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PROCESSING OF GFRP RECYCLATE INTO STRUCTURAL BOARDS COMPOSED SOLELY OF WASTE MATERIALS

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Abstract
Recycling of GFRP composites after their end-of-life, especially GFRP composites with thermoset matrix, has not yet been fully satisfactorily solved - the technologies known so far are not fully economically viable, therefore the exploration of other recycling options is highly desirable. The present study investigates the possibilities of using GFRP waste and waste resin from powder coating in the production of structural boards for the construction industry. GFRP was shredded into chips and test samples with varying bulk densities were prepared by hot pressing. In the first step, the compatibility of the input materials was evaluated. In the next steps, the physico-mechanical parameters of the boards were investigated as a function of bulk density (flexural tensile strength, modulus of elasticity, impact resistance, and water absorption). The results obtained were compared with the properties of commercially available OSB board. The research carried out confirmed the possibility of using GFRP waste and waste binder to produce boards for structural purposes.

***Keywords**: Composite board, GFRP waste, recycling, waste powder coating.*

INTRODUCTION

In today's world, a wide range of materials is being developed that do not have a resolved end-of-life cycle, leading to their disposal through incineration or landfilling once their useful life ends. One such material is glass fiber-reinforced polymer (GFRP). GFRP products encompass a broad spectrum of applications, including various structural profiles in automotive, aerospace, construction industries, pressure vessels, composite rebars, ballistic laminates, and wind turbine blades [1]. The issue of the processing of end-of-life composite materials can be identified as an area that is resonating within the recycling industries today. It is not a simple problem. Of course, some methods can handle GFRP recycling, but they are either very energy-intensive, difficult to implement, or not environmentally friendly. An increasing amount of GFRP waste is being produced and legislation in some countries already prohibits landfilling. Composites made from thermoset resins are not biodegradable; therefore, their disposal and potential reuse need to be addressed upon reaching the end of their service life. With the rapidly growing market for GFRP composites, substantial waste is generated during large-scale production. It is estimated that more than two million tons of GFRP waste are generated annually in the United States [2–4]. The majority of this waste is either landfilled or incinerated, practices that are unsustainable and environmentally detrimental.

An alternative to the two aforementioned disposal methods is the recycling and reutilization of GFRP. Recycling through conventional means is typically challenging and uneconomical due to the nature of the material. Examples of possible fiber processing methods, currently more in a testing phase and scope, are outlined below:

1) Fiber extraction via chemical processes - utilizing the solvolysis process, which involves the separation of fibers from composites under specific pressure and temperature conditions using a chemical solvent with various additives. The process is uneconomical, with the additional disadvantage of the toxicity of the chemicals used [5].

2) Pyrolysis - thermal fiber extraction. Pyrolysis occurs when the material is heated without access to air or with significantly reduced air access. Thermal reactions in the material lead to its decomposition. Undesirable and hazardous substances are transformed into more easily manageable, safer, or at least more filterable substances. Products resulting from pyrolysis are typically pyrolysis gases, oils, solid remnants of processed material (fibers, dust), and carbon residues from the process. The process is energetically demanding, and its application appears economically promising for restoring primarily carbon rather than glass fibers from the composite [6,7].

3) Mechanical processing of GFRP - mechanical disintegration of the original composite into smaller particles, followed by utilization, for example, in construction materials. This recycling method appears to be an elegant solution for the relatively energy-efficient processing of GFRP waste. However, the challenge of this processing method lies in the meaningful utilization of the obtained chips in a new composite material. Several patents describe the preparation of composite boards from such obtained GFRP waste chips. However, in most cases, thermoset resin (based on epoxides or polyesters), which originates from oil, is used as a binder. This reintroduces considerable ecological concerns into the product, even from an economic standpoint, despite utilizing waste material as filler. These products are not competitive with common composite boards such as OSB [2,8].

The article summarizes the research on the possibilities of using GFRP waste and waste resin from powder coating in the production of panels for the construction industry.

The originality of this work lies in the utilization of a combination of chips obtained from crushing GFRP and waste powder coating to prepare a composite board for construction purposes with sufficient mechanical properties.

The preparation involves several steps: crushing GFRP, mixing the obtained chips with powder binder, and pressing into a mold at elevated temperature. This process is schematically depicted in Fig. 1. The aim of this study is the research on properties of manufactured composite boards in three different volumetric weights solely from waste materials and compare these boards with commercially available wood-based OSB boards in terms of mechanical properties, primarily.

Fig. 1 Schematic representation of the process of manufacturing a composite board based on waste materials

MATERIALS AND METHODS

A. Materials

The starting material for preparing GFRP chips (filler in the composite board) consisted of various waste products composed of glass fibers and epoxy or polyester matrices. These included, for example, end-of-life pressure vessels or offcuts from GFRP profiles manufactured by the pultrusion process. The specific composition of the GFRP is not a significant factor; each product has a different ratio of matrix to reinforcement, and in some cases, additional additives such as calcium carbonate or pigment are present. These factors only affect the appearance of the output after crushing, which will be discussed in the following section. Waste powder coating was used as a binder, which is used in the process of powder coating metals, with the curing process of this powder occurring at temperatures around 180 °C. It is a fine powder based on epoxy or polyester. This material was obtained as a waste product from the company MP Colors, which specializes in powder coating. The amount of this waste product is significant. The original material is applied by the powdering process and the material that does not adhere to the desired metal surface is not reused and is currently being landfilled. The production of this waste powder coating material by MP Colors is around 5 tons per month. Considering the number of companies in the Czech Republic engaged in powder coating, the estimated production of this waste material is around 100 tons per month in the Czech Republic alone.

B. Crushing of GFRP

The obtained waste GFRP served as the initial material for crushing. Waste products were cut into pieces using a circular saw to dimensions of approximately 20 cm × 20 cm. These pieces were then subsequently crushed using a single-shaft knife crusher from DEOS Technology s.r.o., model DRJ 44 (see Fig. 2), with a working area of 440 mm × 280 mm, a power of 5.5 kW, segment width of 40 mm, and equipped with a 6 mm mesh screen. The crushing process yielded a chip-like fraction of GFRP ranging from 0–6 mm with a variety of particle shapes and sizes.

Fig. 2 Single-shaft knife crusher (on the left), crushing element (on the right)

C. Characterization of the filler

The obtained chip-like fraction was highly diverse, containing both elongated chips (up to 2 cm) and fine powder. Therefore, characterization was conducted using sieve analysis. Various fractions were separated using sieves with different mesh sizes. This allowed for better evaluation of particle shapes and quantification of individual fractions. Sieve analysis was performed using sieves with mesh sizes of: 5.6 mm, 4.0 mm, 3.2 mm, 2.8 mm, 2.0 mm, 1.4 mm, 1.0 mm, and 0.50 mm. The sieving process itself lasted for 1 minute on a total quantity of 150 g of crushed GFRP waste.

D. Characterization of the binder

The waste powder coating used as a binder is essentially a single-component thermoset based on epoxy, which cures at a temperature around 180 °C. The obtained waste material from MP Colors was characterized using Thermogravimetric Analysis and Differential Thermal Analysis (TG/DTA). This provided a detailed analysis of the powder's behavior at higher temperatures and information about the specific temperature of the onset of the polymerization reaction and the decomposition temperatures of the epoxy powder. The characterization was conducted using the STA 449 F3 Jupiter (Netzsch). Samples were tested in platinum crucibles in a synthetic air atmosphere (50 ml/min, N_2/O_2 ratio of 80/20) with a heating rate of 10 °C/min from 35 °C to 1000 °C.

E. Sample Fabrication

Boards measuring 500 mm × 500 mm and 10 mm thickness were prepared. Ground GFRP recyclate with particle size ranging from 0.5–6 mm was used as a filler.

Tab. I Mix proportions of manufactured composite boards

Board code	Waste powder binder wt. (%)	Waste GFRP chips wt. (%)	Board thickness (mm)	Initial weight of input materials (kg)
EPB-1	50	50	10	2.50
EPB-2	50	50	10	2.88
EPB-3	50	50	10	3.25

Waste powder from powder coating of metals, based on epoxy, was used as a binder. These two components were mixed for 5 minutes in a container using an electric mixer. During the mixing process, the waste powder adheres to individual particles of GFRP recyclate, reaching maximum adherence at a certain point, with the excess powder settling at the bottom of the container. Therefore, a weight ratio of 1:1 for the individual components was chosen (as shown in Tab. I), as at this ratio, the excess powder remains at the bottom of the container in minimal quantity. This ratio was also chosen based on previous testing, which showed that the mechanical properties of the boards were insufficient at lower binder contents. Subsequently, the mixture of GFRP recyclate and powder binder was transferred to a metal mold with a separating foil and pressed to the desired thickness in a heated hydraulic press CBJ 500 at a temperature of 180 °C for 20 minutes. Three boards with different bulk densities were produced: approximately 1000 kg/m^3 (labeled as EPB-1), approximately 1150 kg/m^3 (labeled as EPB-2), and approximately 1300 kg/m^3 (labeled as EPB-3). The different bulk density of the samples was achieved by varying the initial weight of the filler and binder for the preparation of the boards, which were pressed to the same thickness. For the purpose of mechanical property testing, samples measuring 250 mm × 50 mm × 10 mm were subsequently cut from these boards using circular saws. The appearance of the cut samples (EPB-3) can be seen in Fig. 3. To compare the mechanical properties, commercial OSB was used, which was also cut to 250 mm × 50 mm × 10 mm.

Fig. 2 The appearance of the cut samples for determining mechanical properties

F. Bulk density and water absorption

The bulk density of the prepared composites was determined experimentally based on volumetric measurements and the weight of each sample according to equation (1). These measurements were conducted using a digital caliper and digital scales. For water absorption testing, five samples were cut from the prepared boards using an electric saw, each measuring 3 cm × 3 cm × 1 cm. The samples were dried in an electric dryer at 80 °C for 48 hours until reaching a constant weight. Subsequently, the samples were immersed in water for 7 days at room temperature, and their saturated weight was recorded. Water absorption was calculated as a percentage using equation (2):

$$\rho_{bulk} = \frac{Mass\ of\ the\ panel}{Volume\ of\ the\ panel}\ kg \cdot m^{-3}, \tag{1}$$

$$Water\ absorption = \frac{M_{sat} - M_{dry}}{M_{sat}}\ \%, \tag{2}$$

where M_{sat} is the mass of the saturated sample and M_{dry} is the mass of the dried sample.

G. Mechanical properties

Mechanical properties were determined using a three-point bending test according to EN 310:1993 [9]. From each prepared sample board (including the commercial OSB board), five test specimens were randomly selected and cut by an electric wood saw to dimensions of 25 cm × 5 cm × 1 cm to ensure reliability through a probabilistic sampling technique. Loading was applied using a universal testing machine (TIRA test 2710), as shown in Fig. 4, with loading at half-span supports (span of 200 mm) at a loading rate of 50 N/s until failure. Another property tested was the impact resistance. It is a measure of a material's toughness, and its ability to withstand the energy of impact loading or dynamic shock without deformation and cracking. To assess the impact resistance of the composites, the Izod Impact testing equipment was used (a 12 J hammer was used to control the pendulum), following the standard testing method EN ISO 180.

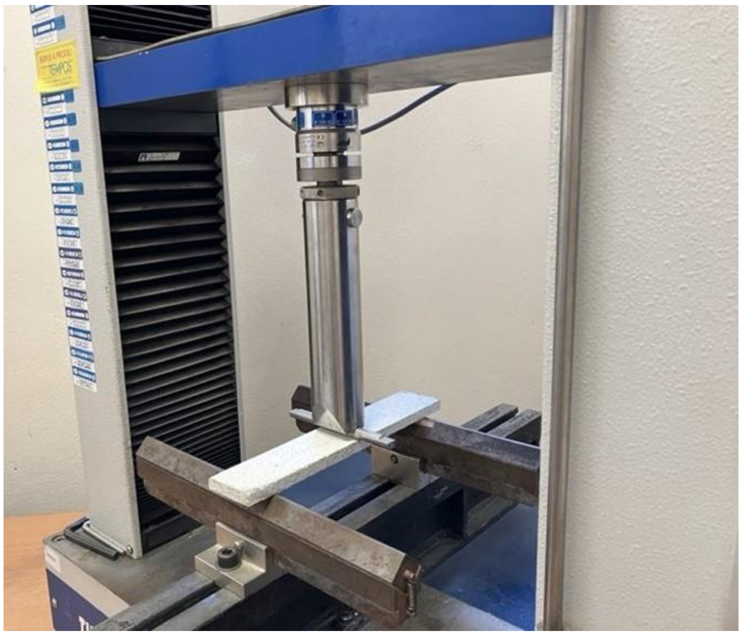

Fig. 3 Mechanical test setup

RESULTS AND DISCUSSION

A. Sieve analysis

The crushed GFRP waste was characterized by sieve analysis to obtain a better understanding of the distribution of sizes of individual chips. The result of this analysis is the weight and percentage share of each fraction, which are depicted in Fig. 5. The resulting fraction distribution is shown in Tab. II.

From the measured values, the distribution of individual particles can be inferred. These are only approximate values because the shape of the particles is very diverse, and these values vary with the duration of the sieving process. However, it provides some insight into the composition of the crushed GFRP waste. The highest proportion of material was captured on the 2.0 mm sieve, approximately 60 %. Other fractions were represented to a lesser extent. The passage through the 0.5 mm sieve accounted for only 3.5 % of the total weight. The proportion of this finest fraction is primarily determined by the content of various additives and also by the resin content in the initial composite material. The higher the content of these substances, the greater the proportion of this finest fraction after crushing.

Fig. 4 Remaining fractions of crushed GFRP waste on the sieves, a) 5.6 mm, b) 4.0 mm, c) 3.2 mm, d) 2.8 mm, e) 2.0 mm, f) 1.4 mm, g) 1.0 mm, h) 0.50 mm, i) <0.5 mm

B. TG/DTA

The waste powder epoxy used in the preparation of the composite board as a binder was tested using TG/DTA analysis to determine the polymerization temperature and the decomposition temperature. The measured values are graphically depicted in Fig. 6 (TG) and Fig. 7 (DTA). Several research teams have conducted thermal analysis of similar epoxy powder intended for metal coating. Thanks to these analyses, it is possible to determine a suitable curing temperature and to identify the decomposition temperature.

The curing temperature is mainly determined by the range in which the powder polymerization occurs. Temperatures for this process generally range from 130–200 °C, with the specific range influenced by the composition of the powder coating. The decomposition process typically occurs in three steps, with the beginning around 250 °C [10–12].

From the graph in Fig. 6, one can observe the mass loss of the sample as a function of increasing temperature. The sample begins to decompose at approximately 250 °C, up to which the waste epoxy powder remains stable. The mass loss at 500 °C amounted to 43 %.

The DTA curve recorded for the waste epoxy powder exhibits an exothermic reaction corresponding to the curing (polymerization) process in the temperature range of 140 °C to 175 °C. This indicates that the required temperature for complete curing is approximately 180 °C.

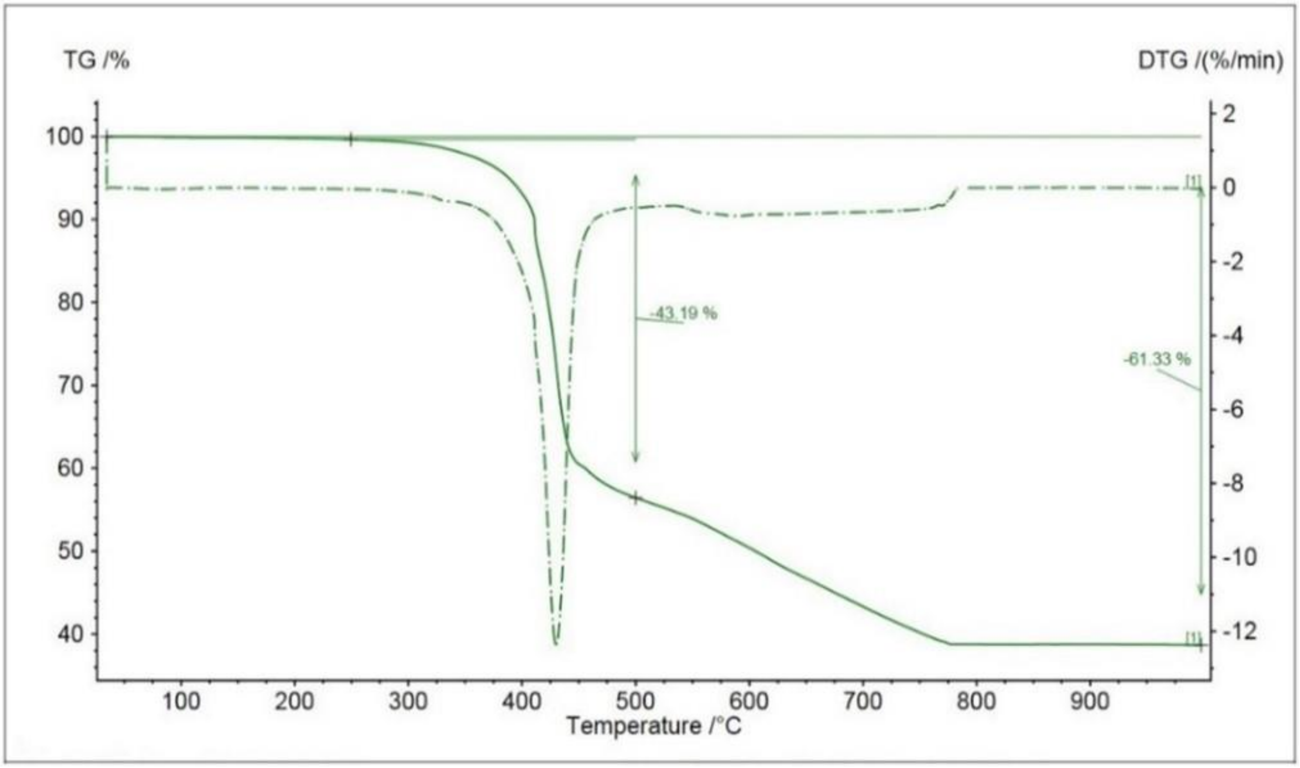

Fig. 6 TG and DTG curve

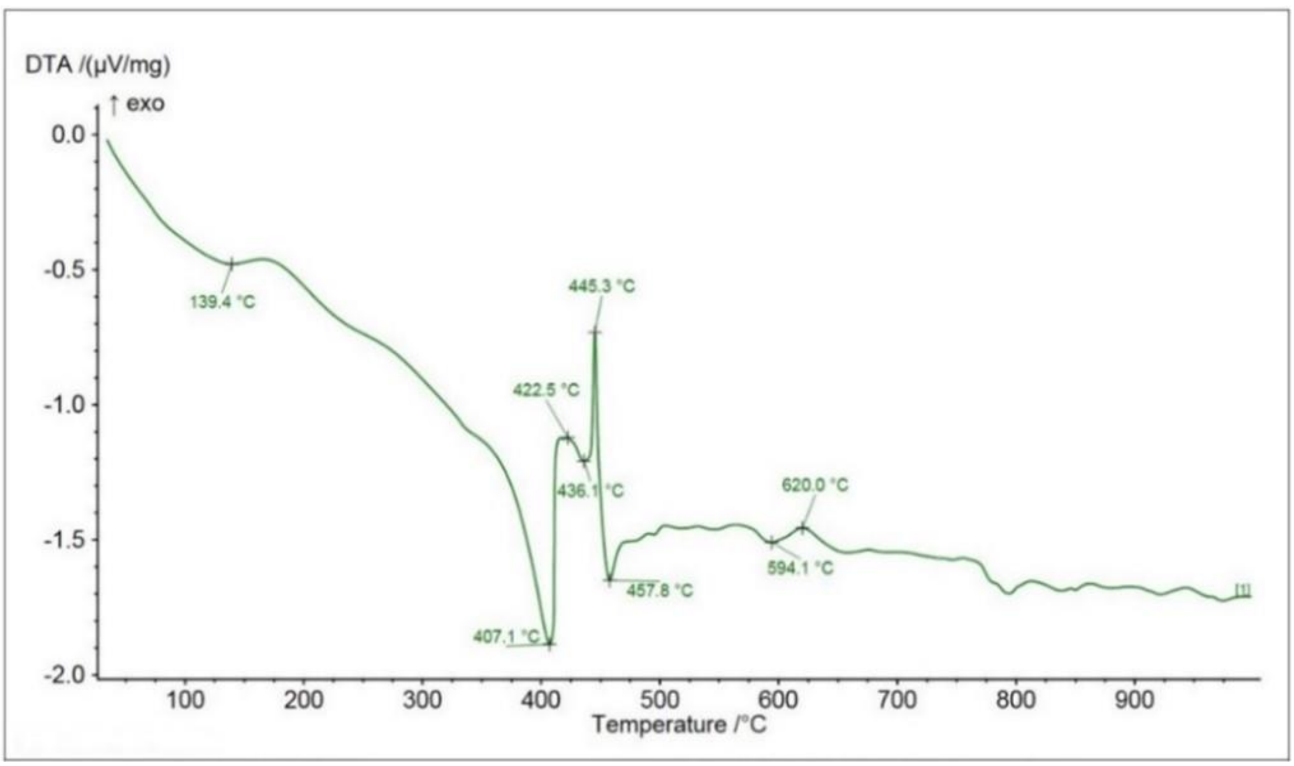

Fig. 7 DTA curve

C. Bulk density

The bulk density of the prepared samples was obtained. The bulk density was determined to be 1028 kg/m^3 for sample EPB-1, 1165 kg/m^3 for sample EPB-2, and 1342 kg/m^3 for sample EPB-3. The commercial OSB had a bulk density of 645 kg/m^3.

Tab. II Sieve analysis

Sieve size (mm)	Weight retained (g)	Percentage retain (%)
5.6	0.3	0.2
4.0	4.6	3.1
3.15	8.2	5.5
2.8	5.2	3.5
2.0	90.8	60.5
1.4	1.3	0.9
1.0	8.9	5.9
0.5	25.5	17.0
<0.5	5.2	3.5

D. Water absorption

Water absorption was compared between the commercial OSB board and the prepared composite boards based on waste materials. The measured values are graphically depicted in Fig. 8. From the graph, it can be observed that the EPB-3 sample had the lowest water absorption at 3.1 %. The EPB-2 sample exhibited similar level of water absorption to that of the EPB-3 sample. The commercial OSB had multiple times higher water absorption (81.9 %) than prepared boards from waste materials. When comparing the results with Lopes et al., their commercial OSB achieved this water absorption after only 24 hours. This research team prepared composite boards from bamboo fiber waste and polyurethane resin. Their results for water absorption after 24 hours were around 10 % for boards with 40 % bamboo fiber content [13]. This indicates very low values for boards made from waste materials. This property could prevent the phenomenon that OSB generally suffers from the deformation of the board due to water absorption. The graph also indicates that as the bulk density of the composite boards from waste materials increases, water absorption decreases.

E. Mechanical properties

The mechanical properties of composite boards based on different wood chips or particles depend on several factors. These factors include the type of filler and binder, bulk density, binder content, and particle orientation. In this study, the mechanical properties of composite boards based on waste materials were compared at three bulk densities with a commercial OSB board based on wooden chips. From the results of the flexural tensile strength (Fig. 8), it was found that the tensile strength of composite boards based on waste materials strongly depends on bulk density. Only the EPB-3 sample had higher flexural tensile strength than the commercial OSB board. This suggests that achieving comparable flexural tensile strengths in composite boards based on waste materials requires a bulk density approximately twice as high as that of the commercial OSB board (645 kg/m^3). A clear increase in strength can be observed when comparing the results of the EPB-1 and EPB-2 samples. The EPB-1 sample achieved a flexural tensile strength of only 5.2 MPa, which is five times lower than the EPB-2 sample, whose bulk density was only approximately 13 % higher. The lower bulk density likely caused a non-compact structure. In this structure, the waste epoxy powder inefficiently binds the GFRP chips, resulting in a porous structure with inadequate mechanical properties. It can be concluded that bulk density is a key factor in determining the mechanical properties of both the boards examined in this study and generally for OSB-type composite boards [14–16].

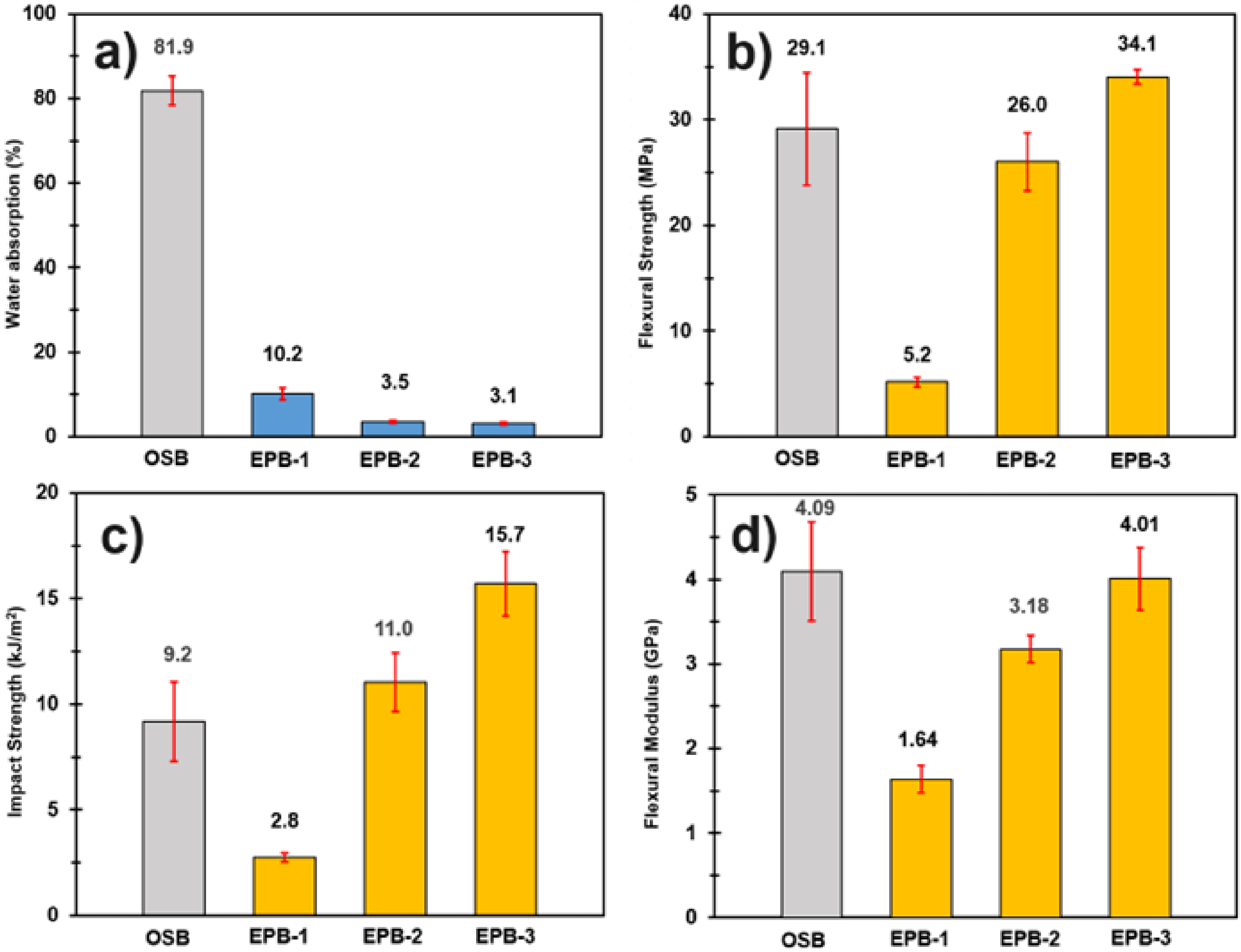

Fig. 8 Graphical representation of a) water absorption, b) flexural strength, c) impact strength, d) flexural modulus

Abobakr et al. conducted a study where they prepared a board using wheat straw for eco-friendly construction. Combined with the polyurethane resin, their boards achieved tensile flexural strengths of no more than 24 MPa. When compared to boards made from waste materials alone, the EPB-2 specimen achieved similar strengths and the EPB-3 specimen achieved higher strengths. It should be noted, however, that their boards had a comparable bulk density to commercial OSB [17].

The flexural modulus is a characteristic property of materials. Specifically, it is the ratio of stress to strain that a material experiences when subjected to bending, with tension and compression occurring on opposite sides of the material. A higher flexural modulus indicates that the material is more resistant to bending, while a lower modulus means that the material is more prone to bending under the applied bending stress. From the graph of achieved flexural modulus values, it can be seen once again that there is a dependence on bulk density. Only the EPB-3 board achieved comparable values to the commercial OSB board.

The results regarding impact toughness are intriguing. The EPB-3 board exhibited approximately 50 % higher impact strength than the commercial OSB board, while the EPB-2 board showed comparable impact strength to the OSB board. This means that these materials have a higher capacity to absorb impact energy. In comparison to the

EPB-3 board, the commercial board demonstrates a brittle character. The toughness of this board is ensured by a higher proportion of binder together with higher bulk density, which limits the initiation and propagation of cracks in the material.

CONCLUSION

The research conducted was focused on the possibilities of processing GFRP waste and waste resin from powder coating in the production of structural boards. The following conclusions can be drawn:

- It was found that a single-shaft knife crusher appears to be a suitable type of crusher for this type of waste.
- Compatibility of GFRP chips with waste powder material, which acted as a binder in the board, was verified. The materials are mixable and a good dispersion of the binder in the material has been achieved.
- With increasing porosity (and decreasing bulk density), the mechanical properties are decreasing.
- The results showed that to achieve similar mechanical properties as the commercial OSB board, composite boards based on waste materials needed to have nearly twice the bulk density. Specifically, sample EPB-3 (bulk density 1342 kg/m^3) achieved higher flexural strength (34.1 MPa) than the commercial OSB board (29.1 MPa). The bulk density proved to be a decisive factor with a significant impact on flexural strength, modulus of elasticity in bending, and impact strength.
- All prepared samples had lower water absorption than the OSB board, which was due to the nature of the filler and binder used and also the higher bulk density.
- Research results have confirmed, that chips obtained from crushing GFRP waste can be used to produce composite boards for construction purposes. Using only waste materials ensures cost reduction compared to commercial OSB boards and has an undeniable benefit for the environment and the handling of GFRP waste in general.

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