Wood - Polymer Composites as an Alternative to the Natural Environment

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Abstract. Along with the growing consumption of wooden and wood-based products, the amount of waste generated during both production and consumption of these products increases. These wastes constitute a rich raw material base, the appropriate use of which can significantly reduce the use of natural wood raw material. Unfortunately, a significant proportion of them, especially of post-use and wood-based origin, end up in landfills. It seems necessary to find ways to use the generated waste. One of them is to use them in the form of strengthening polymer-wood composites. Composites with a wood filler can be a competitive product for materials with an inorganic filler. The wood filler is characterized by lower cost, higher availability and definitely lower density than glass fibers. An additional advantage of composites with wood fiber is their easy recycling and a smaller amount of waste products remaining after combustion. The use of a polymer matrix provides flexibility to the composite and has a positive effect on the ability of the material to stretch under the influence of temperature. The main advantage of the matrix in the form of a polymer is also to provide the product with resistance to the effects of the external environment, especially moisture and water. The main centers for the production of polymeric and wood composites are North America and Europe. Mainly floor, wall and roof platings are created. In addition, they are used as fences, windows and doors as well as additional equipment for platforms, landscape architecture, floor materials and panels.

1. Introduction

The increasing consumption of wood products and wood-based products is accompanied by an increase in the amount of waste generated both during production and as a result of using up such products [1]. This waste provides a rich resource of material that can be put back to good use thereby reducing the utilisation of the natural wood raw material. In practice, production waste is actually recycled while there is still much do be done with regard to the recycling and reuse of the wood contained in worn out wood products. Their utilisation is essential because of the fact that they represent a heavy burden on the natural environment. Due to the necessity to prevent the adverse effects of the increasing stream of waste generated, in the light of the concept of sustainable development, steps need to be taken in order to cause a reduction of the surplus of unmanaged industrial waste. The waste generated by the woodworking industry can managed thanks to the dynamic development of energy production from renewable sources. Wood provides useful biomass for energy generating purposes; it can be effectively utilised by numerous woodworking plants for energy generation using various thermal methods in which waste wood is incinerated [2].
Due to the excessive amounts of waste generated, a lot of woodworking plants implement practices related to the process of energetic recycling, i.e. the use of the waste for obtaining useful materials, substances or energy. The basic recycling processes include thermal transformation of waste where heat plays an important role in the physical or chemical transformation of the waste material [3]. The growing amount of wood waste implies the necessity to find ways of managing it. Such a manner of management should take account of the environmental aspects, and consequently the principles and hierarchy of sustainable waste management. Unfortunately, a significant portion, typically from used-up products or wood-based products, goes to landfill sites. It seems necessary to find ways of utilising the waste generated. One of them consists in using it to reinforce wood-polymer composites.

A composite is a material made by combining two or more other materials which form separate phases and do not mix. In a composite, one of the components is the matrix and the other one is the reinforcement component. The matrix integrates the reinforcement and gives the proper shape to the products, and also determines the physical and chemical properties of the material while the reinforcement additionally improves selected properties of the material. A composite material acquires better or new properties relative to the properties of the initial components. Wood-polymer composites (WPCs) are also known in the Polish and the worldwide literature as wood-plastic composites. These composites are also termed as wood plastics or polymer wood. Another term that can be found in the literature is ‘artificial wood’ [4].

Composites with wood filling can be a competitive product relative to materials with an inorganic filling. In order to examine the cost-effectiveness of replacing glass fibres with wood fillers, an analysis was conducted concerning the life cycle of car door panels [5]. The panels were made from a polypropylene matrix and a filler with a mass content of 40%. The use of organic filler promotes the reduction of the adverse effect of the element concerned on the environment. Furthermore, wood fillers are characterised by lower costs, greater availability and substantially lower density as compared with glass fibres. An additional advantage of composites with wood fibres is that they are easy to recycle and produce fewer by-products during incineration.

2. Ingredients

2.1. WPC fillers

The wood used in composites can be in the fibrous form (wood fibres) or the grain form (wood flour) [5, 6]. Lignocellulosic materials can be used as fillers or reinforcements of thermoplastic polymers in industrial applications [7]. Small fibres with a high shape factor (the length to width ratio) are recommended for use in WPCs because they are more evenly distributed in the matrix than long fibres and provide a greater specific surface area, which improves compatibility [8], and therefore they act as reinforcement. Wood particles have dimensions that are approximately equal in all the directions and can have any shape [9]; then, they act as fillers. However, the initial morphology of the constituents of wood is not constant and is susceptible to changes resulting from the action of shear forces and high temperatures during the WPC processing [10]. Wood fibres provide reinforcement that is characterised by high mechanical strength as well as an advantageous shape factor. However, they cause difficulties in processing with thermoplastics. Wood fibres are also definitely more expensive than wood flour, which why the latter is more frequently used. The use of wood flour as a WPC reinforcement involves difficulties in achieving repeatability of the composites produced. This is due to the lack of standardisation in the production of this filler which results in its varying purity and composition.

The mass content of filler in WPCs is between 10% and 90%. The amount of filler is the criterion according to which wood-polymer composites can be divided into the following three groups [5]:

- low-filled composites with a wood content in the range of 10%-40%;
- high-filled composites with a filler content in the range of 40%-80%;
- liquefied wood where the filler mass content reaches 90%.

Because of such a wide range of filler mass content, the properties of wood-polymer composites are essentially affected by the quality of the fibres used, i.e. their shape and humidity, as well as the repeatability of the parameters that describe this composite [1].

Wood filler [11] is a reinforcement characterised by ready availability which translates into the low price of this material. This filler is environment-friendly owing to the lack of toxic substances and the fact that it can be recycled or biologically degraded. Because of the renewability of this product, it can compete with inorganic fillers. Wood fillers are lightweight materials, which means that the composites that are manufactured using such fillers are distinguished by lower density than comparable composites made using inorganic fibres. They are also strong and abrasion resistant.

The main disadvantages of wood fillers include their flammability as well as the anisotropy of mechanical properties. Additionally, these materials are not resistant to moisture. They are also characterised by varying quality depending on the source of origin.

2.2. Polymer matrix in WPCs

Materials used as composite matrices are thermoplastics, such as polyolefins or PVC, less commonly PS, ABS or biodegradable polymers. Other plastics cannot be used in the manufacture of WPCs due to the melting point exceeding 190-200°C. The temperature value is determined by the decomposition of some constituents of wood, e.g. lignin or hemicellulose [12].

WPCs can be divided into two groups with respect to the type of matrix:

a) polymer as the main matrix material (polymer matrix, WPC);

b) wood as the main matrix material (wood matrix, WPC).

The first group features wood filler introduced to a polymer matrix in the form of wood flour or fibres. The process of obtaining such a composite is known as melt blending or solution casting. Basically, flour is used to facilitate the production, reduce thermal conductivity and reduce polymer consumption [13]. In the other hand, fibres are used in order to improve a number of mechanical properties of the polymer but this can cause difficulties in the processing due to the nature of the fibres. In the other group of composites, the manufacturing process involves impregnation of wood pores, such as vessels and coils, with monomeric or pre-polymeric resins with a low molecular mass, followed by in-situ polymerisation by means of the thermal catalytic method [14, 15]. The polymer that is formed fills the porous spaces inside the wood, thus improving the overall properties of the wood [16].

The matrix in a WPC can be both a pure polymer and a polymer recyclate from polymer waste [5]. This kind of recyclate can be obtained in the production of plastic elements or after such elements are worn out. It is characterised by worse properties than pure polymers which is hugely affected by the fact that it is a more or less complex mixture of these chemical compounds. The lack of homogeneity in the composition of the recyclate makes it significantly more difficult to control the quality of the composite being manufactured [17]. Hence, in the production of WPCs for essential applications or intended for research purposes matrices of pure polymers are used. The percentages of polymers used as matrices in wood-polymer composites in North America and Europe have been shown in Figure 1.
In North America, which is currently the leader in the production of WPCs, the prevailing matrix materials are polyethylenes – 89%. These are followed by polypropylenes – 7%, while PVC matrixes are the least frequently used here – 4%. In Europe, on the other hand, polypropylenes are most frequently used in matrices – 74% while PVC is used in 14% of the production. The remaining 12% are other polymers, of which approx. 8% are recycled materials.

2.3. Mineral fillers in WPC - optional

As an option, mineral fillers, such as glass fibres, talc and carbon fibres, can be used in wood-polymer composites. Mineral fillers can improve multiple properties of wood-polymer composites, such as resistance to moisture, fire resistance or mechanical properties [18]. Typically, mineral fillers are original, i.e. new materials. Some recycled materials are also suitable for use as mineral fillers in wood-polymer composites, e.g. recycled mineral wool [19]. Mineral wool is commonly used for insulation of buildings accounting for approx. 60% of the whole thermal insulation market [20]. As a result, this material fraction is commonly found in the waste stream. It is often considered as difficult to recycle and therefore it is usually placed at landfill sites. In wood-polymer composites with added mineral filler, such as glass fiber, the weight content of such filler is usually 10-20% [21].

2.4. Additions to WPC

Obtaining appropriate characteristics in wood-polymer composites involves the necessity to apply various auxiliary and modifying additives. These include antioxidants, lubricants, colours, flame retardants and compatibilisers (adhesive agents) [11, 22]. The use of antioxidants and stabilisers in the production of WPCs serves the purpose to improve their resistance to ageing and to prevent polymer degradation e.g. under exposure to UV radiation. Lubricants reduce the internal friction in polymers, which makes it easier to form them into finished products. Additives in the form of pigments and colours allow obtaining wood-polymer composites with particular visual and aesthetic characteristics. Compatibilisers, in turn, are used to increase the interfacial adhesion, which in turn significantly contributes to the increase of the degree of homogenisation of the composite constituents [23]. Application of a suitable adhesive agent (compatibiliser) results in the binding of the hydrophilic wood reinforcement with the hydrophobic polymer matrix. Effective methods include fibre modification by acetylation, alkalisation and esterification as well as the use of pro-adhesive agents. Not each of these methods, however, is cost-effective [24].

The main disadvantage of WPCs is their flammability; therefore, flame retardants are used. The most effective method is to incorporate flame retardants during the blending process. Ammonium polyphosphate (APP) is one of the conventional, highly effective and widely used environment-
friendly flame retardants used to improve the flame retardancy of WPCs [25]. In order to enhance the flame retardancy of WPCs, other flame retardants can also be used apart from APP, such as expanded graphite [26], SiO₂ or CaCO₃ [27]. In addition to the above mentioned, several other kinds of inorganic additives can be used, including aluminium hydroxide and magnesium hydroxide [28]. Poor compatibility of these agents with polymer matrices can result in reduced tensile strength and impact resistance as well as elongation at break of the WPCs formed [29, 30].

On order to obtain wood-polymer composites characterised by significant fire resistance, a wood material impregnated with a mixture of boric acid and borax can also be used in the production [31]. Furthermore, the use of the mixture of boric acid and borax improves resistance to microbial corrosion of the WPCs. Reports in the literature also suggest that the addition of nanofillers can enhance fire resistance as well as the mechanical properties and thermal stability of polymer composites [32]. Not many publications, however, focus on the impact of nanofillers on fire resistance and the mechanical properties of WPCs.

Apart from those described above, other additives used in the production of wood-polymer composites include hardeners, anti-adhesive agents, lubricants and foaming agents.

3. Processes related to the production of WPC

The methods that are used in WPC processing [5] include extrusion moulding, injection moulding and hot pressing, used only for laminates. Extrusion moulding is a method that is applied in 70% of the WPC production. This method is economically advantageous and is primarily used in the manufacture of profiles and frames. It consists of two stages. In the first stage, the polymer is mixed with the filler as well as other additives. The second stage is the shaping of the finished product. Obtaining a WPC by means of an injection moulding machine is based on forming ready injection moulding products in previously prepared moulds. For this purpose, a granular material or powdered mixture of ingredients with set mass contents is fed into the injection moulding machine.

The criterion for application of the product is the basis for choosing the processing method. It should ensure obtaining the expected mechanical properties, aesthetic qualities and unit price of the finished product [33].

4. WPC properties

The characteristics of wood-polymer composites [9] depend above all on the components used in the production as well as the method and conditions accompanying the manufacturing process. The use of polymer matrices ensures flexibility of the composite and has a positive impact on the capability of the material to expand under the influence of temperature. The main advantage of polymer matrices is that they make the resultant material resistant to the external environment, and particularly moisture and water [31].

While the matrix provides a WPC mainly with integrating and protective properties, the wood filler affects the mechanical properties of the composite. It determines the stiffness and resilience of the whole material. The increase in the filler content in the material implies an increase in Young’s modulus while its static tensile mechanical properties are compromised. Increasing the content of wood material in the composite also reduces its water resistance. Increased absorption adversely affects the mechanical properties of the composite. For this reason, it is advantageous to apply compatibilisers and chemical modification of the filler in materials with increased filler content in order to improve the mechanical properties of the WPC. The use of lightweight materials, in the form of a polymer matrix and wood filler, in the production of wood-polymer composites means that the product has low density of approx. 1 g/cm³. The low bulk density of WPC and its resistance to external factors makes it possible for the material described here to compete with other composite
materials or with wood itself. WPC materials are characterised by better mechanical properties than pure wood. These materials reach higher values with regard to flexural and compressive strength as well as hardness, and their structure is distinguished by lower porosity than the structure of wood [34]. Furthermore, wood-polymer composites are characterised by higher dimensional stability [35] and materials produced from them do not require to be finished with any protective coatings [36].

5. Application of WPC

The main centres of production of wood-polymer composites are North America and Europe [5]. In North America, WPCs are used primarily to manufacture floorings, wall linings and roofing materials, which all account for approx. 70% of the total production of WPC elements. The remaining 30% comprise fencings, windows and doors as well as accessories used in jetties, footbridges, landscape architecture, flooring materials and panels. The most common products in the European WPC market are hollow and solid sections as well as finishing accessories for construction purposes. In Poland, the production volume of wood-polymer composite materials is several tens of tonnes. The assortment of domestically-produced goods includes floor panels, handrail and balustrade systems, boxes and flowerpots as well as exterior siding panels.

Wood-polymer composites are used in various industries. They include the automotive, furniture and construction industries [5]. In the car industry WPC materials are primarily used in the form of door and roof panels. In Germany WPCs with polypropylene matrices are used to manufacture bumpers, dashboards and steering wheel elements. In the construction industry wood-polymer composites can be used as an alternative material for wood. They are found especially in exterior applications where wood requires to be repeatedly impregnated. Construction products made using WPCs include elements of roofs, floors, handrails, fences, linings, fittings, windows, doorframes and furniture. One of the most commonly used WPC products in the United States is plastic lumber [5]. This is a kind of exterior floor plank consisting of 50% filler in the form of wood fibres and 50% matrix of PEHD from recycled packaging. The production of this material uses 100,000 tonnes of filler annually. WPC materials are also used in the road construction industry. Facilities made using such materials include platforms, footbridges, stairs, guiding rails or motorway barriers. Another branch of economy that uses wood-polymer composites is gardening. Among products made of these materials there are flowerpots, warehouse boxes, pallets, packages and toys.

6. Summary

The problems with quality and repeatability of the characteristics of recyclates can be solved provided that the process of recycling them will be treated as a process of creating new materials, shaped in terms of their most effective applications. The basis way to extend the scope of suitability of waste materials in the production of new goods is by appropriate selection of recyclates mixtures with characteristics of construction materials. Wood-polymer composites are lightweight materials distinguished by high mechanical strength. They have pro-ecological properties related to both the materials used in their production, as the matrix and the filler can be obtained from waste, and the possibility to recycle the worn out composites again. Composites made on such a matrix can also be materially recovered, which in many cases leads to improving some of the performance parameters.

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