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(RESEARCH ARTICLE)

Effect of wood particle size on the water absorption of wood-plastic composites

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Abstract

The main aim of this paper is to present the research findings which come out from the experimental determination of the influence of input raw material properties and composition on the water absorption of wood-plastic composites. During the WPCs production, important raw material parameters such as wood sawdust particle size, wood/plastic concentration ratio or type of plastic matrix can be recognized. In this research study, the aim was to produce WPCs of an acceptable and competitive level of quality which is determined from the final mechanical properties of WPCs. Particle size of wood sawdust used for production of WPC has significant influence on mechanical properties of composites and also on other important properties (water absorption, hardness, frost resistance, etc.). Using a variety combination of influencing variables the final quality of composites and also the operating parameters of the injection molding press can be improved. Their effect can be seen from the quality indicators and from the operating parameters of the injection press which has a direct impact on the production costs. The paper deals with the determination of the impact and the relationship between the input wood sawdust particles sizes, wood/plastic concentration ratio and water absorption of composites. By side intention of authors is to determine the possibilities of waste raw materials usage. The experimental research findings were obtained using a semi-operational injection molding press where the injection is provided by a working screw. As the input raw material, spruce sawdust, HDPE plastic matrix and recycled HDPE, represented by lids from PET bottles, was used. The effect of the input wood sawdust particle size on water absorption was determined according to a combination and default levels of wood/HDPE concentration ratio, using recycled HDPE instead of virgin HDPE and particle size of wood sawdust.

Keywords: Wood sawdust; WPC; Wood-plastic composites; Particle size; Water absorption

1. Introduction

The biomass-plastic composites (BPCs) production process is very well known. The scope of use of these materials today is mainly in the automotive, engineering and electrical engineering industries. Also, various research studies [1, 2, 3] with material and technological variables effect on the production are dealing with. BPCs are produced by thoroughly mixing ground biomass particles and heated thermoplastic resin [4, 5, 6]. The most common method of production is to extrude the material into the desired shape using injection molding or extruding, however, we can see also production of composites using additive manufacturing resp. 3D printing. BPCs may be produced from various virgin thermoplastics but polyethylene based BPCs are by far the most common [4]. Also the additives such as colorants, coupling agents, UV stabilizers, blowing agents or foaming agents are included [7]. The usual composition of BPCs based virgin material is 60 - 65% of high-density polyethylene (HDPE) [4, 8], 30 % of biomass particles without defined granulometry, but the particle sizes up to 2 mm and the additives according to the final application, which helps tailor the end product to the target area of application [3].

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Another hand on the base of amounts of wastes and environment protection is using of waste or recycled materials for BPCs production a big issue for nowadays [5]. Raw materials are crucial for the European economy. They form a strong industrial base and produce a wide range of goods and applications used in everyday life and modern technologies. Reliable and unrestricted access to certain raw materials is a growing concern in the EU and worldwide. Given the continuing strategic importance of raw materials for the EU industry, the Commission is currently implementing a wide range of measures under the EU Raw Materials Initiative to contribute to a secure, sustainable and affordable supply of raw materials [9]. One of the possibilities for the production companies to ensure the EU strategic plan is implementation of the circular economy. The circular economy, also called "green economy", is a new economic model that is the opposite of the current model - the linear economy [10]. The essence of the profit of the current system of "take-produce-throw away" is above all the high consumption of renewable an also no-renewable raw materials, which logically cannot work in the long run. When we add other negative factors to this, such as the use of cheap manpower from developing countries, the population explosion, increasing consumption and the devastating human impact on the environment, we can rightly consider the current system to be unsustainable [10]. Economically, ecologically and socially. On the contrary, the circular model is intended to ensure the competitiveness of countries, their stable economic growth and a healthy environment. The yield in the circular economy is based on the efficient use of natural resources achieved by the efficient recovery of the materials, products and components used. Their constant return to the technical and biological cycle represents the closure of material flows. This radically minimizes waste and the costs of material inputs and energy required for the production of new products. The main features of this concept are the use of renewable energy sources, eco-innovation, rental, sharing or support of local trade. The rising concern towards environmental issues and, on the other hand, the need for more polymer-based materials has led to increasing interest about polymer composites based waste materials [11]. Construction waste is one of the largest waste streams in the EU. The EC Waste Directive 2008/98 targets a more sustainable construction industry, recovering a 70% (by weight) of its non-hazardous construction waste by 2020 [12]: to meet that objective, new solutions must be found to achieve an efficient material recovery.

When producing the products based biomass-plastic composites, various fillers are added to improve the mechanical and physical properties of these composites. Nowadays, there is an increasing emphasis on environmental protection and there is more interest in replacing inorganic fillers with organic fillers, such as biomass for example wood, wheat straw, hay, corn stalks or rice husks. The development of renewable raw material composites has increased considerably in recent years due to their ecological and easy recyclability. Natural fibers are renewable, easily recyclable, carbon dioxide neutral and available in large quantities [13, 14]. The huge advantage of biomass is its relatively low price and easy accessibility. The main challenges in this area is to gain the research findings about waste recovery possibility that can show the possibility and application of wood-plastics composites (WPCs) based waste raw materials. Obtained research findings can be very helpful at WPCs production and shown the possibility of using also waste raw materials for WPC products and using of such a composites for rapid prototyping which is very interesting issue and recovery possibility for nowadays. Therefore the main activities are focused on determination of the material variables effect on mechanical properties of WPCs based waste raw materials. According to our previous basic research, analyses of available research findings [1, 2, 4, 5, 14, 15] and knowledge an important input variables such as raw material´s parameters, especially (type of raw material and wood sawdust particle size) can be recognized during the production of WPCs [13, 14]. Their impact can be seen through the quality indicators; especially mentioned parameters significantly influence the mechanical properties of WPCs (ultimate strength, maximal force, elongation, impact strength, toughness, modulus of elasticity, water absorption, hardness, etc.) [2, 4, 15]. Most important is the role of biomass particle size, in this case the wood sawdust. The highest tensile strength can be achieved by using the smallest possible particles. Particle size also affected the elongation of composites, with increasing the particle size the elongation is decreased [16]. The use of the largest possible particles of wood sawdust will significantly increase the modulus of elasticity in tension. When the percentage amount of wood particles in composites is increased, the flexural strength decreases significantly [17]. The increased percentage amount of wood sawdust in composites has a negative effect on density of composites. The effect on water absorption of composites was also recorded. When the particle size in composites was increased the water absorption of composites was increased too. However, the water absorption of WPC materials is uneven. Some WPC materials absorb more, some less water. When immersing WPC materials in water for up to 24 hours, they absorb amount of water of 0.7 and 3.0 % of their weight. Compared to the water absorption of wood in the same time, it is about 24% [18]. Water absorption of WPC materials leads to several unpleasant events. The best known of these is the spread of fust or the disruption of WPC products. Another unpleasant phenomenon is that the absorption of water can lead to a faster oxidation of WPC products, because water serves as a catalyst during the oxidation of plastic. WPC materials absorb water due to their porosity [18]. When absorbing water, WPC products increases in volume and the pressure increases at the contact points, leading to curvature of the WPC products.

The general purpose of this paper is to present the research findings regarding the effect of particle size and percentage amount of wood sawdust in composites on the water absorption of wood-plastic composites. Authors would like to present this effect also in case of WPCs based virgin thermoplastic and also in case of WPCs based waste raw materials. Such of results are very important and interesting from the production possibilities and applications of WPCs based waste raw materials point of view. Obtained future research findings can be very helpful at WPCs production using 3D printers and shown the possibility of using also waste raw materials for WPC products, and thus increase the environmental responsibility with the environment protection.

2. Material and methods

The main aim of our experiment is to determine the effect of raw material properties (particle size of wood sawdust) on the water absorption of wood-plastic composites. For purposes of determination this effect, the basic raw materials had to be chosen and prepared. HDPE (high-density polyethylene named TIPELIN 1108J from Slovak company Slovnaft a.s. Bratislava, with the melt index 8.0 g / 10 min), HDPE rec. (recycled high-density polyethylene originating from lids of PET bottles) were used as plastic matrices. Spruce sawdust originating from Western Slovakia was obtained from wood processing company without bark. This kind of wood is a typical softwood in Slovakia and are widely and usually cultivated in our country. Samples of spruce wood in the form of a spruce wood chips were obtained from a wood processing company. For processing the spruce wood chips to the form of spruce sawdust the hammer mill STOZA ŠV5 equipped with screen 8.0 mm and 4.0 mm in diameter was used. On Figure 1 can be seen the achieved samples of spruce sawdust after shredding. Shredding on two level was used, for obtaining proper amount of samples with suitable level of fineness. Initially, Retsch Vibrating Sieve Equipment AS 200, according to the EN ISO 17827-1 [19], for analyzing of the particle size distribution (Figure 2) was used. As mentioned above, suitable spruce sawdust for WPCs production was processed by two level of shredding: untreated raw spruce chips (sample 1), spruce sawdust treated by single level shredding (sample 2) and spruce sawdust treated by double level shredding (sample 3) were used. Figure 2 shows the raw material particle size distribution of the three samples obtained by shredding.

Figure 1 Shredding of spruce chips to the samples of spruce sawdust - raw spruce chips (left), sample after 1st level of shredding (middle), sample after 2nd level of shredding (right)

Table 1 Input controllable variables of the experiment [20]

Variables			
Levels	**Wood/Plastic ratio (%)**	**Particle size (mm)**	**Polymer matrix type (-)**
1	0 / 100	0 - 0.5	HDPE
2	10 / 90	0.5 - 1.0	HDPE rec.
3	20 / 80	-	-
4	30 / 70	-	-

In our case, determination of the mutual interaction between water absorption of WPC´s samples, type of the plastic matrix used in WPCs, biomass/plastic concentration ratio and particle size of raw feedstock used in WPCs were chosen [20]. Experimental research was done according to the designed experimental plan where the full factorial experiment was used [21]. Experimental research consisted of 3 influencing parameters, the specific type of polymer matrix - on 2 levels, particle size - on 2 levels and concentration ratio of plastic/biomass where the 90:10, 80:20, 70:30 ratios were used (see Table. 1). Because the experimental research with raw waste materials was dealt and according to given experimental plan raw material for the experiment had been treated. For obtaining the given biomass particle sizes the disintegration and separation processes were used. According to our knowledge as a particle size only particles 0-0.5 mm and 0.5-1.0 mm were chosen [20, 22]. Bigger particles are not usually used during the production of WPCs. For this experiment as a wood component spruce sawdust with up to 0.5 mm and up to 1.0 mm particle size was used (Figure 3), with properties shown on Figure 2. The moisture content of chosen biomass component before mixing, extrusion and injection were measured with the aid of a Kern MRS 120-3 balance. This measurement consisted of heating the raw feedstock (gravimetric method of moisture content measuring) [23] at 105 ± 2°C until a constant weight was achieved. The moisture content of spruce sawdust component on the level of 2% was prepared. For disintegration of PET bottle lids (Figure 4) cutting mill Retsch SM 300 was used.

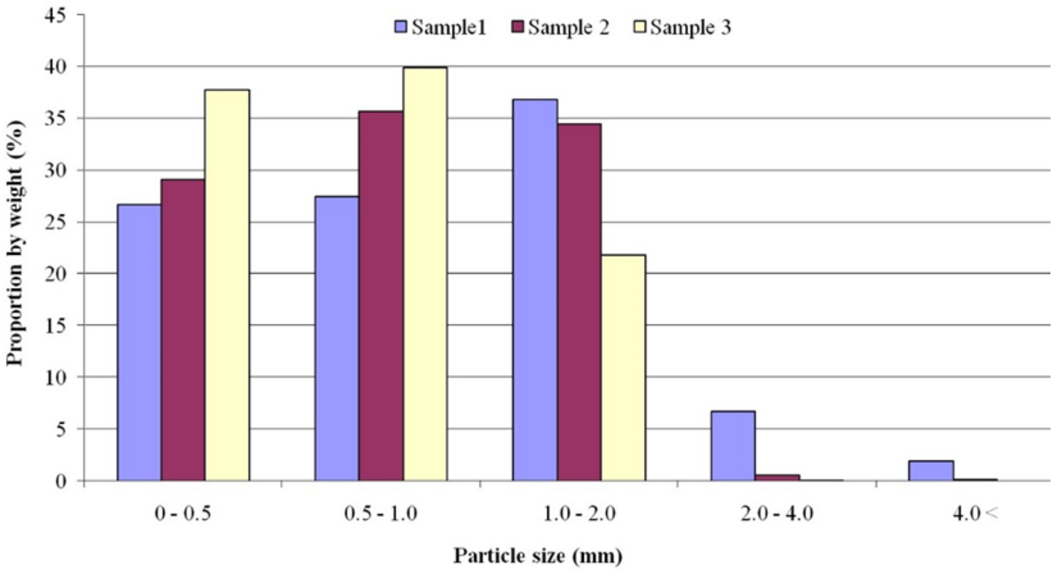

Figure 2 Raw material particle size distribution of the samples studied

Figure 3 Spruce sawdust in samples suitable for WPCs production – up to 0.5 mm sawdust (left), up to 1.0 mm (right)

Figure 4 The disintegration of PET bottle lids

A set number of samples for testing will be produced according to the designed experimental plan shown in Table 2. The used injection mold is produced according to ISO 527-2 / 1A / 10. It is used to injection of normalized tensile test specimens. On the Figure 5 can be seen the shapes of normalized testing specimen after injection. For each set according to the experimental plan at least 12 specimens were produced and during the injection the operating parameters of injection press were recorded. The operating parameters of injection process according to the requirements for proper filling the form have been adjusted for production of specimens with expected quality and to avoid the formation of bubbles inside and to collapsing the specimen sides.

Table 2 Designed composition of experimental research setting for both biomass component type [20]

Number of setting	Polymer matrix type (-)	Plastic/wood ratio (%)	Particle size (mm)
1.	HDPE rec.	90/10	0 - 0.5
2.	HDPE rec.	80/20	0 - 0.5
3.	HDPE rec.	70/30	0 - 0.5
4.	HDPE rec.	90/10	0.5 - 1.0
5.	HDPE rec.	80/20	0.5 - 1.0
6.	HDPE rec.	70/30	0.5 - 1.0
7.	HDPE	90/10	0 - 0.5
8.	HDPE	80/20	0 - 0.5
9.	HDPE	70/30	0 - 0.5
10.	HDPE	90/10	0.5 - 1.0
11.	HDPE	80/20	0.5 - 1.0
12.	HDPE	70/30	0.5 - 1.0
13.	HDPE rec.	100/0	N/A
14.	HDPE	100/0	N/A

Figure 5 Testing specimens after injection – specimen for tensile test (left), specimen for impact test (right)

Figure 6 Extrusion and production of composites granules by twin-screw extruder

The experimental samples production process can be seen in Figure 6. Given wood/plastic ratios had to be prepared by mixing with using a usual electric mixer, weight by using MR 120 balance was controlled. Composites granules for injection by twin-screw extruder LTE26 and final specimens by Mitsubishi 180 MEt III injection moulding machine were produced. Specimens dimensions related to the Standard STN EN ISO 527-3 were produced [24].

As was mentioned above, for each setting according to the experimental plan a specific number of both types' specimens (Figure 5) were produced. Specimen seen on the Figure 5 left is usually used for tensile test, in which a sample is subjected to a controlled tension until failure. Specimen seen on the Figure 5 right is usually used for impact test, which is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. In our case, the effect of particle size on water absorption will be determined by specimens for tensile test and the effect of particle size on WPCs density will be determined by specimens for impact test. Wood-plastic composites can absorb different amounts of water and thus its presence can significantly affect material properties such as electrical insulation resistance, mechanical properties, dielectric loss, dimensions or density. The absorbency of wood-plastic composites is influenced by the final composition of the material [25, 26]. Therefore the following determination methodology of water absorption was used. The WPC specimens were immersed in distilled water and thus exposed to high humidity. Percentage weight gain during immersion was measured by Kern MR 120 digital balance and was calculated by following equation (1) [26, 27]:

$$water\ absorption = \frac{specimen\ weight\ in\ time - initial\ weigth\ of\ specimen}{initial\ weigth\ of\ specimen} . 100\ [\%] \qquad (1)$$

For the determination of WPCs density the digital caliper Mitutoyo 500-196-20 when the length, width and thickness of specimen was measured. These values for the calculation of specimen's volume was used and within the weight of specimens the densities were calculated.

3. Results and discussion

According to the experimental plan (Table 2), testing specimens were produced. Determination of density with specimens shown in Figure 5 right, was provided. On the following Figure 7 can be seen the effect of wood particle size in combination with plastic/wood ratio on the composites density. This figure shown this effect at composites produced from the virgin HDPE matrix and also from the recycled HDPE. We can see that in all settings, composites based recycled HDPE has higher density value. This is caused by using of unspecified sample of lids from PET bottles.

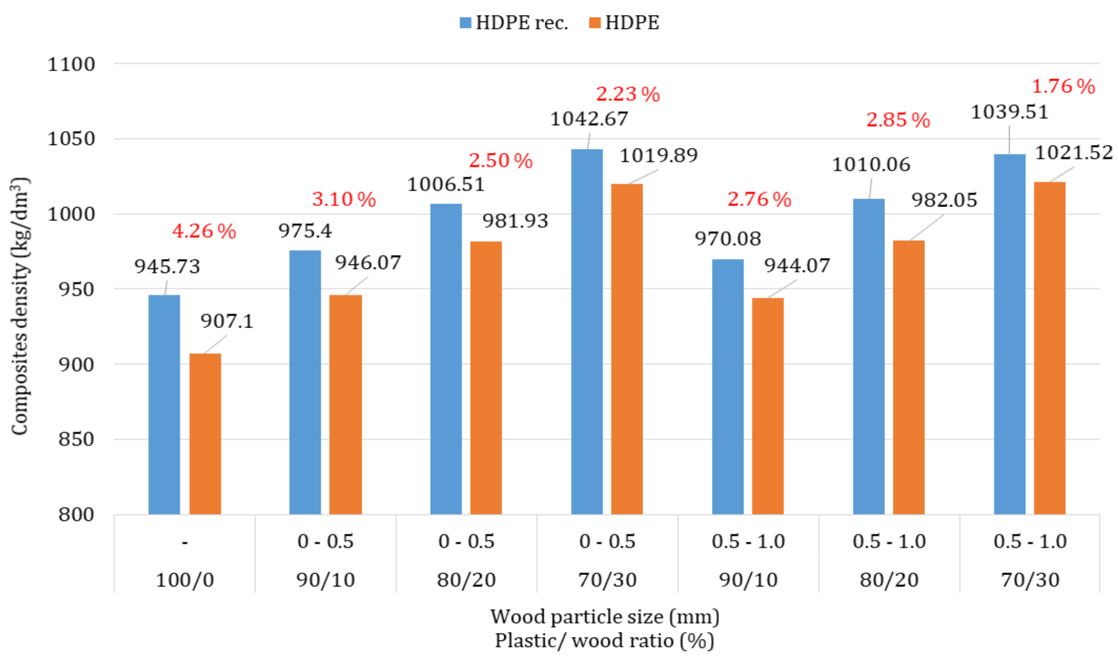

Figure 7 Effect of wood particle size in combination with plastic/wood ratio on the composites density

When we look closer on the effect of wood particle size on the density, we can see that the composites containing smaller particles (0 – 0.5 mm) have higher densities comparing the composites containing higher particles (0.5 – 1.0 mm). This is a logical output because smaller particles have higher compressibility and during the injection process is possible produce composites with higher the density. On Figure 7 we can see also the densities difference (written by red color). If we are increasing the percentage of wood sawdust in composites within the particle sizes the densities difference between composites based virgin HDPE and recycled HDPE is decreasing.

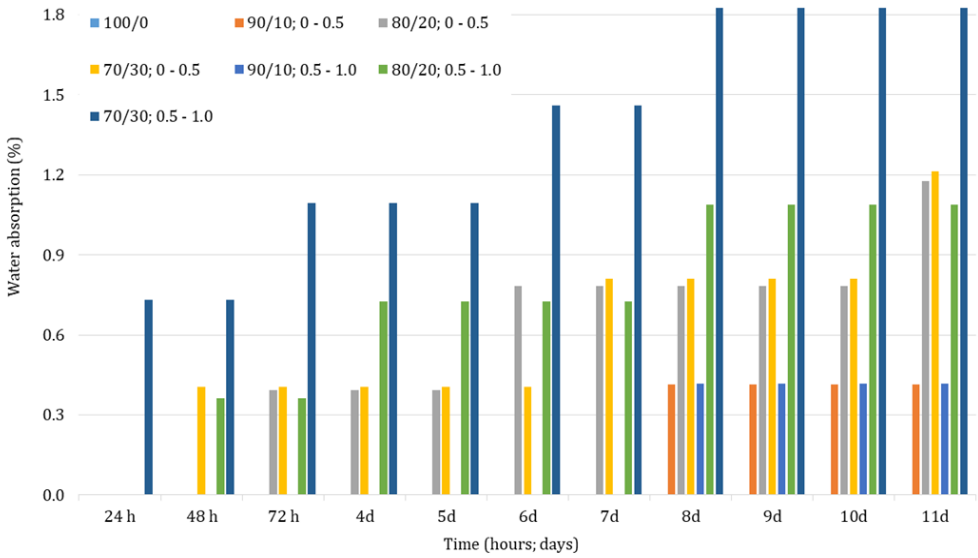

Figure 8 Dependence of water absorption on composite´s immersion time (composites based recycled HDPE)

On Figure 8, the dependence of water absorption on composite´s immersion time is displayed. Here the results intended to a composites based recycled HDPE are presented. Figure 8 showing the comparison between different wood particle sizes within the plastic/wood ratio. The highest water absorption at composites produced from wood particles 0.5 – 1.0 mm and 70/30 plastic/wood ratio was determined. We can see that with increasing particle size of wood sawdust also increases the water absorption of composites.

For better comparison and determination of wood particles effect on water absorption the Figures 9 and 10 were prepared. Figure 9, the dependence of water absorption on composite´s immersion time is displayed, where the composites based recycled HDPE containing particle size 0 – 0.5 mm are compared. We can see that with higher percentage of wood sawdust in composites also increases the water absorption within the immersion time. The step changes can be seen, where the composites with different wood sawdust percentage absorbed water stepwise, e.g. absorption value in % after several days was changed.

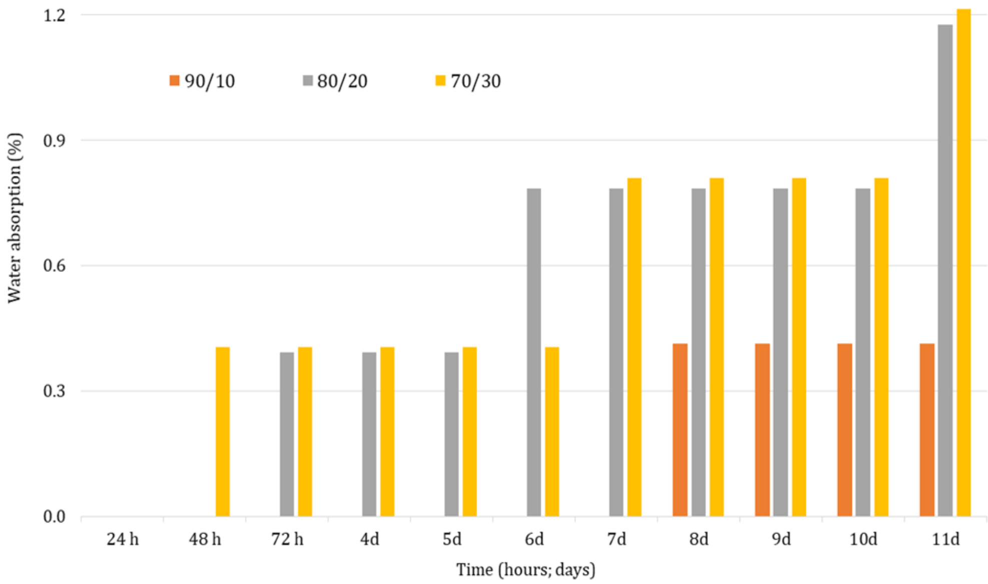

Figure 9 Dependence of water absorption on composite´s immersion time (composites based recycled HDPE, particle size 0 – 0.5 mm)

Figure 10, the dependence of water absorption on composite´s immersion time is displayed, where the composites based recycled HDPE with particle size 0.5 – 1.0 mm are compared. Here the situation is a little bit different. In general, the water absorption with higher percentage values were determined, and also the composites absorbed the water faster than composites from 0 – 0.5 mm particle size. Bigger wood particles influences the bindings creation during composites production and thus also the water absorption.

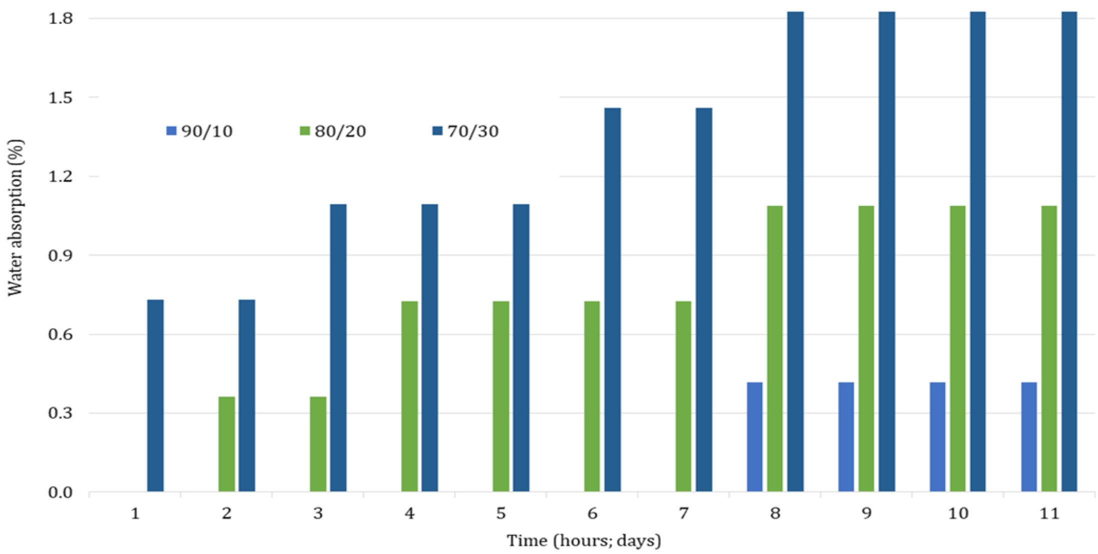

Figure 10 Dependence of water absorption on composite´s immersion time (composites based recycled HDPE, particle size 0.5 – 1.0 mm)

On Figures 11, 12 and 13, the dependence of water absorption on composite´s immersion time is also displayed. But here the composites based virgin HDPE are presented. Figure displayed the comparison between different wood particle sizes within the plastic/wood ratio. The fact with the highest water absorption at composites produced from wood particles 0.5 – 1.0 mm at 70/30 plastic/wood ratio was proven also here. We can see that with increasing particle size of wood sawdust also increases the water absorption of composites. When comparing the water absorption in composites based recycled and virgin HDPE, the composites based virgin HDPE have higher water absorption and also absorbed water faster. This comes out from the differences of plastic matrixes used in both cases.

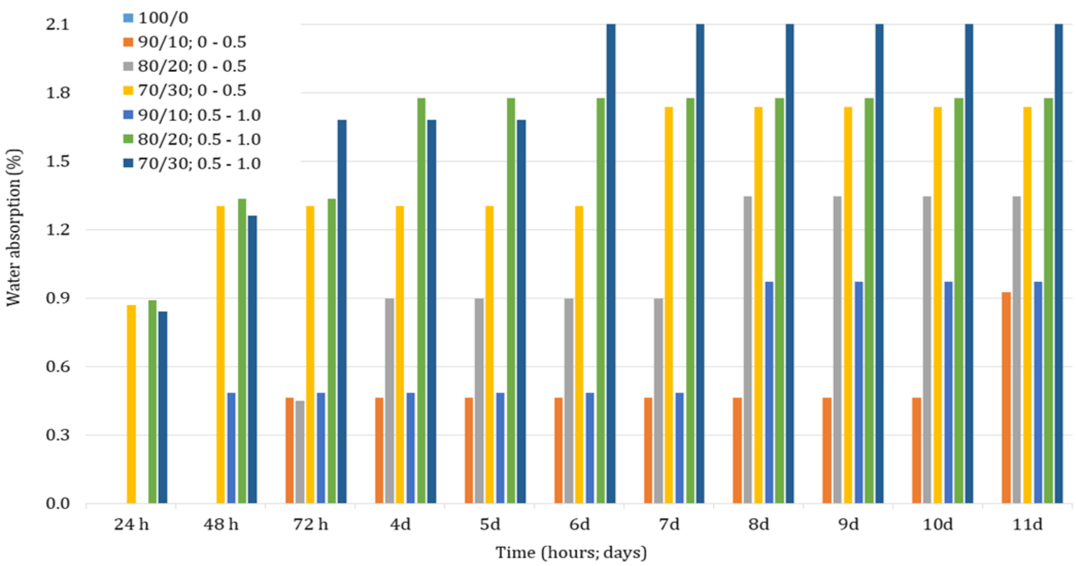

Figure 11 Dependence of water absorption on composite´s immersion time (composites based virgin HDPE)

The general trend in wood particle´s effect on water absorption is the same. We can see that with higher percentage of wood sawdust in composites also increases the water absorption within the immersion time. The same effect has the particle size, with increasing the particle size also increases the water absorption. According to the general comparison, the virgin HDPE seems less appropriate than recycled HDPE from water absorption point of view. On the other hand, this is a positive research finding from the environmental point of view. Whereas composites are mostly used for outdoor applications, water absorption is a very important behavior, even if we can reach better results with recycled wastes.

Results displayed on Figures 12 and 13 shown differences between usage of two different particle sizes. The water absorption is much hugger within the 0.5 – 1.0 mm wood particles. Also the water absorption with higher percentage values were determined, and also the composites absorbed the water faster than composites from 0 – 0.5 mm particle size.

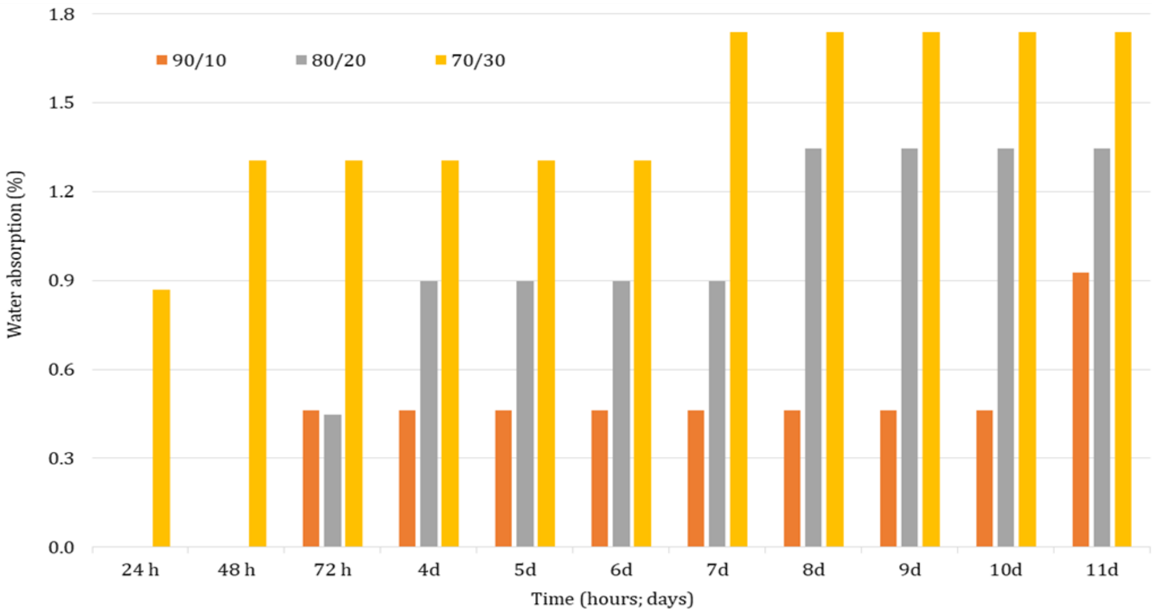

Figure 12 Dependence of water absorption on composite´s immersion time (composites based recycled HDPE, particle size 0 – 0.5 mm)

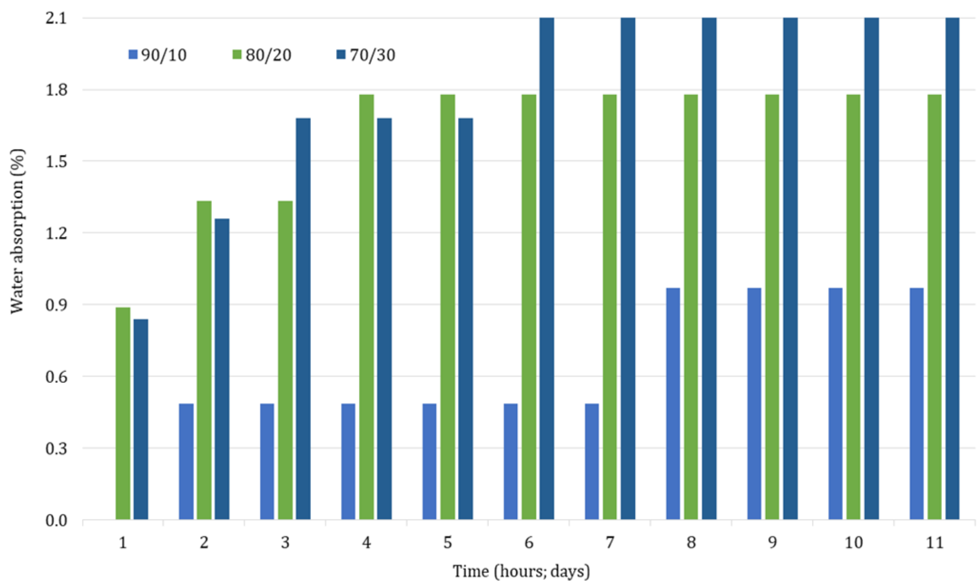

Figure 13 Dependence of water absorption on composite´s immersion time (composites based recycled HDPE, particle size 0.5 – 1.0 mm)

4. Conclusion

Research of plastic and wood raw waste materials recovery was investigated in this research. Presented results of preliminary phase relates to the effect of wood sawdust particle size and properties on water absorption of the WPCs., effect of particle size effect plastic matrix used in composites and effect of wood/plastic concentration ratio.

The main conclusions that can be withdrawn from this study are as follows:

- HDPE recycled originating from PET bottle lids can be used for composites production,
- Composites based HDPE recycled had lower water absorption than composites based virgin HDPE,
- Wood/plastic ratio affects the water absorption, with increasing of this ratio, e.g. with increasing amount of wood sawdust in composites also increases the water absorption,
- Wood sawdust particle size affects the water absorption, with increasing of this ration also increases the water absorption.

Additional phase of this experimental research will concern to research of plastic and wood raw waste materials recovery with using a rapid prototyping technology. Research of basic material composition suitable for 3D printing and development of WPC´s composition based on waste materials which can be used for 3D printing is very ambitious and interesting issue.

Compliance with ethical standards

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Disclosure of conflict of interest

There are no conflict of interest.

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