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SPECIAL SECTION

Wood-based composite materials in the aspect of structural new generation materials. Recognition research

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Abstract. Composite materials are a constantly evolving group of engineering materials, which has significantly changed their current, and potential role as structural materials over the past decades. Composites offer greater strength, stiffness, and less deformation to structural designers than previously available engineering materials. Resin matrix composites are widely used in the transportation, marine, aerospace, energy, and even sports industries. The manufacturing stage has a profound influence on the quality of the final product. This paper presents the production of composite materials by gravity casting in silicone moulds, using an epoxy/polyester resin matrix reinforced with wood chips and shredded glass fiber reinforced composite from recycled wind turbine blades. Some of the fabricated samples were degassed in a reduced-pressure chamber. The mechanical properties of the produced material were then examined. It was noted that the silicone moulds did not affect the resin self-degassing due to the large surface area to weight ratio, and the remaining small air bubbles had a limited effect on the mechanical properties of the samples. The filler used also played a significant role. Composites filled with crushed GFRC showed better strength properties than composites filled with wood chips. The conducted research is aimed at selecting materials for further testing with a view to their use in the manufacture of next-generation wood-based composite structural materials.

Keywords: composite material; wind turbine; wind turbine recycling; plastics; wood-based composites; epoxy resin; polyester resin.

1. INTRODUCTION

The world is confronted with the problem of the lack of a universal and efficient system for the management of waste generated in the renewable energy sector (wind turbine blades at the end of their life or blades that have been broken) [1–3]. It is therefore becoming necessary to undertake projects related to the processing of materials derived from the recycling of wind turbine blades (fillers) [4–7]. The use of these recyclates as reinforcing phases in composite materials for structural materials, where adequate stiffness, strength, and low weight are required, can be invaluable. In addition, there is a growing interest in the use of composite materials with an increased number of phases (components) [8–10]. The main advantage of such a solution is to exploit the intrinsic properties of these components and to achieve properties similar to or better than they stand alone. An important aspect may be the reuse of wind turbine blade recyclates after machining as next-generation structural materials to close the production cycle [10–14]. In order to do this, it is necessary to identify the groups of materials that are most promising in the context of structural components of wood-based composite materials. The process of mechanical shredding of wind turbine blades after their service life is in principle an integral part of the recycling of this type of material (polymers) [11–15]. It is therefore important to ensure that the shredding efficiency is as high as possible while keeping energy intensity as low as possible to balance the energy and environmental input for processing wind turbine raw materials with the benefits of raw material and energy recovery. Thermosetting resins are usually used to manufacture wood-based panels, which are energy intensive and require complex lines. In addition, harmful formaldehyde is formed. The use of chemically cured resins is, in our opinion, a new direction that is undoubtedly worth exploring. A thorough study of the issue will facilitate easier design and control of polymer material cutting processes to ensure the lowest possible environmental burden [16–21].

Current end-of-life (EOL) processing methods for wind turbine blades include storage, incineration, co-processing, pulse shredding, pyrolysis, reuse, and mechanical shredding. Landfilling is the most common method of wind turbine blade end-of-life in the United States [5, 6]. The enormous size of the blades poses quite a challenge for landfill operators, as it is difficult to maintain space efficiency. Weather-resistant composite materials will not easily degrade naturally. However, over time the organic compounds in the material will biodegrade releasing methane and other volatile substances. Incineration reduces the volume of waste and recovers some of the energy from the resin and wood combustion processes. However, wind turbine blades containing glass fiber reduce the calorific value of such materials. The gases emitted from combustion may contain harmful by-products (formaldehyde, carbon monoxide). Co-processing of wind turbine blades is suitable for blade materials containing glass fiber older generation of wind turbine blades). Adding GFRP materials to the manufacture of cement allows both raw

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materials and energy to be reused, but the process itself is expensive [7]. Composites containing glass fiber are burned in a cement kiln, where the energy recovered from the polymer resins replaces coal or natural gas, which are usually used as fuel for combustion. The residual glass fiber is then incorporated into the cement in combination with limestone and clay or shale. Mechanical grinding offers the possibility of reusing shredded composite material to produce new materials. The grinding process can take place in multiple stages, usually the initial stage already taking place at the wind farm site to reduce costs associated with transporting the blades [12, 13]. The material obtained can range from fine powder (dust from cutting with a wire diamond saw) to fragments of about 1 cm in diameter. Solvolysis and hydrolysis are processes that use a solvent to break polymer bonds. These methods are currently only used in laboratory research and their implementation on an industrial scale is still under development. Pulse shredding uses electrical pulses to shred a composite material that is immersed in water between two electrodes that induce pulses of up to 200 kV. The created high-pressure shock waves break the material into smaller fragments [17]. Compared to mechanical recycling, it requires a much higher energy input, thus increasing the cost of material processing. Pyrolysis processes the material at a high temperature of 400–700°C separating the glass and carbon fibers from the polymer matrix. By heating wind turbine blades without oxygen, flammable gas or liquid fuel is released from the polymers, thereby recovering the fibers themselves, which can be reused. However, the strength of the glass ones is reduced by about 50% after this process. It should also be remembered that they may have surface impurities that reduce their ability to reconnect with the polymer matrix. Re-use extends the life cycle of a wind turbine whose components can be used as spare parts. Nowadays, it is also possible to see the use of turbine blade materials as public amenities, e.g., for playgrounds or benches [18]. This publication aims to select the types of matrices, methods for their modification (e.g., by degassing under reduced pressure), compositions, and volumes of reinforcing phases that will be the best elements for manufacturing composite structural materials. The energy demand and a summary of wind turbine blade recycling methods are shown in Table 1. The use of polyester and epoxy resins with a woody biomass infill and a recycled composite will contribute to closing the life cycle of used composites from wind farms. The possible use of the best features of composite materials (strength, ability to carry heavy loads, stiffness) together with natural materials (wood) will help to solve the problem of recycling wind turbine blades that are lying in landfills or undergoing chemical processing that is expensive and often produces harmful substances. The new wood-based composite material will be more weather-resistant than natural wood, due to its polymer matrix.

Table 1
Comparison of end of life (EOL) processes wind turbine composites

EOL process	Circular economy strategy	Energy requirement (MJ/kg)
Landfill incineration	R9 – Recover	0.3 –4.2
Cement coprocessing	R8 – Recycle	–4.2
Mechanical recycling	R8 – Recycle	0.3
Fluidized bed	R8 – Recycle	22.2 (GFRP) 9.0 (VFRP)
Pyrolysis	R8 – Recycle	21.2
Microwave-assisted pyrolysis	R8 – Recycle	10.0
Chemical recycling	R8 – Recycle	19.2
High–voltage fragmentation	R8 – Recycle	16.2
Life extension 5 years	R4 – Repair	1.4 (GFRP) 3.5 (CFRP)

2. MATERIALS AND METHODS

2.1. Matrix material

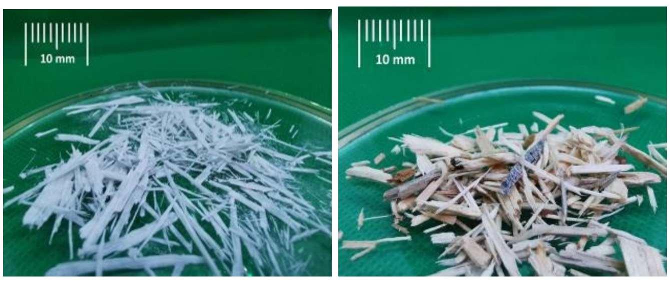
Commercial resins were used to produce the composite material for the matrix material, one being an epoxy resin and the other a polyester resin. The properties of the materials used for the matrix are shown in Table 2.

Table 2
Properties of materials used for the composite matrix

Resin type	Epoxy resin Epidian 652 with IDAR hardener	Polyester resin Poly, Ag-Bet
Colour	Clear	Blue
Density	1.10 [g/cm^3]	1.40 [g/cm^3]
Curing time	48 [h]	72 [h]

2.2. Reinforcement material

Two types of material were used as reinforcement materials. The first was wood chips produced in the process of wood processing in a sawmill, the second was a wind turbine blade shredded to the form of flakes, which was provided for the research by the Anmet company located in Szprotawa (Poland). The regranulate has an irregular flake shape with an approximate thickness resulting from the specifications of the shredder used (Fig. 1a). Anmet



(a) (b)

Fig. 1. Shape of the granules used to reinforce the composites: (a) finely ground composite, (b) wood chips

company deals, in a professional manner, with the disposal and recycling of wind power plant components, among other things, including rotor blades. The composite material created by mechanical shredding comes from a small blade of an older type containing resin and glass fibers from a decommissioned wind turbine. Mechanical recycling (rotational shredding), which produced a flake material, is the least energy-intensive way of obtaining recyclates from blades (0.27–3.03 MJ/kg), compared to chemical processes (63–91 MJ/kg). A higher degree of fragmentation of the rotor blade material would have an impact on the increased energy intensity, which would further increase the production costs of the new generation of composite structural materials, and the amount of dust generated in the process, which is detrimental to humans and the environment [7,8]. Wood chips have been obtained from the processing and recycling of wood at a sawmill. These are commonly used chip sizes for chipboard production (Fig. 1b). In order to find out the granulometric composition of the particles as filler, the materials were subjected to granulometric analysis on a Morek laboratory shaker LPzE-2e MULTISERW. The granulate samples weighed 50 grams, and the analysis itself was conducted dry, setting the sieves on the shaker from the largest to the smallest. Then, after sieving, the material from each sieve was weighed to the nearest 0.01 gram. The results from the granulometric analysis of the samples are shown in Figs. 2a and 2b.

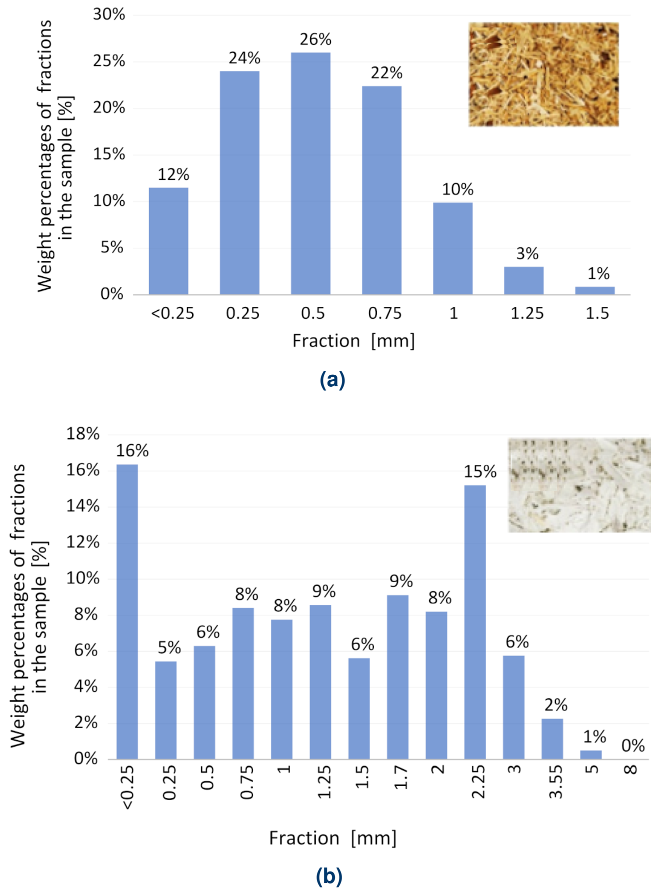


Fig. 2. Result of granulometric analysis (a) wood chips, fractional proportions in the sample, in weight percent, (b) finely ground composite, fractional proportions in the sample, in weight percent

2.3. Prepare test specimens

A total of 325 specimens for strength testing were produced using the gravity casting method in pre-prepared silicone matrices. The matrix was epoxy resin (designated "zeXX") and polyester resin (designated "zpXX"), some of the specimens were degassed in a vacuum chamber to reduce the pressure of 0.08 MPa, which was maintained for 5 seconds (designated zeXX/O and zpXX/O). The filler content was 10, 20%, 40%, and 60% by weight of the composite materials produced. After curing, the samples were kept in a room with constant humidity and temperature for 21 days. They were then subjected to determinations of properties such as tensile strength, impact strength, compressive strength, the density of the produced materials, and their hardness were determined. The results obtained were compared with materials in which the matrix was degassed under reduced pressure.

2.4. Characteristics of testing methods

The shape and dimensions of the cast specimens that are subjected to the tensile test are defined in EN ISO 527-2:2012 [22] and EN ISO 527-3:2019-01 [23]. Static uniaxial tensile testing was conducted on a ZWICK/Roell GmbH, & Co. 8306 tensile testing machine according to EN ISO 527-1, and 108 specimens were tested – 3 specimens for each filling type and matrix type [16, 17]. The crosshead feed rate for the tensile strength measurements was set at 2 mm/min. The specimens were prepared as unnotched beams and the test was conducted using a Charpy hammer type 5113 from ZWICK/Roell GmbH, & Co. with a pendulum with a nominal energy output of 7.5 J at an impact velocity of 2.9 m/s. A total of 108 specimens (3 repetitions per specimen type) were tested [20].

The compressive strength test was conducted on a ZWICK/Roell GmbH & Co. 8306 testing machine. The specimens were compressed to 70% of their height. Three repetitions were conducted for each matrix type and infill type (108 specimens). The density of the materials was determined in accordance with PN-EN ISO 1183-1:2019-05 [24] using an XS105DR Excellence analytical hydrostatic balance from Mettler Toledo with a density kit for non-porous solids. Distilled water [18] was used as the reference liquid with a known density. The hardness test was conducted using the PN-EN ISO 868:2005 [25] standard with a Shore D Durometer from ZWIC/ Roell GmbH & Co., taking 5 measurements on each sample [19].

3. TEST RESULTS

Casting test specimens using a silicone mould has some disadvantages, but also advantages related to the material preparation process. The difficulty in keeping the top layer of the specimen perfectly flat can be considered a disadvantage. A common observation when producing the samples was the formation of a meniscus on the surface of the cast shapes. Hence, there may be slight differences between the dimensions of the samples in the series. The free release of gases into the environment through the silicone mould during gelation and cross-linking can be considered an advantage due to the relatively large resin contact area. Any air bubbles that may remain in the produced materials are small and have less impact on mechanical properties. Prior to cross-linking, a typical composite forms a three-phase system, i.e., it consists of a liquid phase (epoxy/polyester resin), a solid phase (granular filler), and a gaseous phase (entrained air), whereas after outgassing and cross-linking it becomes a single-phase system consisting only of a solid phase. In samples that were not degassed, voids caused by the presence of air bubbles formed during the curing of the resin were clearly visible on the top surface, not present on the bottom surface, where the sample was smooth. In the reduced-pressure samples, such voids were absent on both the top and bottom of the cast samples, indicating good outgassing, which could result in more even or better mechanical properties of the samples.

3.1. Tensile strength

For both wood chip and shredded composite reinforced materials, regardless of the matrix (resin) type, it was found that degassing the mixtures before casting into moulds increased the tensile strength of the resulting materials. A greater increase in strength can be seen for the epoxy matrix deaerated even at lower filler contents. The trend of change as a function of filler content is generally linear. The test results are shown in Figs. 3a and 3b for materials reinforced with wood shavings, and Figs. 4a and 4b for materials reinforced with shredded composite material in the form of straw.

3.2. Impact strength

The results of the test conducted according to PN-EN ISO 179-1:2010 [26] are shown in Figs. 5 and 6. For degassed epoxy resins reinforced with wood shavings, the impact strength is quite similar and does not exceed 4.06 kJ/m^2. In contrast, polyester resin matrix materials reinforced with wood shavings cast by gravity without degassing have much worse results than those subjected to reduced pressure. It can be seen that specimens where air is present have significantly lower impact results. The poorer impact test results may also be due to the porous structure of the wood, which allows the resin to penetrate deep into the chips.

3.3. Compression strength

Air bubbles, which cause discontinuities in the composite material, are undesirable due to their effect on mechanical properties, including compressive strength. Trapped gases in the organic material, e.g., air from wood chips, can cause air diffusion in

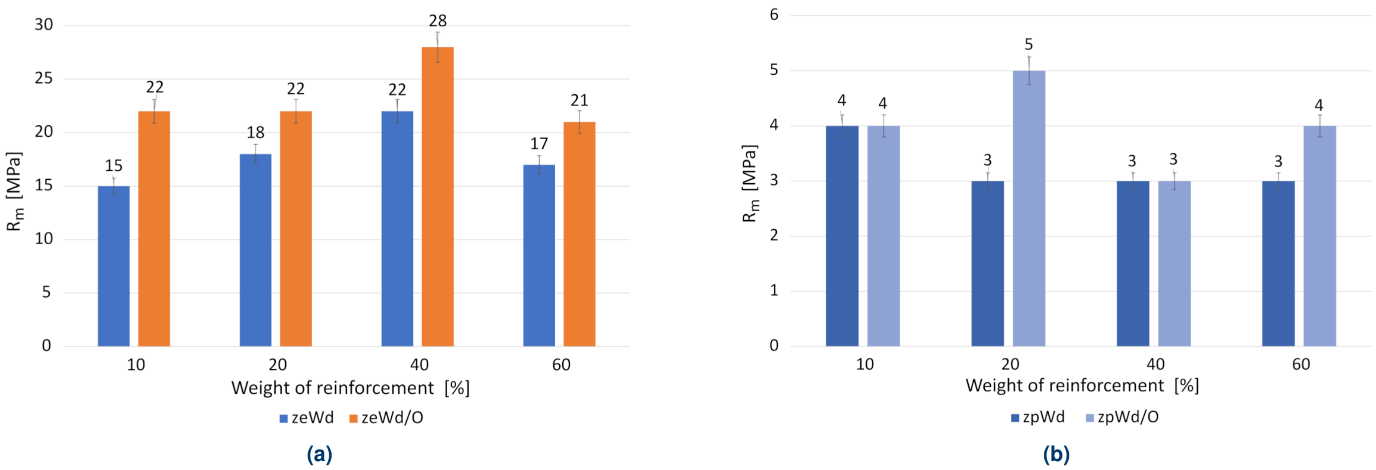


Fig. 3. Result of static tensile strength of wood chip reinforced composites (a) epoxy resin matrix, (b) polyester resin matrix

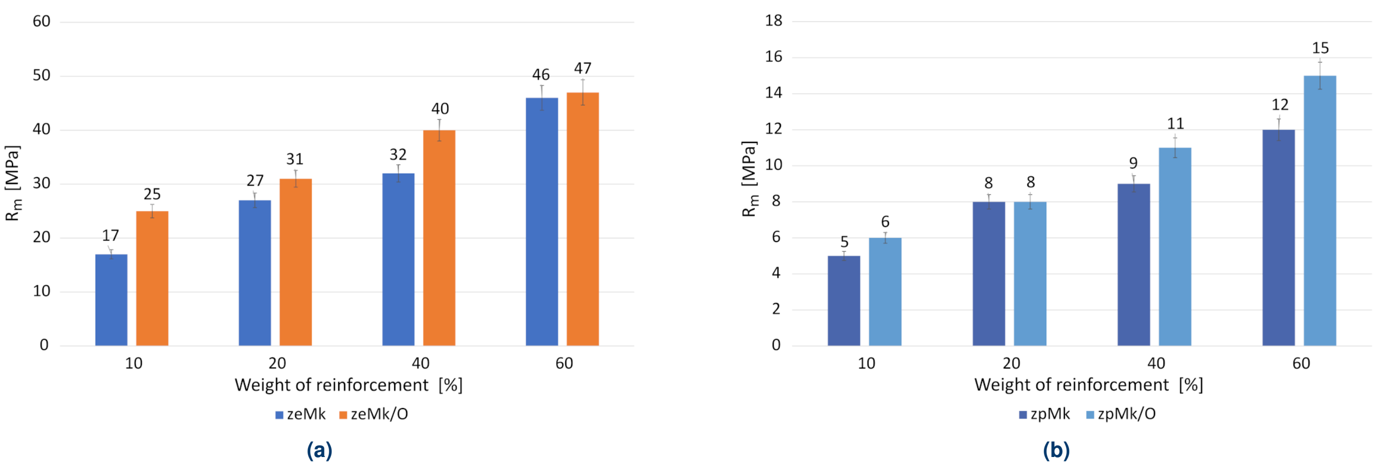
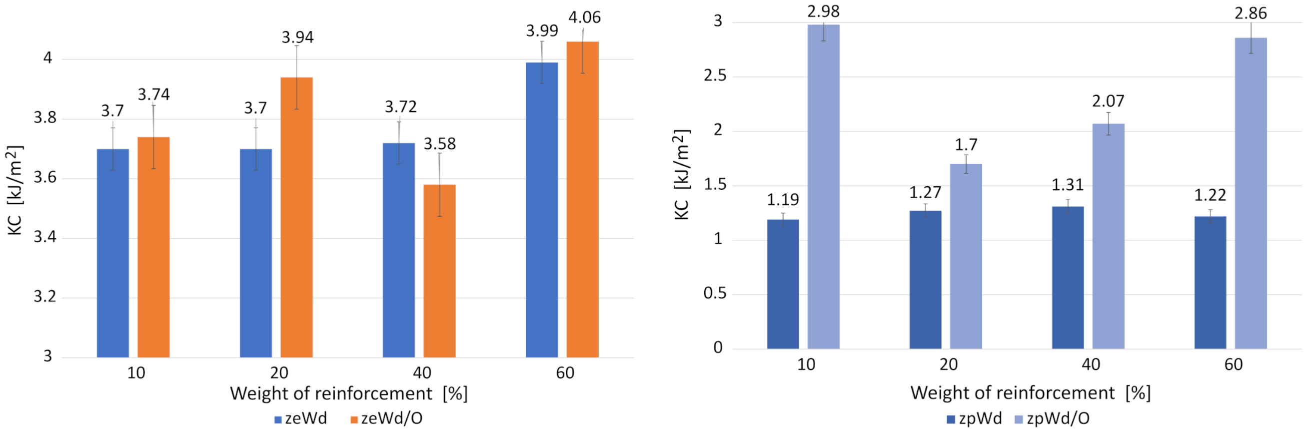
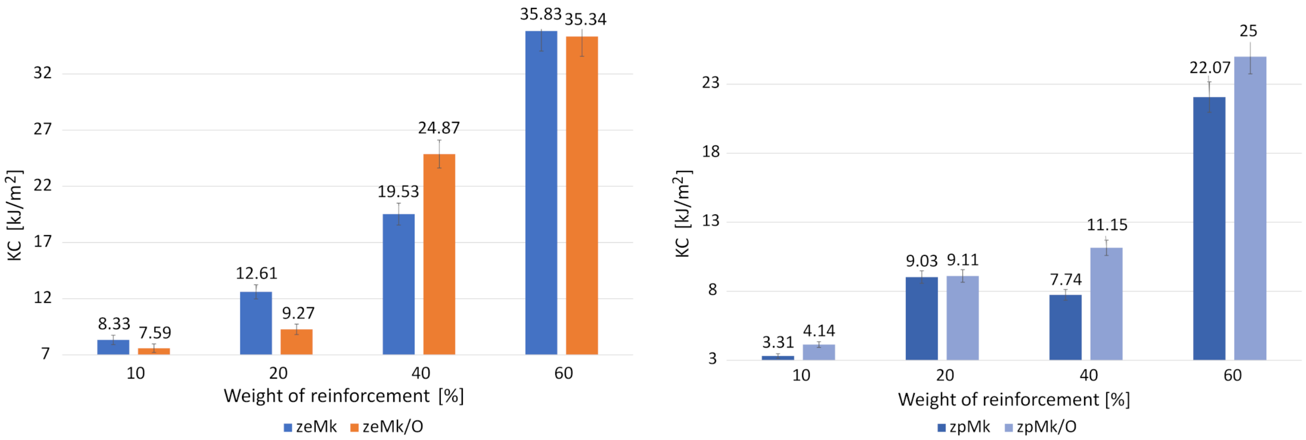


Fig. 4. Result of static tensile strength of finely ground composite (a) epoxy resin matrix, (b) polyester resin matrix



(a) (b)

Fig. 5. Result of impact strength of wood chip reinforced composites (a) epoxy resin matrix, (b) polyester resin matrix



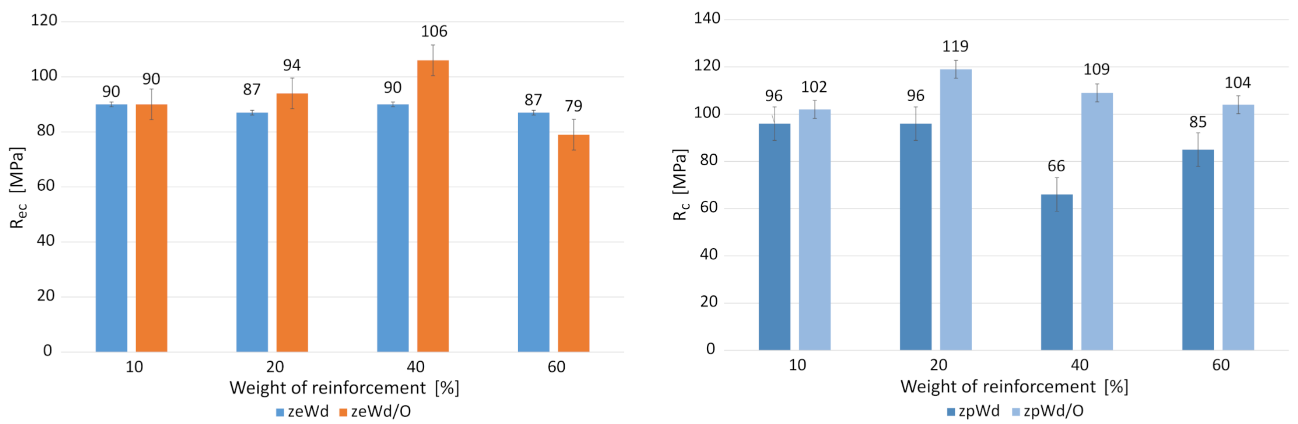
(a) (b)

Fig. 6. Impact result of finely ground composite (a) epoxy resin matrix, (b) polyester resin matrix

the composite material, which affects its mechanical strength. Higher compressive strengths were observed in samples that were not subjected to reduced pressure. The results are shown in Figs. 7 and 8.

3.4. Density determination

The air remaining inside the organic structure of the wood chips is released when they are embedded in the resin, thus increasing the aeration of the liquid phase of the composite, which in



(a) (b)

Fig. 7. Compression strength result of wood chip reinforced composites (a) epoxy resin matrix, (b) polyester resin matrix

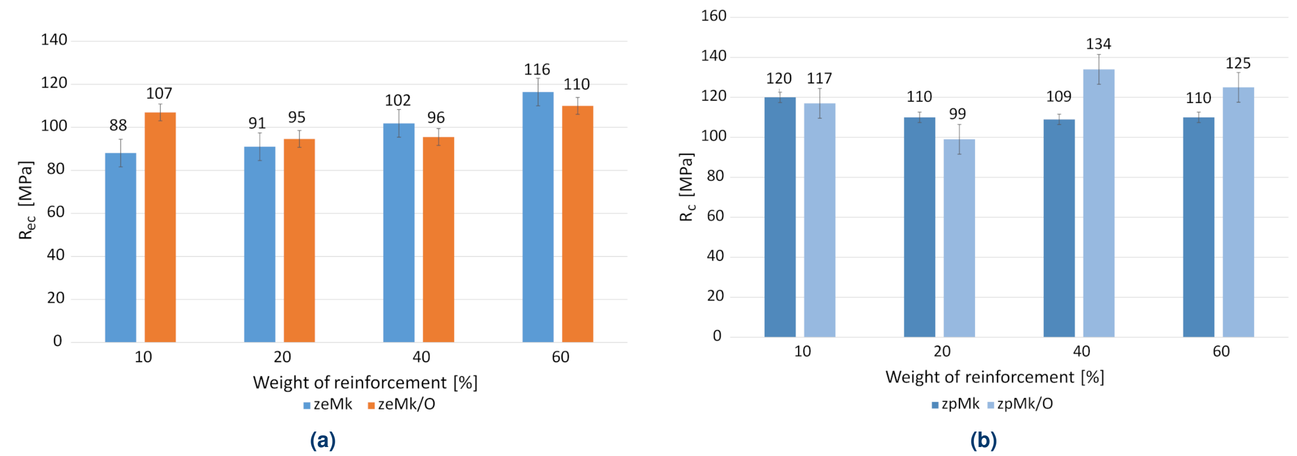


Fig. 8. Compression strength result of finely ground composite (a) epoxy resin matrix, (b) polyester resin matrix

turn affects the difficulty of degassing the material at reduced pressure. Consequently, the higher the filler concentration and its packing in the resin, the higher the air content in the final product. Wood chip particles and smaller parts of the shredded composite material can sediment in the epoxy resin and settle to the bottom of the cast samples, which, in the case of strength tests, can have a major impact on the results obtained. At high filling levels, the density is compensated for by the amount of air. The results of the density determination of the produced composites are summarised in Figs. 9 and 10.

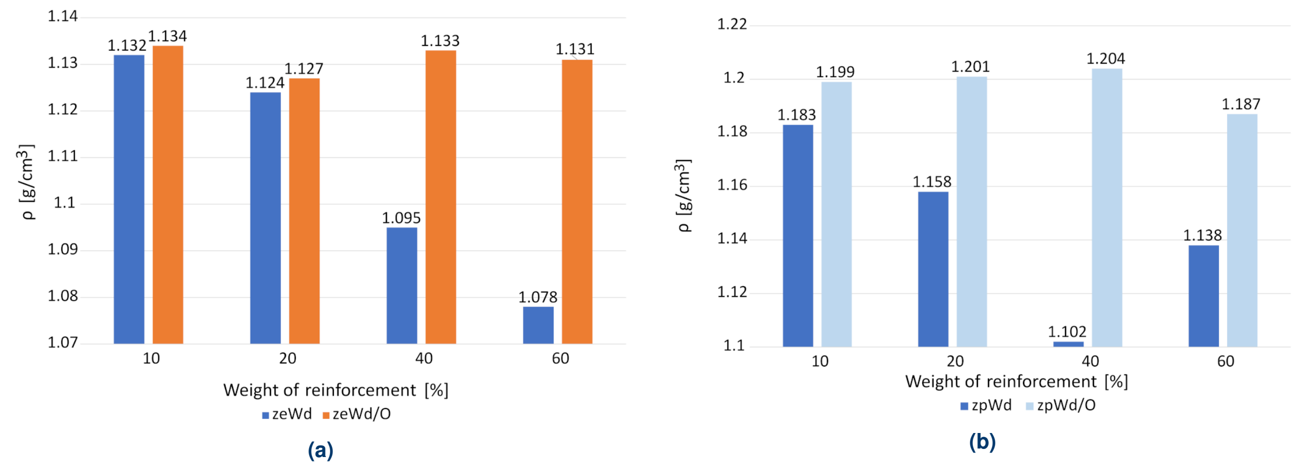


Fig. 9. Density test result for specimens with wood chip reinforcement (a) epoxy resin matrix, (b) polyester resin matrix

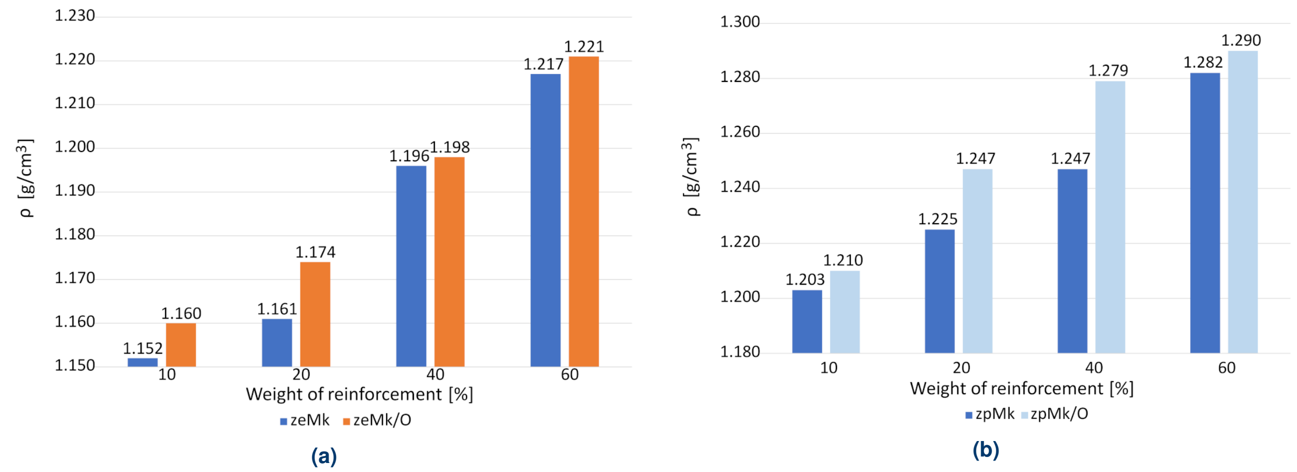


Fig. 10. Density test result for specimens with shredded composite reinforcement (a) epoxy resin matrix, (b) polyester resin matrix

3.5. Hardness

The hardness of heterogeneous composite materials is difficult to determine unambiguously. It is highly dependent on the choice of measurement location, and also on the properties and distribution of the concentration of reinforcing particles in the matrix material. It can often be the case that the sample matrix itself is measured due to the distribution of fillers in the composite volume. The results of durometer hardness measurements are shown in Figs. 11 and 12.

4. CONCLUSIONS

The study was conducted to determine the influence of the manufacturing technique of composite samples with epoxy and polyester resin matrix, reinforced with wood chips or shredded composite material from recycled wind turbine blades, on the results of the mechanical properties of the composites produced by gravity casting. It was noted that:

- The study showed a significant effect of the casting method used for the test specimens on the scatter of measurement results and on the mechanical properties obtained.
- The use of a silicone mould, due to its relatively large contact area, facilitates the degassing of any air that remains in the samples during composite crosslinking.
- The degassing of the resin affects the density of the composite materials produced, and materials with a polyester resin matrix have a higher density than those with an epoxy matrix.
- In composites reinforced with shredded wind turbine blades and wood shavings, the highest hardness was for degassed epoxy and degassed polyester resins.
- Higher impact strength results were achieved with degassed matrix materials.
- Higher static tensile strengths were achieved by composite materials with the degassed matrix.
- The compressive strength of the composite materials depended on the type of matrix (better for polyester resins) and the degassing of the material (degassing at reduced pressure increased the strength of the materials).

Thanks to the study, the most promising material groups (60zeMk/O, 60zeWd/O, 40zeMk/O, 20zeWd/O, and 60zeWd/O) were selected for further exploratory studies.

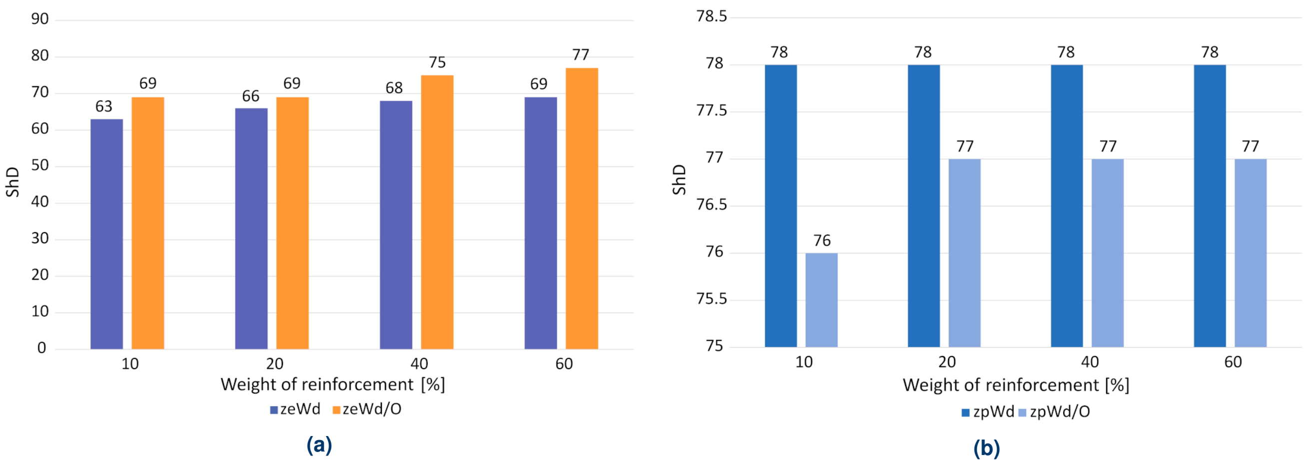


Fig. 11. Shore D hardness result for composite materials with wood chip reinforcement (a) epoxy resin matrix, (b) polyester resin matrix

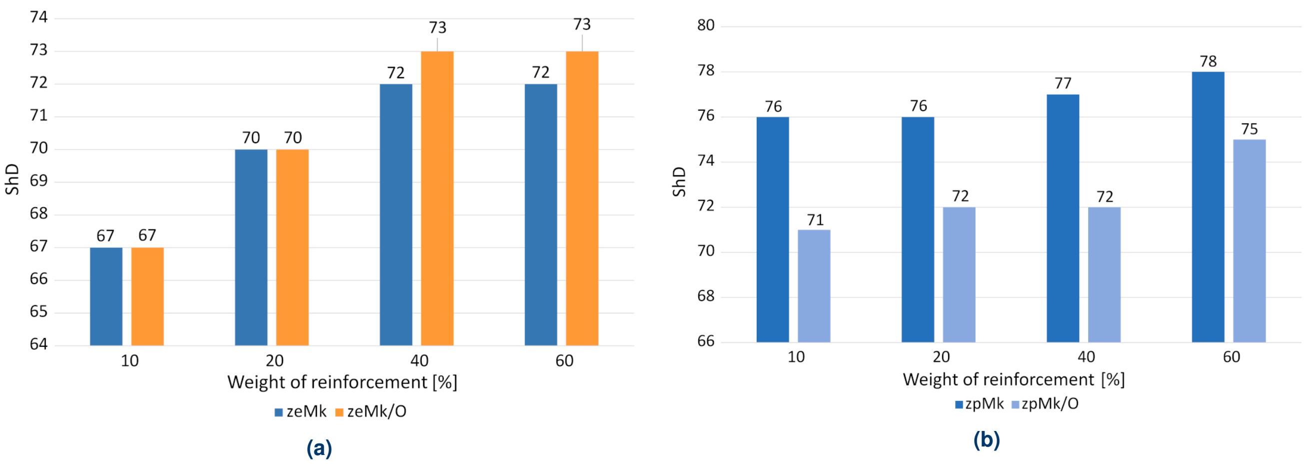


Fig. 12. Shore D hardness result for composite materials shredded composite reinforcement (a) on an epoxy resin matrix, (b) with a polyester resin matrix

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