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Effect of input material composition on the final mechanical properties of WPC based waste materials

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ABSTRACT:

In this paper, the results of experiments are presented which were aimed at determining the influence of input material compositions and properties on the mechanical properties of wood-plastic composites (WPC) based waste raw materials. When WPCs are produced, important raw material parameters, such as the particle size of wood sawdust, the wood/plastic concentration ratio, and the type of plastic matrix can be identified. Using the final mechanical properties of WPCs as a determinant of quality, this study was designed to produce WPCs of an acceptable and competitive level of quality. WPC´s mechanical properties are strongly influenced by the particle size of the sawdust used for production, and also by the kind of the biomass which is used as a biological component of WPCs.Composites parameters and injection press parameters can be improved by combining a variety of influencing variables. Injection press parameters and quality indicators can both be used to analyze their effect on production costs. Wood sawdust particle size, wood/plastic concentration ratio, and mechanical properties of composites are assessed as well as their impact and the relationship between them in the paper. A second objective of the authors is to determine the possibility of reusing waste raw materials. During the experimental research, a semi-operational injection moulding press was used, with a working screw for injecting. Raw materials used in this process include spruce sawdust, HDPE plastic matrix, and recycled HDPE, which incorporates lids from PET bottles. According to a combination and default levels of wood/HDPE concentration ratio, particle size of wood sawdust, type of polymeric matrix, the effect on the mechanical properties (maximal force, ultimate strength, and elongation) of WPCs was determined. Authors would like to present these research findings also through mathematical modelling of relationship between mentioned variables.

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I. INTRODUCTION

Composites made of wood and plastic are very well known. There are also several studies [1, 2, 3] investigating the effect of material and technological variables on the production process. Generally, WPCs are produced by mixing ground wood particles (sawdust) and heated thermoplastic resins [4, 5, 6]. Most commonly, the material used to make plastic injection moulds is extruded into the desired shape with the help of injection moulding machines. Various virgin thermoplastic materials can be used in the production of WPCs, although polyethylene-based WPCs tend to be the most common of all [4]. A number of additives are applied in the manufacture of these products, including colorants, coupling agents, UV stabilizers, blowing agents, and foaming agents [7]. It is usual for WPCs made from virgin materials to contain 60 - 65% high-density polyethylene (HDPE) [4,8], 30 % wood sawdust without defined granulometry, with particles up to 2 mm and additives depending on the application area, which helps tailor the product to fit the area where it is intended to be applied [3]. Waste or recycled materials are often used as raw materials for the production of WPCs due to their abundance and environmental protection [5]. WPCs can also be manufactured using waste materials, which reduces their environmental impact and increases their environmental responsibility. This paper aims to demonstrate the usefulness and application of WPCs based on waste raw materials by designing a series of experiments and their mathematical evaluation. The presented experimental plan allowed for the development of a mathematical model that describes the effects of waste raw materials on the mechanical properties of WPCs. Research findings can be very helpful in WPC production, showing that waste raw materials can be used for WPC products, which will lead to an increase in environmental protection.

Recent years have seen a significant increase in the development of composites made from renewable raw materials, mainly because they are ecologically friendly and are easy to recycle. Composites made from biomass and plastics may contain various fillers to improve their mechanical and physical properties. There is a wide variety of natural fibres available in large quantities [9, 10]. They are renewable, recyclable, carbon dioxide neutral, and renewable. Low prices and easy accessibility are two major advantages of biomass. There are major challenges in this area, including finding out if wood-plastic composites (WPCs) can be made from waste raw materials as well as demonstrating their potential applications. Research findings have shown that waste raw materials can also be used for manufacturing WPCs and can therefore be used for rapid prototyping. This is a very interesting issue and holds tremendous potential for today's technologies. Thus, the main objective of the study is to determine the effects of material variables on the mechanical properties of WPCs made from waste raw materials. In previous basic research studies, we analyzed available research findings [1, 2, 4, 5, 10,11]. We recognized that there were input variables such as waste wood parameters, especially types of raw materials and particle size of wood sawdust during WPC production [9, 10]. 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, 11]. A major factor is the size of the biomass particles, in this case wood sawdust. The highest tensile strength can be achieved by using the smallest possible particles. Furthermore, particle size also affects the elongation of composites, with increasing particle size decreasing elongation [12]. The use of the largest possible particles of wood sawdust will significantly improve the modulus of elasticity in tension. When the percentage amount of wood particles in composites is higher, the flexural strength decreases significantly [13]. The increased percentage amount of wood sawdust in composites has a negative effect on the density of composites.

Research findings are presented in this paper concerning the effects of particle size and the percentage amount of wood sawdust in composites on mechanical properties of WPCs. These effects are also observed with WPCs based on virgin thermoplastics(HDPE) and also when WPCs are based on waste raw materials (HDPE rec.). The application of WPCs based on waste raw materials is very exciting from the point of view of their production and application. These results are of high importance and interest. The results of future research into WPCs production could be used to manufacture using rapid prototyping or 3D printers, and demonstrate that it is possible to use waste raw materials in the production of WPC products, thereby increasing the concepts of environmental responsibility and protecting the environment.

II. MATERIALS AND METHODS

A primary goal of this experiment is to determine the impact of material variables on the mechanical properties of WPCs constructed from waste raw materials. In order to make the process more efficient, you should choose variables with continuous characteristics throughout the whole process. A relevant input variable is one that has an impact on outputs, so it should be chosen accordingly. In order to determine this at the beginning of the experiment, screening experiments are necessary. In our case, according to the latest published research works and our experience, we decided to determine the relationship between mechanical properties, type of plastic matrix used in WPCs, wood/plastic ratio and particle size of wood sawdust. Here is where you can find the levels that were chosen for each variable in Table 1.

Table (1). Variables that can be controlled in the experiment as inputs.

Variables			
Levels	**Amount of wood sawdust (%)**	**Sawdust particle size (mm)**	**Polymer matrix type (-)**
1	0	0 - 0.5	HDPE
2	10	0.5 - 1.0	HDPE rec.
3	20	-	-
4	30	-	-

High-density polyethylene HDPE was used as a plastic matrix made from 100% virgin HDPE and recyclable HDPE (HDPE rec.) derived from PET bottle lids. Slovnaft's TIPELIN 1108J high-density polyethylene with a melt index of 8.0 g / 10 min was chosen as the reference material. Spruce sawdust with particle sizes of up to 0.5 and up to 1.0 mm was used as a wood component. From a wood processing company in Western Slovakia, spruce sawdust containing 8% moisture content and no bark was obtained. In our country, this type of wood is widely cultivated and widely available. In order to generate spruce sawdust, wood chips were processed in a hammer mill STOZA/V5 equipped with 8.0 mm and 4.0 mm screens. For the initial analysis of the particle size distribution (Figure 1), Retsch Vibrating Sieve Equipment AS 200 was used, in accordance with EN ISO 17827-1 [14]. The ratio of wood/plastic concentrations is shown in Table 1. A decision should be made concerning which output variables are to be monitored in the next step. In this analysis, we selected the following output variables: maximal force F_{max} (N), ultimate strength R_m (MPa), and elongation A (%). According to technical standards and WPC´s applications, the following monitored variables (outputs) were chosen. A quality indicator should be represented as an output, and these variables should have a comparative function.A Kern MRS 120-3 balance was used to measure the moisture content of the selected biomass component before mixing, extrusion, and injection. To determine moisture content at this temperature, the raw feedstock was heated to 105°C (gravimetric method) until a constant weight was achieved. Cutting mill Retsch SM 300 was used as a cutting machine for disintegrating PET bottle lids in the second process.

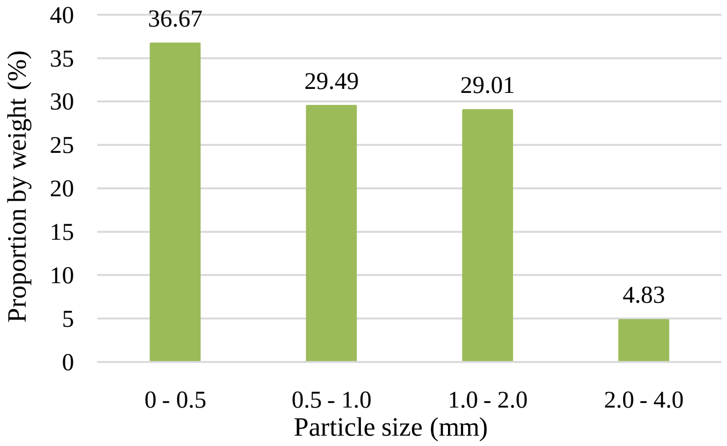

Fig. 1 Wood sawdust particle size distribution

In Figure 2, you can see the production process for the experimental samples. A traditional electric mixer was used to prepare the wood/plastic ratios, while the MR 120 balance was used to control the weights. Brabander twin-screw granulators were used to produce final samples and DEMAG ErgoTech 50-200 injection molding machines were used to produce final samples. Dimensions of samples were produced in accordance with STN EN ISO 527-3 [15]. Based on the experimental plan shown in Table 2, a set number of samples were prepared for testing.It is used for injection of normalized tensile test specimens.

Fig. 2Schematic view of raw material treatment and samples production

Automatic testing equipment will measure the output variables based on tensile testing in the final. To minimize systematic errors, the testing and sample production processes should be randomized [16]. Alternatively, we can increase the number of replications for each measurement, there for we used 6 replications for each setting from the experimental plan.Experiment design results from a two-level full factorial plan with additional levels.

Experiments conducted in accordance with the experimental plan will result in a surface response. An orthogonal view of surface response represents a group of points that form an ongoing surface [17]. This is because the variables influencing the process and the final output are shown along orthogonal axes. Creating a surface response requires us to create a mathematical model that gives us a three-dimensional function as the surface response we would like to create, i.e. a "prescription" under which the points in a coordinate system will be calculated. Several mathematical-statistical software programs are widely used today for the development of mathematical models, since they allow for the testing of hypotheses, comparing obtained data to those expected, and checking the quality of the model itself. Mathematical-statistical software enables the generation of many mathematical models, which describe the process with some precision, so we may choose the model that most closely matches our variables composition and precision requirements. Based on the points of view described above, we can determine which mathematical model is optimal. Because the process has several input variables, we used multifactorial analysis of variance (ANOVA). When two or more variables are compared and analysed on the same variable, ANOVA is applied to evaluate the mean differences between the variables. For all necessary analyses, mathematical and statistical software such as JMP, Statgraphics, etc., is widely used. Our case was also handled by this software.

Fig. 3A WPC samples based on recycled HDPE (left) and a WPC sample based on virgin HDPE (right)

III. RESULTS AND DISCUSSION

Testing specimens (see Figure 3) were produced according to the experimental plan (Table 1). The primary objective of our experiment was to determine how material variables affect WPC´s mechanical properties. We found that the wood/plastic concentration ratio, particle size of wood sawdust, and type of plastic matrix used in WPCs all had an effect on maximal force, ultimate strength, and also elongation of composites [18]. This can be very clearly seen from the following Table 2, where the mean values (from 6 repetitions) of measured outputs variables for each experimental setting are displayed.

Table (2). Mean values of measured outputs variables

Number of setting	Polymer matrix type (-)	Plastic/wood ratio (%)	Particle size(mm)	Maximal force (N)	Ultimate strength(MPa)	Elongation (%)
1.	HDPE rec.	90/10	0 - 0.5	939.98	23.5	52.68
2.	HDPE rec.	80/20	0 - 0.5	906.75	22.85	28.17
3.	HDPE rec.	70/30	0 - 0.5	844.84	21.3	19.82
4.	HDPE rec.	90/10	0.5 - 1.0	929.88	23.33	27.14
5.	HDPE rec.	80/20	0.5 - 1.0	865.82	21.82	22.71
6.	HDPE rec.	70/30	0.5 - 1.0	840.95	21.13	13.47
7.	HDPE	90/10	0 - 0.5	627.73	15.75	101.52
8.	HDPE	80/20	0 - 0.5	568.17	14.32	84.62
9.	HDPE	70/30	0 - 0.5	543.14	13.73	54.08
10.	HDPE	90/10	0.5 - 1.0	639.45	16.12	87.37
11.	HDPE	80/20	0.5 - 1.0	585.66	14.8	69.66
12.	HDPE	70/30	0.5 - 1.0	553.66	14.07	44.91

13.	HDPE rec.	100/0	-	937.38	23.44	440.20
14.	HDPE	100/0	-	739.39	18.55	122.79

As shown in Figure 4, Figure 5 and Figure 6, different variables (plastic/wood ratio, particle size and type of polymeric matrix) have an impact on WPC's mechanical properties during production. Compared with recycled HDPE, virgin HDPE-based WPCs have lower mechanical characteristics [6, 8]. It is generally accepted that recycled HDPE originating from PET bottle lids can be used to make WPCs [19]. When comparing WPC derived from recycled HDPE with WPC derived from virgin HDPE, the difference can reach up to 30% from a maximal force and ultimate strength perspective. There were no reported problems during the production of the samples.

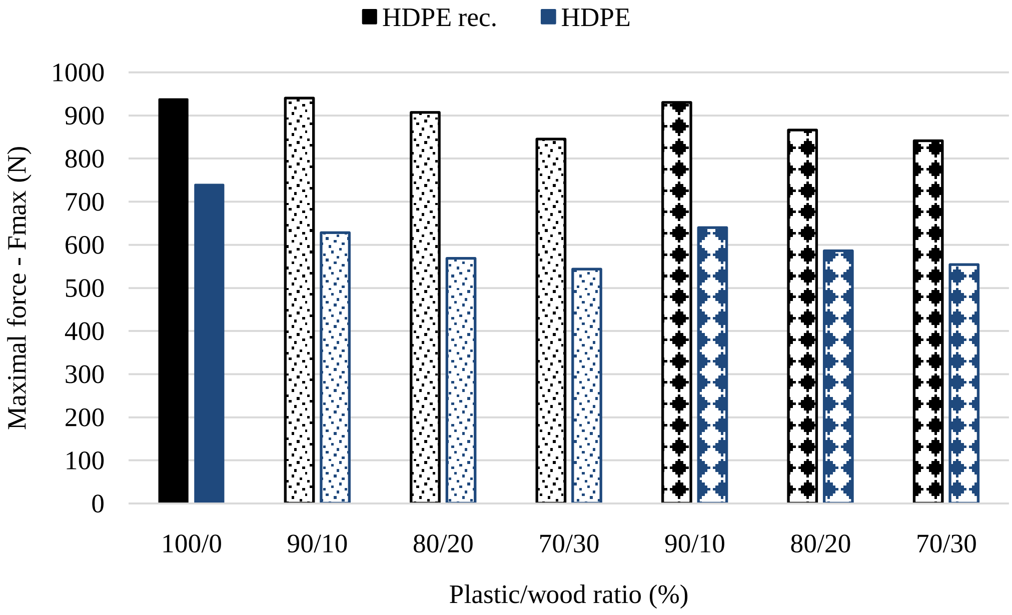

Fig. 4Comparison of maximal force obtained at various plastic/wood ratios, different type of polymeric matrix and particle sizes (up to 0.5 mm – dotted texture, up to 1.0 mm – checkered texture)

Figure 4 shows how the plastic/wood ratio affects maximal force, and figure 5 shows how it affects ultimate strength. Mechanical properties decrease with decreasing the polymeric matrix ratio in basic volume. Mechanical properties of WPC are negatively influenced by the amount of wood sawdust. Both recycled and virgin HDPE yield the same results.Figure 4 illustrates also the impact of wood sawdust particle size on maximum force, while Figure 5 illustrates the impact on ultimate strength. In terms of maximal force and ultimate strength, the size of sawdust particles has a small impact. There will be a much greater impact of wood sawdust particle size on the remaining output, such as elongation[11, 20]. Particle size could be considered more important from this output point of view.

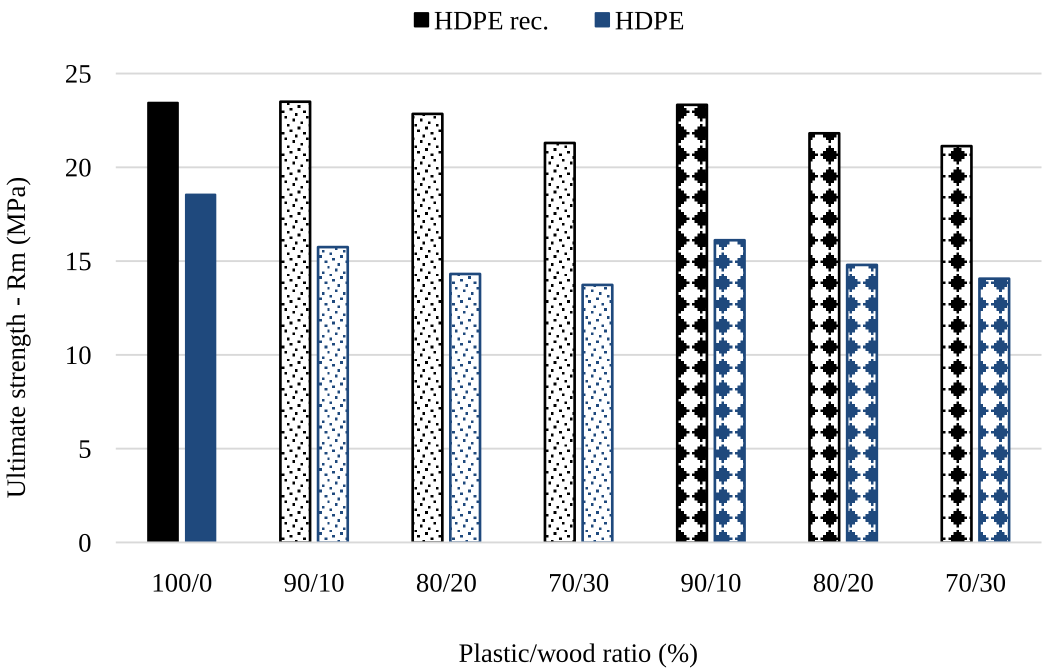

Fig. 5Comparison of ultimate strength obtained at various plastic/wood ratios, different type of polymeric matrix and particle sizes (up to 0.5 mm – dotted texture, up to 1.0 mm – checkered texture)

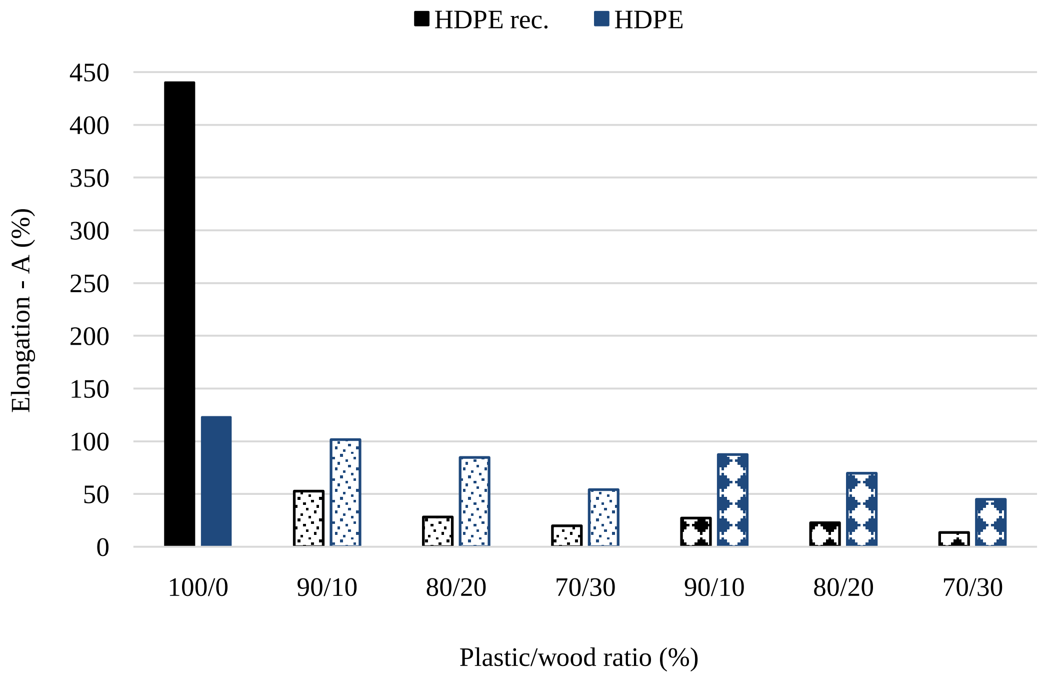

Fig. 6Comparison of elongation obtained at various plastic/wood ratios, different type of polymeric matrix and particle sizes (up to 0.5 mm – dotted texture, up to 1.0 mm – checkered texture)

Figure 6 shows how the wood particle size affects the elongation. Elongationincrease with increasing the wood sawdust particle size in basic volume, when we talk about the WPC. On this figure is displayed when the WPC contains smaller sawdust particle size (up to 0.5 mm) the elongation is smoothly higher. Wood sawdust particle size with combination of different polymeric matrix shows, that in WPCs with recycled HDPE has the presence of wood sawdust higher impact on elongation comparing with WPCs based virgin HDPE.
The output of mathematical-statistic evaluation of measured data shows the results of fitting a multiple linear regression model to describe the relationship between *maximal force* and 3 independent variables.The equation of the fitted model is:

*Maximal force = 678.717 + 301.736*Type of polymer – 4.43081*Amount of wood sawdust – 5.065*Particle size* (N)(1)

Since the *P-value*in the ANOVA table was less than 0.05, there is a statistically significant relationship between the variables at the 95.0% confidence level.The R-Squared statistic indicated that the model as fitted explains 99.5003% of the variability in *maximal force*. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, was 99.313%. The standard error of the estimate showed the standard deviation of the residuals to 13.4656. This value can be used to construct prediction limits for new observations by selecting the reports option from the text menu. The mean absolute error (MAE) of 7.91323 was the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in your data file. Since the *P-value* is greater than 0.05, there is no indication of serial autocorrelation in the residuals at the 95.0% confidence level. In determining whether the model can be simplified, notice that the highest *P-value* on the independent variables was 0.7530, belonging to *particle size*. Since the *P-value* was greater or equal to 0.05, that term is not statistically significant at the 95.0 % or higher confidence level. Table 3 shows 95.0 % confidence intervals for the coefficients in the model. Confidence intervals show how precisely the coefficients can be estimated the amount of available data and the noise which is present.

Table (3). 95.0% confidence intervals for coefficient estimates – model for maximal force

Parameter	Estimate	Standard Error	Lower Limit	Upper Limit
Constant	678.717	16.0273	641.758	715.676
Type of polymer matrix	301.736	7.77439	283.808	319.663
Amount of wood sawdust	-4.43081	0.476082	-5.52866	-3.33296
Particle size	-5.065	15.5488	-40.9206	30.7906

The output of mathematical-statistic evaluation of measured data shows the results of fitting a multiple linear regression model to describe the relationship between *ultimate strength* and 3 independent variables.The equation of the fitted model is:

*Ultimate strength = 16.9597 + 7.525*Type of polymer – 0.105833*Amount of wood sawdust – 0.0611111*Particle size* (MPa)(2)

Since the *P-value*in the ANOVA table was less than 0.05, there is a statistically significant relationship between the variables at the 95.0% confidence level.The R-Squared statistic indicated that the model as fitted explains 99.4528% of the variability in *ultimate strength*. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, was 99.2477%. The standard error of the estimate showed the standard deviation of the residuals to 0.350698. This value can be used to construct prediction limits for new observations by selecting the reports option from the text menu. The mean absolute error (MAE) of 0.02125 was the average value of the residuals. The Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in your data file. Since the *P-value* is greater than 0.05, there is no indication of serial autocorrelation in the residuals at the 95.0% confidence level. In determining whether the model can be simplified, notice that the highest *P-value* on the independent variables was 0.8838, belonging to also*particle size*. Since the *P-value* was greater or equal to 0.05, that term is not statistically significant at the 95.0 % or higher confidence level. Table 4 shows 95.0 % confidence intervals for the coefficients in the model. Confidence intervals show how precisely the coefficients can be estimated the amount of available data and the noise which is present.

Table (4). 95.0% confidence intervals for coefficient estimates – model for ultimate strength

Parameter	Estimate	Standard Error	Lower Limit	Upper Limit
Constant	16.9597	0.417414	15.9972	17.9223
Type of polymer matrix	7.525	0.202476	7.05809	7.99191
Amount of wood sawdust	-0.105833	0.012399	-0.134426	-0.077241
Particle size	-0.0611111	0.404951	-0.994932	0.87271

The following figure 7 shows the effect of influencing variables on mechanical properties (maximal force and ultimate strength). Here we can see the weight of each influencing variable. This figure proves the research findings where the sawdust particle size doesn´t have important effect from the maximal force and ultimate strength point of view.

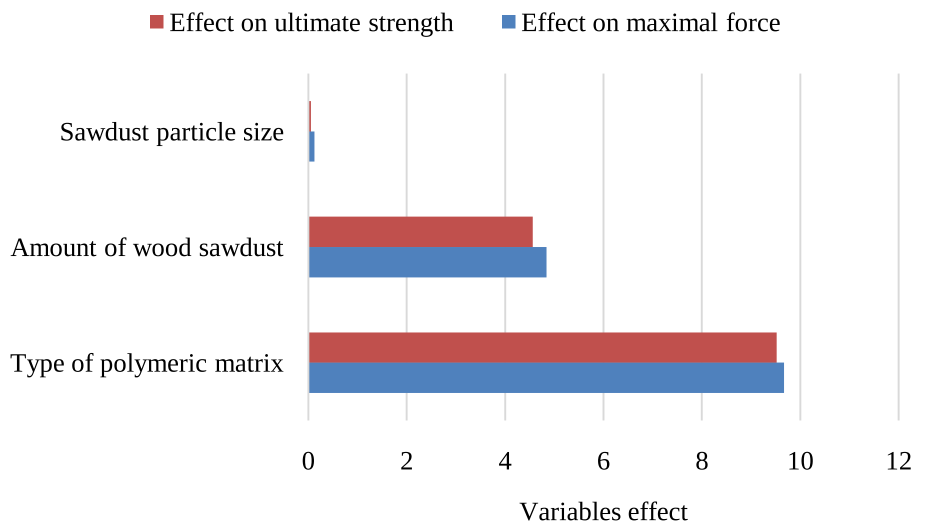

Fig. 7 Parrett's effect diagram

IV. CONCLUSION

The purpose of this research was to study how to recover raw materials such as plastic and wood from raw waste. There is a presentation of preliminary phase results related to the effect that particle size and properties of wood sawdust have on mechanical properties of WPCs. An analysis of the effect of wood/plastic ratio and type of polymeric matrixused in composites is also presented.As a result of this study, the following conclusions can be drawn:

•Composites can be made using HDPE recycled from PET bottle lids.

•The type of polymeric matrix affects the all monitored mechanical properties of composites. Mechanical properties decrease with decreasing the polymeric matrix ratio in basic volume.

•Wood/plastic ratio affects also the mechanical properties of composites. Mechanical properties of WPC are negatively influenced by the amount of wood sawdust.

•Particle size influences in a small scale the monitored mechanical properties. In terms of maximal force and ultimate strength, the size of sawdust particles has a small impact.

•There is a much greater impact of wood sawdust particle size on the elongation. With increasing of particle size with increasing of wood amount the elongation decreases.

The next phase of this research will focus on the recovery of wood and plastic raw waste materials using rapid prototyping technology[16]. The development of waste-based composites that can be used for 3D printing and the study of basic material compositions suitable for 3D printing is an ambitious and exciting endeavour.

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