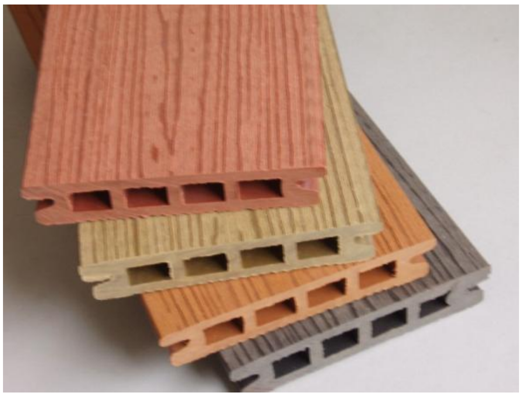
THE UNIVERSITY OF BRITISH COLUMBIA

Vancouver, British Columbia

Wood Plastic Composites (WPCs) as an Alternative to Solid Lumber



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EXECUTIVE SUMMARY

Wood Plastic Composite (WPC) market share has been growing rapidly in the last few decades. The composites are typically used in the commercial residence decking. Other than that, they could be used as rails, floorings, window and door frames and automotive interior. In Chapter 1 of this thesis paper, writer will discuss in detail the advantages and disadvantages that WPC offers to its customers as well as to homebuilders. In addition, there will also discussion on how to manufacture WPC, including the raw materials and the process itself. Lastly, we will analyze how WPC penetrates into the market and take over the traditional solid wood lumbers.

Chapter 2 will provide an in depth discussion on the physical properties of WPC. There are three properties that will be discussed; thermal properties, mechanical properties and manufacturing properties. In thermal test, we will see how temperature affects the mechanical properties. Meanwhile, in the mechanical properties section, we will also learn how additional wood content could increase the strength of the final products. Furthermore, we will analyze how WPC wears the cutting tools compared to other wood products. Lastly, we will provide information on how WPC can hold fastener in place better than its competitors.

One of the advantages that WPC possesses is the fact that it is biodegradable and recyclable. In Chapter 3 of this thesis, writer will provide an in depth discussion on the challenges in the recycling process and how the environmental factors affect the recycling of the composites.

Finally, there will be a thorough summary on the thesis on Chapter 4. As well, writer will provide his personal thought regarding the future of WPC market share in North America.

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CHAPTER 1 – INTRODUCTION

For decades, traditional solid wood decking has always posed many problems for thousands of homeowners. Will Spivey, a resident of Western North Carolina, shared his experience in wood decking in an article written by Tom Kraeutler, "Composite Decking Case Study – A Homeowner's Experience". The article mentioned that Spivey had to repair his CCA treated wooden deck every year due to problems such as warping, splitting and rot. Furthermore, he wished that the next decking replacement would be in another ten years although he realized that he might need to pay greater initial premium (Kraeutler, 2010).

In contrast, the demand for decking keeps increasing. Freedonia Group Inc estimated that by 2013, the decking in the United States would reach 3.6 billion lineal feet with 2.1% annual growth (Freedonia Group Inc, 2009). Therefore, there was a need to invent a new material for the deck so that it could last longer, was more durable and at the same time had low maintenance cost. For those purposes, scientists and industrial representatives have conducted a lot of research in the past and they successfully developed a mix of thermoplastic and wood flour or fiber. They named the product Wood Plastic Composites (WPCs).

The first chapter of this paper will discuss in detail about WPC, the advantages and disadvantages it offers, the production process including its raw materials, how it applies in our daily life and finally how it penetrates into the market.

1.1. History

Historically, the idea of mixing wood fibers and thermoplastic to develop a more durable product was suggested by a number of researchers who realized that wood fibers could be a good replacement for inorganic fillers in thermoplastic such as glass, calcium carbonate and talc (Rowell, 2006). Its abundance, low cost and relatively lower weight made wood fibers a perfect material for fillers and reinforcements (Clemons, 2000). Furthermore, the environmental concern of using renewable materials was also a crucial factor that led to the development of the product (Rowell, 2006).

The first WPC was manufactured in 1983 by American Woodstock, an automotive interior company based in Sheboygan, Wisconsin (Clemons, 2000). Polypropylene and wood flour, in the ratio of 1:1, were mixed and extruded into a flat sheet (Clemons, 2000). The sheet was then formed into various shapes for automotive interior purposes (Clemons, 2000).

In 1990s, the development of WPC grew even more rapidly. Researchers and industrial representatives from both wood and plastic industries held a number of conferences such as the ones in Madison, Wisconsin in 1991 and Toronto, Ontario in 1992 (Clemons, 2000). The objectives were to share ideas and latest technology in Wood Plastic Composites (Clemons, 2000).

Furthermore, they would experiment on the best ratio between the wood fibers and plastics contents. In 1993, Anderson Corporation in Bayport, Minnesota manufactured wood plastic PVC for doors with 40% wood content (Clemons, 2000). This then led to the future production of wood PVC window composites (Clemons, 2000). Another company, Strandex Corp even patented its 70% wood fiber content composites that would be used as building components (Clemons, 2000).

Recently, consumers have started to use WPC in other products such as residential decks, tables, park benches, landscape timbers and floorings (Clemons, 2000). Residential decking market is by far the biggest and fastest growing market for WPC, followed by window and door profiles (Clemons, 2000).

Figure 1. Applications of Wood Plastic Composites in Daily Life

1.2. Advantages and Disadvantages of WPCs

Tangram Technology in its article, “Wood-Plastic Composites, a Technical Review of Materials, Processes and Applications” claimed that “WPCs combine the best features of wood and plastics” (Tangram, 2002). In fact, the inclusion of wood fibers in the production process results in not only a lower production cost but also lower density, UV resistance and high specific strength product. Meanwhile, the thermoplastic part of the matrix acts as a barrier to natural degradation (Rude, 2007). One might ask what else WPC can offer to its consumers that other products cannot fulfill and what the limitations are. This section of the paper will focus on some advantages and disadvantages that the consumers will experience when using WPC.

WPC is a very highly flexible product due to the extrusion process it undergoes. Therefore, it can be formed into almost any kind of shapes according to the needs. Moreover, unlike natural wood products which are prone to biodegradation, water absorption and weather changes, WPC is more durable and mold resistant (Tangram, 2002), making it very suitable for outdoor applications. It is also more cost-effective compared to plastic products due to the low costs of raw materials. Some other benefits of WPC are listed below (Rude, 2007; Tangram, 2002; Anton, 2009):

- The raw materials include wood waste and recycled plastic, thus reducing the cost significantly
- The price is competitive compared to other timber products
- It is available in various types of designs, including wood grain designs and finishes
- It is recyclable, making it environmentally friendly
- The plastic part of the composite makes it resistant to changes of weather condition (humidity and temperature)
- It is UV resistant if UV stabilizers were added in the production process
- It can last two to three times longer than solid wood products without changing its original appearance
- It is easy and less expensive to maintain
- It is safe due to the absence of splinters and chips
- It is easy to install due to the Do-It-Yourself concept
- The warranties offered which typically cover insect damages, splintering and splitting range from 10 to 20 years

In contrast, just like other products, WPC also has some drawbacks. Interfacial adhesion between the wood fibers and the thermoplastic is very limited and depends highly on the coupling agents which initialize the bond (Wolcott, 2010). The problem arises when the wood fiber which has polar nature does not interact well with the thermoplastic which is non-polar. The inadequate interaction might be caused by either insufficient coupling agents used during the process or incorrect coupling agents were used. As a result, the composite will have poor stress transfer, is prone to swelling due to moisture penetration and insect attack on the wood matrix (Rude, 2007). Lubricants, which are also used in the process to smoothen the surface, can also be problematic. Some researchers have proven that certain lubricant such as ZnSt (Zinc Stearate) could decrease the mechanical properties such as the MOE (Modulus of Elasticity) and MOR (Modulus of Rupture) (Rude, 2007). The reasons behind this are the poor distribution of wood fiber, change in thermoplastic morphology and reactions between the lubricants and coupling agents (Rude, 2007).

The drawbacks of WPC are mostly technical problems and thus can be improved by adopting better processes. Meanwhile, there are considerable amount of advantages that one can benefit from using WPC as an alternative to solid wood lumbers; some of them are design flexibility, resistance to weather changes and insects and low maintenance costs.

1.3. Production of WPCs

Manufacturing WPC is not a simple process. Many factors such as melting temperature, mixing process and raw material selection have to be considered to produce decent quality WPCs. One major concern with the production of WPC is the complexity of compounding two naturally different materials; woods and plastics (Tangram, 2002). Unfortunately, the compounding process is the most important step which determines the quality of the finish products (Wolcott, 2010). Insufficient compounding time would result in poor dispersion of plastic into wood particles and poor wetting of the wood fibers. Hence, low mechanical properties of the final products. On the other hand, over compounding will severely damage the fibers (Wolcott, 2010). Another concern is the selection of the raw materials as one type of material would perform better than the others, thus affecting the final quality.

Therefore, it is very crucial to have an excellent and well controlled production process. This segment will discuss in depth about the raw materials used as well as the production methods employed.

1.3.1. Raw Materials

Raw materials play an important part in the manufacturing process. In general, one needs three different materials to produce WPC; namely: woods, plastics and additives.

1.3.1.1. Woods

Wood, in the process, acts as fillers or reinforcements due to its ability to increase the mechanical properties of the final product (Wolcott, 2010). Research has shown that wood fibers contribute to better stiffness and strength when compared to other types of fillers such as glass and talc (Wolcott, 2010). Another role of wood in the process is to lower the usage of polymer in the process (Wolcott, 2010). Not only is polymer expensive, but also can harm the environment.

There are two kinds of wood products that could be used in the WPC production process; they are wood flour and wood fibers (Rowell, 2006). Wood flour used usually range from 40 to 60 mesh in size (Rowell, 2006). Wood fibers, on the other hand, are larger in size and this sometimes can be rather challenging to process. Rowell in his article, "Advances and Challenges of Wood Polymer Composites", noted that wood fibers would eventually shrink in length and width during the blending process (Rowell, 2006). Table 1 below shows the average fiber dimensions taken before and after the process.

Table 1. Fiber Dimensions of Oil Palm before and after Mixed with Polypropylene at 180°C

Average Length					
Before Processing			**After Processing**		
Length (mm)	**Width (mm)**	**Aspect Ratio**	**Length (mm)**	**Width (mm)**	**Aspect Ratio**
1.51	0.18	8.4	0.72	0.13	5.5
2.76	0.30	9.2	0.82	0.14	5.9
6.80	0.87	7.8	0.85	0.14	6.1

Source: Rowell, 2006

Moreover, he mentioned that production with longer fibers may require more advance compounding technology; the one that could evenly distribute the wood in the thermoplastics without damaging the fibers (Rowell, 2006). Therefore, using wood flour will be an ideal solution to the problem as it minimizes the fiber shrinkage issue.

Pine, maple and oak are predominantly used in the WPC manufacturing process (Rowell, 2006). The species selection is influenced mainly by their availability rather than the mechanical properties (Rowell, 2006). Prof. Hansmann, in his article, "Flüssiges Holz", believed that rice husks, bamboo and cellulose could be the alternatives to wood flour (Hansmann, 2007).

1.3.1.2. Plastics

Another main components needed in the process is the polymer. Depending on its reaction to heat, there are two different kinds of polymers; namely: thermosets and thermoplastics (Wolcott, 2010). Thermosetting polymers would polymerize and gain stiffness as temperature increases whereas thermoplastic polymers would melt or soften under the same condition (Wolcott, 2010). Furthermore, polymers are divided into two categories based on their morphology; they are: amorphous polymer and crystalline polymer. While crystalline thermoplastic would melt under high temperature, the amorphous thermoplastics will only soften (Wolcott, 2010). However, at a certain point it will behave like a melting polymer (Wolcott, 2010).

Several kinds of polymers are available. Nonetheless, only a few could be employed in the WPC manufacturing process. Some of them are Polystyrene (PS), Polyvinyl Chloride (PVC), Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE) and Polypropylene (PP) (Wolcott, 2010). All those polymers have one property in common which is having melting or softening point lower than the thermal degradation temperature of wood (≈ 210°C) (Wolcott, 2010). Polymers whose melting point is under 210°C fall under polyolephins category (Wolcott, 2010). Figure 2 below shows the melting point of several different polymers with respect to the wood degradation point.

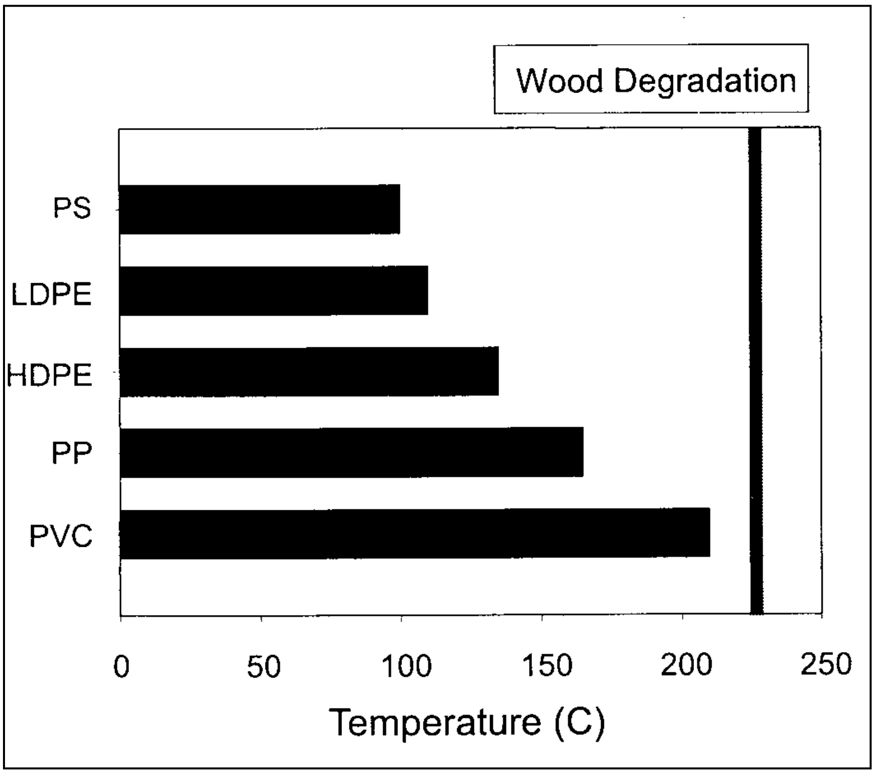

Figure 2. Melting Points of Various Polymers Used in WPC Manufacturing Process

Among those polymers, Polyethylene is the most common material that is used in the production process (Wolcott, 2010). Caulfield claimed that 83% of 685,000 tons of WPC consumed in North America is made of PE (Caulfield, 2005). Polypropylene (PP) comes second with 9% of total production while 7% of WPCs is made of PVC (Caulfield, 2005). The remaining 1% is produced out of other types of polymers (Caulfield, 2005).

Thermoplastics are usually available in the form of pellets, powder, flakes or films as well as from some recycled products such as milk jugs, battery casing, and plastic shopping bags (Wolcott, 2010).

1.3.1.3. Additives

The major purposes of using additives are to improve the diffusion of the wood flour into the thermoplastics, advance the mechanical properties (MOE and MOR) and other miscellaneous purposes such as smooth the surface, protect against UV light and heat and reduce density (Rowell, 2006).

The type of additive that is used the most is compatibilizers. It serves as glue and thus linking the woods and the thermoplastics together. As discussed in the previous section, wood is hydrophobic whereas thermoplastic is hydrophilic. Therefore, to be able to blend the two well, one needs a certain medium which is available in the form of Maleic Anhydride Grafted Polypropylene (MAPP) or Maleic Anhydride Grafted Polyethylene (MAPE) (Rowell, 2006). MAPP and MAPE have a chemical structure in which each end of the molecules can form a bond with either hydroxyl group of wood or melted thermoplastic. Please refer to Figure 3 and 4 below for reactions between the lignocelluloses of woods, MAPP/MAPE and thermoplastics.

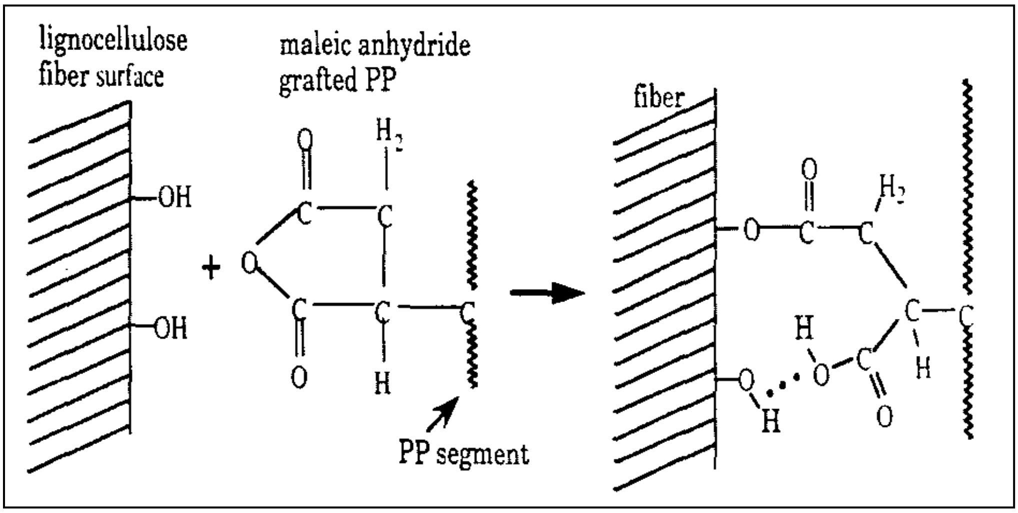

Figure 3. Reaction between Wood Surface and MAPP Forming Ester Linkage

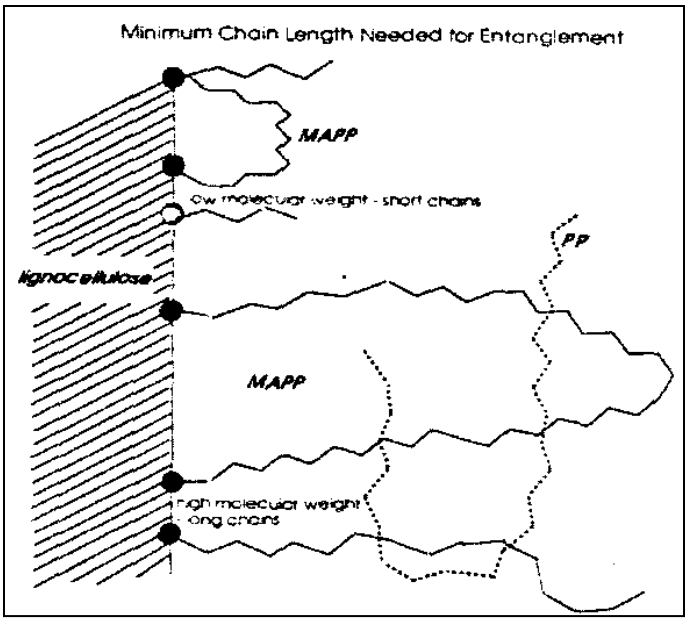

Figure 4. Entanglement of MAPP with the melted thermoplastics

The bonding process occurs in these sequences; first of all, the Anhydride end of MAPP or MAPE would form ester bonds with the hydroxyl group of wood surface (refer to Figure 3) (Rowell, 2006). On the other side of the molecules, the PP or PE segments of the compatibilizers would entangle with the melted thermoplastics (refer to Figure 4) (Rowell, 2006). Thus, MAPP or MAPE is creating a mechanical bond between the lignocelluloses and thermoplastics.

Another common type of additives is the colorant. It is usually used in the process to enhance the color of the finish products. Some colorants may even function as a UV protector (Rowell, 2006). To ensure the consistent color between wood and plastic, colorants have to be added separately to each material before the extrusion process (Rowell, 2006). Otherwise, the final products' surface will exhibit specks of lighter or darker color (Rowell, 2006).

WPC surface color tends to grow fainter over time due to exposure to UV light (Rowell, 2006). Besides UV protector, pigments can also be added to minimize this phenomenon (Rowell, 2006). Another solution to the problem is by co-extruding UV-stable layer over the WPC (Rowell, 2006).

To reduce the density of the final products, foaming agents may be dispersed to the thermoplastic material before the compounding process (Wolcott, 2010). The foam will generate bubbles which will then penetrate into the polymer matrix. A light-weight composite will be obtained after the polymers are melted and blended with the wood flour (Wolcott, 2010).

1.3.2. Production Method

As described briefly in the previous section, the most important step during the production process of WPC is the compounding process (also known as mixing or blending process). The purpose of this process is to disperse the wood flour into the melted thermoplastics. It becomes complicated due to the high physical energy (shear forces) required to melt the polymer (Wolcott, 2010). The blending process occurs in the blending equipment where the polymers are melted. Depending on the type of manufacturing process, there are two different kinds of blending equipment that one can use; they are:

single screw extruder and twin screw extruder (refer to Figure 5 and 6 for detailed diagrams) (Wolcott, 2010).

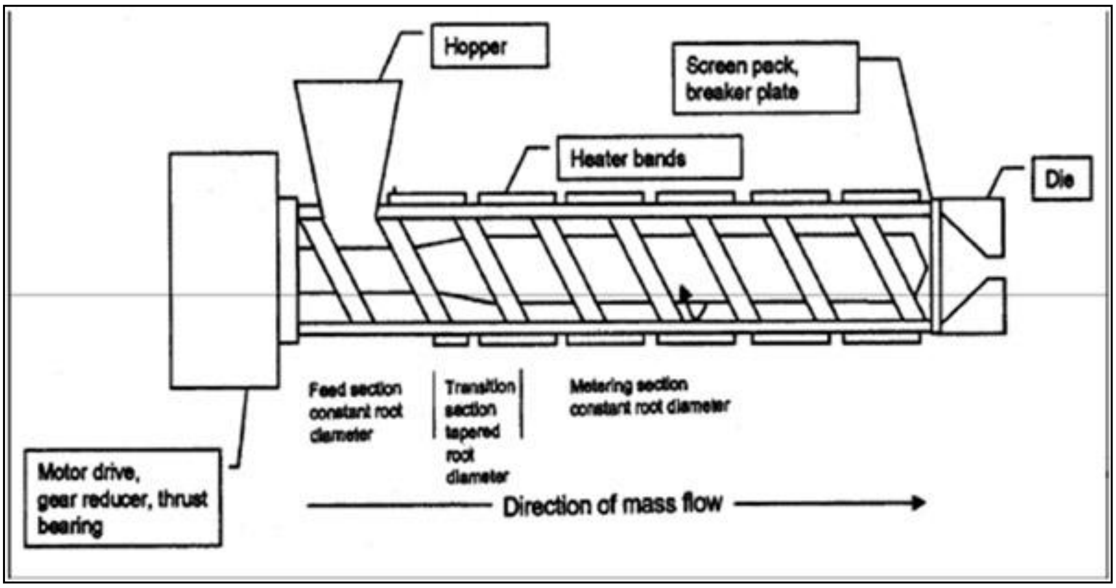

Figure 5. Diagram of Single Screw Extruder

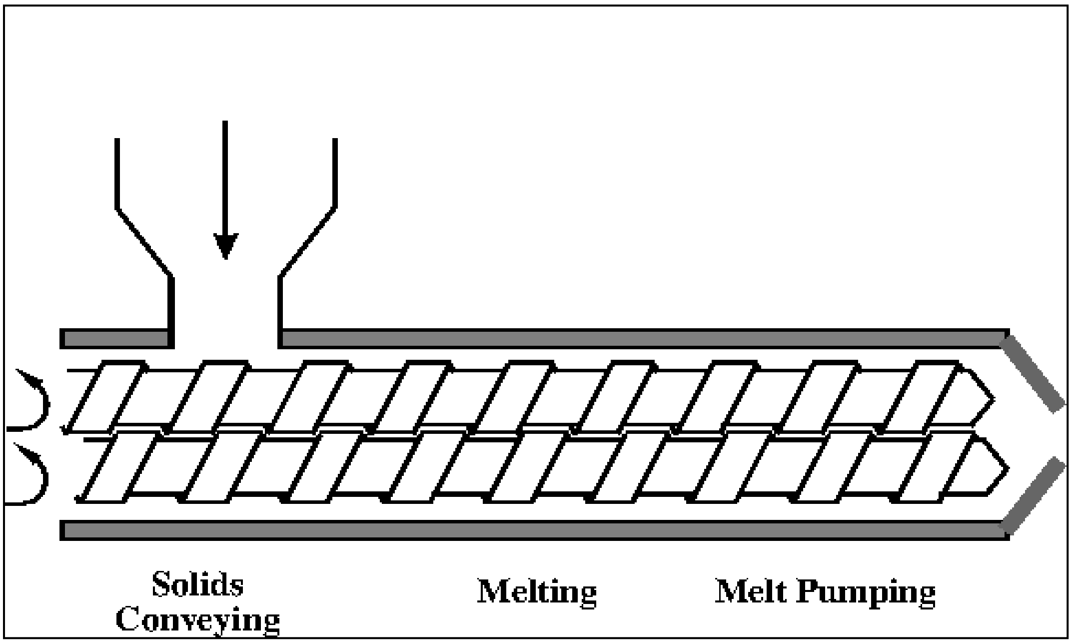

Figure 6. Diagram of Twin Screw Extruder

Single screw extruder uses the screw to deliver the materials that are to be mixed (Wolcott, 2010). The screw itself is the parallel plates that wound about a shaft (Wolcott, 2010). The gap between the screw and the barrel is the area where the shearing forces are applied to the substance (Wolcott, 2010). The friction forces generated help the material to be pushed forward the barrel instead of rotating within the screw (Wolcott, 2010). Wolcott also noticed that the friction forces exerted are proportional to the screw diameter, angle, depth of the gap between screw and barrel and the rotation speed (Wolcott, 2010).

The working principal of the screw is relatively simple. The raw materials are fed into the hopper (refer to Figure 5) and then melted and mixed by the heat generated from the heater bands. The currently mixed dough is then injected into the die resulting in extruded or compounding materials. Single screw extruder is ideally used in the processes which require mixing of highly viscous materials under high pressure and temperature (Wolcott, 2010). In addition, it is capable of processing wide range of thermoplastics into various finished or unfinished products (Wolcott, 2010).

The twin screw extruder is normally used when single screw extruder could not achieve the desired degree of mixed products (Wolcott, 2010). In fact, the 'double screw' feature in the machine provides better mixing due to the intermeshing actions (refer to Figure 6) (Wolcott, 2010). Intermeshing action is defined as the displacement of mixed materials from one screw to another thus allowing better mixing (Wolcott, 2010). Twin screw extruder can further be divided into two categories depending on the direction of its rotation; namely: co-rotating screws and counter-rotating screws (Wolcott, 2010). While co-rotating screws offer great mixing and lower dwelling time, the counter-rotating screw can generate high pressure which could be crucial for certain processes (Wolcott, 2010). Furthermore, co-rotating twin screw extruders produce high shear forces due to the opposite rotating movement of the two screws (Wolcott, 2010). In contrast, counter-rotating screw generate lower shear since the screws move in the same direction (Wolcott, 2010). However, it helps the system to reduce energy intake and temperature (Wolcott, 2010). Unlike single screw extruder, the friction forces are not the one that drives the material to the end of the barrel (Wolcott, 2010). Instead, it is the interaction between the two screws that generate shear forces and assist the material to the die (Wolcott, 2010). The compounding material, out of the extruders, can then either be shaped according to the needs or formed into pellets for further processing steps (Caulfield, 2005). The extruder could produce finished or unfinished products in the rate of 3m/min (10ft/min) (Caulfield, 2005).

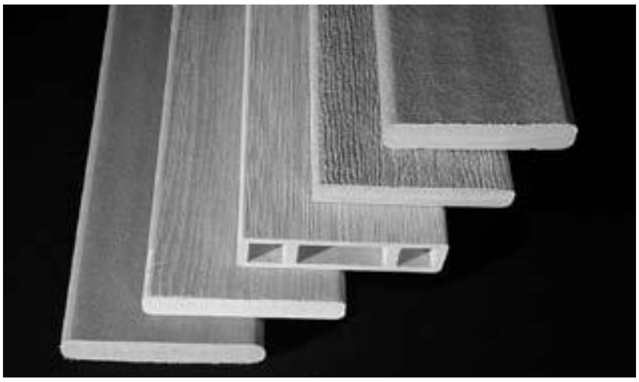

Figure 7. Wood Plastic Composites after the Extrusion Process

1.4. Product Design and Application of WPCs

One of the WPC characteristics is its flexibility. Due to the extrusion process, the compounding materials can be formed to almost any shape (Tangram, 2002). Therefore, there is no certain standard of measurements for most of WPC applications. However, for the structural products such as wall profiles, there is a set of guideline of how thick the profiles should be; for exterior profiles, the normal thickness ranges between 4 – 6mm, whereas interior profiles will be about 2.5 – 3.5mm thick (Tangram, 2002).

Some features, such as stiffening legs, hooks, dividers, snap fittings and interior strengthening wall, that are normally present in plastic products, can also be manufactured by using WPC (Tangram, 2002). Furthermore, WPC can also be designed with internal hollows, strengthening ribs and re-entrant angles – features that are not possible with wood products (Tangram, 2002). Figure 8 and 9 below show various profiles and decking designs.

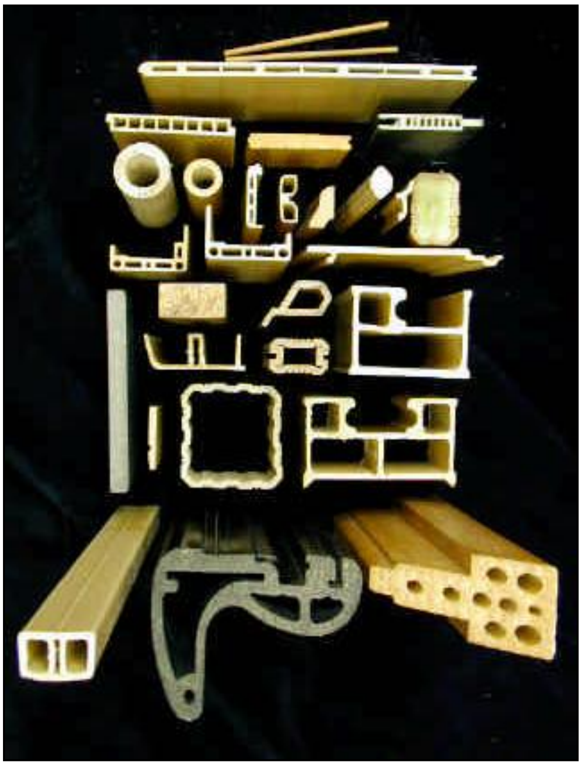

Figure 8. Profile Designs out of WPC

Figure 9. Various Types of WPC Decks

Some companies also combine the wood-filled thermoplastic with unfilled thermoplastic to gain specific attributes without changing the whole production process. To gain durability, one might co-extrude wood-filled PVC core with unfilled PVC surface

(Caulfield, 2005). On the contrary, the combination of PVC core with wood-filled PVC surface allows the surface to be painted or stained (Caulfield, 2005).

Decking industry is the largest consumer of WPC products (Tangram, 2002). Their low maintenance, durability and mould resistance attributes are the main reasons that drag the homeowners away from traditional wooden decks and move to WPCs. Tangram Technology Ltd. stated that WPC products have been consistently in high demand for the last five years (since the year of 1997 considering the time the article was written) and they predicted that the trends will not change in the coming years (Tangram, 2002). The growing market of WPC results in more products manufactured from it, especially those that are previously produced from wood products or plastics (Tangram, 2002). Below are some applications of WPC in other products (Tangram, 2002):

- Door and window frames and components
- Exterior and interior wall profiles
- Docks and railings
- Stairs and hand rails
- Balustrade
- Floors
- Shelves
- Fence posts
- Garden furniture
- Office furniture
- Kitchen cabinets
- Sound proofing cladding

WPC's flexible design has become a very crucial factor in its fast growing market in North America and the world. In addition, its 1-step processing procedure and zero-waste process make it a very ideal solution to the production of other kinds of products such as door frames, rails and floors.

1.5. Marketability of WPCs

If someone takes a look at the product life cycle diagram, then WPC would lay somewhere between introduction and growth phases. As a product that just entered the market recently, WPC has a lot of growth potential, especially from building products with limited structural requirements such as decking, fencing, landscape timbers, riling, moulding and many more (Caulfield, 2005).

Currently, chemical treated lumbers are still inferior to WPC; about 80% of the building products are made of solid lumbers (Caulfield, 2005). However, based on its growth trends in the past, Caulfield predicted that the WPC market share will grow more rapidly in the future (Caulfield, 2005). This, in fact, had been proven by the increase of market share from 2% in 1997 to 8% in 2001 (Caulfield, 2005). The increase in the market share was also helped by the excellent promotions of the benefits one can enjoy from WPCs (Caulfield, 2005). Previous section of this paper has mentioned that low maintenance cost, absence of chips and splinters and durability are few examples of WPCs advantages.

In some cases, WPC can be used in combination with other products. This also helps WPCs to penetrate better into the market. Compared to solid wood lumbers, WPC has lower mechanical properties such as the creep resistance, stiffness and strength (Caulfield, 2005). However, those attributes are not that crucial as WPCs are mostly used in the surface (the one that is visible) instead of the substructure (the material underneath) which requires stronger and stiffer materials such as solid wood (Caulfield, 2005). Therefore, solid wood timbers and WPCs can be used together as they complete each other.

The advantages offered by WPCs also drive the customer to shift from previous products to WPC albeit the higher prices (Caulfield, 2005). Window application would be a perfect example in this case. Even though PVC window is cheaper than WPC window, customer would prefer the later due to better thermal stability, moisture resistance and stiffness (Caulfield, 2005).

In places, such as European countries, where residential wood decking is not very common, WPCs are marketed in other types of products such as wooden profiles, door frames, furniture and automobile interior (Caulfield, 2005).

In Japan, on the other hand, the future of WPC is very promising with the increasing demands on wooden decks, walls and floorings (Caulfield, 2005).

In conclusion, WPCs are relatively new products that just entered the market few decades ago. Nevertheless, they are able to gain the market share rather quickly and even predicted to dominate the market in the near future. Being the primary market for WPCs is wood decking industry. Their durability, low maintenance and mold resistance are key factors that make WPC an ideal solution for residential decks.

CHAPTER 2 – PROPERTIES OF WOOD PLASTIC COMPOSITES

The quality of a product is generally determined by its properties and how well it performs under certain circumstances; good quality products must have excellent properties associated with them that differentiate them from the competitors. Depending on the type of the products, there are several different factors that will define the final properties. In WPC, the final attributes will depend on (Rowell, 2006):

- Volume fraction of wood
- Processing temperature
- Type of additives
- Type of thermoplastic

While volume of wood will affect the mechanical properties of the final product, the processing temperature and the type of thermoplastic used will influence the adhesion between the substances. The additives, on the other hand, would add certain attributes depending on the needs.

This section of the paper is focused on the thermal, mechanical and manufacturing properties of WPCs.

2.1. Thermal Properties

Very little has been published about WPCs dependency on temperature while it is actually a significant characteristic which influences other properties such as mechanical properties (Schildmeyer, 2006). Schildmeyer conducted several tests where WPC panels were exposed to heat. Static tests were conducted at a temperature between 21°C (70°F) and 80°C (176°F) (Schildmeyer, 2006). The goals of the experiment were to observe the changes in stress, strain and MOE of WPC under different temperatures and establish relationship between those properties and the temperatures (Schildmeyer, 2006). WPCs used during the experiment were composed of 58.8% 60-mesh pine flour, 33.8% Polypropylene, 4% talc, 2.3% MAPP and 1% lubricant with respect to the final product mass (Schildmeyer, 2006). The results of the experiments are presented in the Table 2 below.

Table 2. Mean Values of Mechanical Properties in Relation with Testing Temperatures

Temperature (°C)	Tension			Compression		
	$\sigma_{ultimate}$, MPa	ε_{max}	E, MPa	$\sigma_{ultimate}$, MPa	ε_{max}	E, MPa
21.1	18.14	0.0090	3,487.5	48.91	0.0315	3,434.9
30.0	17.49	0.0115	3,047.1	43.54	0.0343	3,074.4
40.0	15.30	0.0128	2,367.1	40.08	0.0367	2,787.5
50.0	14.36	0.0148	1,990.9	35.85	0.0366	2,474.4
65.6	12.77	0.0173	1,794.0	29.47	0.0358	2,059.2
80.0	12.03	0.0193	1,593.9	24.90	0.0357	1,755.7

Source: Schildmeyer, 2006

Based upon the data obtained, Schildmeyer drew the following conclusions. The ultimate stress ($\sigma_{ultimate}$) in tension and compression were both decreasing linearly with an increase in temperature (Schildmeyer, 2006). On the other hand, the maximum strain (ε_{max}) in tension was slightly increasing when exposed to hotter environment; whereas the strain in compression remained relatively constant regardless the temperature (Schildmeyer, 2006). Furthermore, Schildmeyer also noticed that Modulus of Elasticity (E) was reduced in linear fashion in compression and in quadratic fashion in tension (Schildmeyer, 2006).

In conclusion, WPCs have strong dependency on temperature since different thermal conditions may alter the mechanical properties of the material. Furthermore, the use of wood in the process could minimize the bad impacts of heat on thermoplastics since wood is thermally more stable than plastics (Schildmeyer, 2006).

2.2. Mechanical Properties

One might wonder what if more wood is added into the process, will it result in better strength or will it expose the weakness even more? How does larger diameter fiber exactly affect the strength of WPCs? And how does MAPP or MAPE influence the strength of the structure? Those questions have one aspect in common; they are asking on how certain factors such as material selection and/or addition would influence the mechanical properties of the final products.

Wolcott et al conducted few experiments to determine the effect of wood fibres addition on the tensile strength and tensile modulus of WPCs (Wolcott, 2010). Three different types of composites were used in the experiments; they were: PP-wood fibre, HDPE-wood fibre and PS-wood fibre (Wolcott, 2010). The results of the experiments can be seen in Figures 10 and 11 below.

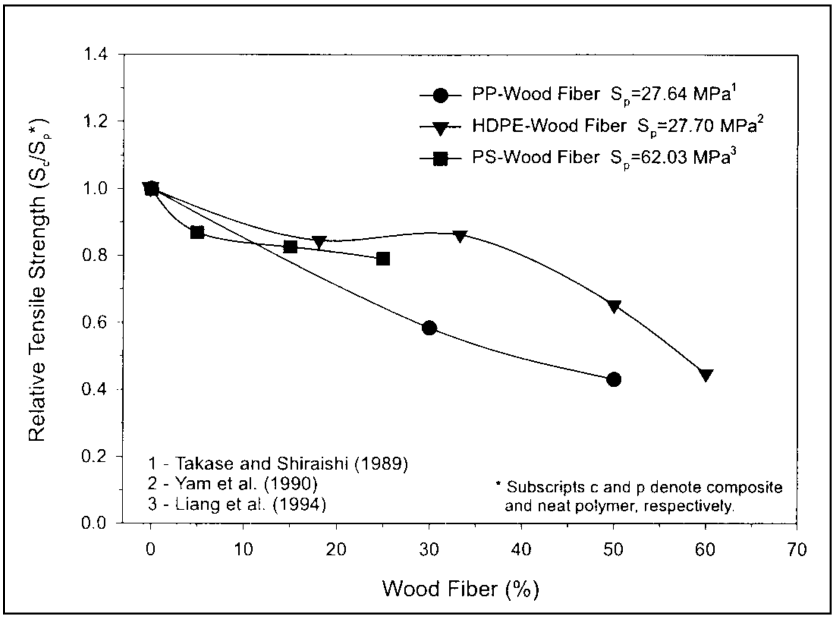

Figure 10. The Changes of WPCs Tensile Strength with the Addition of Wood Fibre Content

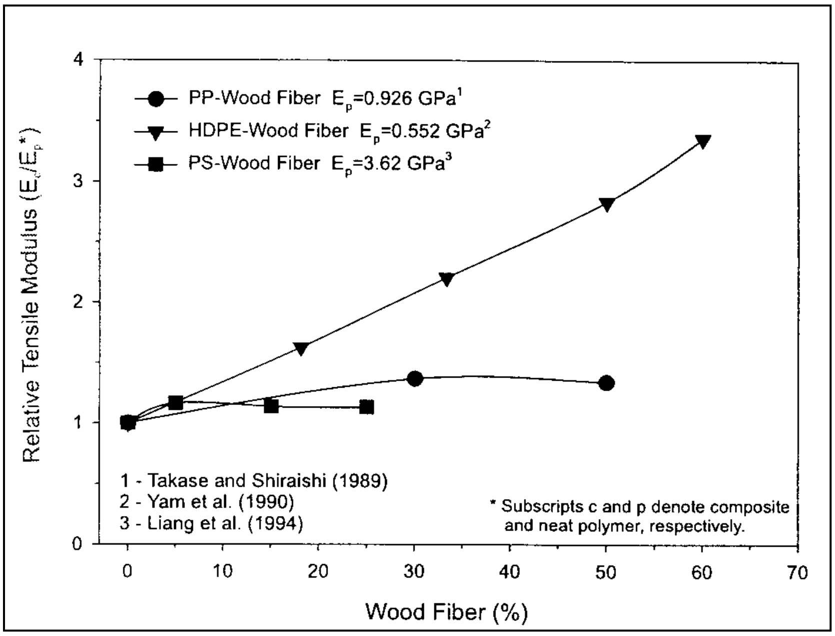

Figure 11. The Changes of WPCs Tensile Modulus with the Addition of Wood Fibre Content

In the diagrams above, tensile strengths of WPCs were decreasing with the addition of wood fibres. However, the tensile moduli were increasing (Wolcott, 2010). Figure 11 also shows that for PP- and PS-based composites, the tensile moduli reached their maximum values at certain points thus making further addition of wood ineffective (Wolcott, 2010). PP-based composites reached their maximum tensile modulus with 30% wood fibre content, while PS-based composites were optimal at 5% wood fibre content (Wolcott, 2010). Meanwhile, there seemed to be no maximum tensile modulus for HDPE-wood fibre matrix as the values kept rising with the addition of wood fibre (Wolcott, 2010).

Optimat Ltd and MERL Ltd also conducted similar experiments with further measurements on flexural strength and flexural modulus (Optimat, 2003). Like tensile modulus, flexural strength of WPC would reach its maximum point before decreasing as wood content increased (Optimat, 2003).

2.3. Manufacturing Properties

After learning the thermal and mechanical properties of WPCs, it is also crucial to have an idea of how well they perform in real life when used for constructional or other purposes. This section of the thesis will provide an in depth discussion on tool wear assessment and how well they can hold the connectors such as screws and nails in place.

2.3.1. Tool Wear Assessment

One of the challenges that industrial wood companies face nowadays is the excessive tool wear. Wear is the condition where the useful life of certain tools has reached its maximum and therefore cannot be utilized any longer. Further use of wore tools would not only affect the finish quality of the product, but also increase the production cost due to the need of higher power consumption (Buehlmann, 2001). Dull saw blade, for example, will result in a low quality cut; usually marked by the existence of excess wood that has not been cut cleanly. For these reasons, wood products manufacturers have to minimize the tool wear as much as possible.

Buehlmann et al had conducted an assessment on how WPCs would affect the wear rate of cutting tools (Buehlmann, 2001). In their experiment, the team used five commercially available WPCs; CHOICEDEK (Producer: A.E.R.T Inc. Springdale, AR), EXCEL decking (Supplier: Cox Industries Inc. Orangeburg, SC), FIBERON (Producer: Fiber Composites Corporation, New London, NC), SMARTDECK (Producer: U.S. Plastic Lumber, Boca Raton, FL) and TREX (Producer: TREX Company, Winchester, VA). The wear of the tool was measured by the size of the Nose Width (NW) on the tip of the tool. Figure 12 below explains the definition of Nose Width.

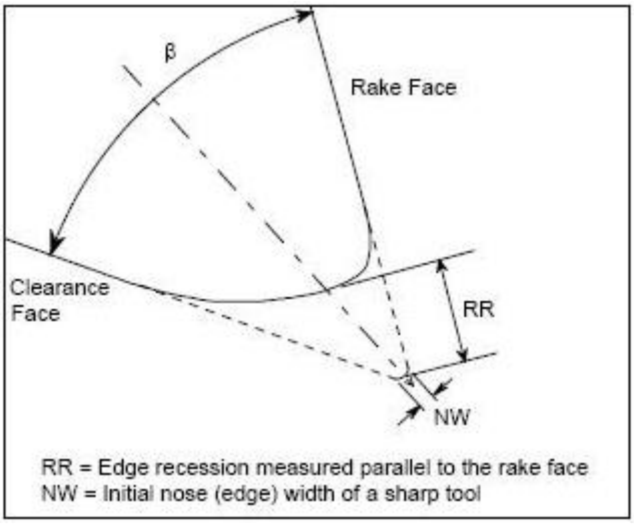

Figure 12. Tool Wear is Measured by the Length of the Nose Width (NW)

Furthermore, the wear was recorded after 31, 63, 94 and 125 feet of cutting. For the experiment, the blades used were made of tungsten carbide with standard 3% cobalt binder with ultra-fine carbide grain (0.5-0.9µm) (Buehlmann, 2001). Before experiment was conducted, the NW of each blade was measured. Those, whose NW was more than 10 microns, were excluded (Buehlmann, 2001). Table 3 and 4 below provide detailed information on the properties of the tool as well as the result of the experiment.

Table 3. Parameters for Tool Wear Assessment

Parameter	Setting
Spindle speed	18,000 rpm
Feed Speed	350 ipm
Depth of cut	1/16 inches/pass
Blade carbide grade	Sandvik H3F
Length of cut	23.5 inches/pass
Cuts per test	16
Number of tests	4
Mode of cut	Conventional

Source: Buehlmann, 2001

Table 4. Length of NW and Standard Deviation for All Materials

Material	Measurement	NW and Standard Deviation				
		0 feet	31 feet	63 feet	94 feet	125 feet
CHOICEDECK	µm	7	40	53	57	65.6
	Std. Dev.	N/A	12.7	13.5	11.5	13.2
EXCEL	µm	9	18.3	20.3	23.4	31.5
	Std. Dev.	N/A	2.2	0.7	3.2	2.3
FIBERON	µm	5	N/A	18	22	25
	Std. Dev.	N/A	N/A	N/A	N/A	3.5
SMARTDECK	µm	7	14.6	21.4	27.4	37
	Std. Dev.	N/A	5.1	2.2	3.7	4.5
TREX	µm	8	15.4	20	22	25.4
	Std. Dev.	N/A	5.8	1.4	2.1	3.6
WHITE PINE	µm	9	10	10	10.4	10.4
	Std. Dev.	N/A	0	0	0.5	0.5

Source: Buehlmann, 2001

From Table 4 above, we learn that CHOICEDECK dulled the tool the most compared to other type of WPCs; whereas, the control sample, the white pine, wore the knife the least. As well, there was a significant difference in the first sample (CHOICEDECK) between the original sample and the one after the blade was run for 31 feet. Furthermore, we can also notice that the results in CHOICEDECK were not very consistent due to the high standard deviation. Buehlmann et al suggested that the wear could come from the impurities involved in the process of manufacturing WPCs (Buehlmann, 2001). From the previous section, we learned that most of the time, WPCs were produced from the scrap wood products and recycled plastics. Those impurities from the recycled materials increase the roughness of the finish products and thus wearing the tool quicker than normal solid wood lumbers.

In conclusion, by looking at the data from this experiment, we know that solid wood lumbers are more tool-wear friendly than WPCs due to the absence of impurities. However, the fact that WPCs can be formed in almost every shape compensates their flaw. This flexibility could reduce the use of saw blades or other cutting tools because the desirable shapes have been achieved from the extrusion process.

2.3.2. Connection Performance

Home builders, nowadays, prefer to use materials that are not only durable and low maintenance, but also the ones that are easy to install and more labor saving. WPCs have satisfied some of those demands by being durable and easy to maintain. However, they have not been accurately tested yet on their performance with screws and nails.

Documented in his article, "Performance of Fasteners in Wood Flour-Thermoplastic Composite Panels", Falk et al conducted some experiments which goals were to gain information on fasteners performance on WPCs and provide comparison to other wood panels (Falk, 2001). In their experiment, Falk used several different types of WPCs depending on the amount of wood flour blended during the production process; they ranged from 20 to 60 percent wood flour by weight. Furthermore, they applied four different actions onto the panels to test their performance under each action. Table 5 below indicates the actions applied on the panel as well as the size of the panels tested.

Table 5. Fastener Test on Wood Plastic Composites

Actions	No. of Specimen	Dimension (Width – Length – Thickness) (inch)
Screw Withdrawal	20	3 – 4 – 1
Nail Withdrawal	20	3 – 6 – 0.5
Lateral Nail Resistance	20	3 – 6 – 0.5
Nail Head Pull-Through	20	3 – 6 – 0.5

Source: Falk, 2001

Screw withdrawal test was conducted to measure the maximum load required to pull a screw (Falk, 2001). Before the experiment, a no. 10 stainless steel sheet metal screw was hand-driven into the panel. Prior to that, the panel was pre-drilled by using a 1/8 inch drill bit until it reached 0.5 inch depth. The depth of the screw inside the panel was roughly 0.67 inch. The result of this test can be seen in Table 6 below.

Table 6. Result of Screw Withdrawal Test

Wood Flour (%)	Mean Screw Withdrawal (Lbs/inch (N/cm))	Coefficient of Variation (%)
20	870 (1,520)	7
30	905 (1,580)	7
40	905 (1,580)	8
50	855 (1,500)	10
60	855 (1,500)	7

Source: Falk, 2001

Similar to screw withdrawal test, nail withdrawal test was conducted to measure the peak load required to pull a nail out of the panel. The nail used in the experiment was a 0.117 inch (3 mm) diameter nail. 10 specimens were pre-drilled by using a 3/32 inch drill bit while the rest were not. The nail was then hand-driven into the 0.5 inch panel such that the length of the nail section was the same on both sides of the panel. Table 7 and 8 below show the results of the experiment for both pre-drilled and non-pre-drilled panels.

Table 7. Result of Nail Withdrawal Test without Pre-drilling

Wood Flour (%)	Number of Samples	Mean Nail Withdrawal (Lbs/in. (N/cm))	Coefficient of Variation (%)
20	10	190 (330)	7
30	9	190 (330)	7
40	10	200 (350)	8
50	10	185 (320)	6
60	10	170 (300)	5

Source: Falk, 2001

Table 8. Result of Nail Withdrawal Test with Pre-drilling

Wood Flour (%)	Number of Samples	Mean Nail Withdrawal (Lbs/in. (N/cm))	Coefficient of Variation (%)
20	10	200 (350)	8
30	10	185 (320)	10
40	10	190 (330)	9
50	10	180 (310)	8
60	10	155 (270)	4

Source: Falk, 2001

Lateral nail resistance test was conducted by driving the nail 0.5 inch into the panel from the side of the specimen. Like the previous experiments, the panels were pre-drilled by using a 3/32 inch drill bit. The result of this test could be seen in Table 9 below.

Table 9. Result of Lateral Nail Resistance

Wood Flour (%)	Number of Samples	Mean Lateral Nail Resistance (Lbs/in. (N/cm))	Coefficient of Variation (%)
20	19	960 (1,680)	7
30	19	895 (1,570)	9
40	19	780 (1,370)	10
50	19	640 (1,120)	6
60	19	515 (900)	8

Source: Falk, 2001

The fourth test, nail head pull through, was conducted to measure the force needed to pull the head of the screw through the panel. Like the nail withdrawal test, half of the specimens were pre-drilled, while the rest were not. The result of this experiment can be seen in Table 10 and 11 below.

Table 10. Result of Nail Head Pull Through Test with Pre-drilling

Wood Flour (%)	Number of Samples	Mean Lateral Nail Resistance (Lbs/in. (N/cm))	Coefficient of Variation (%)
20	10	1,000 (1,750)	6
30	10	1,005 (1,760)	7
40	10	1,020 (1,790)	6
50	8	885 (1,550)	3
60	10	700 (1,230)	6

Source: Falk, 2001

Table 11. Result of Nail Head Pull Through Test without Pre-drilling

Wood Flour (%)	Number of Samples	Mean Lateral Nail Resistance (Lbs/in. (N/cm))	Coefficient of Variation (%)
20	10	1,040 (1,820)	4
30	9	970 (1,700)	7
40	10	1,010 (1,770)	5
50	7	900 (1,580)	4
60	10	730 (1,280)	4

Source: Falk, 2001

From those tables above (Table 6 until 11), we notice that the number of specimens was not consistent as it ranged from 7 to 20 specimens. As we have discussed before, in the Nail Withdrawal test and Nail Head Pull Through experiments, the specimens were divided into two categories; pre-drilled and non-pre-drilled specimens. Therefore each experiment would get 10 specimens instead of 20. However, due to material flaw of the panels, Falk could not use all samples thus choosing only the ‘good’ ones (Falk, 2001). Furthermore, to simplify the analysis of the results, Falk divided the maximum force by the embedded fastener length (Falk, 2001).

In the screw withdrawal test, we notice that there was not a significant difference in the loads required to remove the screws. As well, the variability, as seen in the Coefficient of Variability was rather low. Therefore, we can conclude that wood content does not play a big part on the amount of force needed to withdraw the screws (Falk, 2001).

Like the screw withdrawal test, there was no meaningful difference in the force needed to pull a nail out of the panels. However, the tables showed a slightly lower capacity for the specimens with higher wood content (Falk, 2001). Furthermore, there seemed to be no effect whether the panels were pre-drilled or not.

In the lateral nail resistance test, the results indicated that the lateral resistance was decreased with the increment on wood flour content. This might be caused by the fact that the material was very ductile for the lower wood content (Falk, 2001).

Similar to lateral nail resistance test, wood content played an important part in the nail head pull through test. The capacity of the 60 percent wood content panels was 30 percent less than those with the 20 percent wood content (Falk, 2001). Furthermore, pre-drilling seemed to have no effect on the nail head pull through capacity (Falk, 2001).

Falk then compared the fastener performance on WPCs and other wood products such as plywood, MDF, OSB and particle board. No data regarding the fastener performance of other wood products was disclosed on the paper. However, Figure 13 below should be able to explain the difference in load resistance on various types of wood products, including WPCs.

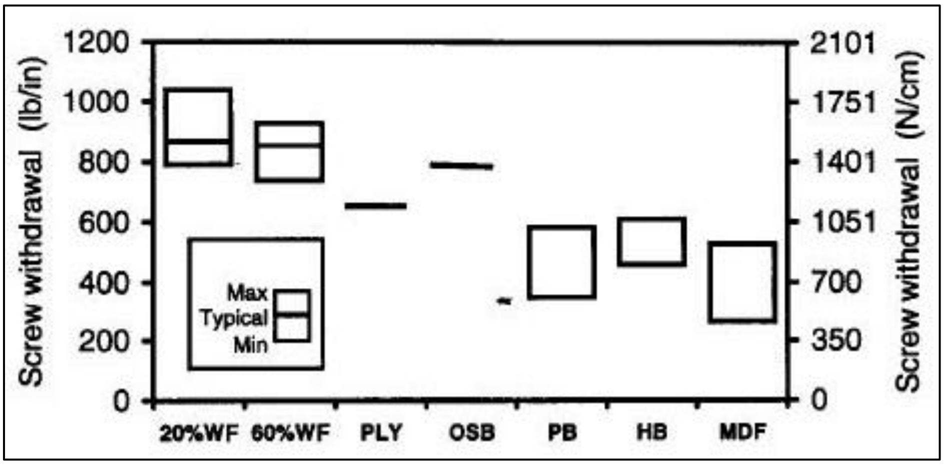

Figure 13. The Load Capacity of Various Wood Products; WF = Wood Flour Content on WPCs

As indicated in the figure above, the resistances of other wood products are still lower than Wood Plastic Composites. Perhaps, only OSB could match the withdrawal rate. The fact that WPCs have more capacity is probably due to the ability of the thermoplastic to conform around the thread of the screws, allowing to better stress transfer on the screws (Falk, 2001).

In conclusion, screw withdrawal and nail withdrawal are not affected by the wood content of WPCs. However, it is a crucial factor in the lateral nail resistance and nail head pull through test as the capacity is decreasing with the increased wood content. Furthermore, pre-drilling does not seem to have a great effect on the resistance of the panel. Lastly, WPCs can hold fasteners better than other types of wood products such as plywood, OSB, particle board, hard board and MDF. This is another advantage for the homebuilders and homeowners as it offers better durability and easiness to install.

CHAPTER 3 – RECYCLING IN WOOD PLASTIC COMPOSITES

Sustainability, nowadays, has become a major concern for buyers in purchasing or choosing products. People's awareness to save the planet has somehow shifted their way of thinking and behaving into consuming green, sustainable and recyclable products, including wood products for their homes. Industrial wood manufacturers, in response to that, try to accommodate those high demands and therefore invented the Wood Plastic Composites as an alternative to solid wood lumber as they are made of recyclable materials such as scrap wood flour and wasted plastics. This section of the paper will discuss in detail on how companies obtain the materials, both the wood flour and the thermoplastics, what the challenges are and finally the environmental effects of the recycling activities.

3.1. Recycling in WPCs

It has been reported that majority of the Municipal Solid Waste (MSW) in the United States was waste wood, waste paper and waste plastics (Winandy, 2004). In 1994, the amount of waste generated in the United States was 190 million tons and the number has kept increasing over the years (Winandy, 2004). These wastes would just be waste products if they were not used for other purposes. With the invention of Wood Plastic Composites whose main raw materials are those mentioned above, the wastes were able to re-enter the manufacturing process and be recycled to produce panels for construction purposes. This part of the thesis will discuss how WPC manufacturers obtain those raw materials.

3.1.1. Wood Based Material

As we have learned from the previous section, wood flour is the one of the main ingredients in the manufacturing process of WPCs. Usually; it comes from the post-industrial wood waste such as wood shavings, chips and sawdust (Winandy, 2004). Other sources would be from the consumers; this includes wood pellets, building construction waste, cardboards and newspapers (Winandy, 2004). Winandy also stated that recently wood pellet industry has been the major sources of wood flour with an estimated 44 percent of reclamation rate (Winandy, 2004). Rice hulls could be an alternative to the wood flour (Winandy, 2004). Nexwood has been reported to use about 9.1 million kg of rice hull in 2002 (Winandy, 2004).

3.1.2. Plastic Material

Similar to wood flour, the thermoplastics used in the production process are also recycled plastics. They typically come from recycled grocery bags and used pellet wrap (Winandy, 2004). In 2004, the amount of thermoplastics used in the process of manufacturing WPCs was estimated to be 204 million kg; of which 95 percent of those amount were recycled products (Winandy, 2004).

3.2. Challenges in Recycling WPCs

One might wonders if WPCs could be recycled after they reached their useful life. The answer is ‘Yes, they can be recycled’ (Winandy, 2004). The thermoplastic nature in WPC makes it possible for it to be recovered (Winandy, 2004). However, there are a few challenges in doing that.

Sometimes, WPCs have already reached its useful life after short period amount of time (8 – 14 years) instead of 10 – 20 years as explained in the previous section. The reasons of this change vary from remodeling the deck pattern which requires a replacement of the deck surface to the existence of splitting, checking and color alternation (Winandy, 2004). While the first problem depends highly on the consumer’s needs, the second problem might actually originate from the recycling activities of the WPCs (Winandy, 2004).

Research has shown that recycling activities of the polymer would result in the new products having less UV and biological resistance as well as their mechanical capacities (Winandy, 2004). As a result, it shortens the useful life of the products compared to the virgin polymer based products (Winandy, 2004). Therefore, WPC manufacturers have to consider this problem when they decide on how to obtain the raw materials; whether by buying wastes from secondary wood manufacturers or recycling the existing products.

3.3. Environmental Effect

The recycling activity also depends highly on how the WPCs are treated during their useful life. Most WPCs are used in the exterior application which in fact relates to degradation of the material performance and recycling potential (Winandy, 2004).

Winandy examined WPCs that had exhibited decay on their surface area and found that there existed mycelium cluster in the interface between the wood flour and thermoplastics (Winandy, 2004). In the exterior, it would look like surface erosion. He also noted that WPC with higher wood content was more prone to this kind of decay compared to those which had less wood content (Winandy, 2004).

Another environmental issue would be UV-degradation. The surface of WPC would slowly degrade with continuous exposure to UV light (Winandy, 2004). The oxygenated functional group in the thermoplastic could lead to further photooxidation when exposed to UV light (Winandy, 2004). Moreover, Winandy also noted that photooxidation occurred more in the post-consumer polyolephins (the type of thermoplastic) than virgin polyolephins.

CHAPTER 4 – SUMMARY

Wood Plastic Composite (WPC) might have been around only for a few decades. Nevertheless, it has offered a lot of advantages to the prospective consumers by being durable, easy to install, biodegradable, UV-resistant, flexible in design and many more. In real life, WPC is normally used as an exterior deck due to its strength and resistance. However, it can also be used for other purposes such as window frame, door frame, automotive interior and railings.

WPC is manufactured by compounding two different kind of materials; wood flour and thermoplastics. They are mixed in certain ratio depending on the desired final properties. Nonetheless, the production process would always be the same. The goal of the extrusion process is to blend the wood flour into the melted thermoplastics. Coupling agent such as compatibilizer is also needed in the process to create an interface between wood cellulose and the thermoplastics. Depending on the degree of mixing needed, there are two different extruders to blend the materials; they are: single screw extruder and double screw extruder. The extrusion process will result in melted mix of wood and plastic. The dough will then be pressed into desired shapes.

Furthermore, some researchers have conducted a few experiments to test the thermal, mechanical and manufacturing properties of WPCs. In the thermal test, it had been proven that temperature was one of the factors that could affect the mechanical properties of the composite. The result showed that with the increasing temperature, the stress level in tension and compression was decreasing, while the strain in tension was increasing. It also affected Modulus of Elasticity (MOE). In both compression and tension, the MOE would decrease with an increase in temperature. It had also been noted that the use of higher wood content would make the composite more stable as wood is thermally more stable than plastic. In mechanical properties test, we learned that the addition of wood in the mix would increase the tensile strength and flexural strength of the final products. However, depending on the type of thermoplastic used, the addition of wood would become ineffective at certain point since it did not increase the strength of the products any further. In tool wear assessment test, we noticed that solid wood lumbers were more tool-friendly than WPCs as they wore the tools less than WPCs. This could be caused by the presence of impurities that were involved in the manufacturing process as they increase the roughness of the final products. However, due to the flexibility WPC offers, the use of blades or other cutting tools could be minimized. In fastener performance test, there were four actions applied on the WPC panels to test the maximum load the panel could withstand. In screw and nail withdrawal test, the wood content did not seem to affect the force needed to pull the fasteners. However, in the lateral nail withdrawal and nail head pull through test, it was evident that higher wood content will result in poor resistance compared to low wood content. As well, we learned that pre-drilling had little to almost zero effect on the force needed to pull the fasteners.

Being made out of recycled materials, WPCs can also be recycled after they reach their maximum useful life. However, there are some challenges in the recycling process that could affect the properties of the composites. Based on research, recycled products would be less UV-resistant than virgin polymer WPCs. Therefore, the recycling activity could potentially reduce the lifespan of the deck. Furthermore, continuous exposure to direct UV light would cause in the development of decay in the interface of wood cellulose and thermoplastics. Also, it will reduce the aesthetic value since the photooxidation reaction would alter the color of the composites.

Regardless of the problems and challenges faced, I am confident that WPCs have bright future in the wood decking market in North America. The advantages they offer are very beneficial for both homebuilders and home owners. Furthermore, they are easy to manufacture and install. In addition to that, through the test and experiments, it is proven that they can challenge other type of wood products such as solid wood lumber, OSB, Particle Board and MDF. I believe in the near future, WPC could broaden its market share to both European and Asian countries.

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