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Study of Mechanical, Physical, and Morphological Properties of Composites Used in Civil Construction

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Estudos das propriedades mecânicas, físicas e morfológicas em compósitos utilizados na construção civil

RESUMO

A busca por materiais sustentáveis no setor da construção é crucial devido ao seu significativo impacto ambiental. A tecnologia dos materiais compósitos surge como uma solução, mas enfrenta desafios tecnológicos na formulação e estabilização da mistura para minimizar o impacto ambiental. Este estudo investigou o comportamento ambiental de compósitos feitos com materiais reciclados de madeira e plástico diretamente da indústria. Foram testadas três composições: 100% de plásticos reciclados, 70% de madeira reciclada e 30% de plástico reciclado, e 70% de madeira reciclada e 30% de PVC virgem. Após usinagem para conformidade com as normas dos ensaios mecânicos, os materiais foram submetidos a testes de tração e impacto. Análises estatísticas identificaram as amostras mais resistentes para uso na construção civil. A análise morfológica revelou espaços e aglomerados nas composições, assim como a distribuição e compatibilidade dos materiais de enchimento. O teste de absorção de água determinou que a composição feita apenas com plásticos reciclados teve o melhor desempenho, devido à sua natureza hidrofóbica, em termos de parâmetros mecânicos, físicos e morfológicos. Este estudo destaca a viabilidade de compósitos sustentáveis na construção civil e a importância da seleção adequada dos materiais para alcançar propriedades desejadas.

PALAVRAS-CHAVE: Sustentabilidade. Materiais compósitos. Materiais recicláveis. Reprocessamento. Comportamento ambiental.

Study of Mechanical, Physical, and Morphological Properties of Composites Used in Civil Construction

ABSTRACT

The search for sustainable materials in the construction sector is crucial due to its significant environmental impact. Composite material technology emerges as a solution but faces technological challenges in formulating and stabilizing mixtures to minimize environmental impact. This study investigated the environmental behavior of composites made from recycled wood and plastic materials directly sourced from the industry. Three compositions were tested: 100% recycled plastics, 70% recycled wood and 30% recycled plastic, and 70% recycled wood and 30% virgin PVC. After machining to comply with mechanical testing standards, the materials underwent tensile and impact tests. Statistical analyses identified the most resistant samples for civil construction applications. Morphological analysis revealed voids and agglomerates in the compositions, as well as the distribution and compatibility of the filler materials. The water absorption test determined that the composition made entirely of recycled plastics performed best due to its hydrophobic nature, in terms of mechanical, physical, and morphological parameters. This study highlights the feasibility of sustainable composites in construction and the importance of proper material selection to achieve the desired properties.

KEYWORDS: Sustainability. Composite materials. Recyclable materials. Reprocessing. Environmental behavior.

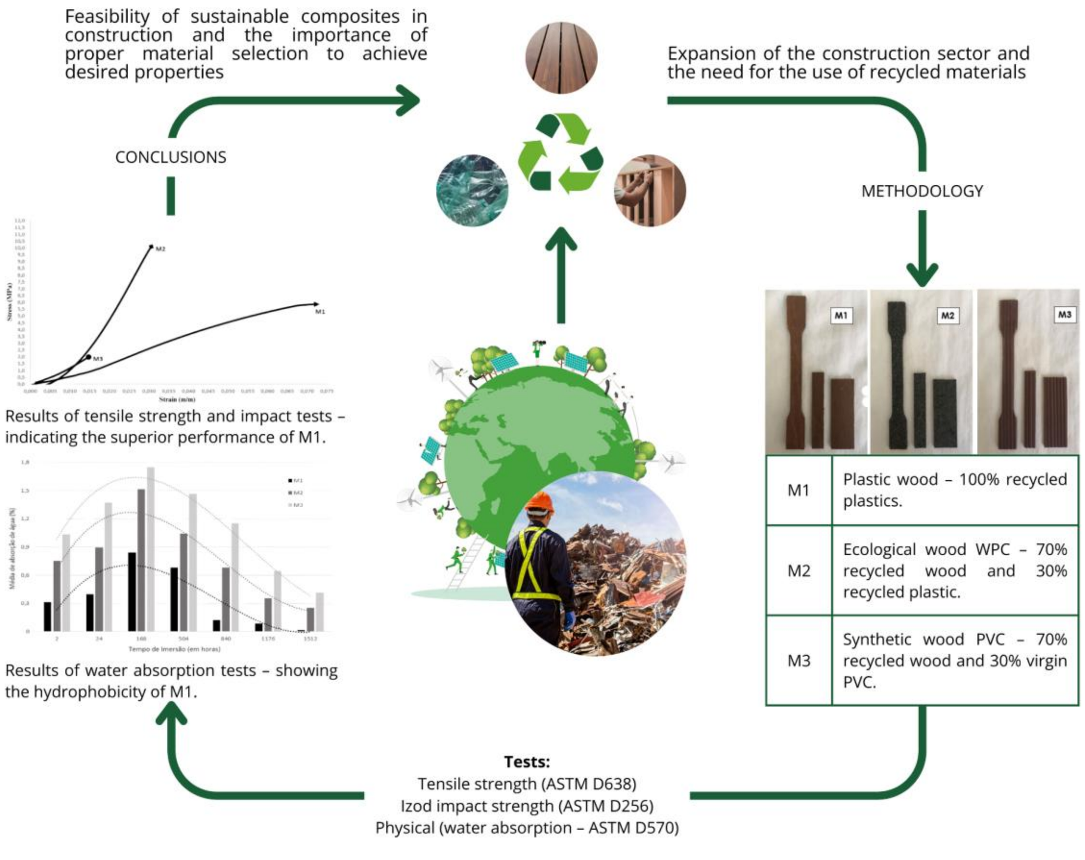
Estudio de las propiedades mecánicas, físicas y morfológicas de compuestos utilizados en la construcción civil

RESUMEN

La búsqueda de materiales sostenibles en el sector de la construcción es crucial debido a su significativo impacto ambiental. La tecnología de materiales compuestos surge como una solución, pero enfrenta desafíos tecnológicos en la formulación y estabilización de mezclas para minimizar el impacto ambiental. Este estudio investigó el comportamiento ambiental de compuestos fabricados con materiales reciclados de madera y plástico directamente de la industria. Se probaron tres composiciones: 100% plásticos reciclados, 70% madera reciclada y 30% plástico reciclado, y 70% madera reciclada y 30% PVC virgen. Después del maquinado para cumplir con las normas de los ensayos mecánicos, los materiales fueron sometidos a pruebas de tracción e impacto. Los análisis estadísticos identificaron las muestras más resistentes para aplicaciones en la construcción civil. El análisis morfológico reveló vacíos y aglomerados en las composiciones, así como la distribución y compatibilidad de los materiales de relleno. La prueba de absorción de agua determinó que la composición hecha únicamente de plásticos reciclados mostró el mejor desempeño debido a su naturaleza hidrofóbica, en términos de parámetros mecánicos, físicos y morfológicos. Este estudio resalta la viabilidad de los compuestos sostenibles en la construcción civil y la importancia de una adecuada selección de materiales para lograr las propiedades deseadas.

PALABRAS CLAVE: Sostenibilidad. Materiales compuestos. Materiales reciclables. Reprocesamiento. Comportamiento ambiental.

GRAPHICAL ABSTRACT



Feasibility of sustainable composites in construction and the importance of proper material selection to achieve desired properties

Expansion of the construction sector and the need for the use of recycled materials

CONCLUSIONS

METHODOLOGY

Results of tensile strength and impact tests – indicating the superior performance of M1.

Results of water absorption tests – showing the hydrophobicity of M1.

M1	Plastic wood – 100% recycled plastics.
M2	Ecological wood WPC – 70% recycled wood and 30% recycled plastic.
M3	Synthetic wood PVC – 70% recycled wood and 30% virgin PVC.

Tests:
Tensile strength (ASTM D638)
Izod impact strength (ASTM D256)
Physical (water absorption – ASTM D570)

1 INTRODUCTION

In developing countries, the demand for infrastructure has significantly expanded due to the global population increase and the accelerated growth of urbanization rates. This has led to an exponential rise in the need for construction and finishing materials, accompanying the rapid development of the sector (Cruz et al., 2019; Hossain; Xu et al., 2019). Additionally, the reconstruction of cities has driven intense construction and demolition activities, with waste accounting for approximately 40% of the total solid waste worldwide. This highlights the large volume of disposal and its environmental impact (Islam et al., 2019), raising serious concerns about health, economic loss of discarded products, and the need to recognize waste valorization as a necessity rather than an option (Al-Salem, 2019).

Since a significant portion of urban solid waste originates from the construction and demolition sector, Ghisellini et al. (2016) brought to light the concept and model of circular economy development in waste management. This rapidly expanding subsector focuses on resource recovery and environmental impact prevention. Consequently, the construction industry and its entire supply chain are responsible for about 30% of greenhouse gas emissions and a significant share of global waste production, estimated at nearly 4 billion tons annually (Kappenthuler; Seeger, 2019).

The inadequate management of construction waste leads to environmental damage and economic losses. Proper management is crucial to minimize this impact, promote the circular economy, and create sustainable practices (IORDACHI, 2023). Therefore, considering sustainability within the construction industry and the circular economy movement is a current reality, which drives research into recycling, reuse, adaptation, and management of construction and demolition waste streams (CHEN et al., 2019).

To achieve sustainable macroeconomic development within the construction industry, significant changes are needed from the actors involved in the sector. This includes implementing more consistent policies that combat resistance to change, leading to greater productivity and higher quality delivery (Cruz et al., 2019). Many actions are being taken, such as increasing recycling, reusing resources, and optimizing raw material consumption. These efforts are reflected in numerous scientific studies focused on sustainability in the construction sector, strengthening the concept of green building (SIDDIQUE et al., 2018; ZHANG et al., 2019; KHAN et al., 2019; WANG et al., 2019).

Sustainability must be integrated into every phase of the construction lifecycle, from design and construction to usage and eventual demolition. The efficient production of construction and finishing materials through the incorporation of recycled or reused components holds immense potential for conserving natural resources and mitigating environmental impacts (KYLILI & FOKAIDES, 2017). As the demand for diversified finished products grows, the use of composites derived from industrial by-products has become a focal point of research and innovation (SINGH et al., 2017).

Wood-plastic composites (WPCs) have experienced rapid growth in recent years, particularly in the automotive and aerospace industries, as well as in construction products and industrial and consumer goods (BI et al., 2018). These composites are often used for exterior building components such as decks, doors, windows, panels, and cladding. The most common plastics used in WPC manufacturing matrices are polyethylene (PE) (RAVICHANDRAN et al., 2019), polypropylene (PP) (HAQUE et al., 2019b), and polyvinyl chloride (PVC) (SENHADJI et al., 2019), both virgin and recycled. Other matrices using thermoplastics like polystyrene (PS) and acrylonitrile-butadiene-styrene (ABS) are also being researched (AMBRÓSIO et al., 2019).

The frequent use of this type of composite in civil construction is due to its rigidity, recyclability, low cost and density, and excellent mechanical properties. This has led researchers to intensify studies on composite manufacturing and ways to further optimize these properties, as the application of the product, particularly as cladding, has garnered significant attention in recent years (MIJIYAWA et al., 2015; LEI et al., 2015).

Studies have demonstrated the high strength of composites made from different wood types combined with polypropylene (PP) (BLEDZKI et al., 2015). Wood fibers and flours, as well as chemical and thermomechanical pulps, have shown excellent performance in composites using polylactic acid (PLA) and polypropylene (PP) (PELTOLA et al., 2014).

The diverse characteristics of different waste materials can significantly influence the mechanical and physical properties of the resulting composites. This study aims to evaluate the environmental performance of composites produced from recycled materials with varying compositions, which are already commercially available for applications such as decking and facade panels. The research focuses on analyzing their strengths and weaknesses to better understand their potential in sustainable construction.

2 MATERIALS AND METHODS

2.1 Obtaining Materials

The materials evaluated in this study were sourced from a distributor specializing in sustainable composites for civil construction and outdoor decoration, located in the metropolitan region of São Paulo, Brazil. The products were supplied as encapsulated or solid planks measuring 3 meters in length, with widths ranging from 10 to 14.5 centimeters and thicknesses between 1.8 and 2.1 centimeters. These planks were subsequently machined into test specimens in compliance with established standards. For the experimental procedures, three distinct commercially available materials, labeled M1, M2, and M3, were selected and are detailed in Chart 1.

Chart 1 - Commercially available composite materials for cladding applications

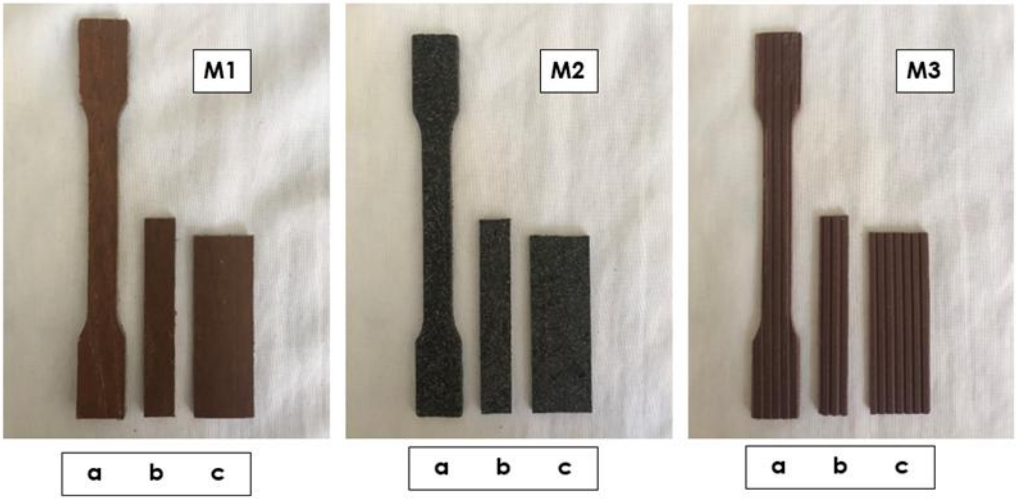
Material Designation	Material Description
M1	Plastic wood – composed of 100% recycled plastics derived from industrial and residential waste.
M2	Ecological wood WPC – composed of 70% recycled wood and 30% recycled plastic.
M3	Synthetic wood PVC – composed of 70% recycled wood and 30% virgin PVC.

Source: Authors (2024).

2.2 Sample Preparation

From the acquired planks, test specimens were machined for mechanical tests (tensile strength (ASTM D638), Izod impact resistance (ASTM D256)), and a physical test (water absorption (ASTM D570)), as described in Figure 1.

Figure 1 - Composite materials of various compositions for cladding applications. Test specimens for tensile strength (M1-a; M2-a; M3-a), impact resistance (M1-b; M2-b; M3-b), and water absorption (M1-c; M2-c; M3-c).



Source: Authors (2024).

To achieve the desired thickness for the samples, a bench planer and thicknesser, model DW733 by DEWALT, was used. With the appropriate thickness according to the standards for mechanical and physical tests, the samples were modeled using Autodesk AutoCAD® 2018 software and cut using a CNC router, model ST6090 by SEQUOYATEC.

For the mechanical tests, eighteen specimens were prepared: eight for the tensile strength test and ten for the Izod impact resistance test. For the physical test (water absorption), three additional specimens were prepared. The quantities mentioned refer to each type of material (M1, M2, and M3), which were machined and subjected to the tests (Figure 1).

The specimens for the tensile test had a length of 62.8 mm, a width of 9 mm, and a thickness of 3 mm, with a neck of 16.15 mm in length and a square cross-section of 3.2 mm. The specimens for the Izod impact resistance test were rectangular with dimensions of 84 mm in length, 12.8 mm in width, and 3 mm in thickness. The specimens that were subjected to the water absorption tests also had a rectangular shape, but with dimensions of 76.2 mm in length, 25.4 mm in width, and 3 mm in thickness.

For the preparation of the specimens from the acquired planks, an approximate loss of 25-30% was considered during the machining process, due to the sample shapes required by the standards and equipment used.

2.3 Mechanical Properties

For the tensile strength test, the specimens were machined into a dumbbell shape (Figure 1a) and tested according to ASTM D638 standards, which establish criteria for plastic materials. The tests were conducted using a universal testing machine, EMIC DL10000, equipped with a 5 kN load cell, at a speed of 50 mm/min at room temperature.

The Izod impact test followed the ASTM D256 standard (Figure 1b), which specifies the requirements for plastic materials. A CEAST Resil Impactor Junior machine with a 2.75J pendulum was used, operating at room temperature.

2.4 Physical Properties

The water absorption test was conducted according to ASTM D570. Before testing, three specimens of each machined material (M1, M2, and M3), totaling nine specimens, were dried in an analog sterilization and drying oven for 1 hour at 107 ± 3°C. The weight of the dried specimens was measured with a precision of 0.001g using a SHIMADZU AUY-220 analytical balance. The conditioned specimens were placed in a plastic container and fully immersed in distilled water, maintained at a constant temperature of 23 ± 1°C for 63 days. The temperature was controlled using a SOLIDSTEEL SSD 15L digital water bath with a stamped and polished AISI 304 stainless steel tank and internal rack.

Seven consecutive weighings were performed at intervals of 2 ± 0.17 h, 24 ± 1 h, 168 ± 1 h, 504 ± 1 h, 840 ± 1 h, 1176 ± 1 h, and 1512 ± 1 h. Samples were removed from the water one at a time, with excess surface water wiped off using a paper towel, and weighed immediately. Three repetitions were conducted for each specimen, and average values were reported. Water absorption in percentage was calculated using Equation (1):

$$WA_t(\%) = \left(\frac{W_{t-}W_0}{W_0}\right) X\ 100, \tag{1}$$

where WA_t is the water absorption (%) at time t, W0 is the dry weight, and Wt is the weight of the sample at a given immersion time.

2.5 Morphological Properties

The fractured surfaces of test specimens from the Izod impact test, prepared with a prior gold coating treatment, were analyzed using Scanning Electron Microscopy (SEM). The microstructural characteristics of the materials were observed and analyzed with a QUANTA 250 microscope (FEI) operating at 10 kV. All analyses were performed at the Complex of Research Support Centers (COMCAP/UEM).

2.6 Statistical Analyses

To determine which of the three composite materials exhibited the greatest resistance under everyday conditions in construction, tensile strength (ASTM D638) and impact resistance (ASTM D256) were mechanically tested. Eight and ten specimens were prepared for these tests, respectively. As only five specimens were required for each analysis, Cook's distance was used to select the most representative data points. Following this selection, an analysis of variance (ANOVA) was performed, along with Tukey's test, to determine if there were significant differences between the samples at a significance level of 5%.

Finally, to assess the extent to which the material compositions provided good tensile and impact strength according to the aforementioned standards, a "desirability" function was employed. Based on the actual values determined by the mechanical analyses, this function aims to find an optimized composite mixture. This method involves applying a dimensionless value to each "response variable" that represents its individual desirability (*di*), expressed by Equation (2):

$$D = \sqrt[m]{d_1 d_2 d_3 \ldots d_m}, \tag{2}$$

with D being the global desirability, d_1, d_2, d_3 e d_m are the individual desirabilities, and m is the number of response variables.

The optimization was analyzed considering Equation (3):

$$d_i(y_i(x)) = \left[\begin{array}{c} 1 \text{ if } y_i(x) < L_i \\ \left[\frac{U_i - y_i(x)}{U_i - L_i}\right]^t \\ 0 \text{ if } y_i(x) > U_i \end{array} \right]. \tag{3}$$

In relation to Equation (3), y_i is the response obtained for the variable studied, $d_i\,(y_i)$ is the individual desirability of the response y_i, U_i is the highest acceptable value adopted for the response, L_i is the lowest acceptable value adopted for the response, and tt is a factor that determines how desirable it is for y_i to approach the minimum, ranging from 0 to 1.

3 RESULTS AND DISCUSSION

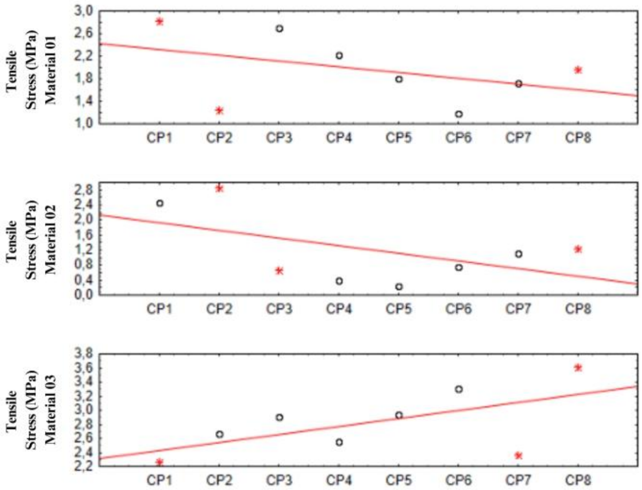
3.1 Mechanical Properties

According to the standards, mechanical analysis of five specimens per material is required. Cook's distance analysis was used to eliminate outliers that could unduly influence regression analysis.

The results for the composites analyzed for tensile strength (ASTM D638) are presented in Figure 2, while the results for impact resistance (ASTM D256) are shown in Figure 3. None of the Cook's distances were ≥ 1. Thus, the three largest distances for each material (M1, M2, and M3) were excluded for tensile strength testing, and the five largest distances were excluded for impact resistance testing.

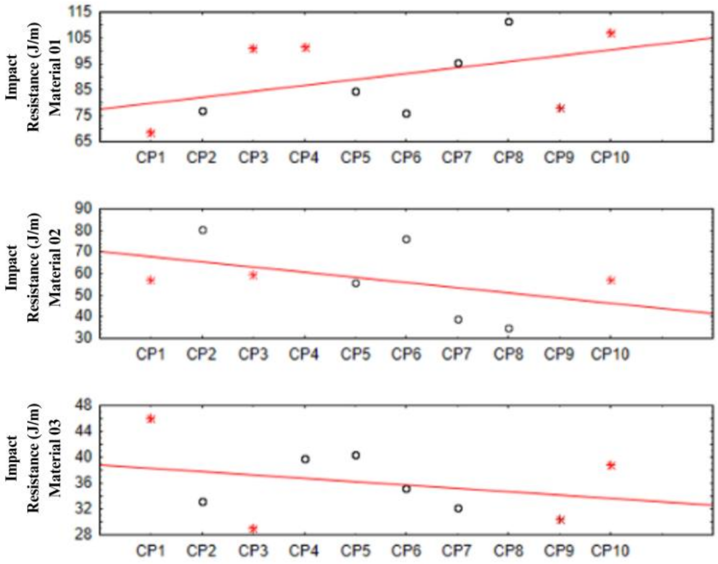
Cook and Weisberg (1982) state that if a data point is a significant outlier in YY, but its Cook's distance is less than 1, there is no real reason to eliminate it since it does not significantly affect regression analysis. However, there is still interest in studying such a point to try to understand why it is not adhering to the model.

Figure 2 - Analysis and elimination of specimen rupture for tensile strength (ASTM D638) using Cook's distance



Source: Authors (2024)

Figure 3 - Analysis and elimination of specimen rupture for impact resistance (ASTM D256) using Cook's distance



Source: Authors (2024)

The specimen measurements for tensile strength (ASTM D638) and impact resistance (ASTM D256), along with their respective Cook's distances, are shown in Tables 1 and 2, respectively.

After determining which specimens remained in the analyses, a curve (Figure 4) was created using the averages of all specimens to verify the tensile strength and impact resistance for the three material types. Then, variance analysis with Tukey's test was applied to check for significant differences between samples at a 5% significance level. The averages and standard deviations for tensile strength and impact resistance of the three tested materials are presented in Table 3. According to the data, no significant differences were found between the materials at a 5% significance level.

Table 1 - Cook's Distance for Tensile Strength Test (ASTM D638) for 100% Recycled Plastic Composites (M1), 70% Recycled Wood and 30% Recycled Plastic (M2), and 70% Recycled Wood and 30% Virgin PVC (M3)

Test Specimen **M1**	Cook's Distance	Test Specimen **M2**	Cook's Distance	Test Specimen **M3**	Cook's Distance
CP 1	--	CP 1	0,195885	CP 1	--
CP 2	--	CP 2	--	CP 2	0,025024
CP 3	0,141627	CP 3	--	CP 3	0,071639
CP 4	0,015585	CP 4	0,07997	CP 4	0,034677
CP 5	0,001661	CP 5	0,082948	CP 5	0,000737
CP 6	0,14641	CP 6	0,002275	CP 6	0,076789
CP 7	0,000071	CP 7	0,061	CP 7	--
CP 8	--	CP 8	--	CP 8	--

-- Represents eliminated test specimens.

Source – Authors (2024)

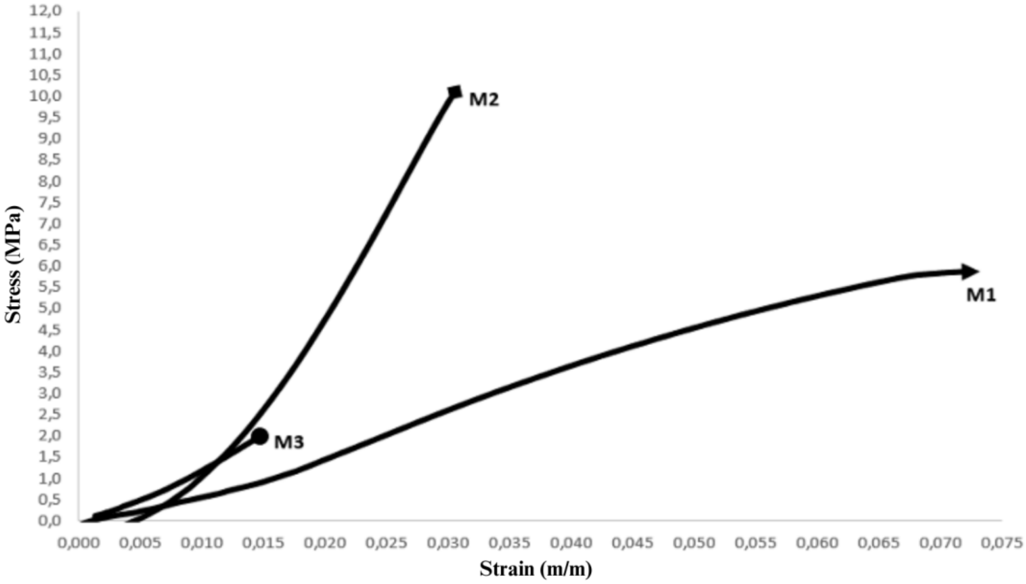
Table 2 - Cook's Distance for Impact Resistance Test (ASTM D256) for 100% Recycled Plastic Composites (M1), 70% Recycled Wood and 30% Recycled Plastic (M2), and 70% Recycled Wood and 30% Virgin PVC (M3)

Test Specimen **M1**	Cook's Distance	Test Specimen **M2**	Cook's Distance	Test Specimen **M3**	Cook's Distance
CP 1	--	CP 1	--	CP 1	--
CP 2	0,027403	CP 2	0,007301	CP 2	0,140903
CP 3	--	CP 3	--	CP 3	--
CP 4	--	CP 4	--	CP 4	0,025589
CP 5	0,005899	CP 5	0,002109	CP 5	0,038905
CP 6	0,076146	CP 6	0,165436	CP 6	0,000591
CP 7	0,00128	CP 7	0,111378	CP 7	0,029704
CP 8	0,090596	CP 8	0,233818	CP 8	--
CP 9	--	CP 9	--	CP 9	--
CP 10	--	CP 10	--	CP 10	--

-- Represents eliminated test specimens.

Source – Authors (2024)

Figure 4 - Analysis of rupture for all specimen samples regarding tensile strength and impact resistance. M1 = recycled plastic; M2 = recycled plastic and wood; M3 = recycled wood and virgin PVC.



Source – Authors (2024)

Table 3 - Averages and Standard Deviations of Tested Materials

Samples	Tensile Strength (MPa)	Impact Resistance (J/m)
M 1	$7{,}12^{b} \pm 0{,}56$	$84{,}66^{a} \pm 13{,}26$
M 2	$16{,}09^{a} \pm 1{,}05$	$55{,}68^{b} \pm 16{,}86$
M 3	$5{,}75^{b} \pm 0{,}72$	$35{,}22^{c} \pm 3{,}76$

Identical superscripts in the same column, for the same response variable, indicate averages without statistically significant differences at 5% significance level using Tukey's Test. M1 = recycled plastic; M2 = recycled plastic and wood; M3 = recycled wood and virgin PVC.

Source – Authors (2024)

As shown in Figure 4 and detailed in Table 3, among the three analyzed materials, the lowest tensile strength was observed for Material 3, while the highest was observed for Material 2. The incorporation of recycled wood into the composition increased the tensile modulus compared to composites made of recycled plastics (M1) and recycled wood with virgin PVC (M3). This can be attributed to the greater rigidity of the incorporated wood fibers, as the material could withstand twice the stress compared to the one made solely of recycled plastic.

Studies by Lei et al. (2015) on wood composites with melamine, a substance used in plastic manufacturing, demonstrated an initial increase in tensile strength, which decreased as more substance was incorporated, reaching a maximum positive effect at 3% by weight. This occurs due to the interaction between wood and plastic, which enhances stress transfer efficiency from the matrix to the filler material, thereby improving tensile strength.

Najafi et al. (2006) studied composites made from sawdust agglomerated with recycled polypropylene (PP) and polyethylene (PE). They found that the mechanical properties of the materials were statistically similar to those made with virgin plastics, confirming that using recycled material does not significantly impact the final material quality.

Another composite analyzed, containing wood, plastic films, cardboard, and mineral wool, was compared to a reference material made solely of wood fibers and PP as the polymer. The former showed weakened mechanical properties by 10 to 25%, depending on the waste content in the composite (Hyvärinen et al., 2019).

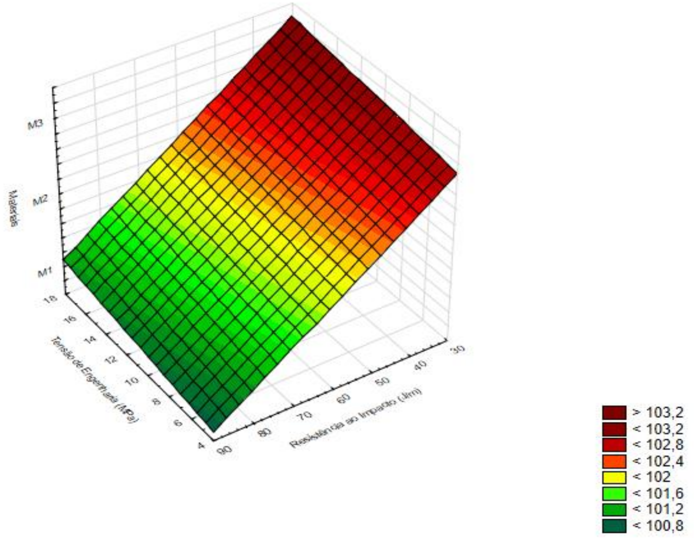
In a study by Moreno and Saron (2017), the tensile strength of a composite made from pine wood waste and recycled PE, with 30% by weight of filler, was measured at 12.3 MPa, a value close to that observed for Material 2, which also contains 30% recycled plastic. Similarly, Ebadi et al. (2016) found low variation in tensile strength in composites made from low-density PE with up to 30% filler addition. Additionally, Turku et al. (2017) demonstrated that samples molded by injection from recycled polymer blends exhibited greater strength and stiffness compared to those made from commercial PE (virgin plastic), with tensile strength ranging from 10 to 12.5 MPa.

The choice of plastic type significantly affects composite strength. For example, polystyrene (PS) composites have achieved tensile strengths of up to 23.12 MPa, while PE composites achieved only 7.39 MPa. Furthermore, the plastic content in the composite also plays a crucial role, with utilization rates above 50% providing better stability. Applications of PS and PP offer higher mechanical properties than virgin PVC (Ratanawilai & Taneerat, 2018).

Regarding impact resistance, the highest value was identified for M1, while the lowest was for M3 (Table 3). Thus, the composite made entirely of recycled plastic demonstrated adequate resistance to deformations and fractures according to ASTM D256 standards, supporting loads twice as high as recycled wood and plastic composites (M2) and four times higher than recycled wood with virgin PVC composites (M3). These findings align with those of Hyvärinen et al. (2019), where a greater amount of recycled plastic in the composites resulted in higher impact resistance compared to other tested composites. In an Izod impact test conducted on composites made from pure PP combined with 25% wood flour, a reduction in impact resistance was observed. This reduction indicates that PP and wood composites become brittle or less ductile, confirming the behavior of M1, composed solely of recycled plastic, which exhibited the highest impact resistance index (Haque et al., 2019a).

It was also observed that the composites exhibited distinct elongation behavior under rupture conditions (Figure 4). The addition of virgin PVC (M3) in the composition showed a sharp decline in ductility compared to the other materials studied, revealing linear deformation—a characteristic behavior of composite materials (Callister, 2012). Figure 5 illustrates that the total strength was proportional to Material 3, composed of recycled wood and virgin PVC, meaning it exhibited the lowest identified tensile and impact strength values. This indicates that applying high loads to the M3 composite could cause rupture within a short period. Nukala et al. (2022) demonstrated that wood-polymer composites exhibit physical properties comparable to virgin polymers and wood, making them potentially suitable for various structural applications.

Figure 5 - Response surface analysis for the three materials concerning deformation and stress.
M1 = recycled plastic; M2 = recycled plastic and wood; M3 = recycled wood and virgin PVC.



Source: Authors (2024)

When evaluating mechanical results, it is essential to consider the type of material incorporated into the composite and the method of its production. Among other factors, the quality of the materials used influences the mechanical behavior of the composite (Todkar & Patil, 2019).

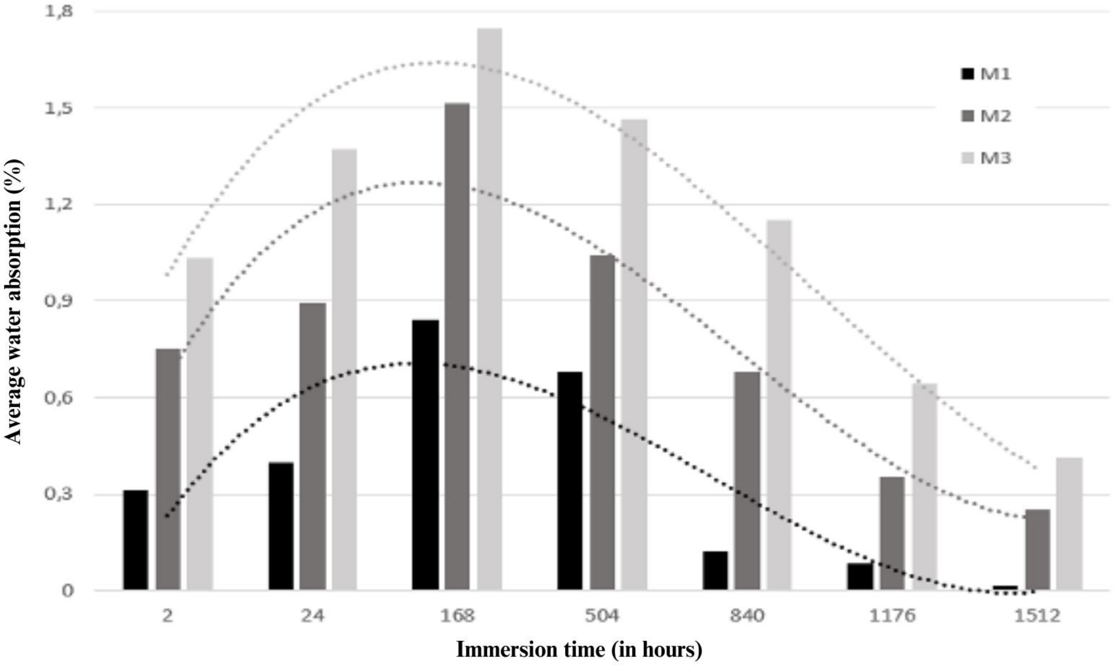
3.2 Water Absorption Properties

The water absorption test was essential to investigate the material's behavior and durability under environmental conditions, especially since these materials are commonly used in outdoor leisure areas such as pool decks, where exposure to the elements is constant.

The results of the water absorption of the three types of materials (M1, M2, and M3) after immersion in distilled water for sixty-three days are shown in Figure 6. According to the ASTM D570 standard that tests water absorption in plastic materials, the sample is considered saturated when the total weight increase is less than 1% compared to the previous recorded weight, after one week of immersion, or one hundred and sixty-eight hours. Thus, it is observed that M1 absorbed little moisture due to its hydrophobic nature, as it is a material composed only of recycled plastics, having its absorption peak (below 1%) in one week, without considerable subsequent soaking, showing a notorious ability to repel water and return to its initial stage. This behavior was presented in the work of Faure et al. (2019), where the authors evaluated the degree of water absorption in wood and plastic composites used in decks, in different sizes and thicknesses, and at different immersion times, proving different performances.

However, in materials M2 and M3, the amount of water absorption gradually increased with the incorporation of wood into their compositions, mainly attributed to the hydrophilic component present in the wood and the empty spaces that allow liquid retention and swelling of the part. As in these two types of materials the wood content is greater than that of plastic, the gaps between the two components are larger, which increases the difficulty in covering the existing voids, weakening the shared bond between wood and plastic, observed in Figure 6.

Figure 6 - Comparison of average water absorption for the tested materials.
M1 = recycled plastic; M2 = recycled plastic and wood; M3 = recycled wood and virgin PVC.



Source: Authors (2024)

A study by Hosseinihashemi et al. (2016) demonstrated that the presence of fewer voids in thermoplastic composites helps to make the material less susceptible to moisture absorption due to the reduction of hydrogen bonds between groups, mainly wood and water molecules.

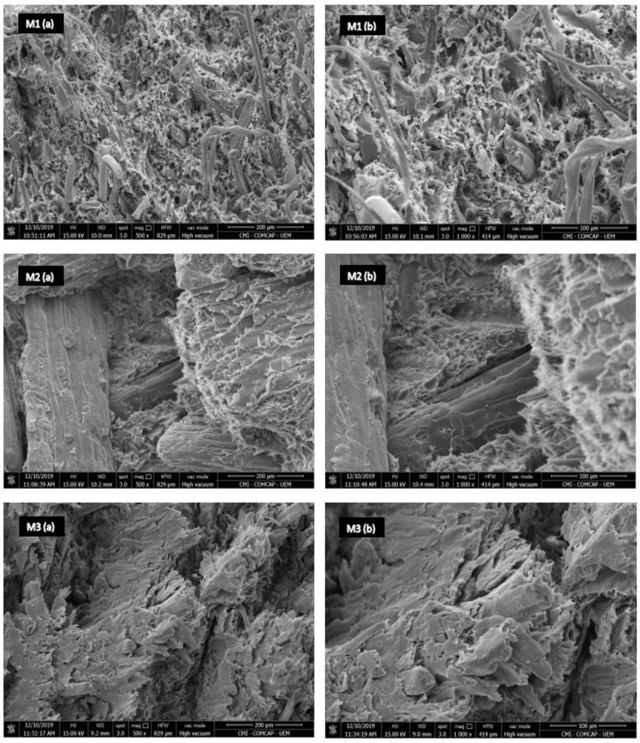
An evaluation conducted with plastic and jute composites found that a higher amount of fiber in relation to plastic exhibited a tendency towards increased water absorption in immersion tests over a period of two and twenty-four hours, with a significant variation towards lower absorption when the percentage of plastic was increased (BALAN & RAVICHANDRAN, 2019).

Youssef et al. (2019) studied wood-plastic composites in different compositions and observed that the hydrophobic behavior of the material increased when the amount of plastic in the structure was higher, explaining that the higher wood content led to a more pronounced swelling in the sample, with greater weight and thickness, which confirms the test performed on the samples, where comparing M1, composed only of plastics, with M2 and M3, which contained wood in the composition, the former had better performance in not absorbing water, without considerable swelling.

3.3 Morphological Analysis

The microstructure of the fracture surface of the test specimens after the impact tests was examined using Scanning Electron Microscopy (SEM), as shown in Figure 7, for the three tested materials.

Figure 7 - Scanning Electron Microscopy (SEM) of composite fragments after impact tests.
M1: recycled plastic; M2: recycled plastic and wood; M3: recycled wood and virgin PVC.
Scale: 200 µm (a) and 100 µm (b), respectively.



Source: Authors (2024)

Despite the three materials presenting voids in their compositions, M1 exhibited a more compact structure, which made it more resistant to impact and water absorption. Larger voids were more evident in M2 and M3 due to their wood content, which impaired the mechanical and physical properties of the composites. Through SEM analysis, it was possible to observe the distribution and compatibility between the composite fillers. M2 showed stacked plate-like structures, which partially increased its mechanical strength, as confirmed by the tensile strength test (Figure 4).

Cracks were easily observed between wood and plastic, which could be attributed to the hydrophilic nature of wood and its weak adhesion to plastic, creating cavities and/or fractures that accelerated water absorption and reduced mechanical properties. This indicates that the incorporation of wood into plastic tends to be sensitive during the composite processing stages. The reduction in fiber length affects fiber dispersion and orientation, likely due to high temperatures and forces during material molding (LEI et al., 2015).

4 CONCLUSIONS

Based on the research conducted, it can be concluded that the composite composed of 100% recycled plastic demonstrated the best mechanical performance due to its hydrophobic capacity, as confirmed by the water absorption test. The impact test showed satisfactory results, withstanding higher stresses compared to the other materials studied. Additionally, by fulfilling its ecological function, the M1 composite is entirely made of recycled material, which contributes to minimizing waste discarded into the environment, especially plastic. Therefore, composites derived from recycled materials, such as plastic, can serve numerous purposes and applications in daily life, particularly in the construction sector, where they can be used as cladding materials with increased reliability based on the analyses developed, as technical information regarding material behavior is often inaccessible to the average consumer.

This highlights the need for research and development of modified products that, while contributing to environmental protection and preservation, utilize waste as a way to reuse and add value to solid waste. In this sense, the use of waste in the formulation of composites strongly contributes to sustainable development and environmental care.

The implementation of recycled materials in civil construction as substitutes for materials derived from natural resources is feasible, considering the mechanical, physical, and morphological properties presented in this research. This approach contributes to the economic viability of industrial-scale production. Utilizing raw materials aimed at sustainability ensures that the entire production process becomes cleaner and contributes to reducing environmental impact.

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DECLARATIONS

AUTHOR CONTRIBUTIONS

When describing each author's contribution to the manuscript, use the following criteria:

- **Study Conception and Design**: Prof. Dr. Luciana Cristina Soto Herek and Prof. Dr. Edneia Aparecida de Souza Paccola conceived the central idea of the study and helped define the objectives and methodology.
- **Data Curation**: Mr. Adriano Pereira Cardoso and Felipe Nakamura Bassani organized and verified the data to ensure its quality.
- **Formal Analysis**: Prof. Dr. Luciana Cristina Soto Herek and Prof. Dr. Flávia Aparecida Reitz Cardoso conducted the data analyses, applying specific methods.
- **Funding Acquisition**: This study did not receive any financial resources.
- **Investigation**: Mr. Adriano Pereira Cardoso conducted data collection and practical experiments.
- **Methodology:** Mr. Adriano Pereira Cardoso and Felipe N. Bassani developed and adjusted the methodologies applied in the study.
- **Writing – Initial Draft**: Prof. Dr. Edneia Aparecida de Souza Paccola and Mr. Adriano Pereira Cardoso initiated the drafting process.
- **Writing – Critical Review**Prof. Dr. Luciana Cristina Soto Herek and Prof. Dr. Flávia Aparecida Reitz Cardoso reviewed the text, improving clarity and coherence.
- **Final Review and Editing**: Prof. Dr. Luciana Cristina Soto Herek, Prof. Dr. Edneia Aparecida de Souza Paccola, and Felipe Nakamura Bassani reviewed and adjusted the manuscript to ensure compliance with journal standards.
- **Supervision**: Prof. Dr. Edneia Aparecida de Souza Paccola coordinated the work and ensured the overall quality of the study.

DECLARATION OF CONFLICTS OF INTEREST

We, **Edneia Aparecida de Souza Paccola, Adriano Pereira Cardoso, Felipe Nakamura Bassani, Flávia Aparecida Reitz Cardoso, and Luciana Cristina Soto Herek,** declare that the manuscript entitled "**Study of Mechanical, Physical, and Morphological Properties of Composites Used in Civil Construction**":

1. **Financial Ties:** No funding institution or entity was involved in the development of this study.
2. **Professional Relationships**: We maintain professional relationships: Prof. Dr. Edneia Aparecida de Souza Paccola and Prof. Dr. Luciana Cristina Soto Herek work at Cesumar

University in the Graduate Program in Clean Technologies (PPGTL), where Mr. Adriano Pereira Cardoso and Master's student Felipe Nakamura Bassani are supervised by Professors Edneia and Luciana, respectively. Prof. Dr. Flávia Aparecida Reitz Cardoso is affiliated with UTFPR (Federal Technological University of Paraná) and collaborates externally on postgraduate research.

3. **Personal Conflicts**: We form a research group conducting studies on topics related to solid waste, recycling, the environment, and sustainability.