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Matrices in Wood Plastic Composites: A Concise Review

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***Abstract* – Rising environmental pressure, new ways of using naturally-based composite materials, as well as technical innovations, has lead manufacturers to application of those materials (with the goal of reducing the consumption of financially demanding, non-recyclable types of reinforcements – e.g., fiberglass). Wood Plastic Composites (WPCs) are a product developed in 1980s. They consist of wood flour (natural fillers), polymer blends and suitable additives (to improve mechanical properties, rheological properties and production process). Technologies of WPC composite materials production frequently include extrusion, injection moulding, pressing (thermoforming), calendaring and fused layer modeming / laser sintering. When choosing a suitable matrix, it is necessary to pay attention to the processing temperature – max. T_{max} = 200 °C. At a higher temperature, natural reinforcements are decomposed. The submitted paper includes information about plastic matrices from previous studies and provides comprehensive view in the given area.**

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1. Introduction

Wood Plastic Composite (WPC) is created by combining polymer, filler and suitable modifiers (additives in a certain relation). A main function of additives is to improve a mechanical properties of a final product, provide a chemical stability and more easily mixing of added components (such as: coupling agents, foaming agents, lubricants, ultraviolet light stabilizers, etc.), the latter capable of influencing the final properties of the composite based on the requirements of the manufacturer and the final consumer.

Interest in these composite materials is increasing, encompassing both industrial applications and basic research. They are environmental friendly because are derived from agricultural waste and recycled plastics. The wood reinforcement consists of co-product like trimming from sawmills, breakdown of urban and demolition wood, or logging trimmings and slash. These materials can be machined to resemble wood, with WPC's workability being reasonably good. However, there exists a lack of quantitative data concerning their machinability index [1], [2], [3].

WPC materials offer a number of advantages: good insulation, thermal and acoustic properties, low specific weight, resistance against biological deterioration for outdoor applications, a relatively low cost of manufacturing (compared to production of composite materials with synthetic fibers) and power inputs. The WPC final product can be recycled and reused, biodegradability, environmental friendly, healthier working conditions in production. The life cycle is longer than solid wood, and maintenance cost is low [4], [5], [6], [7], [8].

The main disadvantages of WPC materials are mentioned [4], [5], [6], [7]:

- low resistance to UV radiation (there are changes in the molecular structure),
- insufficient compatibility at the fiber-matrix interface,
- high flammability index (its resistance to extreme temperature is low compared to wood),
- limited choice of matrix due to the risk of fiber decomposition at high processing temperature (resistance up to temperature approx. 200 °C),
- hygroscopicity of natural filler (contact with water – fibers "swell"),
- the toughness is lower than the plastic,
- the bending strength is lower than hardwood,
- creep performance is poor (compared wood).

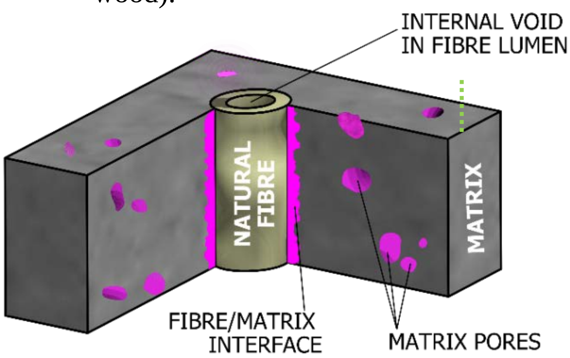


Figure 1. The compatibility between the fiber and matrix interface affected by the moisture content

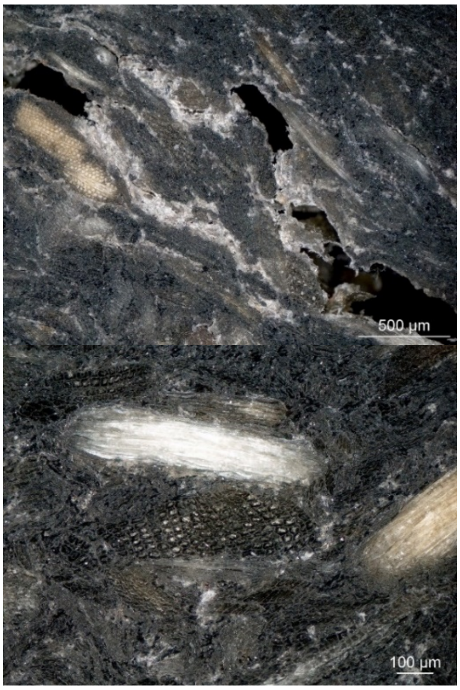


Figure 2. Interface High-density polyethylene (HDPE) matrix and wood particle, avoids between wood particle and plastic matrix (WPC product) [9]

The water-absorbing fibers increase their volume in the composite – fibers "swell". The results in weakened adhesion at the matrix versus reinforcement components interface, and subsequent deterioration of mechanical properties are presented in Fig. 1. For this reason, it is necessary to thoroughly dry the fibers before the composite is manufactured (humidity should be maintained at 1 %). The adverse properties of the fibers can be modified: through physical or chemical processes, or by the addition of suitable binding agents – e.g., silane. Properties of wood plastic composite (WPC) are described in Fig. 3.

high	COST	low
low	FLEXURAL MODULUS	high
high	THERMAL CONDUCTIVITY	low
low	CORROSION RESISTANCE	high
difficult	WORK-ABILITY	easy
difficult	FIRE RESISTANCE	easy
low	ENVIRONMENTAL IMPACT	high

IDEAL MATERIAL

Figure 3. Properties of wood plastic composite [10]

2. Matrices Applied to WPC Products

Composite materials with natural fibers fully replace common or rare woods in the furniture and flooring manufacturing industry (application of WPC appeared in the mid-1950s, with the production of a wooden flooring tile made of: PVC-wood flour). The content of natural fiber increases the stiffness of the resulting product (depending on the type of components). Biodegradable plastics – e.g., PLA (as a substitute for ABS, PP or PS) may be applied to furniture manufacture in conjunction with fibers (bamboo, flax, cotton, etc.). In the case of flooring, wood flour is usually applied as reinforcement. There are a number of companies on the market offering flooring products (outdoor and indoor) varying in quality and price (depending on the technology used, the composition of the material and the country of origin, their specification is the matter of patents and research activities). The priority in the construction sector is to find suitable substitutes for conventional building materials [11].

Examples of the use of WPC materials are shown in Figures 4 and 5.

Figure 4. Part of car door made of wood plastic composite [11]

Figure 5. Compostable cups and furniture legs (company: JELUplast Germany, up: PLA matrix + 50 % wood fibre / down: PP matrix + 50 % wood fibre) [12]

One of the options is the application of the natural fibers – due to the relatively low price, lightweight, renewability, biodegradability and suitable structural (specific) properties. Similarly, the application is justified in the automotive industry.

The application of NFRP/WPC materials reduces the weight of the vehicle and greenhouse gas emissions (reduction in the weight of the vehicle by 100 kg results in the reduction of volume of the CO_2 emitted into the air by 9 g/km). The use of composite materials with natural fillers in different industries is shown in Fig. 6 [12], [13].

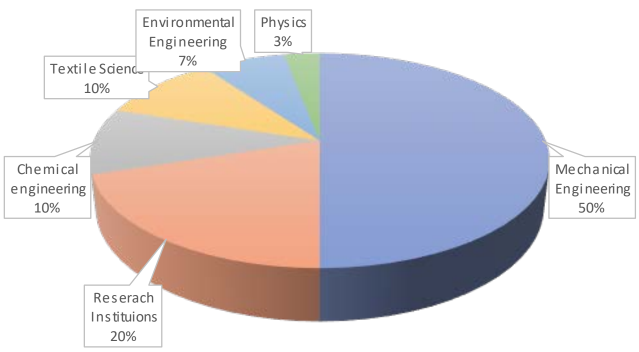


Figure 6. Use of composite materials with natural fibers in different industries [14]

The choice of the matrix depends on several factors; however, the primary selection criterion is the processing temperature of the plastic as the cellulose fibers are susceptible to thermal degradation (the limit temperature is approx. T = 200 °C, some literature sources cite a 200-220 °C interval). Thermoplastics are polymeric materials that are easy to form in a certain thermal range and retain this forming property (without changing their chemical properties). The process of their hardening is, as if, reversible – after reheating, they can be converted back into a liquid state and shaped (this property distinguishes them from thermosets). Most thermoplastics are high molecular polymers, where macromolecular chains are linked to each other by weak van der Waals bonds (e.g. polyethylene), stronger dipole-dipole bonds (e.g., nylon) or forces present between aromatic systems (e.g., polystyrene). Thermoplastics dissolve well in organic compounds. The most common thermoplastics applied in WPC materials include polyethylene, polypropylene, polyvinyl chloride. Applied thermoplastics in WPC product [3], [15], [16], [17], [18], [19], [20]:

- *polyethylene* (PE) has a relatively low melting point of 106-130 °C (depending on branching/density of PE), which allows the use of cellulose fiber fillings. It is sufficiently fine, with low water absorption (below 0.02 % after 24 hours of immersion), highly resistant to chemicals (including sulfuric, hydrochloric and nitric acids). It has a relatively high oxidation resistance compared to other polyolefins. On the other hand, it is flexible enough, but not very strong. Compared to solid wood, PE shows a higher coefficient of thermal expansion-contraction. Its relatively low strength allows it to be used in composite flooring where it meets the standard load resistance requirement (100 lb /ft^2). PE is classified according to its various forms, depending on the molecular weight and the degree of branching of the chains and the method of production. Polyethylene forms according to A. A. Klyosov – Table 1. Among the mentioned forms, polyethylene with high molecular weight HDPE, is applied most frequently. By selecting the HDPE matrix, Simonsen (2004) ensured greater protection of products (with natural fibers) against H_2O. It is possible to apply flax, sisal palm fibers with HDPE matrix. In short – natural reinforcement compared with unreinforced polymer [16], [21].

- *polypropylene* (PP) belongs to the group of polyolefins, similar to polyethylene. It is produced in the process of a monomer (propylene) additional polymerization. The result of polymerization is polypropylene – a material with high strength, toughness and resistance to corrosion, abrasion, impact, acids and bases. The chemical and electrical properties are similar to polyethylene, but it has better mechanical properties (tensile strength of 30 to 35 MPa) and lower density (0.90-0.91 g.cm^{-3}). However, compared to the above-mentioned PE, it is more brittle. Structure of PP largely determines chemical and other properties of polypropylene. The MFI (Melt Flow Index) of polypropylene, typically used for the WPC extrusion process, ranges from 2 to 5 g/10 min. However, the MFI value typical for polypropylene cannot be compared with that of polyethylene, as this index is measured at different temperatures (190 °C and 230 °C, respectively). Polypropylene has lower water absorption than polyethylene, 0.01 % at 24 h submersion (some studies report a value of 0.008 % at 24 h submersion). As for the thermal expansion of polypropylene, it is similar to that of HDPE, PP, PVC, ABS and nylon, in the interval ranging from 4 to 13 x 10^{-5} l/°C [16], [17], [18], [22].

Table 1. Classification of polyethylene forms [16]

Abbreviation	***Name***
HDPE	High-Density Polyethylene
HMW-HDPE	High-Molecular Weight High Density Polyethylene
UHMW-HDPE	Ultra-High-Molecular Weight High-Density Polyethylene
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
VLDPE	Very Low-Density Polyethylene

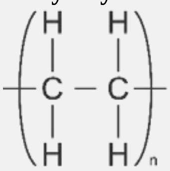
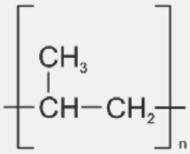
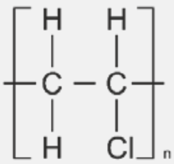
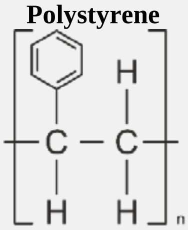
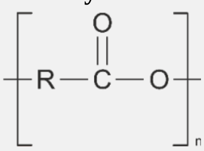
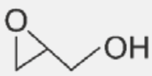
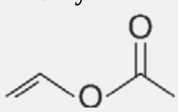
Table 2. Typical properties of PP applied to the production of NFRP (Profax 6501)

Property	***Value***
Melt Flow Rate	4 g/10 min
Density (at 23 °C)	0.9 g.cm^{-3}
Tensile stress at yield	34 MPa
Tensile elongation	12 %
Flexural modulus	1.4 GPa
Noteched IZOD impact strength (at 23 °C)	39 N

- *polyvinylchloride* (PVC) is the second most mass-produced plastic. It is produced by polymerization of vinyl chloride on the free radicals basis. There are two forms of polyvinyl chloride – hard and softened. The hard form is made without plasticizers with a tensile strength of 55-60 MPa. The vitreous state is achieved at 85 °C, Plasticized PVC is made by adding plasticizers accounting for 20-50 % of the content. By increasing the plasticizer concentration, the strength decreases and the elongation increases. It is suitable for the production of pipelines, pipes, and window frames; it is not used in such quantities for the production of WPC boards. On the other hand, it reduces the price of the final composite material. Compared to PP or PE resin, the PVC matrix has significant disadvantages, which include low thermal stability and high brittleness (for example compared to HDPE). The high brittleness of PVC at ambient temperatures is caused by a relatively high glass transition temperature of PVC (in range 70-90 °C). One of the beneficial PVC properties is its inherent resistance to ignition, however, in the combustion itself, the harmful, ecologically unacceptable HCl, is emitted. PVC decomposes at a temperature of 148 °C, which causes corrosion of functional parts of the press and, therefore, requires the use of corrosion-resistant steels and protective coatings. Polyvinyl chloride has a higher water absorption than polyethylene and polypropylene – 0.1 % at 24 h submersion [16], [17], [18].

Currently, studies are underway to verify the application of polymethyl-methacrylate (PMMA), Nylon 6 (melting temperature 216 °C) or Nylon 12. For example: in conjunction with wood flour (of more than 60 %), Nylon 12 offers increased bending and tensile strength [23].

Table 3. Pros and cons of applied matrices [3], [24]

Pros	***Name***	***Cons***
↓ density, ↑ impact toughness, good electrical insulation, ↓ water absorption, ↑ corrosion resistance	**Polyethylene** 	↓ strength and stiffness, flammable, hard to glue together, ageing under heat and thermal oxidation
cost-effective, relatively lightweight, ↑ resistance to chemicals	**Polypropylene** 	↑ brittleness, flammable, hard to glue together
↑ chemical resistance, ↑ tensile strength	**Polyethylene** 	non-biodegradable, unsuitable for food packaging, highly reactive when mixed with acetal
cost-effective, ↑ electrical insulation properties, resistance to creep, surface hardness, easy to process	**Polystyrene** 	brittleness under photooxidation, tendency to form cracks, brittle, flammable, ↓ resistance to petroleum product
hard, rigid plastic, possible applications in its recycled state	**Polyester** 	↓ heat resistance, ↓ solvent resistance
↑ resistance against bases, water resistance, good mechanical / thermal / electro-insulating properties	**Epoxid** 	higher production cost compared to vinyl esters
↑ chemical resistance, better mechanical properties compared to polyester	**Vinylester** 	higher production price compared to polyester, higher shrinkage values upon curing

Note: ↑ – high values of the property / ↓ – low values of the property

Similarly, biopolymers and biodegradable polymers can be used as an adequate substitute for thermoplastics (e.g., polylactic acid – PLA, polyhydroxyalkanoate bases – PHB / PHBV).

PLA and PHB matrices have properties similar to PP matrices (PLA melting point = 150-162 °C, density in the range of 1.21-1.25 g.cm^{-3}, PHB melting point = 168-182 °C, density in the range of 1.18-1.262 g.cm^{-3}), they can be processed similarly to polyolefins. In conjunction with the PLA matrix, it is possible to apply jute, abaca, linen, wood, hemp, kenaf and bamboo fibers (PLA matrix + long hemp / cotton fibers → tensile strength up to 61 MPa, Young's module 8 GPa → application in pressed parts in the automotive industry). A major disadvantage of composite materials with a PLA matrix is their low thermal stability and toughness. When it comes to thermoset matrices, it is possible to apply polyester (PES), epoxies and vinyl esters [3], [25].

Comparison of pros and cons of synthetic matrices is shown in the Table 3.

3. Conclusion

Wood plastic composites are materials consisting of polymer matrix, natural reinforcement, and additives in some ratio. The choice of the matrix depends on several factors; however, the primary selection criterion is the processing temperature of the plastic as the cellulose fibers are susceptible to thermal degradation (the limit temperature is approx. T = 200 °C). Based on this requirement it is possible to apply thermoplastic and thermoset matrices. The most common thermoplastics applied in WPC materials include polyethylene, polypropylene, polyvinyl chloride. Currently, studies are underway to verify the application of PMMA or Nylon/and biopolymers and biodegradable polymers.

WPC materials are not currently recyclable (does not exist suitable technology). Biopolymers and biodegradable polymers are being developed to be used as an alternative solution for non-recyclable plastics in WPC products.

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