Mechanical properties: wood lumber versus plastic lumber and thermoplastic composites

Propriedades mecânicas: madeira versus madeira plástica e compósitos termoplásticos

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Abstract

Plastic lumber and thermoplastic composites are sold as alternatives to wood products. However, many technical standards and scientific studies state that the two materials cannot be considered to have the same structural behaviour and strength. Moreover, there are many compositions of thermoplastic-based products and plenty of wood species. How different are their mechanical properties? This study compares the modulus of elasticity and the flexural, compressive, tensile and shear strengths of such materials, as well as the materials' specific mechanical properties. It analyses the properties of wood from the coniferae and dicotyledon species and those of commercialized and experimental thermoplastic-based product formulations. The data were collected from books, scientific papers and manufacturers' websites and technical data sheets, and subsequently compiled and presented in Ashby plots and bar graphs. The high values of the compressive strength and specific compressive and tensile strengths perpendicular to the grain (width direction) shown by the experimental thermoplastic composites compared to wood reveal their great potential for use in compressed elements and in functions where components are compressed or tensioned perpendicularly to the grain. However, the low specific flexural modulus and high density of thermoplastic materials limit their usage in certain civil engineering and building applications.

Keywords: Polymer composite. Strength. Specific property. Density. Material selection.

Resumo

A madeira plástica e os compósitos termoplásticos são vendidos como alternativas à madeira. Entretanto, normas técnicas e estudos científicos afirmam que não se pode considerar que os dois materiais tenham o mesmo comportamento estrutural e resistência. Além disso, existem muitas composições de madeira plástica e de compósitos termoplásticos e centenas de espécies de madeira. Quão diferentes são suas propriedades mecânicas? Este estudo compara o módulo de elasticidade e a resistência à flexão, à compressão, à tração e ao cisalhamento de tais materiais, assim como suas propriedades mecânicas específicas. São analisadas as propriedades de madeiras de árvores coníferas e dicotiledôneas e de madeira plástica e compósitos termoplásticos comercializados e experimentais. Os dados foram retirados de livros, artigos científicos, websites e documentos técnicos de fabricantes e apresentados em gráficos de Ashby e de barras. Os altos valores de resistência à compressão e de resistência específica à tração e à compressão perpendicular às fibras exibidos pelos compósitos experimentais comparados à madeira revelam seu potencial para uso em elementos comprimidos e sob compressão ou tração perpendicular às fibras. Porém, o baixo módulo de elasticidade específico e a elevada densidade dos produtos feitos com termoplásticos limitam sua aplicação na construção civil.

Palavras-chaves: *Compósito polimérico. Resistência. Propriedade específica. Densidade. Seleção de material.*

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Introduction

The product commercially known as plastic lumber can be exclusively made of plastics or can be a plastic composite (CARROLL *et al*., 2001). In both cases, it is manufactured with the dimensions (BOLIN; SMITH, 2011; BAJRACHARYA *et al*., 2014) of and for similar uses as wood lumber (CARROLL *et al*., 2001; BENTHIEN; THOEMEN, 2012; BAJRACHARYA *et al*., 2014). Currently, plastic lumber is primarily produced based on thermoplastic matrices (NAJAFI; HAMIDINA; TAJVIDI, 2006; KLYOSOV, 2007) and is mainly used for compound benches, tables, decks, building facade coverings, pergolas and piers, and elements and structures that are commonly built from wood lumber.

There is a trend to continued market growth of plastic lumber and wood-plastic composites (a type of plastic composite produced with wood particles as filler), both in North America and in Europe (BOWYER *et al*., 2010). In 1995, approximately 50 thousand tonnes of them were consumed in both regions. In 2002, 600 thousand tonnes were consumed in North America and about 650 thousand tonnes in Europe, while in 2009, about 1000 and 1150 thousand tonnes were consumed, respectively, in such places (BOWYER *et al*., 2010). Regarding solely wood-plastic composites, there is a global production growth trend (CARUS *et al*., 2014), where it is primarily used for decking (CARUS *et al*., 2014; HAIDER; EDER, 2010). Specifically in 2010 and 2012, the European, North American and South American production reached 220 and 260, 900 and 1100, and 10 and 20 thousand tonnes, respectively (CARUS *et al*., 2014).

Manufacturers sell plastic lumber products, claiming they are more durable, safer and need less maintenance than wood products and can therefore effectively be substituted into non-structural or semi-structural components. In addition, because plastic lumber is commonly manufactured from residues and post-consumer plastics, its use minimizes the amount of trash going to landfills and the need for virgin material (NAJAFI; HAMIDINA; TAJVIDI, 2006; BAJRACHARYA *et al*., 2014), so manufacturers also market their products as environmentally superior to wood lumber.

A life cycle assessment (LCA) of alkaline copper quaternary (ACQ)-treated lumber in comparison to wood plastic composite (WPC) decking shows that the latter has a significantly higher environmental impact than the former (BOLIN; SMITH, 2011). Nevertheless, in terms of durability and maintenance, studies have shown that plastic lumber provides a better performance than wood lumber (WINANDY; STARK; CLEMONS, 2004; GARCÍA *et al*., 2009; AZWA *et al*., 2013; NDIAYE; GUEYE; DIOP, 2013; WEI *et al*., 2013) and are also economically advantageous in the long term, as their maintenance can be performed less regularly and using simple products, such as soap and water. Plastic-based products also absorb less water (STARK, 2005; CHEVALI; DEAN; JANOWSKI, 2010; NAJAFI; KORDKHEILI, 2011; BENTHIEN; THOEMEN, 2012; LEU *et al*., 2012; AZWA *et al*., 2013; CHAVOOSHI *et al*., 2014; YOUSSEF; EL-GENDY; KAMEL, 2015), which contributes to a longer useful life, as effects such as swelling (KLYOSOV, 2007), component buckling (KLYOSOV, 2007), decrease in mechanical strength (STARK, 2006; STRÖMBERG; KARLSSON, 2009; MORRELL *et al*., 2010; NAJAFI; KORDKHEILI, 2011) and biological degradation (STRÖMBERG; KARLSSON, 2009; HEMMATI; GARMABI, 2012; NAUMANN; STEPHAN; NOLL, 2012; AZWA *et al*., 2013) are minimized. However, can they really substitute wood lumber products? The two types of materials (wood lumber and plastic lumber) have very different mechanical properties.

Affirming generically that wood lumber is more or less strong or stiff than plastic lumber and thermoplastic-based composites is incorrect, and using plastic lumber as an alternative for wood lumber is not simple, considering the wide variety of wood species and compositions of thermoplastic-based products. The simple difference between the mechanical properties of wood and plastic lumber makes their components distinct in terms of dimensions, volume and mass, as well as in terms of the amount of elements used in a specific situation, such as a deck substructure.

Thus, the aim of this study was to compare the density, the modulus of elasticity (flexural modulus), and the static flexural, compressive, tensile and shear strengths of wood from coniferae and dicotyledon species from the Northern and Southern Hemispheres with the equivalent properties of commercialized and experimental thermoplastic-based product formulations. This research also intended to compare the materials' specific mechanical properties (mechanical property to density ratio).

Because there are many variables that affect the mechanical properties of thermoplastic products, such as the method of manufacture (injection moulding or extrusion), the wood species used to produce the lignocellulosic fillers, and the testing procedures, the proposal of this paper is not to compare particular values, but rather to provide general mechanical properties, showing, using plots, the area in which such materials reside.

Methods

Data were collected from the literature on 57 coniferae and 183 dicotyledon wood species, also known as softwoods and hardwoods, respectively, from the Northern and Southern Hemispheres. Additionally, data on 25 commercialized plastic lumber compositions were obtained from manufacturer's websites and technical guides and other literature. Data on 146 polymeric and composite experimental formulations were from in scientific papers. Some materials' density and mechanical strength values were collected from graphs contained within the papers analysed, as some of them did not present tables with the exact values of the properties. Thus, some of the values showed in and plotted in the graphs of this paper may not be the same as those of the original research, but rather they are close approximations.

The static mechanical properties of the materials were compared using Ashby plots (ASHBY, 2005) and bar graphs. The Ashby plots relate the density of each material to its respective mechanical properties. The properties studied were the modulus of elasticity (flexural modulus), flexural strength, compressive strength parallel and perpendicular to the grain, tensile strength parallel and perpendicular to the grain, and shear strength. In turn, bar graphs were used to compare the materials' specific mechanical properties, such as specific flexural modulus and strength.

Technical standards used in mechanical tests on the analysed materials

Mechanical data were collected from studies that used different standards to obtain values for the materials' density, modulus of elasticity and strength. In the case of experimental thermoplastic products developed by researchers, the tensile properties were measured in all studies using ASTM D638 (AMERICAN…, 2014a), but the flexural properties were measured a variety of standards such as ASTM D143 (AMERICAN…, 2014b), ASTM D4761 (AMERICAN…, 2013) and ASTM D6272 (AMERICAN…, 2010a), although most used ASTM D790 (AMERICAN…, 2010b). The same phenomenon was observed for commercialized thermoplastic products' flexural properties, as well as their tensile, compressive and shear properties. Different data have also been collected from different books for some wood species. Thus, as some variation of the strength values may occur when a material is tested using different technical standards, the goal of this paper is not to compare exact values but rather general mechanical properties, showing in the plots the areas in which the properties of such materials reside.

Thermoplastic-based products' compressive and tensile strength parallel (direction of length) and perpendicular (direction of width) to the grain

When papers did not clearly presented the composites' density values, they were unappreciated in this study, even though the percentage and density of each material in the composites' formulation were described. Since many factors and procedures in the manufacturing process can change the density of the produced materials, it was considered that applying a simple rule-of-mixture to calculate the composites' densities would lead to unreal values.

In turn, none of the analysed papers, books or manufacturers' websites provided data on all the static mechanical properties analysed in this research. Therefore, the analysis and graphs presented for each property covered in the Results section do not embrace all the considered wood species and thermoplastic-based product compositions. However, when the papers or manufacturers presented only the strength parallel or perpendicular to the grain, it was considered that both values were equal, for compressive and tensile strength.

This assumption was made because the materials used to compound a thermoplastic composite or plastic lumber – plastic, lignocellulosic and/or mineral filler(s) and additives – are generally mixed with no concern for the orientation of the fibres, when glass or wood fibres are used, for example, although the fibre orientation can have a huge influence on the composites' mechanical properties (JOSEPH *et al*., 2002; MIGNEAULT *et al*., 2009; YOO; SPENCER; PAUL, 2011; SINGH *et al*., 2014; VÄNTSI; KÄRKI, 2014). Among the 20 analysed papers, none provide procedures for the production of fibre-oriented composites in the preparation of the tested samples. Thus, for this type of material whose fibres are randomly oriented in many directions during the manufacturing process, the distinction between strengths parallel and perpendicular to the grain makes no sense.

Thermoplastic-based product compositions

The range of thermoplastic product compositions analysed is wide. It includes specimens made of pure virgin or recycled high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP) and acrylonitrile butadiene styrene (ABS). It also includes composites that mix such plastics with fillers such as wood flour, wood fibre, bark fibre, rice hulls, hemp fibre, flax fibre, sugarcane bagasse fibre, calcium carbonate, carbonized and uncarbonized cow bone powder, silica fume, kaolin, talc, and glass fibres and with additives such as coupling agents and lubricants. There are also variations in the percentages of each component used.

In addition, the wood species from which the wood flour and wood fibre are produced may differ from reference to reference. Some wood species used to compound the thermoplastic products tested in the analysed papers are Pinus radiata (ADHIKARY; PANG; STAIGER, 2008; BEG; PICKERING, 2008), Populus deltoides (NOURBAKHSH; ASHORI, 2009), Cunninghamia lanceolate, Cryptomeria japonica, Taiwania crytomerioides (KUO *et al*., 2009), Pinus ponderosa, Quercus alba, Pseudotsuga menziesii, Gleditsia triacanthos (FABIYI; MCDONALD, 2010), Pinus nigra (BUYUKSARI; AYRILMIS; AKBULUT, 2012) and Populus tremuloides (YEMELE *et al*., 2010). Some papers, such as Adhikary *et al*. (2011) and Leu *et al*. (2012), used wood flour from many wood species belonging to the same genus to produce the WPCs.

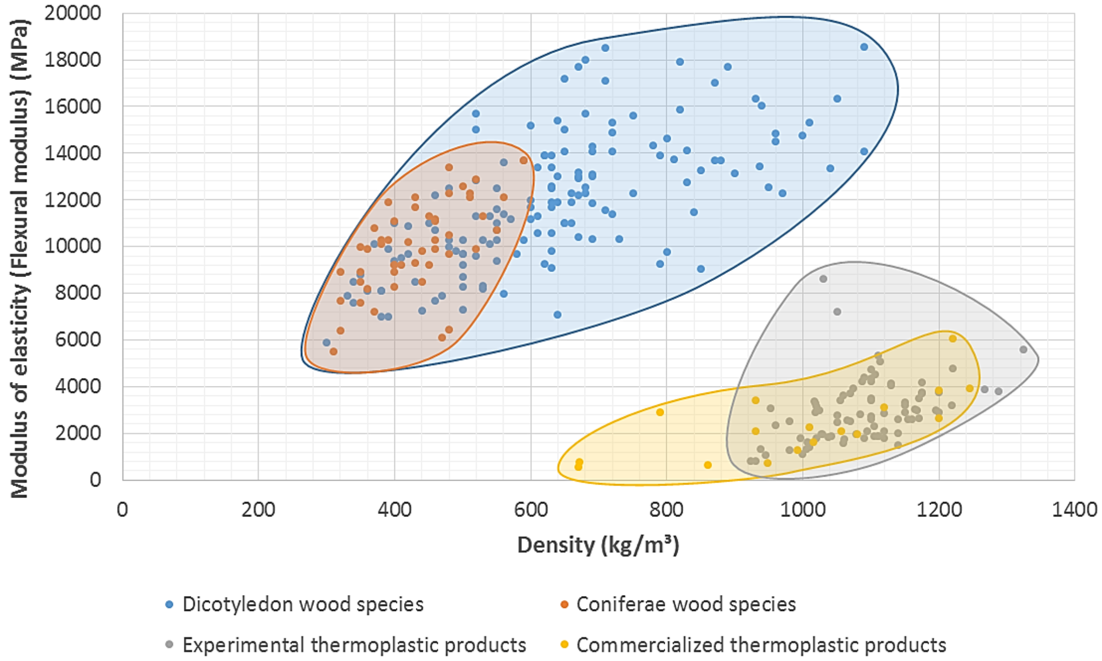
Results

A comparison between the mechanical properties of the wood lumber species and those of the plastic lumber and wood plastic composite materials is presented in the subsections below.

Modulus of elasticity (flexural modulus)

The highest values of the modulus of elasticity among the thermoplastic products were found in PP-, HDPE- and PVC-based composites, and all are in the same region, between 5000 MPa and 9000 MPa, as the wood species' lowest values (Figure 1). When analysing only the commercialized thermoplastic products, the highest flexural modulus is close to 6000 MPa, close to the five lowest wood species' flexural modulus among the 195 species analysed for this property.

Figure 1 - **Ashby plot presenting the modulus of elasticity vs. the density for various wood species and thermoplastic products**



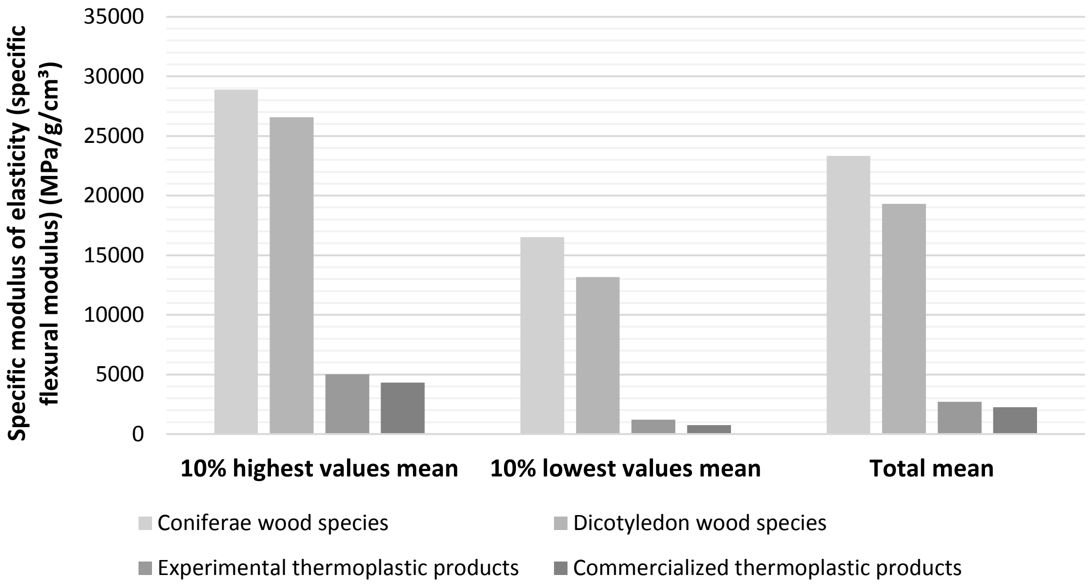
The thermoplastic products that exhibited values of the modulus of elasticity comparable to those of the wood species have a much higher, as can be observed on the specific flexural modulus graph (Figure 2). Moreover, none of the thermoplastic-based products have a specific flexural modulus that is higher than that of any wood species, even comparing the highest values of the former (8359 MPa/g/cm³ and 4967 MPa/g/cm³ for experimental and commercialized products, respectively) to the lowest of the latter (12978 MPa/g/cm³ and 10648 MPa/g/cm³, for coniferae and dicotyledon species, respectively). The highest specific flexural modulus values for the experimental thermoplastic products were also found in PP-, HDPE- and PVC-based composites.

Flexural strength

The highest values of flexural strength among the thermoplastic products are in the same region, between approximately 80 MPa and 120 MPa, as the highest flexural strength values of the *coniferae* wood species and the average values of the *dicotyledon* wood species (Figure 3). If analysing only the commercialized thermoplastic products, the highest flexural strength is close to 40 MPa. Only the experimental thermoplastic products considerably exceeded that value: the highest flexural strength value found for this type of material was 119 MPa, reached by a composite made from PP, carbonized cow bone powder and lubricant, investigated by Asuke *et al.* (2012). In fact, a pure ABS product and nylon (6 and 66)-based and PP-carbonized cow bone powder composites reached the highest thermoplastic flexural strengths. All other plastic products analysed (PP-, HDPE- and LDPE-based) reached maximum flexural values between approximately 50 MPa and 70 MPa. It has been found in literature PP-wood flour and PP-wood fiber composites that reached static flexural strength over than 80MPa (NDIAYE; GUEYE; DIOP, 2013) and 90MPa (KARMARKAR *et al.*, 2007), respectively, while (KIM *et al.*, 2008) presents PP-cotton fiber composites that reached more than 200MPa; however as the composites' density values were not presented in the papers, the data were not considered in this study.

PP-carbonized cow bone powder and PP-uncarbonized cow bone powder exhibited the highest specific strength, followed by nylon composites. Similar to the flexural modulus, the thermoplastic products that exhibited values of flexural strength comparable to those of wood have a much higher density. This aspect can be seen in Figure 4.

Figure 2 - **Specific modulus of elasticity of various wood species and thermoplastic products**



Note: the mean of the 10% highest values, the mean of the 10% lowest values and the total mean of the materials' specific flexural strength were calculated using data from 50 *coniferae* wood species, 145 *dicotyledon* wood species, 83 experimental thermoplastic product compositions from 14 different papers and 17 commercialized thermoplastic product compositions from 12 manufacturers.

Figure 3 - **Ashby plot presenting the flexural strength vs. the density of various wood species and thermoplastic products**

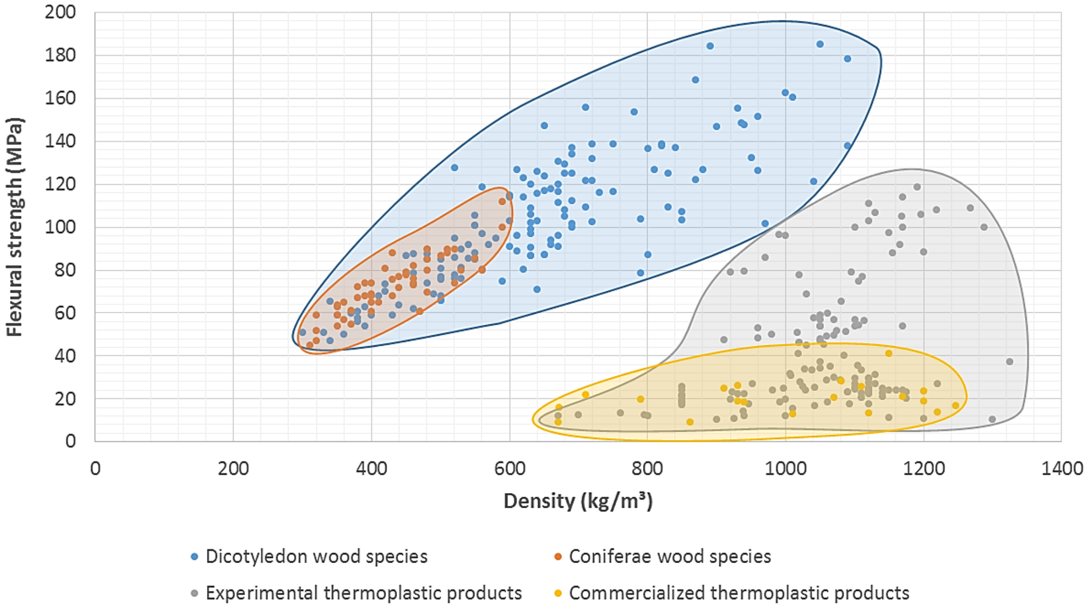
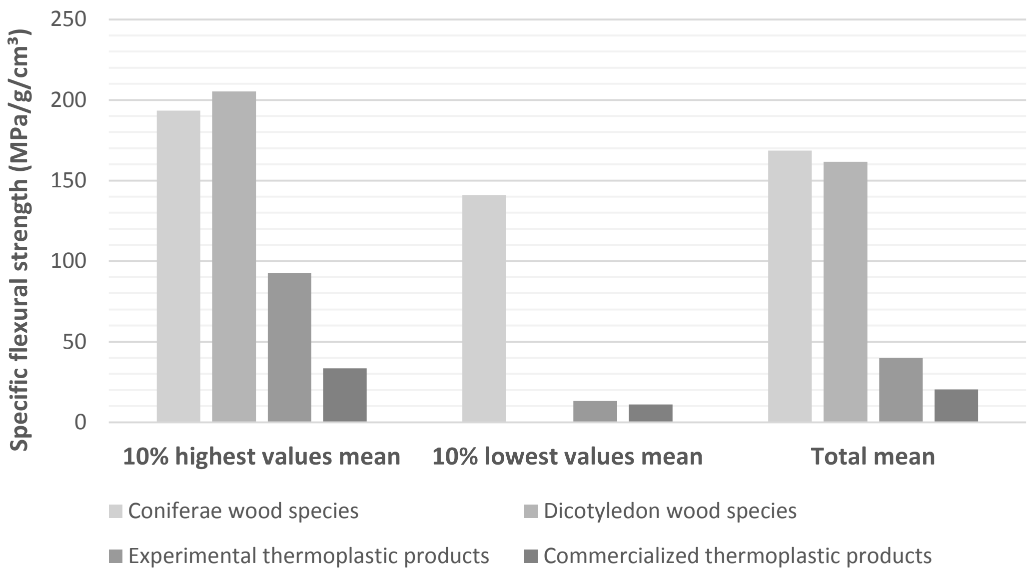


Figure 4 - **Specific flexural strength of various wood species and thermoplastic products**



Note: the means of the materials' specific flexural strength were calculated using data from 50 *coniferae* wood species, 145 *dicotyledon* wood species, 141 experimental thermoplastic product compositions from 19 different papers and 20 commercialized thermoplastic product compositions from 18 manufacturers.

Tensile strength parallel to the grain

Only one thermoplastic-based material produced by a manufacturer has a tensile strength parallel to the grain similar to that of some wood species and, specifically, to the average of the *coniferae* species (about 67MPa); all other commercialized thermoplastic products have inferior tensile strengths parallel to the grain (Figure 5). Among the experimental thermoplastic products, strength values above 50 MPa were reached by nylon-based composites, while PP-, HDPE- and LDPE-based composites reached maximums of approximately 40 MPa, 35 MPa and 30 MPa, respectively. Some papers described PP/wood flour/fire retardants (ARAO *et al.*, 2014), PP/talc/wood flour (GWON *et al.*, 2010) and PP-wood fiber and PP-cotton fiber (KIM *et al.*, 2008) composites as having static tensile strength parallel to grain close to 50MPa, while another article showed a recycled HDPE-hemp fiber composite with tensile strength equal to 60MPa (LU; OZA, 2013). However, as the composites' density values were not presented in the papers, the data were not considered in this study.

Both *coniferae* and *dicotyledon* wood species have specific tensile strengths parallel to the grain that are much higher than those of thermoplastic products (Figure 6). Polymer composites (HDPE (BEDFORD…, 2015) and various plastics (ECO-TECH…, 2006)) made with glass fibres and additives and nylon-based products and composites (filled with plant fibres (OZEN *et al.*, 2013), microcrystalline cellulose (KIZILTAS *et al.*, 2014) and silica fume (RAJA; KUMARAVEL, 2015)) exhibited the highest thermoplastic specific strength values for the commercialized and experimental products, respectively.

Figure 5 - **Ashby plot presenting the tensile strength parallel to the grain vs. the density for various wood species and thermoplastic products**

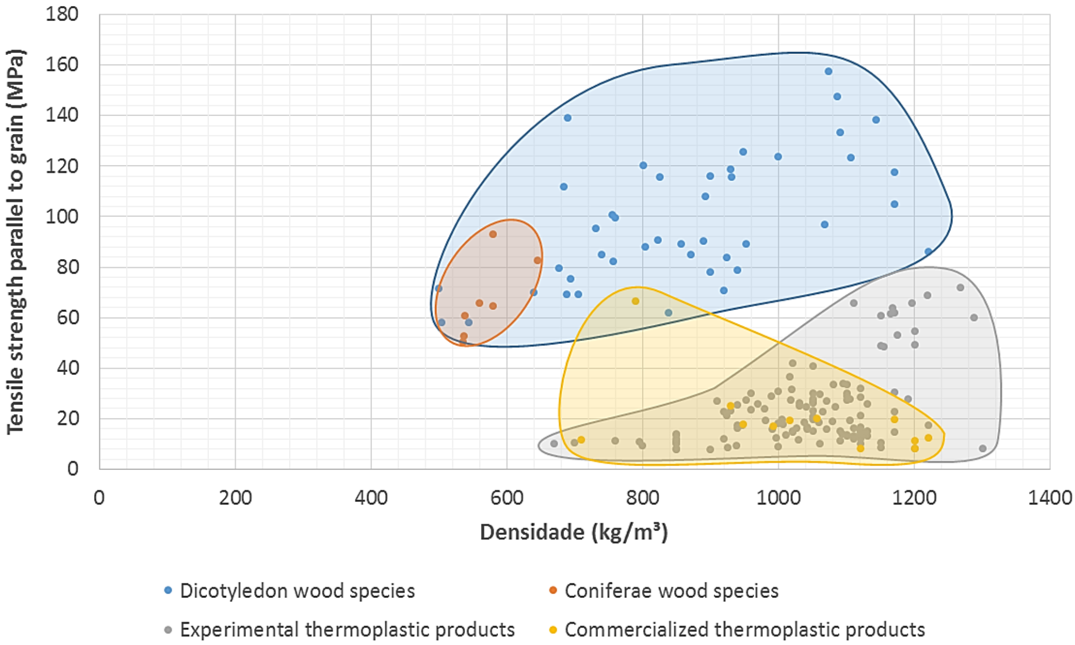
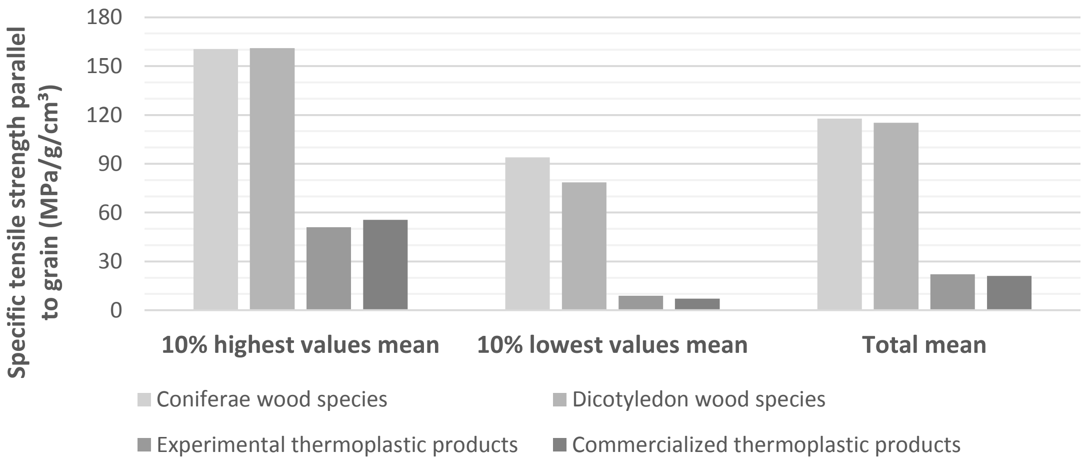


Figure 6 - **Specific tensile strength parallel to the grain for various wood species and thermoplastic products**



Note: the means of the materials' specific flexural strengths were calculated using data from 7 *coniferae* wood species, 43 *dicotyledon* wood species, 127 experimental thermoplastic product compositions from 17 different papers, and 12 commercialized thermoplastic product compositions from 9 manufacturers.

Tensile strength perpendicular to the grain

Researchers studying thermoplastic composites and manufacturers of this type of material rarely measure the tensile strength perpendicular to the grain. In addition, it was considered that the strength perpendicular and parallel to the grain tend to be very similar in thermoplastic products. Thus, the thermoplastic strength values used to generate the Ashby plot (Figure 7) and bar graph (Figure 8) for the tensile strength perpendicular to grain are practically the same as those used to generate the Ashby plot (Figure 5) and bar graph (Figure 6) of the tensile strength parallel to the grain, with few exceptions.

Figure 7 shows that the lowest values of the tensile strength perpendicular to the grain belong to *coniferae* wood species and some *dicotyledon* wood species. Many experimental thermoplastic products exhibited extremely high strengths. The nylon-based composites have the highest strength, exceeding 70 MPa. On the other hand, some experimental products have strengths in the range of *dicotyledon* wood, i.e., below 14 MPa. Many commercialized thermoplastic products have higher tensile strengths perpendicular to the grain than wood, but a few are also in the range of the *dicotyledon* wood species.

Approximately 84% of the analysed *dicotyledon* wood species present densities below 900 kg/m³, while approximately 91% of the analysed thermoplastic products have densities above 900 kg/m³. However, the experimental thermoplastic products show greatly superior strengths. Therefore, they have higher specific tensile strengths perpendicular to the grain (Figure 8).

Compressive strength parallel to the grain

Few papers were found that presented the compressive strength of thermoplastic products. In addition, some papers that contained these data lacked values for the composites' density. Only two papers ((ASUKE *et al.*, 2012; RAJA; KUMARAVEL, 2015)) were found that provided both types of information for thermoplastic-based composites.

Figure 9 shows that the commercialized thermoplastic products have the lowest compressive strength parallel to the grain. Nevertheless, its highest strength values, between 25 MPa and 50 MPa, are similar to those of many *coniferae* and *dicotyledon* wood species. On the other hand, experimental plastic-based products have significantly higher compressive strengths parallel to the grain, reaching almost 200 Mpa. However, all of the experimental plastic-based products whose data are plotted in Figure 9 are pure nylon products (RAJA; KUMARAVEL, 2015), nylon-silica fume composites (RAJA; KUMARAVEL, 2015), PP-carbonized cow bone powder (ASUKE *et al.*, 2012) or PP-uncarbonized cow bone powder (ASUKE *et al.*, 2012).

Figure 7 - **Ashby plot presenting the tensile strength perpendicular to the grain vs. the density for various wood species and thermoplastic products**

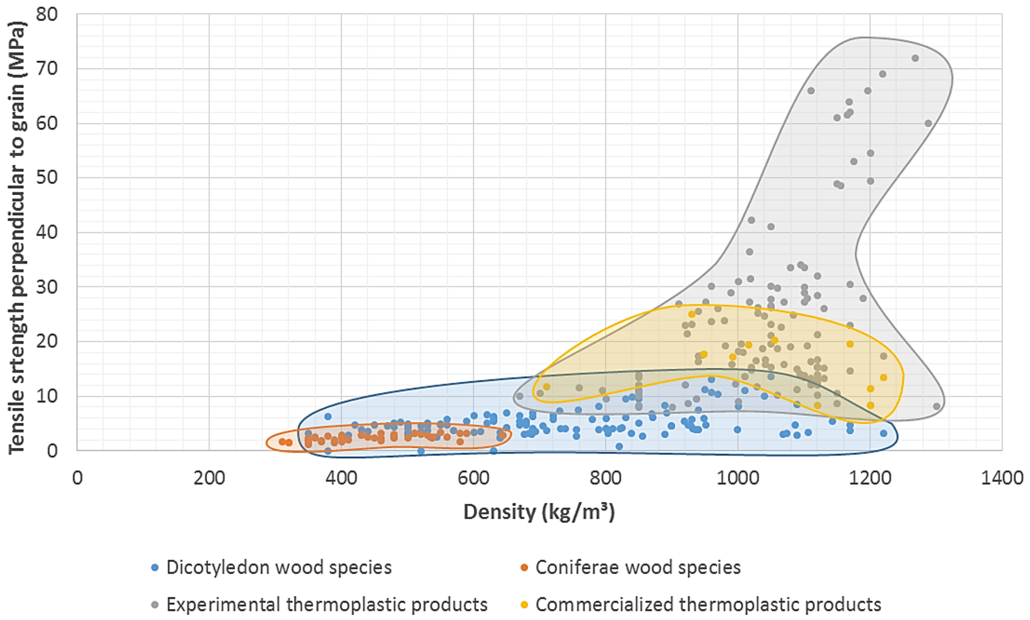
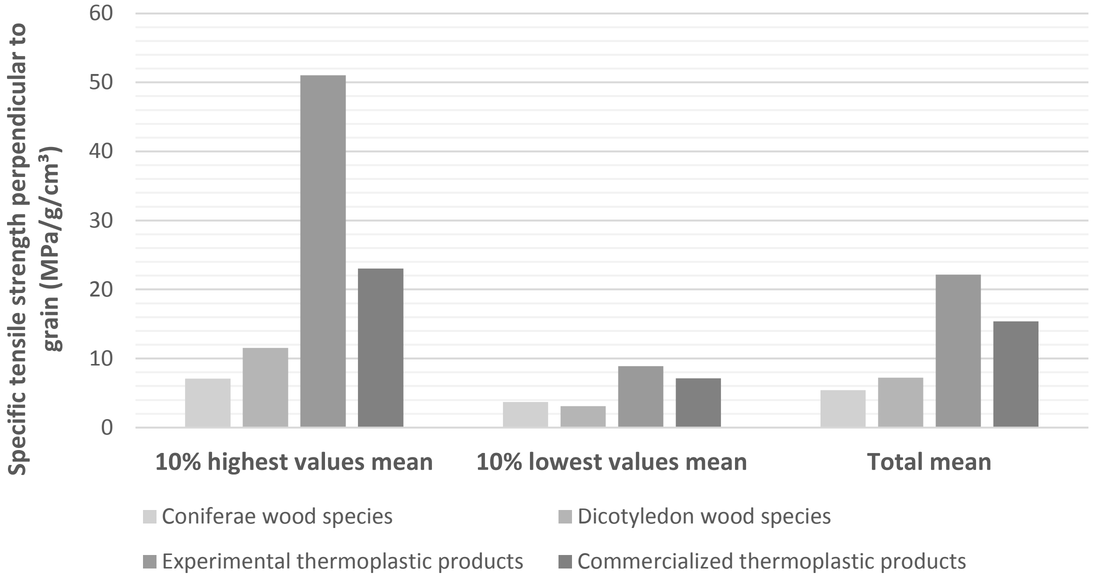
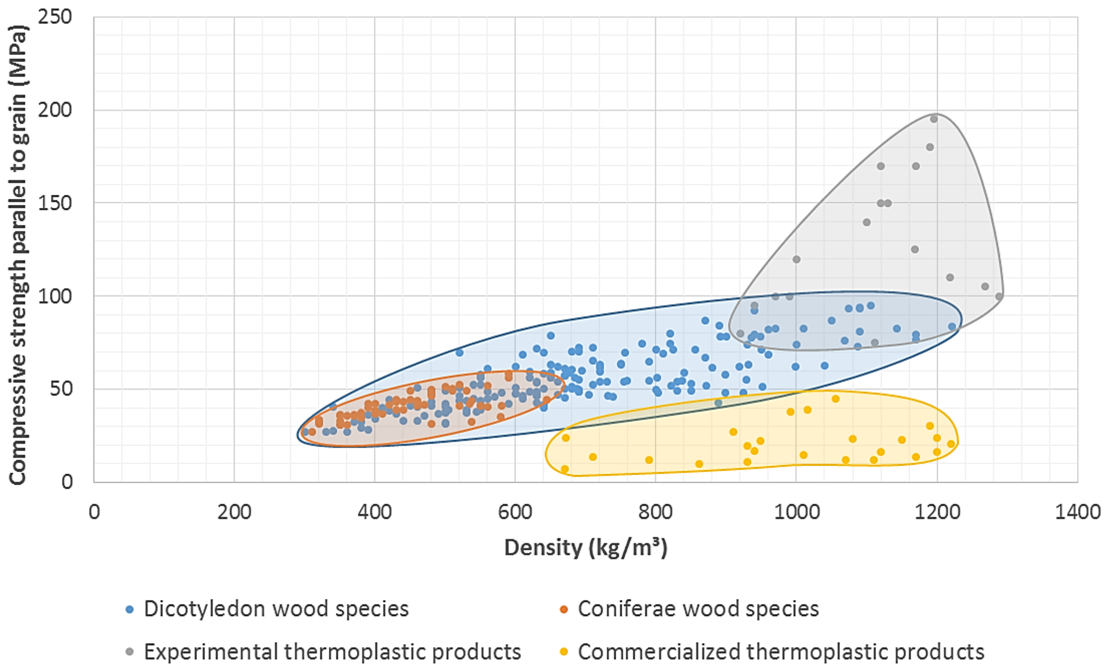


Figure 8 - **Specific tensile strength perpendicular to the grain for various wood species and thermoplastic products**



Nota: the means of the materials' specific flexural strengths were calculated using data from 44 *coniferae* wood species, 130 *dicotyledon* wood species, 127 experimental thermoplastic product compositions from 17 different papers, and 11 commercialized thermoplastic product compositions from 9 manufacturers.

Figure 9 - **Ashby plot presenting the compressive strength parallel to the grain vs. the density for various wood species and thermoplastic products**



One study on composites made from various percentages of PP, wood fibre, microtalc and coupling agent shows compressive strengths ranging from approximately 20 MPa to 30 MPa (GARCÍA *et al.*, 2009); another, on composites made from PP and mica, show compressive strengths ranging from approximately 25 MPa to 40 MPa (OMAR; AKIL; AHMAD, 2011). An investigation on the compressive strength of recycled polyethylene (PE)- and LDPE-oyster shell powder composites presents strength values between approximately 3 MPa and 7 MPa

(CHONG *et al.*, 2006). However, these three studies did not measure the composite densities. (CARROLL *et al.*, 2001) presents the composites' densities and compressive strength values, but the latter were measured only for extreme situations, such as very cold (-23.3 °C) or hot days (40.6 °C). Therefore, they were not considered in this analysis.

Although the means of Figure 10 are based on few data on experimental product compressive strengths, it shows that the mean of the 10% highest values of the experimental thermoplastic products' specific compressive strength parallel to the grain exceeds almost 45% of the wood species values. However, when the mean of the 10% lowest values and the total mean are analysed, the differences between the three types of material are lower. In general, the commercialized thermoplastic products are at least 2.5 times less efficient than the other materials.

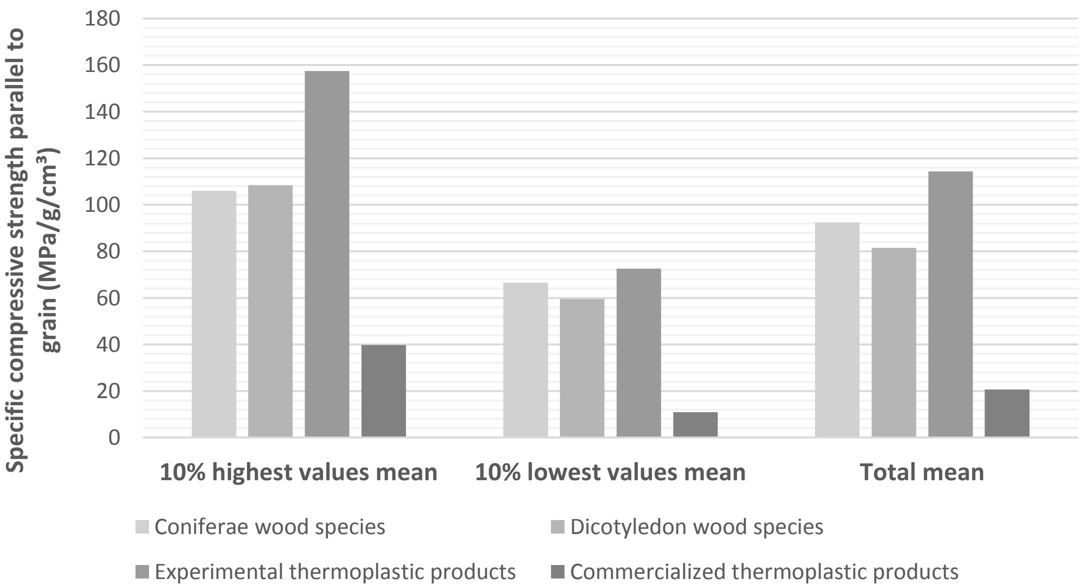
Compressive strength perpendicular to the grain

As with the tensile strength perpendicular to the grain, the thermoplastic strength values used to generate the Ashby plot (Figure 11) and bar graph (Figure 12) are practically the same as those analysed in the section about the compressive strength parallel to the grain, with few exceptions.

Figure 11 shows that the lowest values of the tensile strength perpendicular to the grain belongs to *coniferae* and *dicotyledon* wood species and to some commercialized thermoplastic products. Experimental plastic-based products have the highest compressive strengths parallel to the grain, some almost as high as 200 MPa. Nonetheless, all experimental plastic-based product data plotted in Figure 11 are for a pure nylon product, nylon-silica fume composites, PP-carbonized cow bone powder, or PP-uncarbonized cow bone powder, as studied by Raja and Kumarave (2015) and Asuke *et al.* (2012). In turn, some commercialized thermoplastic products show a higher compressive strength perpendicular to the grain than wood.

Experimental products show the highest specific strength (Figure 12). Commercialized products have a higher specific strength than the *coniferae* and *dicotyledon* wood species, but the results of these three groups are not so different.

Figure 10 - **Specific compressive strengths parallel to the grain of various wood species and thermoplastic products**



Note: the means of the materials' specific flexural strength were calculated using data from 57 *coniferae* wood species, 188 *dicotyledon* wood species, 17 experimental thermoplastic product compositions from 2 papers and 24 commercialized thermoplastic product compositions from 19 manufacturers.

Figure 11 - **Ashby plot presenting the compressive strength perpendicular to the grain vs. the density for various wood species and thermoplastic products**

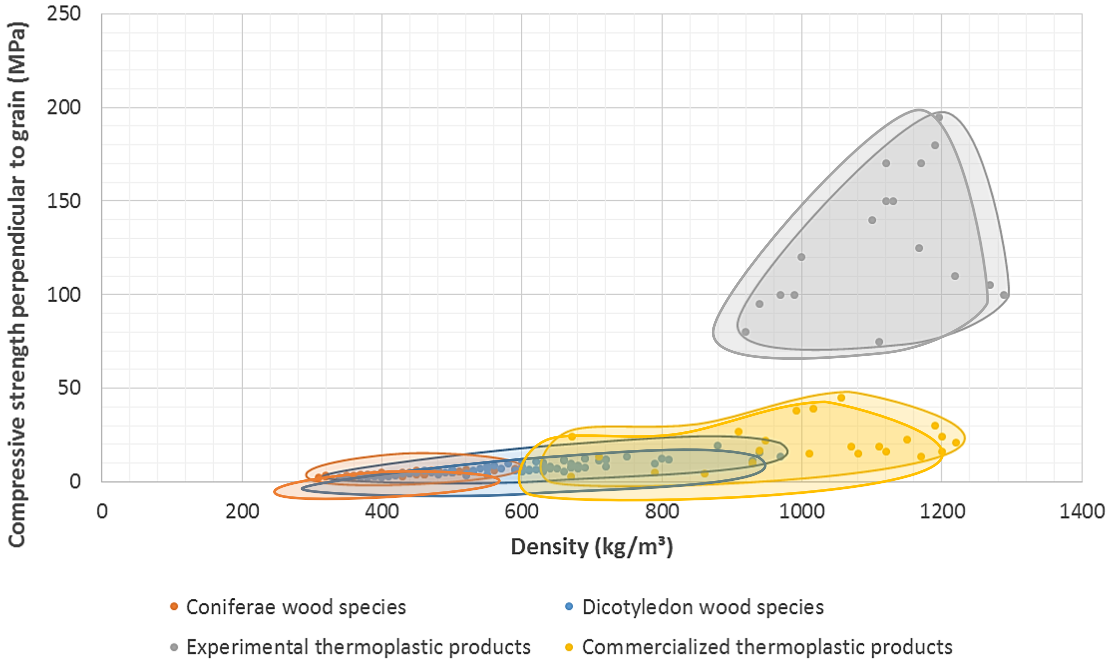
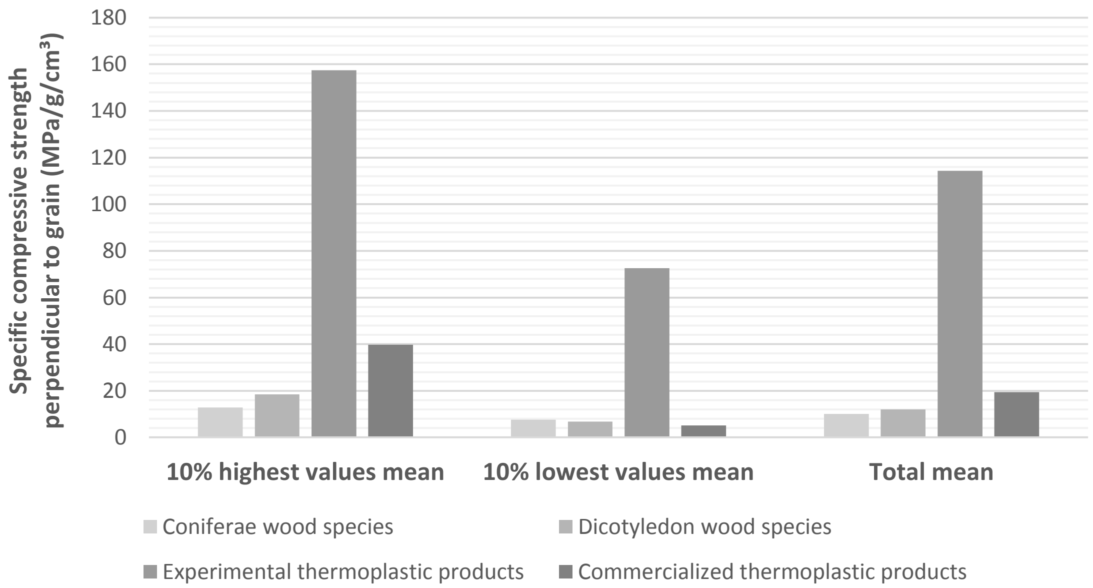


Figure 12 - **Specific compressive strength perpendicular to the grain for various wood species and thermoplastic products**



Note: the means of the materials' specific flexural strengths were calculated using data from 47 *coniferae* wood species, 75 *dicotyledon* wood species, 17 experimental thermoplastic product compositions from 2 papers, and 24 commercialized thermoplastic product compositions from 19 manufacturers.

Shear strength

No papers measuring the shear strength of thermoplastic products were found. Of the 25 commercialized thermoplastic products analysed, such information was available for 6. However, based on the few data gathered on thermoplastic composite shear strengths, Figure 13 reveals that the values are in the same range as those of the wood species, between 5 MPa and 19 MPa, although a few wood species exceed this value.

Figure 14 shows that the specific shear strengths of the *coniferae* and *dicotyledon* wood species are similar and that those of the commercialized thermoplastics were lower by a minimum of 60%. The HDPE-additive product has the highest thermoplastic product shear strength to density ratio, 19 MPa/g/cm³.

Figure 13 - **Ashby plot presenting the shear strength vs. the density for various wood species and thermoplastic products**

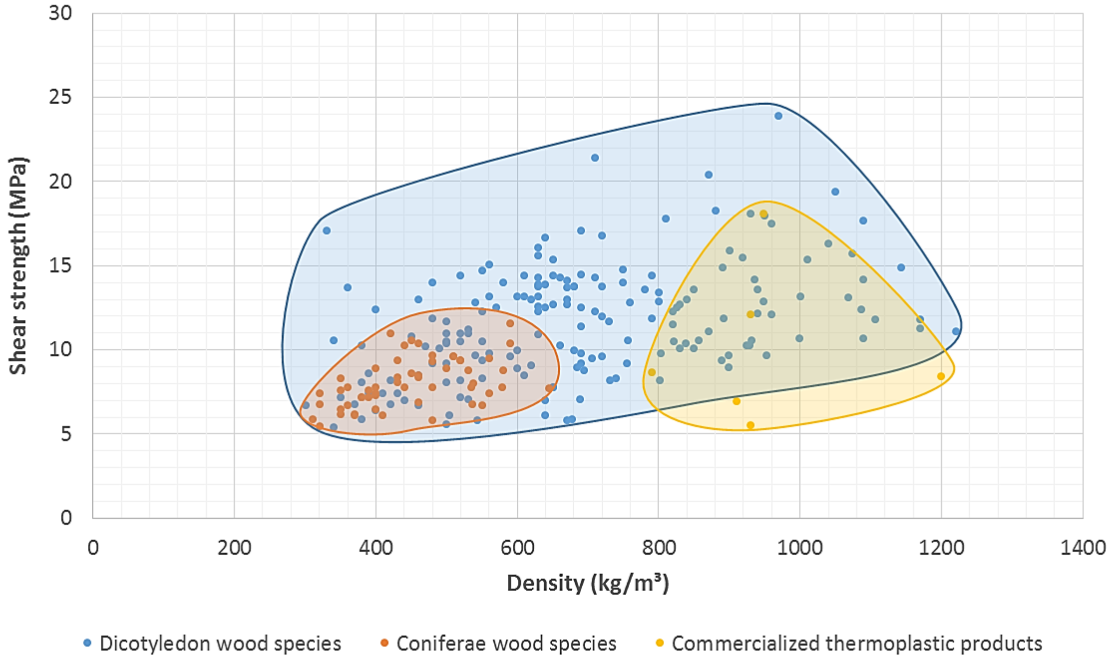
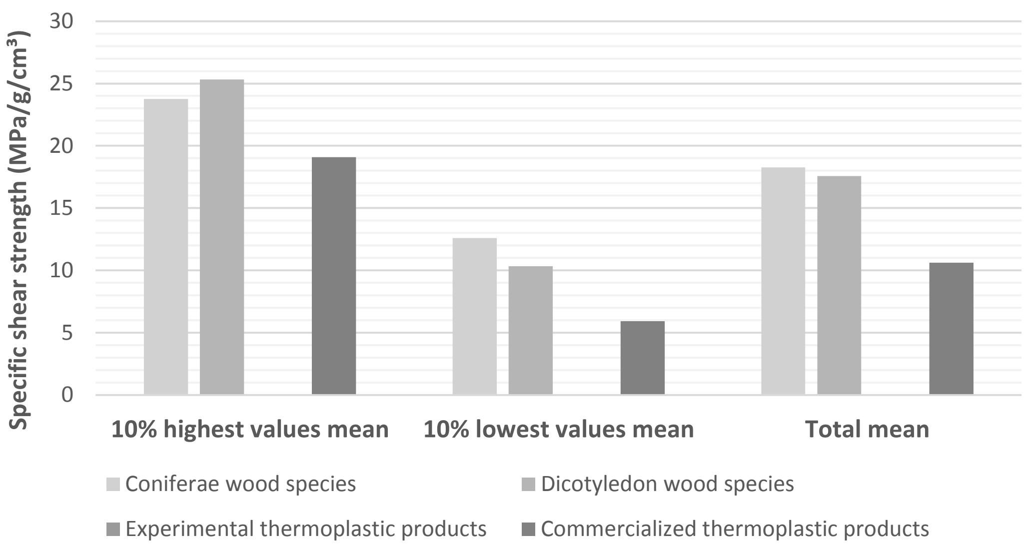


Figure 14 - **Specific shear strengths of various wood species and thermoplastic products**



Note: the means of the materials' specific flexural strengths were calculated using data from 55 *coniferae* wood species, 179 *dicotyledon* wood species and 6 commercialized thermoplastic product compositions from 5 manufacturers. No papers were found on the shear strength of thermoplastic products.

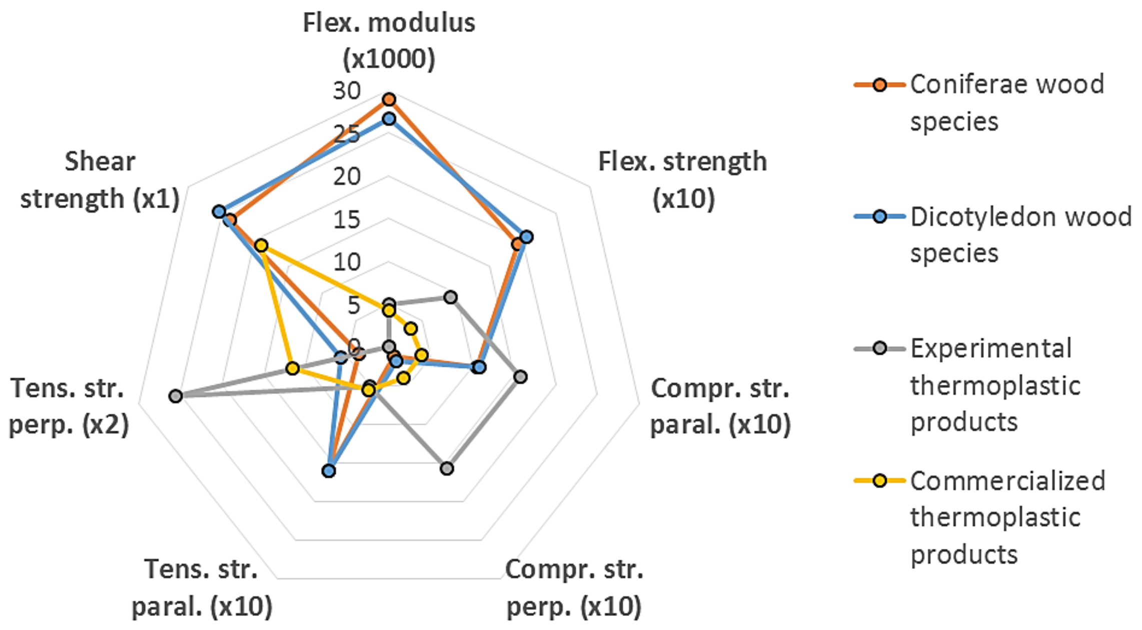
Discussion

Thermoplastic products showed great potential for functions in which wood lumber components are compressed or tensioned perpendicularly to the grain, as they have significantly higher specific strengths. Due to its better durability and maintainability, plastic lumber could be an alternative to wood lumber under such mechanical situations.

On the other hand, excluding strengths perpendicular to the grain, the specific compressive strength parallel to the grain is the only property in which the analysed thermoplastic products were, in general, superior to wood, and then, only for experimental products were. Commercialized thermoplastic products are still very far from achieving similar strength values to wood. However, few papers presenting the compressive strength of thermoplastic products have been found. This may cause a lack of data for specific researches, such this, and raise difficulties for the development of new thermoplastic composites and ways to use them, such as alternative building constructive systems and components, as also stated by Bajracharya *et al.* (2014) in study on glass fibre reinforced mixed plastic composites. In this respect, it should be noted that if the papers Carroll *et al.* (2001), Chong *et al.* (2006), García *et al.* (2009) and Omar, Akil and Ahmad (2011), for example, had presented the composites densities, probably the specific compressive strength means (both parallel and perpendicular to grain) would be much lower, since these papers show composites' compressive values ranging from 3MPa to 40 MPa, while the plotted values range from 75MPa to 195MPa. In spite of that, the extremely high compressive strength values shown by the plotted thermoplastic composites reveal their great potential for use in compressed elements.

For all other properties, wood is still more efficient than thermoplastic products and composites, i.e., to support a given load, thermoplastic-based elements need to be much larger and heavier than those of wood (Figure 15). This makes the design of structures and elements constructed with thermoplastic-based materials more complex, as they will occupy much more space or otherwise require many more components to satisfy a structural or semi-structural function, compared to wood. This is also a problem in the construction phase, as thermoplastic-based elements tend to be many times heavier than wood (in general, at least 2 times for elements under flexural loads (Figure 4) and 2.5 times for those under tensile loads parallel to the grain (Figure 6)), which make them difficult to transport and handle.

Figure 15 - **Material specific properties: mean of 10% highest values. Unit: MPa/g/cm³**



In this respect, Kozłowski and Władyka-Przybylak (2008) and Ndiaye, Gueye and Diop (2013) relates wood polymer composites and plastic composites reinforced by natural fibers, respectively, as having high strength to weight ratio. At least when compared to wood, this study found contrary results, although it embraces not only wood polymer composites and natural fiber-thermoplastic composites. Actually, the finds of this study are in agreement to English and Falk (1996), which showed that polyolefins and wood plastic composites have higher density and lower flexural strength and modulus of elasticity (stiffness) than Southern pine and Douglas fir; and also in agreement to Benthien and Thoemen (2012), which related that wood-plastic composites panels have higher specific weight than wood-based panels. In this sense, the specific properties values calculated in this study indicates that researches on lighter and stronger materials (polymeric matrices and fillers), i.e, presenting better strength to density ratio, are necessary. The exhibited Ashby plots show that the densities of the wood species vary from approximately 300 kg/m³ to 1200 kg/m³, while those of the thermoplastic products vary from approximately 650 kg/m³ to 1300 kg/m³ (Figure 16). Among the 171 thermoplastic products compositions analysed, 152, 89%, have values greater than 900 kg/m³, while among the 245 wood species (*coniferae* and *dicotyledon*) analysed, 31 have values greater than 900 kg/m³, approximately 13% (Figure 17). Moreover, although the use of coupling agents in the composites' formulation generally enhance their mechanical properties compared to composites made without them (STARK; ROWLANDS, 2003; KARMARKAR *et al*., 2007; LEI *et al*., 2007; ADHIKARY; PANG; STAIGER, 2008, 2010; KIM *et al*., 2008; GWON *et al*., 2010; GUPTA *et al*., 2012; WANG *et al*., 2014; HONG *et al.*, 2014; IGARZA *et al.*, 2014; REN *et al*., 2015; IZZATI ZULKIFLI *et al*., 2015), the better interaction and adhesion between the polymeric matrix and the fillers provided by compatibilizers were not sufficient to produce composites with specific flexural properties and tensile strength parallel to grain even close to wood. For this purpose, effective ways to enhance their mechanical properties and, consequently, their specific properties, could be used concurrently, such as the selection of polymeric matrices with a determined melt flow index (LU *et al*., 2006; KIM *et al*., 2008; HOMKHIEW; RATANAWILAI; THONGRUANG, 2014; TABKHPAZ SARABI *et al.*, 2014), the using of high-aspect-ratio fillers (STARK; ROWLANDS, 2003; KLYOSOV, 2007; ASHORI; NOURBAKHSH, 2010; LU; OZA, 2013) and the incorporation of fibres into the composites with a fixed orientation (JOSEPH *et al*., 2002; MIGNEAULT *et al.*, 2009; YOO; SPENCER; PAUL, 2011; SINGH *et al*., 2014; VÄNTSI; KÄRKI, 2014), in spite of randomly oriented fibres.

For the specific flexural modulus, the thermoplastic-based products showed lower property values than wood, even considering the best ratios presented by the former compared to the worst ratios of the latter. This is a real limitation for their usage in civil engineering applications, as also stated by Bajracharya *et al*. (2014), as they exhibit a high deformation under small loads.

Figure 16 - **Variation of the density of the wood species and thermoplastic products**

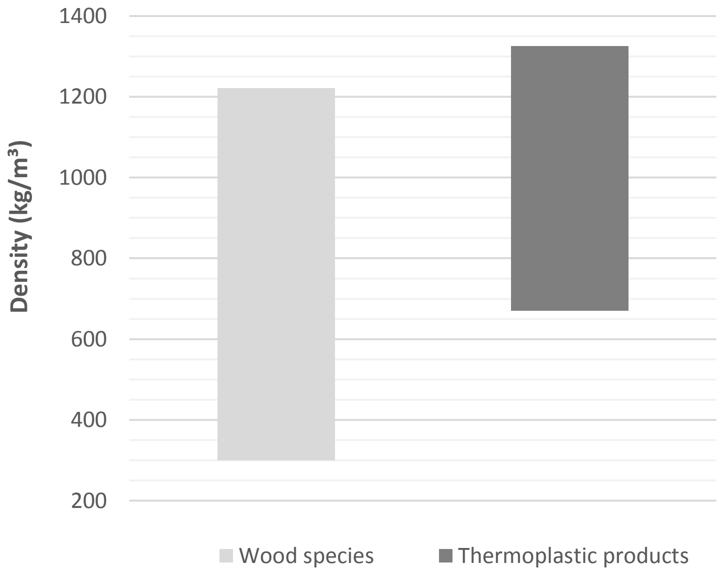


Figure 17 - **Percentage of wood species and thermoplastic products that present density value in the specified intervals**

Therefore, if it is intended that plastic lumber be a real alternative to wood lumber, not only for the materials' durability and maintenance issues but also the mechanical properties necessary to construct small buildings and structures, great advances are needed. In turn, as affirmed by English and Falk (1996, p. 193), "[…] it is expected that as more is learned about these areas, additional commercial applications for composites will develop.".

Conclusions

Can thermoplastic-based products really substitute for wood lumber in structural or semi-structural functions? The results of this paper demonstrate that:

(a) thermoplastic products show great potential for use in functions where wood lumber components are compressed or tensioned perpendicularly to the grain, as the former have much greater specific strengths. Due to its superior durability and maintainability, plastic lumber could be an alternative to wood lumber under such mechanical situations;

(b) the extremely high values of compressive strength shown for the studied experimental thermoplastic composites, compared to wood, reveals their great potential use in compressed elements;

(c) regarding the thermoplastic-based products' specific flexural modulus, even considering their best ratios compared to the worst ratios of the wood species, the former still show lower property values, which can be translated to a high deformation in comparison to wood. This is a real limitation for their usage in civil engineering and building applications;

(d) studies on lighter and stronger materials (polymeric matrices and fillers), i.e., presenting a better strength to density ratio, are necessary. While only 13% of the 245 wood species show a density higher than 900 kg/m³, approximately 89% of the 171 thermoplastic products have densities higher than that. This fact makes the design of structures and elements and the construction phase more complex; and

(e) very few data were found on the compressive and shear strength of plastic lumber and thermoplastic composites. There is a need for studies that focus on these properties to provide more data for a comprehensive comparison.

Thus, although it is inferior to wood in several mechanical properties, for some structural or semi-structural functions, plastic lumber and thermoplastic composites are alternatives to wood lumber. In addition, the use of high-aspect-ratio fillers and specific fibre orientations are effective ways to produce thermoplastic composites with mechanical properties that are closer or similar to those of wood.

The next step of the research will be compare other properties, such as hardness and impact strength, of wood from *coniferae* and *dicotyledon* species from the Northern and Southern Hemispheres with that of commercialized and experimental thermoplastic-based product formulations.

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