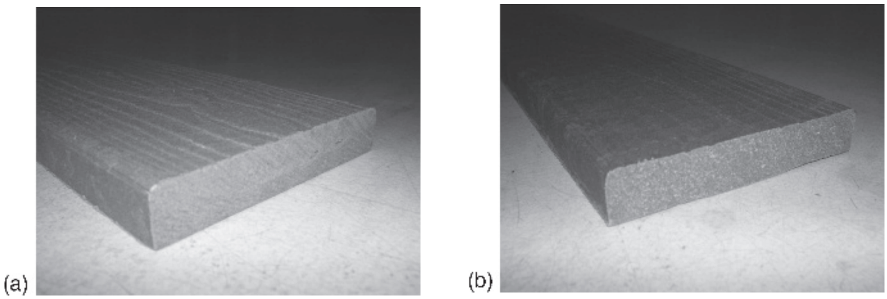

Figure 1.15 Evergrain/Epoch.

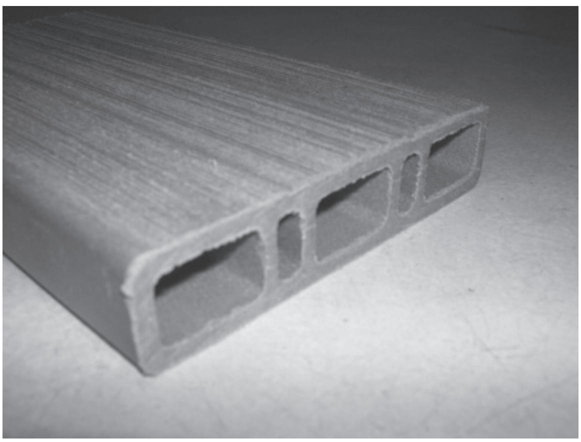

Figure 1.16 Ultradeck. See color insert.

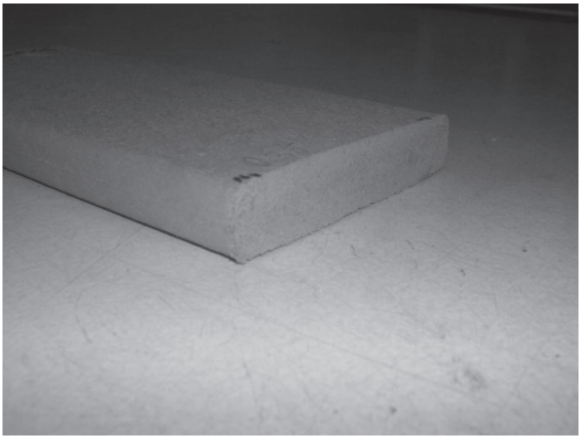

Figure 1.17 Boardwalk.

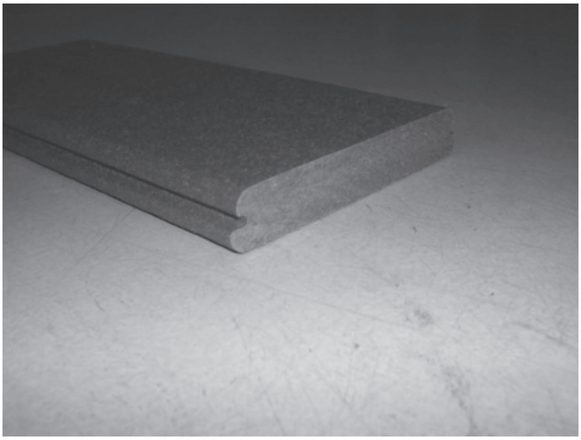

Figure 1.18 CorrectDeck.

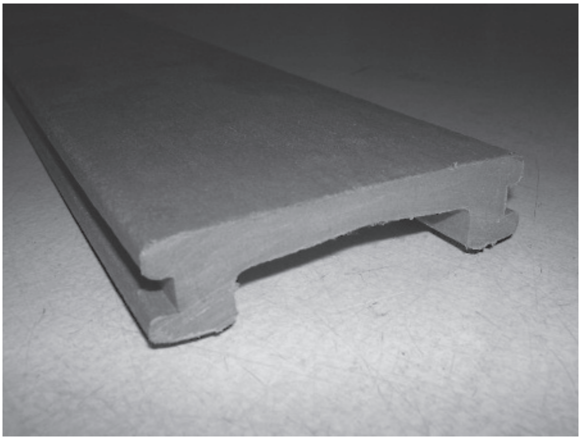

Figure 1.19 USPL (Carefree).

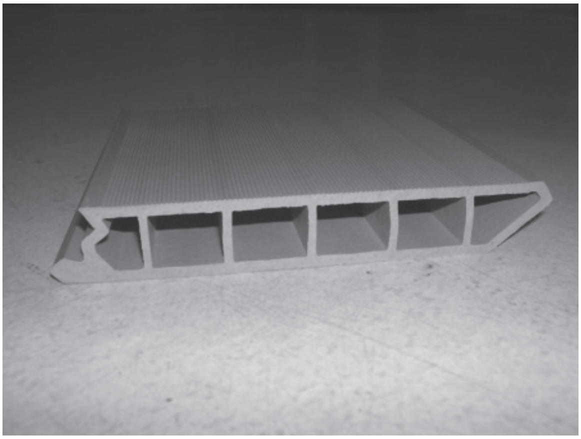

Figure 1.20 Millenium.

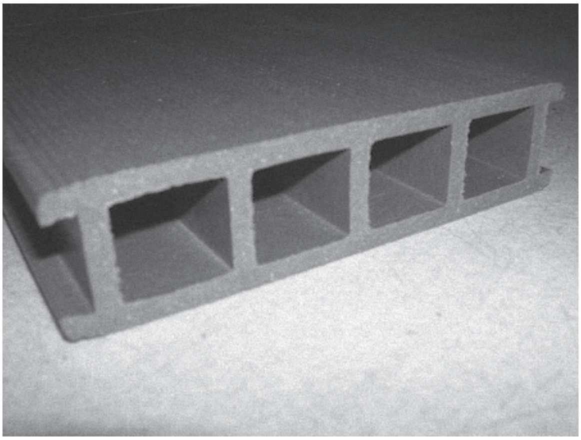

Figure 1.21 Xtendex.

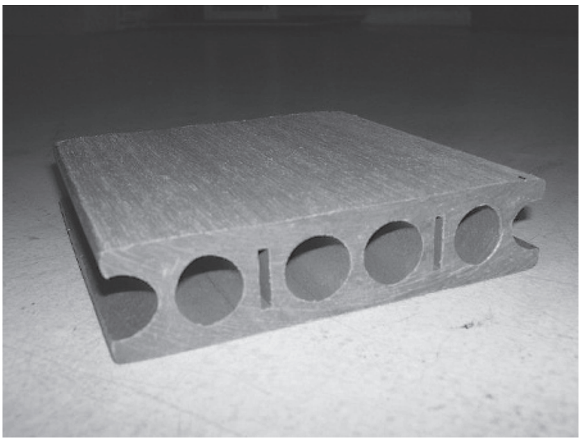

Figure 1.22 Life Long. See color insert.

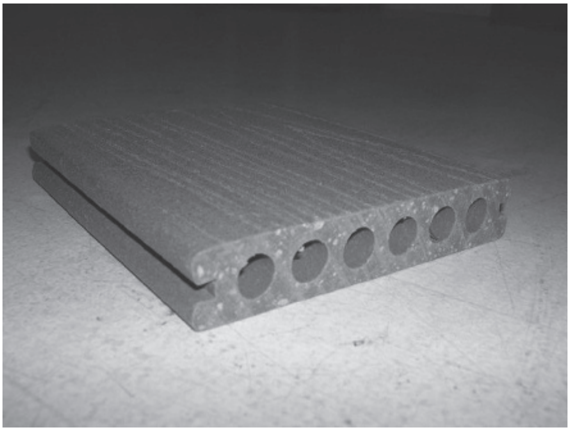

Figure 1.23 Cross Timbers

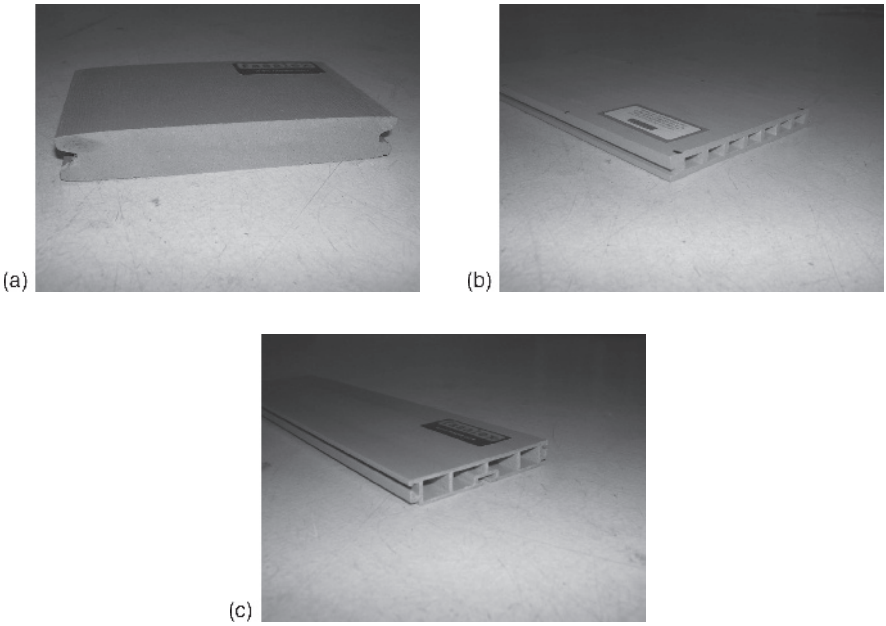

Figure 1.24 Fasalex (Austria)

Table 1.1. The reason is simple: as WPC boards are competing in the market with common lumber, their price should be in the same ballpark. In practical terms, their cost should be no more than 2–3 times higher than that of wooden boards, and that increase should be justified by, say, aesthetics (good looks and

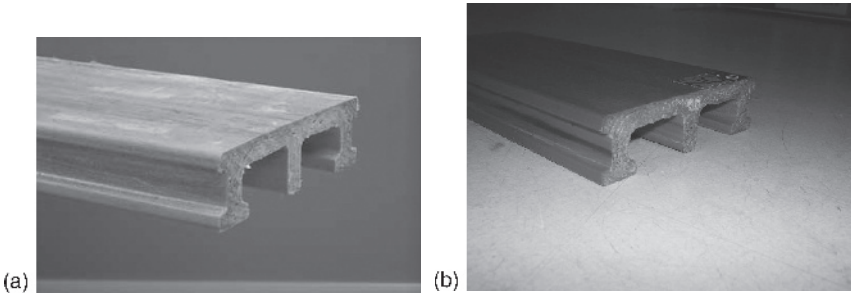

Figure 1.25 An experimental composite board.

the absence of knots, splinters, warping, and checking), acceptable mechanical properties, good durability, low maintenance, lack of microbial degradation, resistance to termites, and possibly even fire resistance. Many customers would pay a premium price to have such a material on their decks. So far, only three plastics named above (PE, PP, and PVC) can fit into the respective pricing category, at the same time having properties necessary for the WPC material to pass the building code.

Types of wood used for decking include pressure-treated lumber, redwood, cedar, and other imported wood. Pressure-treated lumber encompasses for about 78% of wood demand of decking in 2006. WPC building materials consist of a blend of cellulosic fibers and industrial grade polymers, such as polyethylene, polypropylene, and polyvinyl chloride. “Cellulosic fiber” or “wood” in this context is (ligno)cellulosic fiber, such as wood flour, rice hulls, and so on, typically in the form of milled wood products or particles of waste lumber, bleached cellulose fiber or natural fiber of different grades and origins. WPC materials are made by mixing (compounding) plastic and (ligno)cellulose fiber with additives (lubricants, coupling agents, pigments, antioxidants, UV stabilizers, antimicrobial agents, etc.), and manufacturing, using a high volume process such as extrusion or compression or injection molding.

WPC: PRICING RESTRICTIONS

In WPC decking and railing, plastic is filled with natural fiber, such as wood flour, rice hulls and by-product residues from the papermaking industry. Again, there are countless types of natural fiber, obtainable from countless plant sources, however, either a scale is not there, or an availability is restricted, and/or price is too high. Rice hulls cost is about 3¢/lb, wood flour about 3–5¢/lb, bleached fiber by-product (as a blend with minerals) of paper mills between 3 and 9 ¢/lb

TABLE 1.1 WPC decking and railing systems and manufacturing companies, as described in manufacturer's ICC-ES reports

No.	Deck	Manufacturer	ICC-ES report number and date	Cellulosics	Solid or hollow
		Polyethylene-based products			
1	ChoiceDek, Dreamworks, LifeCycle, MoistureShield, A.E.R.T.	Advanced Environmental Recycling Technologies; Weyerhaeuser	NER-596 2/1/2006	Not reported (52% Wood fibers)	Solid
2	Epoch/Evergrain	Epoch Composite Products	ESR-1625 6/1/2005 NER-630 (Legacy)4/1/2006	50% Wood fibers	Solid
3	EverGreen	Integrated Composite Technologies	N/A (referenced by Principia Partners, 2006)	Wood flour	Solid and Hollow
4	EverX, Latitudes, Veranda	Universal Forest Products Ventures II	ESR-1573 6/1/2005	50% Wood flour	Solid
5	Fiberon, Perfection, Veranda	Fiber Composites; LMC	22–41 (Legacy) 10/1/2004	50% Wood fibers	Solid
6	GeoDeck	LDI Composites	ESR-1369 6/1/2005	Rice hulls, Biodac	Hollow
7	Lakeshore	Bluelinx	ESR-1573 6/1/2005	50% Wood flour	Solid
8	Life Long	Brite Manufacturing	ESR-1279 6/1/2005	50% Wood flour	Hollow
9	Monarch	Green Tree Composites	ESR-1084 2/1/2005	55% Wood flour	Solid
10	Nexwood	Nexwood Industries	BOCA 99-8.1 (January, 2000) not current	60% Rice hulls	Hollow
11	Oasis	Alcoa Home Exteriors	ESR-1425 6/1/2005	55% Wood flour	Solid
12	Premier	Composatron Manufacturing	ESR-1481 6/1/2005	50% Wood flour	Solid
13	Rhino Deck	Master Mark Plastic Products	ESR-1461 6/1/2005	50% wood fibers	Solid
14	SmartDeck	SmartDeck Systems	N/A Not current		
15	Tendura	HB&G Building Products; Tendura Industries	N/A (referenced by Principia Partners, 2006)	60% Wood flour	Solid
16	TimberTech	TimberTech	ESR-1400 6/1/2005	50% Wood flour	Solid and open profiles

			Polyethylene-based products		
17	Trex	Trex Company	ESR-1190 6/1/2005	50% Wood flour	Solid
18	UltraDeck	Midwest Manufacturing Extrusion	ESR-1674 11/1/2004	60% Wood flour	Hollow and Solid
19	XTENDEX, E-Deck	Carney Timber	NER-695 (Legacy) 11/1/2004	60% Rice hulls	Hollow
20	WeatherBest, LP Composite, Veranda	Louisiana Pacific	ESR-1088 6/1/2005	60% Wood flour	Hollow and solid
			Polypropylene-based products		
21	CorrectDeck	Correct Building Products	ESR-1341 6/1/2005	60% Wood fibers	Solid
22	Cross Timbers	Elk Composite Building Products	ESR-1590 6/1/2005	Wood flour	Solid
23	K-Decking	Kenaf Industries	N/A (referenced by Principia Partners, 2006)		
			PVC-based products		
24	Boardwalk	CertainTeed	NER-576 3/1/2004	35–45% Hardwood fiber	Solid
25	Millenium	Millenium Decking	ESR-1603 6/1/2006	Wood fiber	Hollow
26	Procell	Procell	ESR-1667 11/1/2006	Flax fiber	Solid

(processed). There is no other natural fiber known to be used in common WPC deck boards on commercial scale, except—on a limited scale—flax, obtained with a good discount.

In order to increase stiffness of composite boards, some WPC manufacturers add mineral fillers to a composition. Why and how minerals increase stiffness, we will consider later. At this point, we would only notice that there are only a few industrially available minerals, which are not prohibitively expensive, for the same reason we have mentioned earlier. Only a few manufacturers of WPC materials use such fillers as calcium carbonate (6–10 ¢/lb), talc (15–20 ¢/lb), and, again, mineral-filled by-products of paper mills (3–9 ¢/lb, processed). In general, all ingredients, combined, should keep material cost of WPC at about 30–40 ¢/lb, or $0.60–1.10 per lineal foot of a deck board because the weight of WPC deck boards is commonly in a range of 1.8–2.8 lb/ft. With manufacturing costs often to be approximately equal to material costs, WPC boards cost about 60–80 c/lb, or $1.20–$2.20 per lineal foot, and in fact are sold for about $2.20–2.80 per lineal foot. As one can see, there is not much room in WPC costs for expensive plastics, fillers, and additives. Compared to retail prices of common 2 × 6 pressure-treated lumber boards, which are around $0.90–1.20 per lineal foot, one can see a challenge that WPC boards face in the market.

Consumer Reports magazine (July 2004, p.22) has quoted the following price figures for 100 ft^2 of a deck (just boards; the cost of railings, stairs, supporting structures, and labor is not included):

- Wood, $190–450. It corresponds to $0.95–2.25 per lineal foot (2″ × 6″ board).
- WPC, $300–720. It corresponds to $1.50–3.60 per lineal foot.
- Plastic or vinyl, $400–1,000. It corresponds to $2.00–5.00 per lineal foot.

Note: As a concrete example, a local lumberyard (Newton, MA) sells in October 2006 2 × 6 pressure-treated boards for $14.24/16 ft. ($0.89/ft.) and Trex deck boards for $41.60/16 ft. ($2.60/ft.). Almost a 3-fold price difference.

Now, regardless of the shape of the WPC board, the materials it consist of, or the aesthetics of the board, the deck board should pass the building code requirements, which are "bind" with respect to materials used. That is, the very same code is for both common wood boards or rails and WPC boards or rails. The principal Acceptance Criteria (AC) for decking and railing systems, the ICC-ES (International Code Council Evaluation Service) AC 174 "Acceptance Criteria for Deck Board Span Ratings and Guardrail Systems (Guards and Handrails)," effective since July 1, 2006, does not differentiate between different kinds of materials decking and railing systems are made from. Wood, steel, concrete, or WPCs, the final product should pass the same building code. This is quite a challenging task for WPC materials.

What are the criteria? Let us come back to our generic WPC deck and boards the deck assembled with.

WPC: BRANDS AND MANUFACTURERS

WPC decking and railing systems brands and manufacturers are given in Table 1.1.

Consumer Reports magazine (July 2004, p.24) has described its investigation of 19 deck materials, three of them were wood (pressure treated, natural cedar, and tropical hardwood), four plastic lumber (Eon, CertainTeed Ever New Vinyl, Brock, and Carefree), one aluminum (LockDry), and 11 WPC boards (Veranda, ChoiceDek, Evergrain, WeatherBest, Trex, Boardwalk, GeoDeck, Timbertech, ChoiceDek, CorrectDeck, and Monarch). Five of them were granted the Best Buy status (board cost per 100 ft^2 is indicated, by the magazine data):

- Eon (plastic lumber), $440
- Veranda, $320
- ChoiceDek, $300
- WeatherBest, $440
- GeoDeck, $430

The magazine has also noted that the following two deck board brands provide with the greatest range in styles:

- Evergrain (four colors and three sizes), $460
- Trex (five colors and sizes), $330.

The rest of the deck board materials were (in the order of residual rating)

- Certainteed Ever New Vinyl (plastic lumber), $1,000
- Brock (plastic lumber), $700
- Boardwalk, $400
- LockDry (aluminum), $700
- TimberTech, $500
- Carefree (plastic lumber), $420
- CorrectDeck, $720.
- Monarch, $590
- ACQ pressure treated lumber, $190
- Cedar natural wood, $320
- Ipe tropical hardwood, $340.

FLEXURAL STRENGTH

The most obvious requirement is that the deck should not collapse under a certain reasonable weight (load). What is a reasonable weight though? The code specifies it as service load and employs a “fail” term rather than “collapse.” The ICC requirement

A typical hot tub for, say, five persons has dimensions of 93″ × 78″, hence, it occupies an area of 50.375 ft^2. Total weight of the hot tub consists of its own weight (1100 lb), water (350 gal, or 2,900 lb), and people (5 × 200 lb = 1000 lb), for a rather heavy scenario, total 5,000 lb. Therefore, the hot tub produces a uniformly distributed load of about 100 lb/ft^2.

is a uniformly distributed load of 100 lb/ft.^{2} of a deck. This roughly correlates to a load that a common hot tub, filled with water and having five adult occupants in it, would uniformly distribute on its support.

However, the ICC code also requires a 2.5× safety factor, on top of the 100 lb/ft.^{2} requirement, that is, a deck should hold a live uniform load of 250 lb/sq.ft. Pretty stringent, isn't it?

What about WPC deck boards? Chapter 7, in this book covers this issue in detail. As a brief example, let us consider two WPC boards—Trex and GeoDeck. Trex has reported that flexural strength of their boards (solid boards of 5.5″ width and 1.25″ thickness) is 1423 psi. It means that a Trex board placed on two joists at 16″ span would have a break load derived from the formula

$$S = PLh/8I$$

where

S = flexural strength (1423 psi in this case)

P = break load, or a center point break load (lb)

L = span (16″ in this case)

h = board height/thickness (1.25″ in this case)

I = moment of inertia, equal to $bh^3/12$ in this case of a solid board, with b = board width, 5.5″. For a standard Trex board, the moment of inertia is equal to 0.895 in^4.

From the above equation, a break load (an ultimate load) for a standard Trex board equals to 509 lb. This would translate to an ultimate uniformly distributed load of 1667 lb/ft^2.

The latter value was calculated using a standard formula for an ultimate uniformly distributed load:

$$W = 16 \times 144 \times S \times I/bhL^2$$

where

W = uniformly distributed load

b = board width

and other factors are defined above.

As one can see, a Trex deck is able to hold 1667 lb/sq.ft. which is more than six times higher than the ICC required load including the necessary safety factor.

Similar calculations for GeoDeck deck show that at flexural strength of the board (hollow boards of 5.5″ width and 1.25″ thickness and moment of inertia of 0.733 in.^{4}) of 2782 psi, a break load at 16″ span (center point load) would be 816 lb. This would translate to an ultimate uniformly distributed load of 2670 lb/ft^2, which is more than 10 times higher than the ICC required load including the necessary safety factor.

These examples illustrate that the flexural strength of composite deck boards is quite satisfactory. It is several times higher than the respective building code requirements. Indeed, out of hundreds of thousands of composite decks installed in the United States, none is known to be collapsed during service from the beginning of composite boards appearance.

How strong a WPC deck board can be? We know that wood is very strong, at least for the same purposes WPCs are intended. As it is shown in Chapter 7, flexural strength of wood can reach 20,000 psi. In WPC, wood fiber is blended with a much weaker polymer matrix, which for high-density polyethylene has flexural strength of about 1400 psi (Chapter 2). In a very simplified case, when, say, 50% plastic–50% wood fiber is *ideally* blended into the WPC, and wood fiber is oriented along the flow, that is, longitudinally, the flexural strength would be equal to a symmetrical superposition of the flexural strength of the matrix and the fiber, which is about 10,700 psi.

In reality, flexural strength of wood–HDPE composites is of 1500–4400 psi for commercial deck boards, up to 5000 psi for laboratory WPC, obtained at carefully controlled conditions, and up to 9000 psi, obtained in laboratory conditions and in the presence of coupling agents. At the lower end of this range are Trex boards, which, according to the manufacturer's data, have a flexural strength of 1423 psi. According to the author's data, Trex boards have a flex strength of 1900–2200 psi (Table 7.13). At the highest end of this range are wood flour (pine, 61–63%) filled HDPE composites, obtained in finely optimized and carefully controlled conditions, using best available lubricants and having flexural strength of 4670 ± 90 psi (without coupling agents) and 9100 ± 150 psi (in the presence of 3% Polybond 3029) (Jonas Burke, Ferro Corporation, private communication). Hence, in the last case flexural strength of the WPC reaches 85% of the theoretical maximum of 10,700 psi.

FLEXURAL MODULUS AND DEFLECTION

If flexural strength is directly related to a break load of a board (in this context) placed on supports, flexural modulus is directly related to a deflection of a board, placed on supports, under a certain load. Unlike the flexural strength of composite boards, typically significantly exceeding building code requirements at commonly accepted spans (such as 16 in. on center), flexural modulus of plastic-based composite boards often puts certain restrictions for their installation.

There are two main situations concerning deflection of boards that may not pass the building code requirements: deck boards at a certain span (distance between neighboring joists) and stair tread at a certain span. Let us consider these situations using the same examples: Trex composite deck boards and GeoDeck composite deck boards. These examples would illustrate general shortcomings of plastic-based composite deck boards in terms of their flexibility and deflection.

Deck Boards

The building code requires that the maximum load at certain deflection of the test span shall be recorded (ASTM D 7042, Section 5). A common load requirement for measuring deflection of deck boards is uniformly distributed live load of 100 lb/ft^2.

If one is to choose common requirements for flooring, a deflection shall not exceed 1/360 of the span (The BOCA® National Building Code/1999, Section 1604.5.4).

Deflection under uniformly distributed load is determined by the following formula:

$$D = 5WbL^4/384 \times 144 \times EI$$

where

W = uniformly distributed load (100 lb/sq.ft in this case)

D = deflection, in inches, at the load W (should not exceed 16″/360 = 0.0444″ in this case)

b = board width (5.5 in. in this case)

L = support span, in inches

E = flexural modulus, psi

I = moment of inertia, $in.^4$

For Trex boards (E = 175,000 psi as reported by Trex, with $I = 0.895\ in.^4$), deflection under uniformly distributed load of 100 $lb/in.^2$ at 16-in. span would be 0.021 in., which is within the building code requirements. However, at support span of 24 in., deflection at the same conditions would be 0.105 in. that significantly exceeds the allowable limitation (24″/360 = 0.0667 in.).

For GeoDeck boards (E = 374,000 psi, $I = 0.733\ in.^4$), deflection under uniformly distributed load of 100 $lb/in.^2$ at 16-in. span would be 0.012 in., which is within the building code requirements. Furthermore, at support span of 24 in., deflection at the same conditions would be 0.060 in., which is also within the allowable limitation (0.0667 in.).

As a result, for Trex boards (5/4 × 6) maximum decking span at 16 in. at 100 lb/ft^2 is allowed (ICC-ES Report ESR-1190), and for Geodeck (5/4 × 6) at 24 in. is allowed (ICC-ES Report ESR-1369). Only two WPC deck boards, GeoDeck and TimberTech (ICC-ES Report ESR-1400) are allowed to employ 24-in. span on decks; three more WPC commercial deck boards are allowed to have 19–20-in. span; 14 WPC commercial deck boards on ICC-ES record have 16-in. allowable span; and one WPC board has allowed only 12-in. span on decks.

These records show that flexural modulus of commercial WPC deck boards (and the respective span on decks) certainly has room for improvements. This in turn will improve quality of WPC boards and save money and material on deck joists. This conclusion is supported by consideration of support spans for stair treads (see below).

Stair Treads

The building code requires that the maximum deflection of deck boards used as stair treads under concentrated load of 300 lb placed at midspan shall be 1/8 in. (3.2 mm) or 1/180th of the span (AC 174, Section 4.1.1; 2000 International Building Code, Section 1607.1). For 16-in. span, the allowed deflection is either 0.125 in. or 16″/180 = 0.089 in.

At a span of 16 in. on center, deflection of stair tread under 300 lb of load will be approximately defined by the following equation:

$$D = PL^3/48 \times EI$$

where
D = deflection, inches
P = 300 lb, center point load
L = span, 16 in.
E = flexural modulus
I = moment of inertia.

For Trex solid board (see above) deflection at a span of 16 in. would be equal to 0.163″. It is too much for both criteria, which is 0.125″ and 0.089″ allowable deflection. The span would not pass.

Even for a span of 12 in., with the allowed deflection of 12″/180 = 0.067″, the deflection for this solid board under concentrated load of 300 lb would be 0.069″, which is slightly higher than the allowed one (L/180). Indeed, in ICC-ES Report ESR-1190 maximum stair tread span for Trex boards is listed as 10.5 in.

For hollow GeoDeck, a calculated deflection at a span of 16 in. would be equal to 0.093 in., which is slightly higher than 16″/180 = 0.089″, but within the allowed 1/8 (0.125) in. Direct experiments with GeoDeck boards as stair treads showed that the 16″/180 deflection was reached at an average 301 lb, which is satisfactory compared with the designated 300 lb.

Overall, for 12 WPC deck board brands for which allowable stair tread span is on ICC-ES record (published in the respective ICC-ES reports), only two (CorrectDeck and GeoDeck) have allowable span of 16 in., six have allowable span of 12 in., and four have allowable span of 10.5″, 9″, or even 8 in.

This again shows that stiffness of commercial WPC deck boards (and the respective span on decks and stair treads) certainly can and should be improved. This in turn will improve the quality of WPC boards and bring them closer in this regard to stiffness of real wood. This is one of the most challenging tasks for WPC materials.

In a similar manner, as it was discussed in the preceding section, we can ask—how stiff a WPC deck board can possibly be, if not filled with mineral fillers? We know that wood is very stiff, at least in applications WPCs are intended for. As it is shown in Chapter 7, flexural modulus of wood is about 1,500,000 psi. Polymers are much more flexible, and flexural modulus for HDPE is at best at 150,000 psi (Chapter 2). Again, in a very simplified case, for 50% HDPE – 50% wood fiber composites, in which both principal ingredients are ideally mixed and wood fiber is oriented along the flow, that is, longitudinally, the flexural modulus would be equal to a symmetrical superposition of the flexular moduli of the matrix and the fiber, which is about 825,000 psi.

In reality, for industrial WPCs, exemplified again with Trex, it is 175,000 psi, which is about five times less. For best laboratory WPCs, flexural modulus is close to 700,000 psi in the absence of coupling agents (696,000 ± 30,000 and 717,000 ± 33,000 psi for a wood flour-filled HDPE in the presence of two different lubricants) and slightly higher in the presence of coupling agents (727,000 ± 25,000 and 773,000 ± 13,000 psi, respectively; Jonas Burke, Ferro Corporation, personal communication). Hence, in the last case flexural modulus of the WPC reaches 88–94% of the alleged theoretical maximum of 825,000 psi. It fits rather well with a similar 85% figure for flexural strength of experimentally available WPC with respect to the alleged theoretical maximum (see the preceding section).

Composite decking has become a large established category of building products, particularly for decking and railing systems and related outdoor structures, such as deck stairs. Composite building products present significant advantages over traditional materials, and, as a result of it, composites are one of the most rapidly growing segments of the building products industry. The WPC deck boards segment in particular is estimated in 2005 at $766 million, and in 2006 (forecast) at $929 million. In addition, composite railing systems contributed $190 million in 2005 and $271 million in 2006 (forecast). It makes a total of $956 million in 2005 and $1.2 billion in 2006 (forecast) [1].

THERMAL EXPANSION–CONTRACTION

This is a rather unpleasant phenomenon of decks made of WPC boards, hence, a very important area for R&D of WPC. Almost exclusively (except specially engineered and aerospace-designed materials), all solid materials expand almost linearly (in every direction) with increasing temperature and contract with decreasing temperature. It is this degree of expansion–contraction that can make the phenomenon an unpleasant one, and at the same time challenging for designers with plastic and composite decking. Would consumer like it if the ends of deck boards would quite visibly stick out of the deck frame for extra several inches on a hot day and completely disappear under the deck frame on a chilly night? Well, may be not that much as several inches, but··· how much?

The coefficient of linear expansion–contraction (CTE, for coefficient of thermal expansion) is a measure of the "how much." In fact, the coefficient numerically describes a fraction of the board length that would be added to (expansion) or subtracted from (contraction) per 1°C temperature. If, for example, a 20-ft WPC board is elongated by 1/2 in. when the board surface temperature increased from 70 to 130°F, the coefficient of linear expansion is $0.5''/240''/60$ deg $= 3.47 \times 10^{-5}$ 1/deg. This, by the way, is in the neighborhood of a very typical value for expansion–contraction of WPC boards.

Wait a minute, one would say—is not the 130°F a little bit too high a temperature, even on a hottest day?

No, it is not too high for some situations. Commonly, on a summer afternoon a deck surface temperature is higher than the air temperature. To be more specific, it is 40° higher in the North and 50° higher in the South. Hence, if the air temperature increases from 70° in the morning to 90° in the afternoon, by about 2 P.M. a deck surface temperature will be about 130° (North) and 140° (South).

For neat plastics, the CTE is about twice as much compared with WPC boards, which are about 50% filled with nonplastic materials, which is wood fiber and sometimes minerals. As the coefficients of expansion–contraction of both wood fiber and minerals are about ten times lower than those for WPC materials, hence, the reduction in the coefficient's value for filled WPC. In reality, the picture is somewhat more complicated because it is the expansion–contraction of wood *along the grain* that is 10 times lower compared to common WPC. Expansion–contraction of wood across the grain is close to that of WPC. That is, an orientation of wood fiber in a WPC material can increase or decrease the coefficient of expansion–contraction.

The longer the fiber (the higher is the fiber aspect ratio) and the more it is oriented longitudinally, along the deck board, the lower is the coefficient of thermal expansion–contraction. Overall, for different commercial WPC deck boards the coefficient is in the range of 2×10^{-5} to 5×10^{-5} 1/°F. In other words, some commercial WPC boards can expand–contract by 250% higher than others. These "overexpanded" decks are very noticeable and sometimes cause complaints from the deck owners.

The WPC decking products have realized an annual growth sales at an explosive rate of over 30% per year over the last 10 years [3]. WPCs were projected to grow at a rate of 23% in 2006 in terms of volume, reaching 608 million lineal feet and approximately $1.2 billion in market, value [1]. By 2011, the market for composite decking is expected to surpass $2 billion, or a third of the overall decking market according to estimates from The Freedonia Group [2]. Among the advantages being recognized by consumers for the last decade are lower (compared to wood) maintenance requirements, including no need for staining, sealing, and painting, higher resistance to termites and wood-destroying microbes, the absence of knots and splinters, and environmentally friendly characteristics compared to preservative-treated lumber.

There are two principal ways to decrease a magnitude of expansion–contraction of WPC deck boards. First, to change the formulation of WPC material (less plastic, different fillers, higher fiber aspect ratio) and/or the extrusion regime (the faster the extrusion speed, the more longitudinal is the orientation of the fiber). Second, to better restrain boards on the deck, employing more powerful nails or screws. The moving forces of expanding–contracting boards can be neutralized and blocked by powerful fasteners. Certainly, in these cases the stress has to go somewhere, and it can be expected that at some point the restraint would manifest itself into torsion damage in the joist substructure underneath, or into damage of the boards themselves. However, for these WPC boards (exemplified by GeoDeck) that were observed to be resrained enough on a real deck and not to thermally expand–contract, such damages have not been noticed. However, when fasteners (screws) were being removed, these boards were producing sounds like a guitar string. Hence, they indeed "held" a good deal of stress.

Overall, values of expansion–contraction of WPC boards are largely unpredictable and represent highly empirical values. To make composite deck boards with truly minimized coefficients of thermal expansion–contraction is a very challenging task, not resolved as yet in the industry.

SHRINKAGE

Unlike linear thermal expansion–contraction, which is a completely reversible phenomenon, shrinkage of WPC boards is a one-way, irreversible, though limited process. If contraction of deck boards on a chilly night or during winter seasons opens a gap (sometimes 1/8 to 1/4 of an inch on long decks), the gap is typically closed on a warm day or during summer seasons. However, when boards shrink, the gap is never closed back (Figs. 1.26 through 1.29).

Shrinkage happens when a plastic-based board, extruded and pulled from the die, cool too fast. Too fast means that stretched long polymer molecules, coming from the die, do not get enough time to settle, to come back to their thermodynamically favorable coiled form. They are "trapped" in the board solidified matrix in an unsettled, stretched shape.

To be exact, these "distorted in space" polymeric molecules continue to get rearranged into their energetically minimized shape, but at ambient temperature rates of this rearrangement are too slow, about 100 million times slower than those at hot melt temperature. If it would take 5 s for a polymer molecule to coil from its stretched shape at hot melt temperature, at ambient temperature it would take about 16 years.

However, on a deck on a hot summer day, it might take only a few weeks. In the North, it might take a year or two (see the insert).

How were those temperature-dependent figures for deck shrinkage obtained?

Let's take hot melt temperature (HDPE-based WPC) as 300°F (about 150°C). The temperature coefficient for polymer molecules conformational rearrangements, which is a change in speed of the process by each 10°C, approximately equals to 4. This value for so-called cooperative processes is significantly higher than common temperature coefficients, typically between 2 and 3.

In this case, a temperature drop from 300°F (about 150°C) to ambient 70°F (about 20°C) would result in 4^{13} slower rate of the polymer molecules rearrangements, which is approximately 10^8, or 100,000,000 times.

Five hundred million seconds approximately equal to 139,000 h, which is 5800 days, or 16 years.

Increase of temperature from 70°F (about 20°C) to 140°F (60°C) on a deck would accelerate the rearrangement of polymer molecules in $4^4 = 256$ times, which is from 16 years to 23 days of hot temperature on the deck.

At 200°F (about 90°C), deck boards would further accelerate the rearrangement of polymer chains in $4^3 = 64$ times faster than that at 60°C (see above), which is in about 9 h. This is a common annealing time period for WPC deck boards.

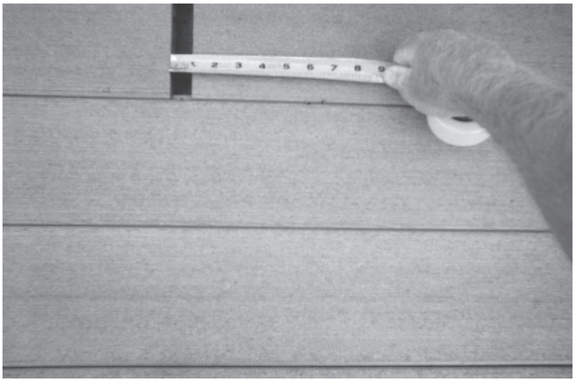

Figure 1.26 An 1-in. gap due to shrinkage of composite deck boards on a deck.

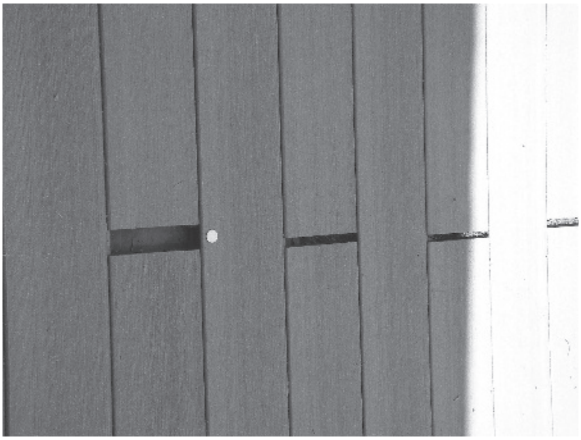

Figure 1.27 Shrinkage of WPC board.

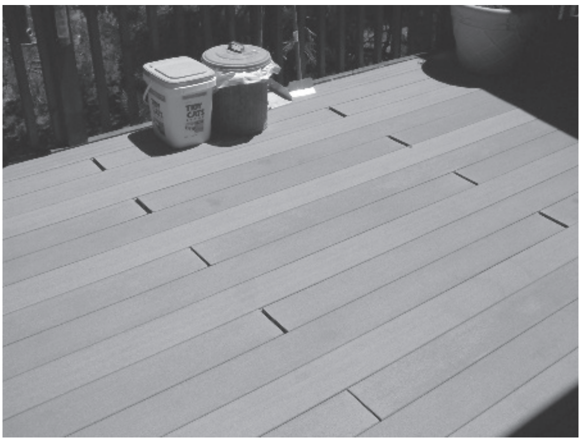

Figure 1.28 Shrinkage of WPC boards.

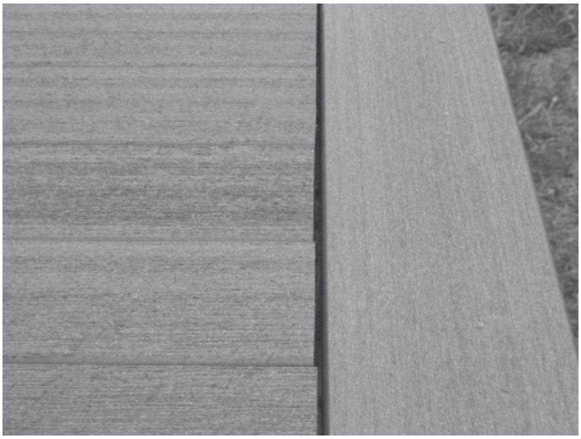

Figure 1.29 Shrinkage of WPC boards.

In order to eliminate shrinkage, WPC boards are treated by annealing them in a chamber between 180 and 200°F for about a day (see color insert).

It should be noted here that shrinkage is observed, and a respective annealing is required, as a rule, only for profile (hollow) WPC boards. Solid boards, because of their mass, are cooled much slower than that of hollow boards, hence cooling time for solid boards is typically long enough to have stretched polymer molecules to settle in their coiled form. Therefore, shrinkage often is an issue only for hollow WPC boards.

The amount of postmanufacturing shrinkage has several variables and depends on the WPC formulation (especially the percentage of plastic in formulation), the extrusion speed, the cooling regime, the density of the resulting board, and the downstream pooling (and the rate of pool). While still hot, the rate of shrinkage is rapid, so the faster the cooling rate, the higher the postmanufacturing shrinkage. In its worst case, postmanufacturing (in-service) shrinkage reaches 0.3–0.5% of the board length, which is 3/4″–1¼″ for a 20-ft long board. For shorter boards, shrinkage is proportionally smaller.

SLIP RESISTANCE

Slippage on a deck is a very serious matter. A broken limb can financially devastate a good company, particularly if it is not an isolated case.

Generally, WPC deck boards are more slippery than the wood boards. It is easy to verify using a simple experimental setup. Take a 4-ft. conditioned (not wet) board, fix it at a certain angle, place onto the board a leather-sole shoe with a chunk of a heavy metal in it (to increase the weight of the shoe for its stability on the board), and slowly (or step-wise) incline the board until the shoe starts to slide down. With a wood board (such as pressure-treated lumber), it will happen at an angle of about

29° (at the ratio of an opposite side of the triangle to the adjacent side, which is at the tangent ratio of about 0.55). With WPC boards, the same shoe will start sliding down at an angle of about 16–26° for different WPC materials with brushed or unbrushed board surface (the tangent ratio between 0.28 and 0.48). These tangent ratio values in a simplified case are called the coefficient of friction of the board

An Angle of the Triangle (Deg) Versus the Tangent Ratio Table (the Coefficient of Friction)

16	0.29
17	0.31
18	0.33
19	0.34
20	0.36
21	0.38
22	0.40
23	0.42
24	0.45
25	0.47
26	0.49
27	0.51
28	0.53
29	0.55
30	0.58
31	0.60
32	0.62
33	0.65
34	0.67
35	0.70
36	0.73
37	0.75
38	0.78

The coefficients of friction should be determined in more controlled conditions and using professional equipment, as it will be shown below in this book in Chapter 11, but for illustrative purposes the experiment described above would be good enough. It will show that WPC boards are commonly more slippery than wood boards, that some WPC boards are more slippery than others, and that wet boards, both wood and WPC, are less slippery than dry boards. The last statement sounds counterintuitive, however, thanks to the capillary effect of wood and WPC materials, it is, as a rule, true. For the shoe to slip down, wet wood and WPC boards should be inclined up to 34–36° (the coefficient of friction of 0.67–0.73).

At more controlled laboratory conditions, the coefficient of friction for dry wood boards is about 0.70–0.90 and that for dry WPC materials is typically between 0.40 and 0.65.

There is a common perception, but not supported by building code documents (or supported by some outdated documents) that the coefficient of friction for any materials made for walking surfaces should be not less than 0.50, in order to be safe. Not all WPC deckboards would satisfy this (unofficial) criterion.

In order to minimize slippage, some WPC manufacturers texture the surface of their material (typically brushing or deep embossing). It is known that some types of plastic, for example, low-density polyethylene, are noticeably less slippery (have higher coefficient of friction) than other plastics (for example, high-density polyethylene). However, making of WPC boards with predetermined and controlled traction properties is generally not among WPC manufacturers concerns as yet.

WATER ABSORPTION, SWELL, AND BUCKLING

WPC materials will absorb variable amounts of moisture, some more, some less. Why so, it will be discussed later. When immersed into water, they absorb moisture typically between 0.7 and 3% by weight after 24 h of the immersion. This can be compared to water absorption by wood, such as pressure-treated lumber, which absorbs about 24% water by weight after 24 h of immersion. When immersed into water for much longer time, commercial WPC materials absorb up to 20–30% of water, wood more than 100% by weight.

Water absorption by WPC materials may lead to a number of unpleasant events. One is board distortions, swelling, and buckling (Figs. 1.30 and 1.31). Another is mold propagation. Also, saturation of WPC boards with water sometimes decreases flexural modulus of the boards, hence, results in a higher deflection under load. Besides, water absorption leads to a faster board deterioration, oxidation (water is a catalyst of plastic oxidation), and other negative consequences.

WPC materials absorb water due to their porosity. The base plastic material of WPC, such as neat HDPE, practically does not absorb water. However, after being filled with

Figure 1.30 WPC deckboards distortions, swelling, and buckling.

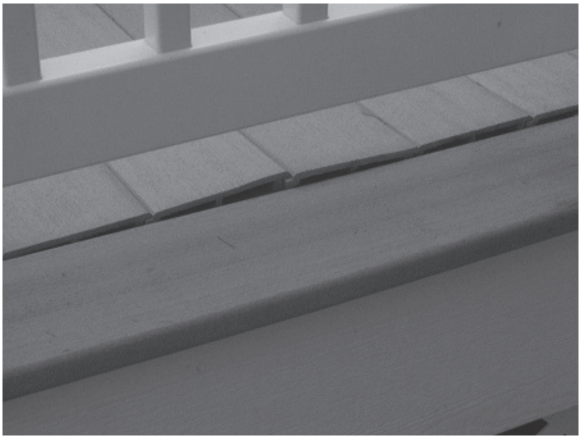

Figure 1.31 A typical appearance of a composite deck in case of buckling or thermal expansion of WPC boards.

cellulose fiber, minerals, and pigment additives (which often contain free metals, serving as effective catalysts of plastic oxidation), and during processing at high temperatures, plastic undergoes rather noticeable degradation, depolymerization, which leads to VOC (volatile organic compounds) formation. Along with it, moisture in cellulose fiber is converted to steam at hot melt temperatures and also adds to microbubbling in the hot melt. Steam and VOC make the material foamed, with noncontrolled porosity. This noticeably decreases the density of the final WPC product. For example, Trex's specific gravity (density) theoretically should be 1.10 g/cm^3, in reality it is reportedly 0.91–0.95 g/cm^3 (Trex data). Even the very fact that the range of density is listed indicated that this parameter is poorly controllable. These densities indicate that porosity of Trex material is between 16 and 21%. When the material is immersed, water fills this void volume.

How the theoretical specific gravity (density) of WPC can be calculated?

Trex example (50% HDPE, 50% wood flour).

100 g of the composite material contain 50 g of HDPE (d = 0.96 g/cm^3) and 50 g of wood flour (d = 1.30 g/cm^3). Each of these components takes the following volume:

HDPE 50 g/0.96 g/cm^3 = 52.083 cm^3,

Wood flour 50 g/1.30 g/cm^3 = 38.462 cm^3.

Therefore, total volume of the 100 g of the composite will be 90.545 cm^3. Hence, specific density of the composite is 100 g/90.545 cm^3 = 1.104 g/cm^3.

Water absorption accelerates mold growth because water is a necessary component for microbial life. Typically, materials that have moisture content of 19% or lower do not support the growth of mold. This amount of moisture can be retained in the very thin upper layer of WPC profiles in humid, moist areas, with inadequate deck ventilation, for an indefinitely long time. In cases where installation instructions are violated and deck boards are installed too close to the ground, or they can be installed high enough, but the deck is "boxed" and completely isolated underneath, creating a perfect "greenhouse," which is moist and wet—in these cases moisture content in WPC deckboards can exceed 20–25% and stay long enough at that level. These are very favorable conditions for mold growth and possibly creating the respective health issues.

> Most composite decking manufacturers utilize high-density polyethylene, (HDPE), polypropylene, or polyvinylchloride (PVC) as polymer matrix, and wood flour or rice hulls as the principal filler for their products. Some manufacturers also add mineral fillers, such as talc. These and other changes in compositions make composite materials to vary in their appearance, shape, strength, deflection, moisture absorption, fade resistance, microbial resistance, slip resistance, flammability, and other properties, which will be discussed later in this book.

That is why installation instructions for many composite decks prescribe a deck to be installed at least 12 in., and preferably 24 in. from the grade or rooftop, or provide a wider space between boards (such as 3/16″ or even 1/4″). Some installation instructions say that failure to adhere to proper ventilation may void the warranty.

When WPC boards absorb water, they swell. When the boards are in close contact with each other, a very high pressure can develop in the area of contact, reaching several thousand pounds (Fig. 1.32). This may lead to boards buckling.

> Composite decking materials are manufactured under heat and pressure to encase the cellulosic fiber in the plastic, resulting in a product with high resistance to weathering, moisture, insect infestation, and decay. In reality, the encasement is never complete, which leaves room for water absorption, thermal- and UV-induced oxidation with oxygen from the air, and microbial contamination.

Typically, for WPC boards to be buckled they should be contacted with water for a long time, days and weeks. However, the lower the board density and higher the swell, the more likely boards would buckle after their shorter exposure to water. Buckling typically results from an improper installation of a composite deck—causing a prolonged contact with water (from outside or from inside of deckboards, such as for hollow boards), lack of proper gapping, and so on.

In order to minimize water absorption by WPC boards, they should have as high a density that their formulation allows. To achieve this goal, a proper amount of antioxidants should be introduced to the formulation.

Antioxidants slow down the plastic degradation under high temperature, attrition, and so on, hence, minimize the VOC formation and the respective decrease of density. Moisture in the ingredients also leads to a decrease of the final density of the material, hence, cellulose fiber should be dried, if necessary. Last, but not the least, vented extruders remove VOCs and steam from hot melt and greatly increase density of the final product.

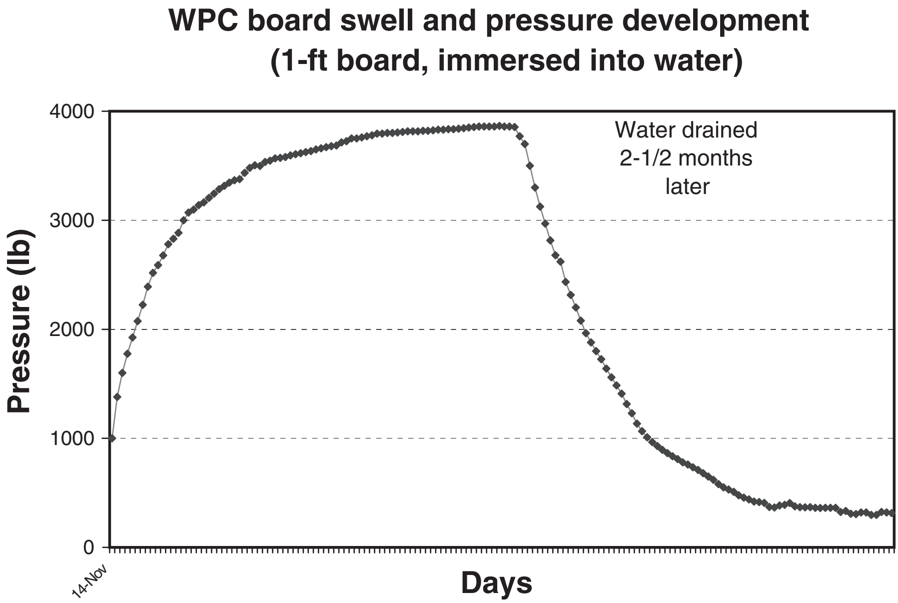

Figure 1.32 Pressure development by a composite deck board (13.5-in. long and 5.5-in. wide) immersed into water, for 2-1/2 month. The initial pressure, caused by holding clamps, was 1000 lb. After 80 days, water was drained and the board was getting dry with the resulting pressure release for the following 2-1/2 months .

MICROBIAL DEGRADATION

On May 28, 2004, the Superior Court of New Jersey certified a nationwide class action in a case originally filed in 2000 against Trex Company, Inc. and ExxonMobil Corp. The case alleged that the Trex product was defective. A press release by the Law Offices of Marc B. Kramer, P.C., which announced the class action on June 2, 2004, said: "In addition, although the Company claims that the product does not need sealants, after the product exhibits mold, the Company allegedly recommends that consumers apply sealants."

While we are not going to discuss here merits of the class action and history of the case, we just point out at the words "after the product exhibit mold···" apparently recognized by the manufacturer.

Mold of the product was one of the main reasons of the class action against Trex. This is how serious it can be. Deck Forum (http://www.mrdeck.com/deck_forum_trex.html) contains many complaints about mold on Trex decks, such as

> ··· had a black mold problem that was coming up from the inside ··· Even after stripping and acid wash, this material would still have the black mold come back up in a few months (10/02).
>
> ··· It was molding from the inside out (11/03).

··· terrible mold and stains (02/04).

··· The deck is absolutely covered with dark spots which do not come off with cleaning (03/04).

··· I built a Trex deck in 2003 that gets full sun all day long. This past summer it developed mold spots all over it (02/05).

The issue of where mold is coming from and in which form is covered in detail in Chapter 13 in this book. In this introduction overview, we just mention that appearance of mold on some WPC decks and stairs (Fig. 1.33) can be made more likely by certain types of a WPC formulation (and less likely by other compositions of WPC), by improper deck installation, and by climatic conditions.

WPC formulations that invite mold are those with a relatively high porosity (typically made using moist wood fiber) and, hence, having lower density that it might be in the final product. Particularly, it happens if the WPC profile is extruded in the absence or with not enough amounts of antioxidants. Typically, these WPC materials absorb more water than other WPC products in the market. Formulations that make mold on the deck is less likely, contain not only antioxidants but also minerals, which create a natural barrier for microbial degradation of WPC materials. Obviously, biocides and other antimicrobial agents in the formulation help to prevent or slow down mold on decks.

Figure 1.33 Mold stains on a WPC.

Figure 1.34 Black mold on a WPC material.

As an example, a WPC post sleeve is shown in Figure 1.34. It was made with no added antioxidant, unlike regular post sleeves. As a result, it absorbed water in the amount of 3% per bulk material (after 24 h under water) compared with a regular value of 1%, and after some outdoor exposure developed black mold.

Improper installation of WPC decks is associated typically with lack of ventilation at the bottom of the deck and/or deck level too close to the ground, particularly when ground is wet. Water in these decks is retained for a long time and that in turn creates more favorable conditions for mold to grow. Naturally, in wet areas rain water absorbed by decks dries out much more slower than in dry areas, which may lead to mold on decks (see, for example, Fig. 1.35).

Figure 1.36 illustrates a curious case, when WPC rails, quite resistant to mold, were wrapped into corrugated carboard for shipping. Being stored in a wet and warm place, the cardboard was heavily infested and almost completely destroyed by mold. Otherwise intacted composite handrails were soiled with metabolic products of the mold.

Unfortunately, antimicrobial components (often as much as $15–50/lb) are often too expensive to be affordable by WPC deck manufacturers. Biocides for plastics

Figure 1.35 Mold on a composite deck board.

are commonly designed aiming at a quite a different, higher, price structure, which takes place in, say, small plastic-made biomedical devices. If there is a cost, for example, $10 for a two ounce device and $50/lb for a biocide, the latter cost is still affordable at 0.1% biocide load. This would increase cost of the device by 0.6¢, or by 0.06% of the total cost of the product. However, 0.1% of the $50/lb biocide in WPC deck boards that cost otherwise $0.30/lb would increase the cost of boards by 5¢, that is, by 17% of the cost.

Realistically, at 0.2% of an effective antimicrobial agent in a WPC formulation and the allowable price of the formulation to be increased by 1¢ (cost of materials), cost of the biocide should not exceed $5/lb.

Figure 1.36 Black-colored metabolic products of *Gonatobotryum* and *Epicoccum* on the surface of composite handrails.

TERMITE RESISTANCE

In the list of homeowners' problems, termites rate ranks very high. According to the Boston Globe, which in turn refers to Bay Colony Home Inspections, between 20 and 25% of the homes sold in most areas of New England have termites or have had them in the past. Toward the South of the United States problem is higher. And, of course, termites not just live around the house. In many cases, termites eat as much as 80% and more of all the structural components of a house, including its deck, if it has one. According to Home Inspection data, in 70% of the above cases the termites have been treated and returned.

There are several main types of termites. Some of them require elevated moisture content, such as dampwood termites (Fig. 1.37). Some live deep inside wood, such as drywood termites (Fig. 1.38). Some live in colonies in the ground and build tunnels, using wood as their food (Fig. 1.39). These pictures were provided with permission by Specialty Termite, Inc. (Pleasanton, CA).

WPC materials are commonly very resistant to termites. Despite that wood fibers are not completely—as a rule—encapsulated into the plastic matrix, and form a sort of continuing chains across WPC materials (unless the ratio of plastic to fiber is really high, more than 80%), termites cannot get into the plastic matrix. At best, termites can only slightly trim cellulose fiber at the WPC surface.

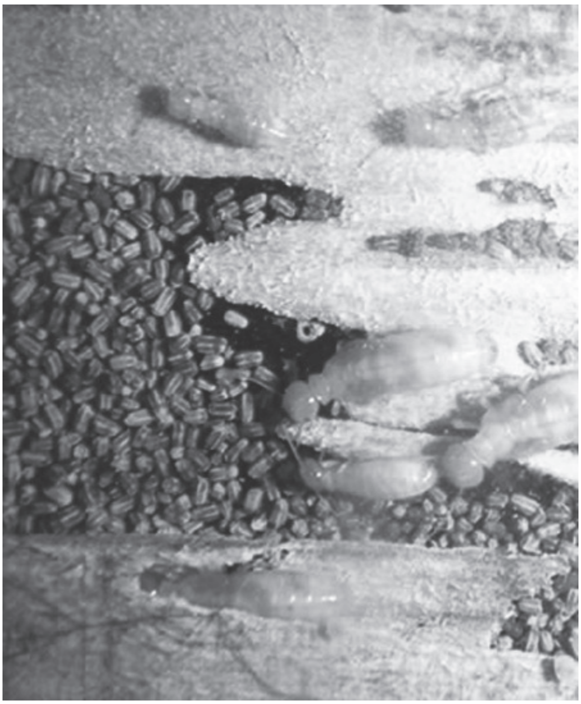

Figure 1.37 Dampwood termites on wood (© Specialty Termites, Inc.).

Figure 1.38 Drywood termites on a wood post base (© Specialty Termites, Inc.).

As a result, weight loss of WPC materials by termites is negligible, if anything. Let us consider GeoDeck composite board as an example. It was subjected to termites collected from a colony of subterranean termites *Reticulitermes flavipes,* according to a procedure given in ASTM D3345-74. Five of 1.00 × 1.00 × 0.25 in. blocks of Southern Yellow Pine sapwood and five blocks cut from WPC board were exposed to termites for 8 weeks. With the wood samples, weight loss due to termite action was of 9.1 ± 0.7%. With the WPC samples, two out of five samples were practically untouched (no weight loss), and an overall average weight loss was 0.2 ± 0.2%.

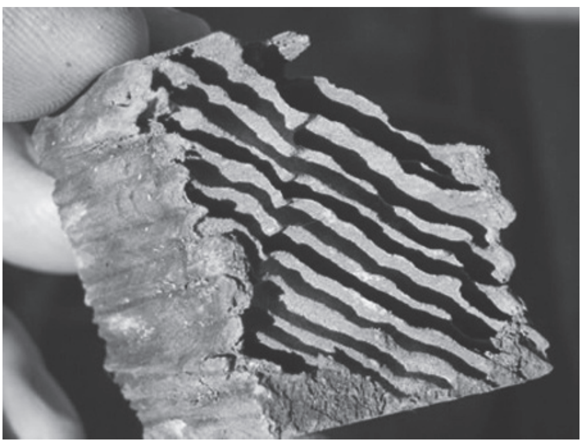

Figure 1.39 Subterranean termite damage in wood (© Specialty Termites, Inc.).

Here are few examples of termite resistance ratings, showed in the respective company records:

- Trex, rating 9.6
- GeoDeck—No attack, rating 10
- Nexwood—No damage, rating 10.

One can see that commercial WPC deck boards are dramatically more termite resistant than wood lumber.

FLAMMABILITY

Polyethylene and polypropylene-based WPC materials are flammable (see, for example, Fig. 1.40).

Flammability of materials is characterized by many different ways, one of them is the flame spread index (FSI). As reference values, FSI for inorganic reinforced cement board surface is arbitrarily set as 0, and for select grade oak surface as 100 under the specified conditions. FSI for ordinary wood species is typically between 100 and 200, and for some special cases it is as low as 60–70. An average FSI for about 30 different wood species is 125 ± 45.

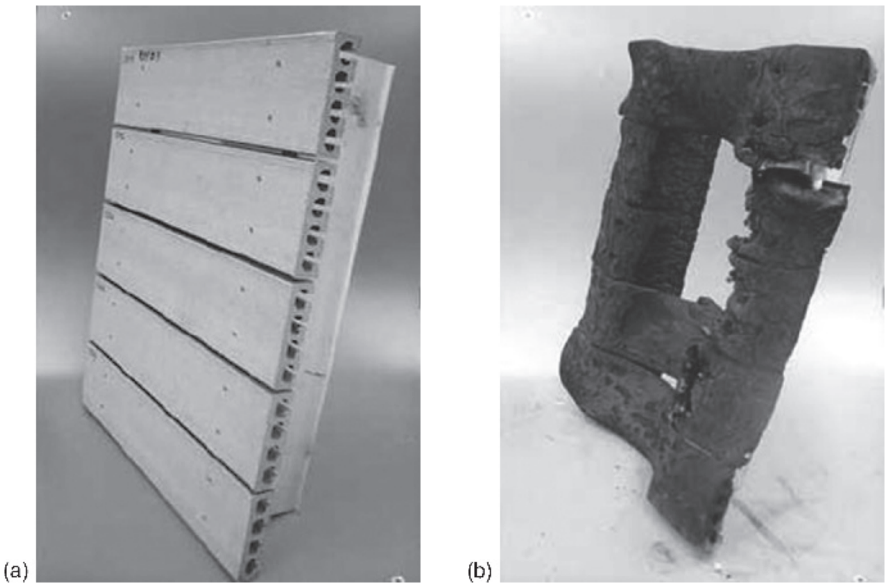

Figure 1.40 WPC deck boards before and a few minutes after ignition (by permission from the University of California Forest Products Laboratory).

For comparison, wood fiber-filled HDPE hollow boards have an FSI around 150, solid boards about 80–100, WPC hollow boards containing minerals have an FSI around 100, and PVC-based wood-filled deck boards typically have an FSI between 25 and 60.

Both ordinary wood species and most of WPC deck boards belong to Class C category of flammability in terms of flame spread. There are four basic categories, or classes, for flame spread index: Class A, with FSI between 0 and 25; Class B, with FSI between 26 and 75; Class C, with FSI between 76 and 200; and below Class C, with FSI above 200 (unclassified materials). Classes A, B, and C sometimes are called Classes I, II, and III.

Until recently, the flammability of WPC decks was not even a concern. Decks were not supposed to be inflammable. What is a point if the house would burn and the deck would stay, right? Then it was recognized that brushfires often ignite a house via the deck. Now legislatures of several states, California first, are working on a new law, according to which decks should be fireproof to some extent. This poses a new challenge for WPC decks. The new law is scheduled to be effective in the state of California starting January 2008.

Technically to make a WPC deck of a low flammability is not difficult. Principally, there are two ways to go—either to load a WPC formulation with flame retardant components or to employ PVC (or other low-flammable plastics) as a base plastic for WPC. Chapter 14 considers these issues.

As always, optimization is a name of the game. PVC is not considered as an environmentally friendly material. When ignited, the resin releases hydrogen chloride (HCl), a toxic and volatile strong acid. If not stabilized properly, PVC can release HCl under direct sunlight, at high temperature of a hot deck surface on a sunny summer day. Some flame retardants, particularly polybrominated diphenyl esters, are also far from being benign. Mineral flame retardants, such as aluminum trihydrate and magnesium hydroxide, are required at a high loading level (up to 40–50% w/w) to be effective.

Considering that plastic often takes 40–50% w/w of flame retardants, there is no room for wood filler in WPC, which will not be WPC anymore but rather a mineral-filled plastic. At any rate, replacement of wood fiber of 3–5 ¢/lb with mineral flame retardant of 20–30 ¢/lb would significantly increase the cost of the resulting material. All these questions pose a great challenge to WPC manufacturers aiming at fireproof composite deck boards.

OXIDATION AND CRUMBLING

One of the most unpleasant, damaging, and unexpected features of some WPC materials happened to be their elevated vulnerability to oxidation, leading to board crumbling (Figs. 1.41–1.44). In the progress of crumbling, the WPC board shows tiny and then developing cracks, its surface becomes dustier and softer, until one can easily scratch it, leaving deep tracks. Eventually, the board can collapse under its own weight.

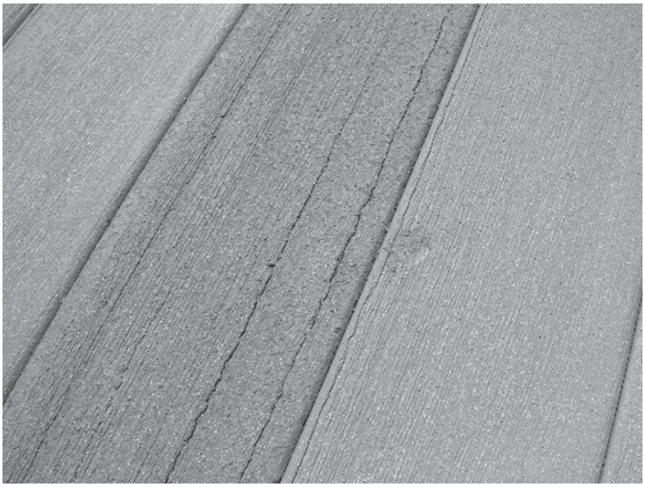

Figure 1.41 An intermediate step of crumbling of Cedar tongue-and-groove composite deck board (Arizona).

There are number of factors leading to accelerated WPC oxidation, and lack of antioxidants (in the initial, incoming plastics), and/or insufficient amounts added to the formulation is the most important of them. Adding antioxidants aims both at preserving the plastic during the processing at high temperatures and protecting the WPC profile during service on a deck under the damaging effects of sunlight, air oxygen, water, pollutants, and other elements.

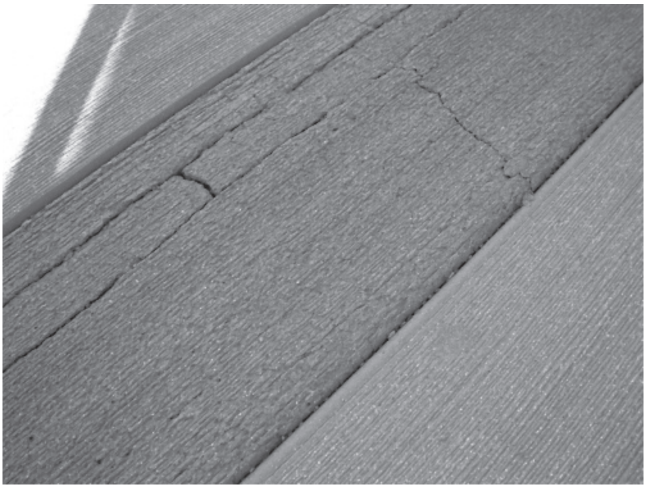

Figure 1.42 An advanced step of crumbling of Mahogany tongue-and-groove composite deck board (Arizona).

Figure 1.43 An advanced step of crumbling of Mahogany tongue-and-groove composite deck board (Arizona).

Briefly, antioxidants quench free radicals that are formed in the process of plastic degradation by oxygen and initiated by temperature and UV light, and assisted by moisture, stress, presence of metals, and other catalysts of plastic oxidation. If not intercepted by antioxidants, the polymeric plastic is degraded (depolymerized) so much that it loses its integrity and ceases to be a plastic anymore. It is converted to a loose powderous material, mainly a filler.

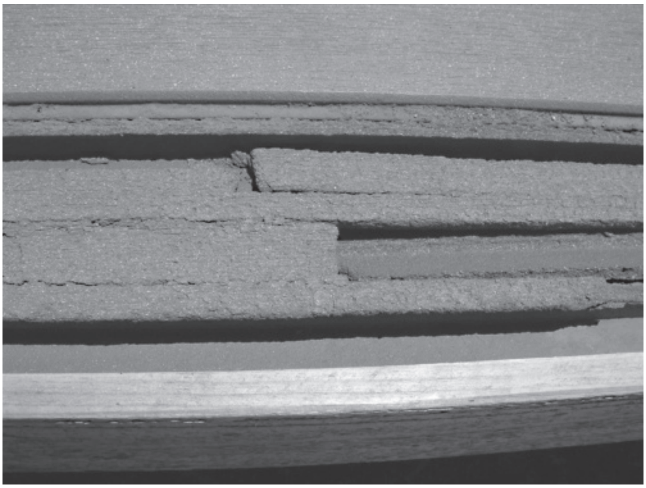

Figure 1.44 Catastrophic failure of Mahogany tongue-and-groove composite deck board due to an oxidative degradation (Arizona).

Other factors that accelerate WPC oxidation, hence, decrease durability and shorten a deck's lifetime, are decreased density (specific gravity) of the board compared with the maximum density for the same board, presence of metals (in pigments, lubricants, and other additives), moisture content, and unsettled stress in boards. Decreased density is the result of an increased porosity of the boards, due to moisture presence in the initial ingredients of the WPC (of wood fibers first of all) and plastic degradation during the processing (due to overheating, excessive shear and/or lack of antioxidants). An excessive porosity allows oxygen to permeate into the WPC material "from inside," significantly increasing the accessible surface area, along with the rate of oxidation. Metals, particularly free metals, often are efficient catalysts of plastic oxidation. Moisture is also an effective catalysts of plastic oxidation.

Until recently, the effects of these factors and their quantitative manifestation were practically unknown and not even recognized, neither in the WPC industry nor in academic research in the area. That is why the acute deterioration and crumbling of some WPC boards turned out to be quite unexpected and puzzling, and resulted in some cases in an avalanche of warranty claims. These cases will be considered in detail in chapter 15. It turned out that the progressive deterioration and crumbling have resulted from WPC oxidation, and as soon as it was recognized, measures were taken. The OIT (oxidative induction time) parameter was introduced into characterization of WPC products and evaluation of their lifetime in the real world, on real decks.

Essentially, the OIT value quantitatively describes a lifetime of a composite (or actually any organic-based) material during its accelerated oxidation in pure oxygen at an elevated temperature, such as 190°C. For example, for unstabilized (without added antioxidants) WPC materials the OIT can be as low as 0.3–0.5 min. The lifetime of such WPC boards in the South (Arizona, Texas, Florida) can be as low as only several months. The "lifetime" in this context is a time period by the end of which the consumer can see there is something wrong with the deck and calls for help. In real terms, the deck owner contacts with the manufacturer and files a warranty claim.

For partially stabilized WPC materials, the OIT can be between 1 and 10 min (Fig. 1.45). A number of commercial WPC deck boards being sold in the market falls into this range. Depending on the deck profile (solid or hollow) and the board density, and, of course, on location/geography/climatic conditions, the lifetime of the deck can vary, but there is a risk that these boards would not live long enough to see the end of their warranty time period, particularly in the South.

For well-stabilized WPC board, the OIT can be in the range of stabilized plastics (15–100+ min).

Figure 1.45 shows the OIT values for commercial wood–plastic decking boards. Twelve of them have OIT lower than 10 min. This is a troubling observation because these boards can be time bombs for the manufacturers. Boards with OIT above 15–20 min are not going to suffer from their deterioration and crumbling due to oxidation, at least caused by hot summer season temperature and UV light. Certainly, these boards can be damaged by other mechanisms (water, mold, bacteria, or algae),

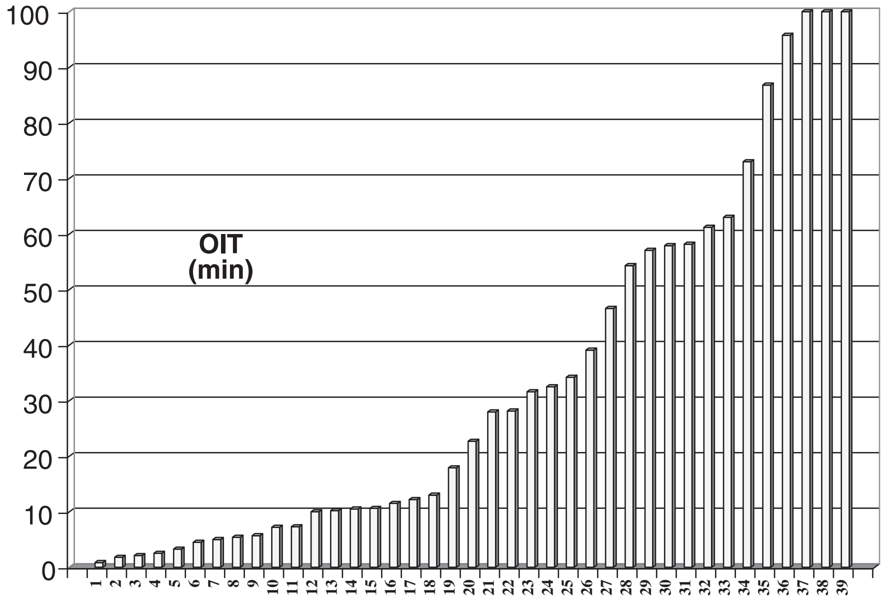

Figure 1.45 The oxidative induction time (OIT) values for commercially available WPC deck boards. The manufacturers and board names are numbered in the order of increasing of the OIT values.

or can be broken by force, or burned by fire (which is a very rapid oxidation), but there are means to minimize each of these effects as well. All these aspects are also covered in this book.

PHOTOOXIDATION AND FADING

Fading is generally an accepted feature of WPCs, probably because people get used to it with common wooden decks; hence, this phenomenon has a kind of grandfather status. However, some composite materials fade less than others, and some much more (Fig. 1.46).

Clearly, customers generally prefer to have their deck not fading at all. However, they are either not informed on the prospective fading or do not know that some WPC practically do not fade, or accept the fading as it is. When the sun irradiation on their deck is uniform throughout the day, it does not create a problem. However, in many cases just after several months the difference in color of their deck is too noticeable (see Fig. 1.1).

Figure 1.46 shows a difference in fading (in terms of lightness) of 32 commercially available WPC deck boards after 1000 h of the accelerated weathering. A difference between ΔL (on the Hunter Lab color scale) is between 0.4 and 35 L units. In a simplified manner, one unit is the first shade difference that the naked eye can

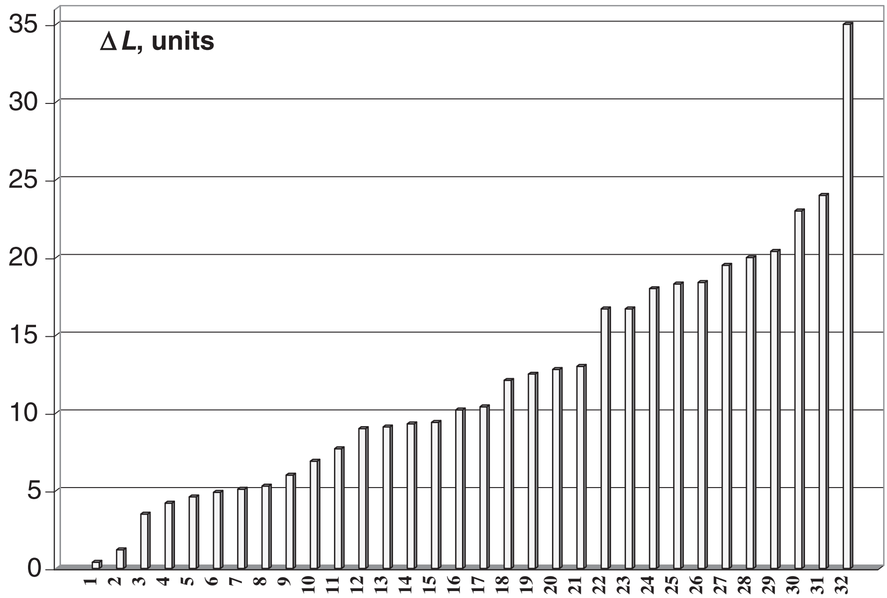

Figure 1.46 Fading of commercial WPC boards in terms of lightness (L in the Hunter Lab color scale) shift after 1000 h of accelerated weathering (vertical axis) in Q Sun-3000 weathering chamber at 0.35 W/m^2 at 340 nm, 102:18 min (UV light: UV light + water spray) cycle, 63°C black panel temperature. Δ*L* values vary from 0.4 to 35 units/1000 h, that is in almost 100 times, for the boards available on the market. Since some boards can be outdated compared to current manufacturing, they are not named but numbered.

normally detect. That is, a difference in lightness by 0.4 units one cannot detect, while 35 units of fading from, say, the initial $L = 53$ to $L = 88$ results in the final lightness of almost a white sheet of paper.

It is rather difficult, if possible at all, to quantitatively translate the fading in the weathering box to the real world. However, some very approximate comparisons can be made. Depending on the material color, one day in the weathering box under “standard” conditions (340 nm, 0.35 W/m^2, 102:18 cycle, 63°C black panel temperature) often corresponds to 9 ± 4 days of natural weathering in the U.S. Midwest and New England. This figure is often called the “acceleration factor.” In Arizona and Florida, the acceleration factor is about 40% of the above, that is, around 3.5.

Hence, a detectable level of lightness change ($\Delta L = 1$) for the WPC board with the lowest degree of fading in Figure 1.46 (0.4/1000 h) will be reached in Midwest and New England after about two and a half years, and a level of $\Delta L = 5$ (a surely noticeable change of lightness) will be reached after at least 15 years, taking into account some slowing down of the fading process with time. On the contrary, a detectable level of lightness ($\Delta L = 1$) for the WPC board with the highest degree of fading in Figure 1.46 (35/1000 h) will be reached in these geographical areas after about 10 days, and a level of $\Delta L = 5$ will be reached after about 2 months. This is confirmed on direct observations.

Indeed, if one is to place some commercial composite deck boards outside under direct sunlight, their fading would be noticeable after only a couple of weeks. This can be observed for boards in Figure 1.46 with $\Delta L = 20/1000$ h. Approximate calculations show that the "theoretical" figure, based on the acceleration factor of 9 ± 4 (see above), would be equal to 19 ± 8 days, which is close to the observed time period.

Fading of composite materials depend on many factors, some of them are related to the WPC composition (wood fiber content, type of cellulosic fiber, amount of UV stabilizers and antioxidants and amount and type of colorants) and some to the outdoor conditions (covered or open deck and amount of moisture on the deck and other climatic conditions). It does not appear that processing of WPC and the profile manufacturing noticeably affect the material fading.

WOOD–PLASTIC COMPOSITES—PRODUCTS, TRENDS, MARKET SIZE AND DYNAMICS, AND UNSOLVED (OR PARTIALLY SOLVED) PROBLEMS

WPC Products

At present, a lion's share of WPCs goes for decking and railing systems (deck boards, stairs, posts and post sleeves, handrails and bottom rails, post caps, balusters, and other small accessories), and similar structures attached to the exterior of dwellings, as well as boardwalks. A relatively small amount of commercially produced WPC goes for siding, fencing, pallets, roofing tiles, and window frame lineals. Other products, such as pilings, railroad ties, marinas, window blinds, and sound barriers, are rather experimental, not commercial as yet, or sold at a very small fraction compared to principal WPC products. Automotive products (interior panels, trunk liners, spare tire covers, package trays, etc.) form a separate category of composite products, often use long cellulose fiber, and fall into a quite different price category. They will not be considered here.

The Public View: Perception

The public view of WPCs is hard to evaluate more or less objectively. Many have never heard of WPCs. Many prefer "real wood," and they are hard to blame. Wood is an excellent material, far exceeding WPC in many properties, first of all in strength and stiffness, in slip resistance, and in many types of wood—in fire resistance (except PVC-based wood composites). Common wood, however, is an inferior material compared to WPC with respect to water absorption, microbial degradation, and durability. There are exceptional types of wood that satisfy a taste of a sophisticated customer, but these types are too expensive for a general market.

Overall, great many customers have gladly accepted the appearance of WPC in the market, though many are doubtful and many have rejected them outright. Nevertheless, WPC-based building products are capturing the market with pretty high speed for the last 10 years.

What is so attractive in WPC products? This question is fair only with respect to WPC decks because other products have not attracted enough attention in the market. Well, WPC decks, as a rule, look pretty good. I have one. Anyone can walk on them barefoot without any precautions to get a splinter in the foot. There are no splinters whatsoever. Then, WPC decks indeed require minimum maintenance. And maintenance with wood decking means—first of all—regular staining and painting. WPC decks do not require them because they are colored for life, when contain colorants, and do not fade. Though, very few WPC deck boards do not fade. In the South, decks often require treatment with antimicrobial and antitermite chemicals. WPC boards do not require it, as they are much more resistant to biological degradation.

It should be noticed here that bioresistance of WPC deck boards is diminished with the increase of wood fiber content (above 40%) and increased with mineral content (silica, calcium carbonate, talc, etc.).

WPC decks require, though, normal washing, cleaning, and other care, as conventional wood decks do. It is obvious that a barbeque on a deck would unavoidably lead to grease and fat stains; when potato salad is dropped upside down on a deck (and there is no other way for potato salad to drop, as everyone can testify), made of either wood or WPCs, leaves stains, which are not easy, though possible, to remove. In fact, it is much easier to remove grease from WPC deck than from a wood deck.

Overall, a WPC deck is much more durable than a wooden deck and requires much less work in a long run. This is certainly attractive for some people. However, it requires a steep payment upfront. This is repulsive for other people. Both features of WPC affect the public acceptance, and both are considered as a practicality issue.

A key issue in public perception regarding a new product in building industry is an appreciation of the product by both builders and homeowners. It seems that WPCs hit the right spot. Deck installers commonly like WPC deckboards as safe to work with due to lack of splinters, easiness to cut, saw, nail, and screw (except polypropylene-based WPC deck boards that are too tough, but, however, this problem is generally solved with development of special fastening systems). These properties of WPC deckboards result in an ultimate goal of any installer for hire to be accomplished: a good speed of deck installing, hence, a faster and a better pay.

Another important factor in the success in the the builder's market is the market accessibility for the product. Technically it means a speedy way from the plant's warehouse to a lumberyard, to distributors, dealers, suppliers, retailers, and to the end user. This is called "strong channel position to access the market" and "distribution channels." This leads to a competitive advantage of some manufacturers compared to others.

WPC Market Size and Dynamics

The U.S. market for two major WPC products, that is, decking and railing components, amounted $1.3 billion in 2006 (projection), approximately 22% of total decking and railing (wood, plastic lumber, vinyl, WPC). Fifteen years back, in the beginning of 1990s, total decking and railing dollar market was about two times smaller, and a share of wooden decks was as much as 97% (compared with the present 73%), while a share of WPC decks was 2% (compared to the present 22%). The rest was and is the only plastic-made decks and rails (1% in 1992, and 5% in 2006).

Figures on composite decking and railing systems, particularly forecasts, vary a great deal among analysts. For example, the Freedonia Group has forecasted in 2002 that WPC decking and railing sales will be of $680 million in 2006 [6]. According to Principia Partners, this volume was significantly exceeded as soon as in 2004 ($820 million), further increased in 2005 ($956 million), and was projected at $1,195 million for 2006 (Table 1.2), which is almost 80% higher than the Freedonia Group projection. Clearly, all these figures, particularly when they show the precision of up to 0.1% (as shown above), have a rather limited value and depend on many

TABLE 1.2 Total (all materials) and WPC decking and railing market size in North America [1–5]

Product	2004	2005	2006 (projection)
	Dollar value (million)		
WPC decking	670	766	929
WPC railing	150	190	271
WPC decking and railing	820	956	1,200
Total decking (all material)	2,570	2,960	3,170
Total railing (all materials)	1,860	2,150	2,280
Total decking and railing (all materials)	4,430	5,110	5,450
	Lineal feet (million)		
WPC decking	450	479	590
WPC railing	12	14	18
WPC decking and railing	462	493	608
Total decking (all materials)	3,650	3,760	3,990
Total railing (all materials)	220	230	240
Total decking and railing (all materials)	3,870	3,990	4,230

different and variable factors. What is undisputable is that WPC building materials, first of all WPC decking and railing, are steadily displacing conventional wooden decking and railing from the market. From 2001 to 2011, WPC decking expenditures are forecasted to grow at a compound annual growth rate of 22%. Similarly, a share of WPC decking in the market is forecasted to grow from 7% in 2002 to 14% in 2007 and to more than 30% in 2011.

The composite decking segment has realized compound annual growth rates (CAGR) in excess of 20% over the last 10 years. It was predicted that a CAGR will further grow for composite decking at 26% from 2002 to 2011. According to another set of numbers, wood–plastic decking represented approximately 7% of the overall decking market in 2001 and is expected to represent almost 14% in 2007. Among other factors, the wood-decking segment stands to be significantly affected by the withdrawal of chromated copper arsenate (CCA) preservaties for residential pressure-treated wood market, as it is described in Chapter 13. CCA is no longer used for consumer application effective from December 31, 2003.

The above growth figures reflect both "physical" (lineal) growth and cost of materials and labor. For example, "physical" growth of decking and railing, in lineal feet, from 2004 to 2005 was about 4% (total, for all materials), whereas dollar growth was twice as much. Overall, "physical" amount of total decking and railing (all materials) in 2004–2005 is related to their dollar amount of $1.14 and $1.28 per lineal foot, respectively.

According to Principia Partners, an industrial consulting firm, specializing in building products (among other materials and manufactured goods), WPC decking and railing reached $956 million in market value and 493 million lineal feet in 2005, and $1.2 billion and 608 million lineal feet in 2006 (projected).

One can see that the "physical" amount of WPC decking and railing is related to their dollar amount of $1.77 in 2004 and $1.94 in 2005, and $1.97 in 2006 (projected) per lineal foot, which is 52–55% higher than that of total decking and railing (all materials). Compared to 4 and 8% in lineal and dollar growth for total decking and railing, respectively (all materials), from 2004 to 2005, growth of WPC decking and railing represented 6 and 17%, respectively. In 2006, WPC decking and railing are expected to grow by 24 and 26%, respectively. Of the total of $956 million for WPC decking and railing systems in 2005, boards were worth $766 million and railing systems $190 million (Principia Partners).

The very recent data by Principia Partners show that annual growth in WPC decking in 2005 and 2006 was 14% and 21%, respectively, and that in railing systems was 27% and 43%, respectively.

Regarding a combined North American and European WPC market, in 2002 it was of 685,000 metric tons, that is, 1.51 billion lb [7].

Competition on the WPC Market

Principal players on WPC market are described in Table 1.1, and their financial standing is outlined very briefly in Table 1.3.

TABLE 1.3 The competitive landscape ([8, 9] with additions)

Company (years)	Revenues ($ million)	Comments
Trex		Public company; market leader; supplier to Home Depot
2003	210	
2004	254	
2005	294	
TimberTech		Private company; early entrant; only 30% of revenues is by WPC
2003	65	
2004	83	
2005	112	
Fiber Composites		Private company; supplier to Home Depot
2003	45	
2004	72	
2005	90	
A.E.R.T. (Weyerhaeuser)		Public company; sells its ChoiceDek through Lowe’s stores nationwide
2003	44	
2004	49	
2005	70	
Louisiana Pacific Specialty Products		Public company; only 5% of revenues is by WPC; 2005 sales data are taken from (Natural & Wood Fiber Composites, v. 5, No. 3, 2006, p. 2)
2003	41	
2004	67.1	
2005	70.5	
Nexwood Industries		Went out of business in 2005
2003	35	
2004	25	
2005	5	
Epoch Composite Products		Private company; only 10% of revenues is by WPC; makes compression-molded Evergrain composite decking
2003	30	
2004	55	
2005	82	
Mikron Industries		Private company; window lineal producer; only 15% of revenues is by WPC
2003	25	
2004	(N/A)	
2005	(N/A)	
Certainteed		Public company; less than 1% of revenues is by WPC
2003	20	
2004	15	
2005	12	
Kadant composites		Subsidiary of a public company; 112% sales growth between 2002 and 2003, then sales leveled off because of shrinkage and crumbling problems. In 2003 and 2004, both
2003	17	
2004	17	
2005	19	

TABLE 1.3 (*Continued*)

Company (years)	Revenues ($ million)	Comments
		problems were solved at the plant. In October of 2005 was acquired by LDI, formed LDI Composites, a private company
Correct Building Products		Private company; polypropylene-based WPC decking
2003	15	
2004	16	
2005	20	
Elk composite Building products		Polypropylene-based WPC decking
2004	15	
2005	27	
UFP		Supplier of its brand Veranda composite decking to Home Depot
2004	33	
2005	42	
Green Tree Composites		A private company
2004	15	
2005	18	
Master Mark Plastics		A private company
2004	15	
2005	18	
Brite Manufacturing		A Canadian company
2004	12	
2005	12	
Composatron		A private company. Produces more WPC railing products compared to WPC decking
2004	11	
2005	18	
Procell		A private company. A relatively new WPC entrant with PVC-based flax-filled composite decking
2004	7	
2005	14	
Alcoa Home Exteriors		Sold to Ply Gem Industries at the end of 2006
2004	3	
2005	9	
Integrated Composite Technologies		A private company
2004	5	
2005	10	

Unsolved (or Only Partially Solved) R & D Problems

A recent meeting of a few dozen of manufacturers of WPCs and their R & D representatives had—as a central event—a brainstorming session. That session had as a principal goal to identify the most "burning" issues in WPCs to be solved in years to come.

The indentified issues are as following, in no particular order. I am reproducing the list below, first, to show the "burning" issues as they are identified by WPC manufactures; second, to indicate that most of them, if not all, are discussed in the following chapters in this book; and the third, in order to illustrate how many issues are considered to be important and not solved for the WPCs:

- Fundamental research on accelerated weathering
- Effects of wood extractives on the look and properties of WPCs
- Effects of recycled resins on properties of WPCs, and quantitative characterization of recycled resins compared to virgin ones
- Plastics for structural (engineering, load-bearing) WPC materials
- Long-term creep issues in WPC decking
- Stain resistance of WPC products
- Fade resistance of WPC products
- How to make WPC products superior to wood
- How to reduce density of WPC products in controlled way, without the presence of moisture in raw materials
- Polymer alloys to improve properties of WPCs
- Fire resistance of WPCs
- Surface biocides as an economical way to increase microbial resistance
- Consistency in mechanical properties of commercial WPCs
- Simple ways to measure rheology of WPC hot melts to characterize and predict performance of WPC products
- Simple ways to measure durability of WPC; clear criteria of durability
- New low-density fillers for WPC materials
- Modeling of material properties of WPC products
- Improved ways of fiber dispersion in plastic matrix
- Decrease thermal expansion–contraction of WPC products
- Assessment of UV stabilizers in WPC products
- Effective flame retardants for WPC products
- Development of WPC products for ground contact applications
- Antioxidants and UV stabilizers for WPC roofing shingles, tiles, and slates
- Plastic and cellulose fiber degradation during extrusion: qualitative evaluation and countermeasures
- Fasteners for WPC deck boards: short- and long-term issues

- Abrasion resistance of WPC deck boards
- Slip resistance of WPC deck boards: science and practical measures to increase it
- Recycled nylon for WPC products

The above list shows that WPCs face a long way to go in order to realize their potential, have their properties improved, and replace wood decking, railing, and roofing materials providing their benefits both from structural and aesthetic, and environmental point of view.

REFERENCES

1. *Composite Decking, 2004 vs. 2005*, Principia Partners, Jersey City, NJ, 2006.
2. *Composite& Plastic Lumber*, The Freedonia Group, Cleveland, OH, 2006.
3. *Composite Decking & Railing*, Principia Partners, Jersey City, NJ, 2004.
4. J. Morton. Wood-plastic composites: taking it to the next level. In: *WPC Conference 2004 "Realizing the Full Potential"*, Principia Partners, Baltimore, MD, October 11–12, 2004.
5. *Focus on Decking*, The Freedonia Group, Cleveland, OH, 2003.
6. *Composite and Plastic Lumber*, The Freedonia Group, Cleveland, OH, 2002, p. 68.
7. W. Sigworth, L. Walp, R. Bacaloglu, and P. Kleinlauth. The role of additives in formulating WPC. In: *The Global Outlook for Natural Fiber & Wood Composites 2003*, New Orleans, LA, December 3–5, 2003. Principia Partners, *7th International Conference of Wood-Fibre Plastic Composites*, Madison, WI, May 19–20, 2003.
8. N. Beare, J. Courtney, and S. Ratledge. New ways of assessing capital and building the value of your WPC business. *WPC Conference 2004 "Realizing the Full Potential*", Baltimore, MD, October 11–12, 2004.
9. *Natural & Wood Fiber Composites*, Vol. 4, No. 10, Principia Partners, Cleveland, OH, 2005, p. 3.