

Circular Design: experiments for the recovery of polymeric waste through mechanical recycling

Design Circular: experimentos para
recuperação de resíduos poliméricos por
meio de reciclagem mecânica



Tayná Steiger Mai

Undergraduate student
Industrial Design Course, UFSM
taynas.mai@gmail.com





Ana Paula Palhano

Undergraduate student
Industrial Design Course, UFSM
ana.palhano@acad.ufsm.br



Felipe Luis Palombini

Professor, Department of Industrial Design
and Graduate Program in Architecture,
Urbanism and Landscaping, UFSM
felipe.palombini@ufsm.br



Carolina Iuva de Mello

Professor, Department of Industrial Design
and Graduate Program in Architecture,
Urbanism and Landscaping, UFSM
carolina.mello@ufsm.br



ABSTRACT

Polymers are widely used in the manufacture of everyday artifacts, particularly due to their low cost and versatility. However, this also makes them one of today's biggest environmental villains. Efforts have been made to minimize its impact, such as the concept of Circular Economy, which seeks to reinsert materials into the production process after their end of life, thus avoiding the accumulation of waste in nature. In this context, the role of the designer is essential and this paper aims to report experiments carried out with the mechanical recycling of post-consumer thermoplastic polymers with the aim of better understanding the possibilities of their application in the project of new artifacts. From a methodological point of view, this is an exploratory research that seeks to deepen the understanding of the topic. Finally, it should be noted that greater control over the possibilities and restrictions of polymer recycling will allow designers to act more effectively in favor of sustainability.

KEYWORDS

Design; Recycling; Polymers.

RESUMO

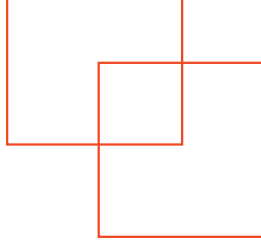
Os polímeros são amplamente utilizados na fabricação de artefatos cotidianos, especialmente por seu baixo custo e versatilidade. Entretanto, isso também fez dele um dos maiores vilões ambientais da atualidade. Esforços vêm sendo feitos para minimizar seu impacto, como a noção de economia circular, que busca reinserir os materiais no processo produtivo após o fim do seu ciclo de vida, evitando, assim, o acúmulo de resíduos na natureza. Nesse contexto, a atuação do designer se mostra fundamental e o presente artigo visa relatar experimentações realizadas com a reciclagem mecânica de polímeros termoplásticos pós-consumo com o intuito de compreender melhor as possibilidades de sua aplicação em projetos de novos artefatos. Do ponto de vista metodológico, trata-se de uma pesquisa exploratória que busca aprofundar a compreensão do tema. Por fim, ressalta-se



que um maior domínio acerca das possibilidades e restrições da reciclagem dos polímeros permitirá aos designers uma atuação mais efetiva em prol da sustentabilidade.

PALAVRAS-CHAVE

Design; Polímeros; Reciclagem



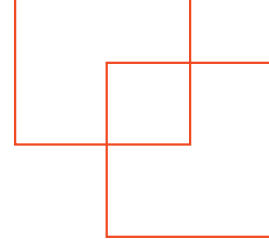
INTRODUCTION

The concept of circular economy arises with the intention of preventing all the labor force and economic value used in a product from being lost through disposal. Or that a way to recover it only begins to be considered after the end of its life cycle. The objective of this approach is for products to exist in a closed system, where they can be reused, recycled, or remanufactured to continue circulating on the market or become raw materials for new products (ELLEN MACARTHUR FOUNDATION, 2013).

The designer's role in this context is fundamental. In sustainable and circular projects, the entire life cycle of a product is considered with the aim of minimizing environmental impacts at all stages, from material extraction to usage, with the aim of avoiding disposal. When designing a product for the circular economy, materials, production processes, distribution, storage, how one will use the product, and how its recovery will take place after the end of its life cycle must be taken into account (MANZINI; VEZZOLI, 2002).

Polymers are one of the most used materials in industrial consumer goods, especially thermoplastics. Their production grew along with the industry of the 20th century and they became part of the composition of various everyday objects due to their versatility, lightness, malleability, low cost, and density. (MARTINS, 2020). Currently, however, they present themselves as one of the biggest environmental villains (GALL; THOMPSON, 2015) and efforts are being made to prevent polymers from continuing to pollute soils, rivers, and oceans.

Until other materials emerge that can compete with polymers in terms of cost, lightness, and easy moldability, and replace them in a way that is beneficial to nature, a way of dealing with the production of consumer goods that need to be made from thermoplastic polymers is through the design of products that aim for recycling at the end of their life cycle. Thus, based on the above, this paper intends to report experiments with the recycling of thermoplastic polymers, in an academic environment, with the aim of better understanding the possibilities of applying the secondary material in projects of new artifacts.



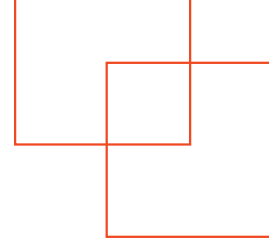
From the point of view of objectives, this research is exploratory, aiming to deepen the understanding of the study topic. The experiments were carried out at the Three-Dimensional Studies Lab (LABETRI) at the Federal University of Santa Maria (UFSM), being recorded through notes and photographs, so that the knowledge generated could serve as a basis for future projects. This is an experimentation project with primary verification of the process of recovering polymeric waste through mechanical recycling.

DESIGN FOR CIRCULAR ECONOMY

The current economic model is what we call a linear economy, which is based on an extraction-production-disposal system. In this model, products are produced, distributed, used for some time, and then discarded. Everything on such a large scale nature cannot sustain the amount of waste generated. As a counterpoint to this system, the concept of circular economy emerges. This proposal is inspired by the cycles of nature itself, which regenerates and maintains balance, having its goal as the concept of a product's "end of life" being replaced by a production model in a closed circuit, without losses, optimized for disassembly, recycling, reuse, or to serve as biological nutrients (MCDONOUGH; BRAUNGART, 2013; ELLEN MACARTHUR FOUNDATION, 2013).

For this to happen, taking into account the existence of two metabolisms on the planet is important: biological and technical. Biological metabolism regards biodegradable materials from renewable sources, which can return to nature as nutrients. Technical metabolism feeds on technical nutrients, i.e., materials from the industrial cycle, for example, metals and polymers from non-renewable sources (MCDONOUGH; BRAUNGART, 2013). For both cycles to remain fully operational, one must not contaminate the other (MCDONOUGH; BRAUNGART, 2013).

In this context, the role of designers is to stop considering the product in isolation and start interpreting it as part of a complex set of interactions (BONSIEPE, 1978). Vezzoli and Manzini (2008, p. 37) argue that "environmental requirements should be considered necessary from the very first stage of product development". To design products

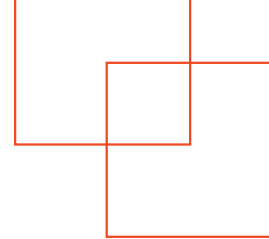


with a lower environmental impact and aimed at the circular economy, planning the product's life cycle in order to minimize negative environmental impacts at all stages is essential. According to Kazazian (2005, p. 55, translated), “fundamentally, the ecological product does not exist. Any product will have environmental impacts”. Therefore, it is ideal to observe the appropriate strategies for each phase, consistent with the product being developed, with the intention of minimizing the implications it will have on the environment as much as possible.

When thinking about a sustainable product, the materials used are the first issue to be noticed by the general population and, possibly, by designers. The selection of materials with a lower environmental impact is a strategy to be used and the assessment of this impact can be observed in the extraction of its raw material, in the transformation method in the production phase, and in the level of complexity of recovering it after use (MANZINI; VEZZOLI, 2002). In other situations, however, the selection of a material with greater durability can be the decisive factor in guaranteeing an increase in life cycle, by avoiding rapid replacement.

Redesigning the product structure can ensure a reduction in the amount of material required for manufacturing, as well as minimizing scrap. The use of energy resources is also a factor to be taken into account when choosing production processes, location of manufacturing facilities, means of transport for distribution, and storage (MANZINI; VEZZOLI, 2002), this is because “the product itself, sold as an independent and homogeneous element, is an illusion. Taking this product to market requires, in addition to infrastructure, a multitude of other products for its manufacture, transportation, and use.” (KAZAZIAN, 2005, p. 36, translated).

Therefore, designing a product for the technical cycle demands that the project takes into account strategies for reuse, repair, remanufacturing, and recycling (ELLEN MACARTHUR FOUNDATION, 2013). A structure that facilitates disassembly, for example, can extend the life cycle of the product, as it facilitates repair and makes technology updates viable (MANZINI; VEZZOLI, 2002). Furthermore, it can extend the life of materials, as it allows components from different materials to be separated and used in remanufacturing or recycling. When there is disassembly and separation, the possibility for recycling



to be more efficient arises, minimizing the quality loss of the recycled material. In Brazil, waste separation is mainly performed by low-income workers who can only profit if the material has enough market interest to be sold and then recycled. This makes it necessary to assess the disassembly and recovery issue as both an environmental and a social-related matter (PALOMBINI, et al. 2017).

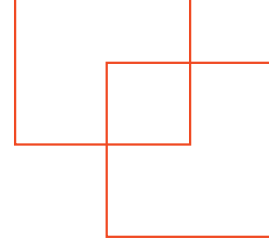
In this context, it is also important to understand the reasons why products are discarded after use. They can deteriorate through intensive or inappropriate use, structural wear and tear of the material over time, or accidents caused by the user, as well as technological obsolescence, and cultural and aesthetic changes, among others (MANZINI; VEZZOLI, 2002). Analyzing the feasibility of using biodegradable or compostable materials is a strategy that could be adopted in single-use products, such as packaging, ensuring that at the end of their use time, the components can feed the biological cycle (ELLEN MACARTHUR FOUNDATION, 2013).

In this way, the relevance of studying materials and processes for design in a circular economy context stands out, especially concerning their recycling possibilities. In contemporary times, polymers prevail as one of the most commonly used materials in everyday artifacts. For this reason, studying it is justified so that, when its use cannot be reduced or avoided, a product can be designed responsibly, aiming at the recovery of the post-consumer polymeric material.

THE PROBLEM OF POLYMERS

The widespread use of polymeric materials in recent decades was due to several factors, such as their physical characteristics of malleability, low density, the possibility of applying different colors, durability, and their relatively low cost. Polymers also provided new creative possibilities for designers, as with this moldable material a wide diversity of shapes could be achieved. However, polymers' wide use has made them a leading role in discussions about pollution, because they are the waste with the most implications for nature today, followed by glasses and metals (MARTINS, 2020; PALOMBINI; CIDADE, 2022).

According to a UN report, seven billion tons of polymers generated

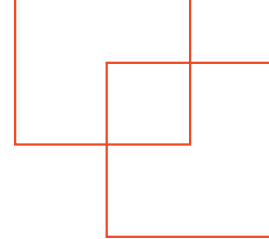


between 1950 and 2017 became waste, with three-quarters going to unmanaged landfills or ending up in nature and oceans (UNEP, 2021). Because they are quite durable, polymers remain in the environment for centuries after being discarded, and their low density means they are easily carried away by wind and water, which is one of the factors that cause pollution of the oceans and remote areas (RYAN, 2015). Besides, a large part of synthetic polymers is derived from oil, a non-renewable source that, during its extraction, contributes to environmental degradation and the uncontrolled greenhouse effect (WWF, 2022).

Polymers in water, in particular, cause a lot of commotion and concern. The first report on the impact of polymer waste on the marine environment was released in 1960 and today the material represents around 85% of the trash found in the oceans (UNEP, 2021, p. 03). The annual volume of polymers arriving at sea is estimated to be 11 million tons, and that figure will almost triple to 29 million tons by 2040 (THE PEW, 2020). Polymers in the ocean affect the marine ecosystem and have fatal consequences for animals, which can ingest parts of objects leading to lacerations, or even making them suffocate or drown with plastic bags (UNEP, 2021). Removing and recovering this huge amount of debris from the oceans and coastal areas is not easy (PALOMBINI et al., 2018) and can, together, end up removing small animals that live around it. It is therefore necessary to prevent waste from even reaching the oceans, which involves appropriate management of disposal on land.

The Ellen MacArthur Foundation (2013) suggests that the circular economy is the key element in reducing the environmental impacts caused by polymers, through three approaches: (i) eliminating polymers we do not need, replacing them with other materials, and creating reusable packaging or refill systems; (ii) circulate the plastic we need, with redesign for circularity, through reuse, recycling, and composting; and (iii) innovate at unprecedented scale and speed, through new technologies and business models that enable the transition to the circular economy.

In this paper, experiments were carried out on recycling post-consumer polymers, leading to the understanding that this is an alternative that should be used when it is not possible to reduce the



use or reuse the product. However, it is understood that, in an ideal context of circular economy, this approach must be considered during the product design stage, so that not only the recyclability potential of the selected materials can be analyzed, but also the energy expenditure of its subsequent recycling, as well as the market value of the polymer after the process.

RESULTS AND DISCUSSIONS

The first part of the research consisted of choosing the materials that would be tested, taking into account the six most common types of polymeric materials, which are polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). The characteristics of each of them were analyzed to understand the feasibility and complexity of their mechanical recycling.

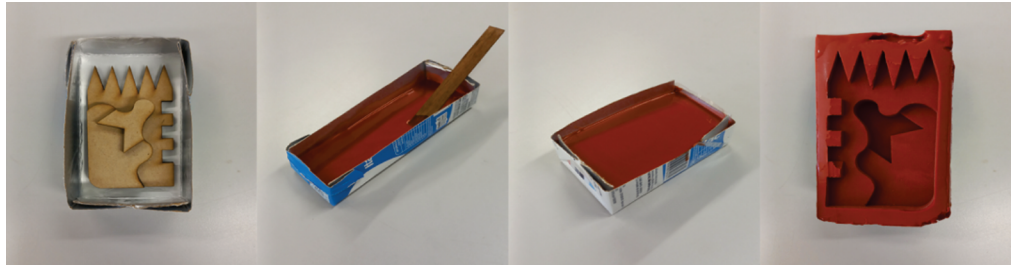
PET was discarded as a possibility because it is the polymer with the currently highest recycling rate (PICPLAST, 2022). PVC was also discarded as it is a material that can release toxic gases, and LDPE because its most common application is in bags and bags, having a very thin thickness and low density that would make testing difficult. Among the HDPE, PP, and PS options, we selected the first two, as they are more abundant in packaging and, consequently, in domestic waste, which would make them easier to collect in large quantities.

After deciding on the material, to understand the particularities and behavior of these two polymers in the recycling process, tests were carried out with each one of them. An oven and a silicone rubber mold were used to perform the tests. The mold was designed to have variations in height, curves, and edges, precisely to observe how each secondary polymer would behave in these shapes during melting.

The mold was made from a model made up of 3 layers of 6 mm thick MDF (medium-density fiberboard), which were cut with CO2 laser equipment and glued together, with the largest one measuring 8 x 10 cm. The differences in heights and sizes were used to observe how heat would act through different thicknesses of the silicone. The MDF model was placed in a rectangular shape made from a milk carton package, into which silicone rubber was poured. The material used in the process was rigid red silicone rubber from Redelease. The desired

amount was mixed with 5% catalyst and then poured into the mold containing the model. After 48 hours, the silicone rubber was removed from the mold (Figure 1).

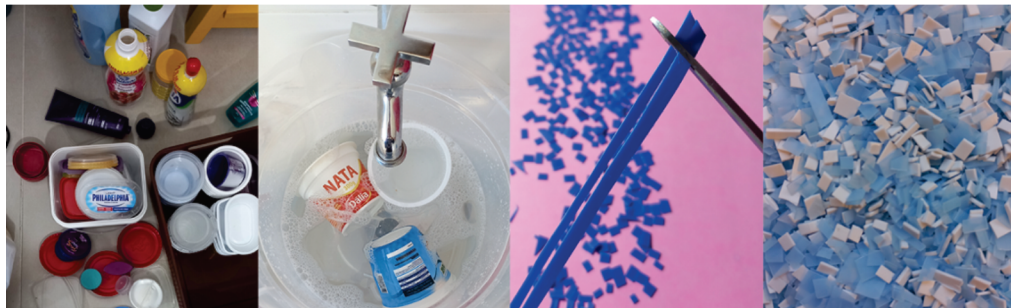
Figure 1 – Silicone rubber mold production.



Source: Authors.

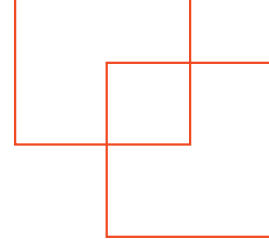
Regarding the selected polymers, several packages of both types were collected, which were sanitized in a bucket of water and then cut. The initial cuts were made by hand, using scissors and a utility knife, as large quantities of material were not needed for the primary experiments, so the pieces needed to be small to facilitate melting and shaping in the mold. Figure 2 demonstrates this process.

Figure 2 – Selection, washing, and cutting of PP and HDPE packaging.



Source: Authors.

The polymer melting tests were carried out in an industrial oven, available at LABETRI, with the assistance of the responsible technician. It is important to highlight that this is a furnace designed to reach high temperatures and, therefore, suffers temperature fluctuations at low temperatures, as is the case in the thermoplastic melting tests carried out. For the first test, in which polypropylene would be used, the oven was preheated for 15 minutes, gradually increasing the temperature until it reached 170°C. Polypropylene pieces were placed on the top of the silicone rubber mold, which was then positioned inside the oven.



For two hours, the oven was opened every 20 minutes and the mold was removed to observe the polymer melting. In addition, by using a metallic object, the material was squeezed and pushed in to fill the smaller parts of the mold.

As the polypropylene melted and, consequently, flowed throughout the mold, more material was added to fill it up to the top. After two hours, the mold was removed from the oven, and let it cool for five minutes to unmold it. When the polypropylene began to be removed, there was some difficulty in releasing it from the mold, as the material concentrated at the bottom had not completely melted, probably due to the walls of the mold being thicker and the temperature reached there was not high enough to melt the material. Several parts of the mold also tore during removal.

So, carrying out a new test with the polypropylene was necessary, opting to add the material to the mold little by little and, this time, vaseline was brushed on the silicone rubber before placing the polypropylene. The test began with filling only the lowest layer of the mold, at a temperature of 170°C, and, due to the smaller amount of polymer, the oven was opened every 20 minutes the first two times. After that, the temperature was increased to 180°C, to observe the behavior of the material, with the oven being open every 30 minutes. This approach had a better result since it made the polymer more malleable, making it easier to compact with a metal rod. At each oven opening, the mold was removed and a little more material was added on top. Because the surface of the first test had a very grainy appearance, an MDF layer was cut into the upper shape of the mold, and used to compress against the polymer leaving the surface smoother. The result of this experiment was much more satisfactory, all parts of the piece underwent melting and the application of pressure resulted in a much less porous piece (Figure 3).

Figure 3 – Experiment with polypropylene.



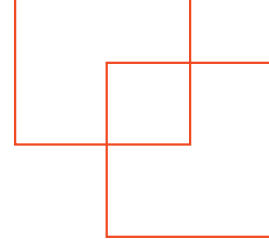
Source: Authors.

For the third experiment, high-density polyethylene (HDPE) was used. Vaseline was brushed on the mold and the pieces of material were gradually placed in layers, in the same way as the previous test. This polymer has a lower melting point temperature, with an indication of around 135°C being found in the literature (GROOVER, 2017). Initially, this was the temperature set in the oven, and, being observed that the polypropylene softened when kept in the oven for 30 minutes, it was decided to keep the polyethylene for this period as well. What was noticed, however, was that the HDPE was not melting enough, making it difficult for the pieces to come together in the mold, even when pressed with a metal object. Because of this, it was decided to gradually increase the temperature, every 30 minutes, after the mold was placed back in the oven, to observe the behavior of the material. In total, the mold was removed from the oven nine times and the final temperature was 180°C, as was the polypropylene. Figure 4 demonstrates this process.

Figure 4 – Experiment with high-density polyethylene.

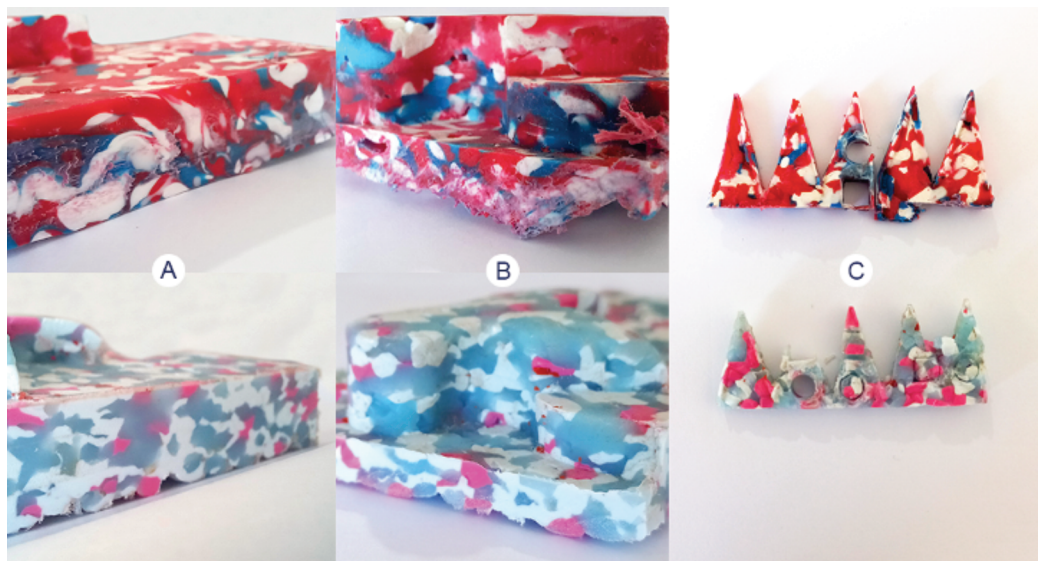


Source: Authors.



Once the PP and HDPE pieces were ready, cutting and finishing tests were carried out, also at LABETRI (Figure 5). Starting with the saw cut, each piece was sawn close to the pointed end, with the HDPE piece having a smoother surface after cutting and the PP piece having a rougher appearance. Afterward, a finishing test was carried out with a bench sander, on the side of each piece, and the result was similar to sawing, with the HDPE surface becoming quite smooth, and the PP surface a little rougher, probably requiring longer sanding time with a different sandpaper grain size. Finally, a test was carried out with laser cutting. The pointed part of the pieces was used, which had already been sectioned, as it was thinner (approximately 5 mm). Regarding this cut, it was noticed that it deformed the material a little, as it uses heat, resulting in a less precise result. PP was cut more easily by the laser, while HDPE required greater power for the machine to perform the cut.

Figure 5 – (A) sanding, (B) saw cutting, and (C) laser cutting tests.



Source: Authors.

As cutting the packaging with scissors was a very laborious and time-consuming process, it was decided to grind the polymeric materials in a knife mill, in the Polymer Transformation Laboratory of the Technical Industrial School of Santa Maria (CTISM). As had been done previously, PP and HDPE packaging was sanitized and separated by type of polymer and color. Initially, the goal was to crush the polymers according to type and shade. In the Laboratory, however, it

was realized that the material that had been gathered was not enough to be crushed separately, as the knife mill was large. It was then decided to combine HDPE and PP and crush them together, differentiating them by shades, as only the white HDPE packages had enough quantity to go through the mill separately (Figure 6).

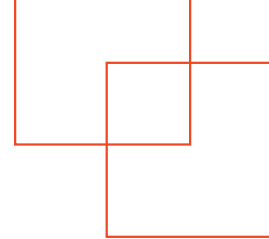
Figure 6 – Polymer Grinding.



Source: Authors.

To prove whether the process of melting polymeric materials would be possible with domestic equipment, an experiment was carried out using a clothes iron, which can reach up to 200°C. A small polymer sample was placed on a sheet of parchment paper, which was then folded, covering the material. To prevent direct contact between the iron and the paper, a cotton tissue was placed. For 20 minutes, the iron was kept in contact with the sample, varying the side to ensure that all polymer fragments had contact with the heat. When the equipment was turned off, after a few seconds the sample was cooled down and the parchment paper could be removed.

This experiment demonstrated that it is possible to perform melting using this domestic equipment, but it is a process that requires a lot of time and active dedication from the person carrying out the activity. Therefore, it is only viable when you want to produce small, low-complexity products. Using a sample from this experiment, an attempt was made to bend the material (Figure 7). The objective was to discover how the material would behave when folded, accepting molding, or breaking, to analyze this possibility for future projects. At LABETRI, part of the sample was placed in contact with a heated metal and, upon



softening, it was bent at an angle of approximately 90°. The result showed that the method is possible, but would need to be improved regarding temperature and time control, so as not to wear out the material. It was also necessary to carry out finishing work on the piece to remove melting residue. For this reason, it was decided not to continue exploring these folds.

Figure 7 – Bending experiment.



Source: Authors.

The last polymer melting experiment was carried out in a hydraulic press (Figure 8) at the Wood Chemistry Laboratory, of the Forestry Engineering undergraduate course at UFSM. The press has two plates that heat up, allowing the material to be melted. The technician responsible for the Laboratory provided a metal mold to carry out the test, which was 4 mm thick, 6 cm wide, and 26 cm long. Before the test, the press was turned on and preheated for approximately one and a half hours. The mold was placed on a thin aluminum plate and 45 g of PP and HDPE were placed inside the mold. Another aluminum plate was positioned on top of the mold. Because the mold is comprised only of a lateral part, to facilitate the removal of the polymer, sheets of parchment paper were placed between the top and bottom parts of the mold and the plates. These components were placed in the press at a temperature of 180°C for 20 minutes (Figure 8). They were removed from the press twice to add more polymer to the mold and placed again for the same temperature and time. When removed from the press, the polymer required approximately two minutes for it to solidify again so that the parchment paper could be removed. In total, 90 grams of material were placed in the mold. At the end of pressing, the sheets of paper were removed from the surface, and the polymer was demolded using a pocket knife.

Figure 8 – First experiment on the press.

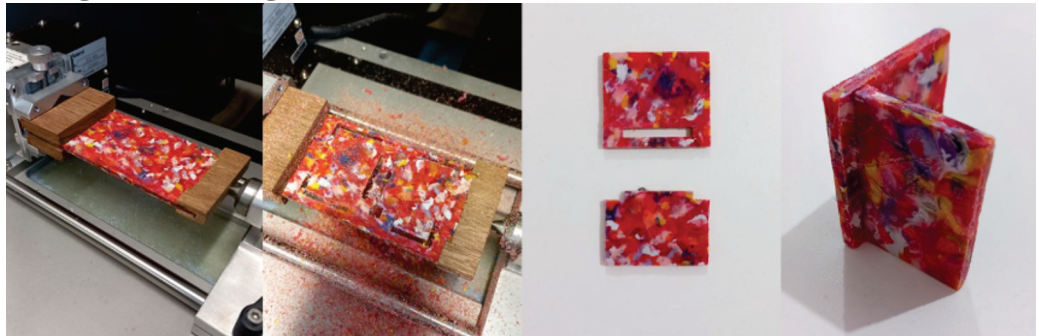


Source: Authors.

The result was quite satisfactory, as pressing allowed the polymer to be more compacted, presenting a more precise shape with a smoother surface at the end of the process. It was noticeable, however, that not enough material was placed at the edges of the mold, causing a porous appearance in these parts.

After carrying out tests with the material, it was investigated how the polymer sheets would be connected for the subsequent production of artifacts. To test the most viable way of joining parts, the sample developed in the press was used, with three experiments being carried out: screwing, welding, and cutting fittings on a CNC mill/MDX-40A 3D. The sample was divided into parts, separating the most compact piece for testing on the CNC equipment (Figure 9). First, a fitting model was created in Rhinoceros 3D, which was then transferred to the CNC software, which performed the cutting in 1 hour and 15 minutes. It was necessary to lightly abrade the pieces by hand with sandpaper so that they both fit together, which resulted in a very firm union.

Figure 9 - Fitting test on the CNC machine.



Source: Authors.

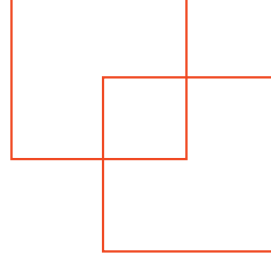
For welding (Figure 10), a metal was heated and the ends of the part were placed in contact with it. When the material was visibly melted, the two ends were pressed together for a few minutes. The result on the outside, after finishing with a craft knife, was quite satisfactory, as the colored surface of the material prevents the joint from being visible. On the inside, however, the excess melted polymer was difficult to remove and could even cause the joint to break. The screwing test (Figure 10), in turn, was a little difficult, as it needed to be very precise due to the 4 mm thickness of the piece. The result was a very firm union, however, not very aesthetically satisfactory.

Figure 10 – Welding and screwing tests.



Source: Authors.

Among the possibilities for joining parts, fittings were those that demonstrated a more precise result, with less possibility of failure and less need for finishing. However, as the CNC machine used had a small cutting area, it was decided to test the laser cutting process again, but on a more modern cutting machine, in the CTISM Laboratory. With the assistance of the responsible technician, a corner of one of the panels was cut at different speeds and powers until the ideal parameters were reached, which were a 4 mm/s speed and 95% power. This result was



quite satisfactory, causing little melting and no burning of the material.

Therefore, the tests carried out made it possible to verify the feasibility of mechanical recycling of PP and HDPE in an academic context, using low-complexity and relatively accessible resources. The results were positive and demonstrated possibilities for future applications in artifact projects using secondary polymeric material.

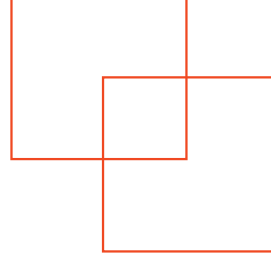
CONCLUSIONS

This paper aimed to highlight the relevance of the theme of sustainability in design and the need to insert circular premises in projects, focusing on the mechanical recycling of polymers. In general, the experiments reported in this research served to explore the possibilities that post-consumer polymers can bring, demonstrating their recyclability even in small-scale situations. The studies carried out aim to serve as a basis for future activities with these materials to be carried out more quickly, avoiding failed attempts.

Tests carried out in the furnace were important for understanding the characteristics of PP and HDPE, in order to understand their behavior during melting, comprehending, for example, that the process should be done in layers to ensure that all parts were reached by the heat. And, although these experiments were carried out in an industrial oven, it is important to highlight that, as these polymers do not require high temperatures to melt, domestic ovens can also be an alternative, provided, of course, that they are no longer used for the preparation of food.

Melting with iron and inside the mold makes it viable to develop simple artifacts such as cup holders, key chain pendants, hooks, and buttons, and can also be used in contemporary jewelry pieces (CIDADE et al., 2021). Using the press, it is possible to produce larger products, such as parts aimed at furniture design. This form of polymer recycling provides even more added value with the possibilities of color combinations of collected materials, which result in blended surfaces and unique patterns.

It can be concluded that recycling these polymers is viable with this equipment, but they require a relatively long time, which impacts energy costs. It is important to understand its relevance as an



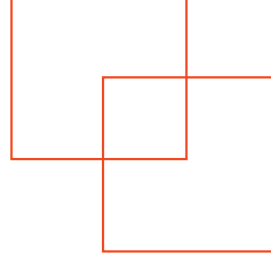
experimental material for students, both in terms of raising awareness about the need to include sustainability as a design requirement as well as stimulating perception about materials and creativity in ways of applying it.

Regarding the characteristics of the materials after heating, it can be noted that the only difference that draws attention is the consistencies, with HDPE being more viscous than PP, even when its temperature was equal to 180°C. This factor, however, did not influence the final result, with the two samples having very similar appearances, even in the cutting tests with the saw and the finishing with sandpaper.

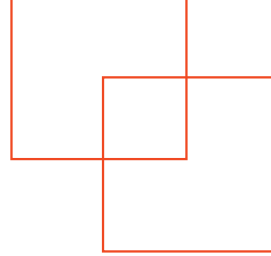
One can hope that the tests and results presented in this paper could stimulate other researchers and contribute to the development of more actions related to the recycling of post-consumer polymers. Despite having been carried out in an academic environment, the experiments demonstrated the general viability of the process and, as future work, we intend to apply the knowledge generated in initiatives that can generate income for organizations that select recyclable materials, combining environmental and social sustainability.

REFERENCES

- BONSIEPE, G. Teoría y práctica del diseño industrial: elementos para una manualística crítica. Gustavo Gili, 1978.
- CIDADE, M. K. et al. Experimental Study for the Valorization of Polymeric Coffee Capsules Waste by Mechanical Recycling and Application on Contemporary Jewelry Design. Em: MUTHU, S. S. (Ed.). Sustainable Packaging. Singapore: Springer-Nature, 2021. p. 85–110. DOI: https://doi.org/10.1007/978-981-16-4609-6_4
- ELLEN MACARTHUR FOUNDATION. Towards a circular economy: Economic and business rationale for an accelerated transition. 2013.
- GALL, S. C.; THOMPSON, R. C. The impact of debris on marine life. Marine Pollution Bulletin, v. 92, n. 1–2, p. 170–179, 15 mar. 2015. DOI: <https://doi.org/10.1016/J.MARPOLBUL.2014.12.041>
- GROOVER, M. P. Fundamentos da moderna manufatura, v.2. Rio de Janeiro: LTC, 2017
- KAZAZIAN, T. Haverá a idade das coisas leves: design e



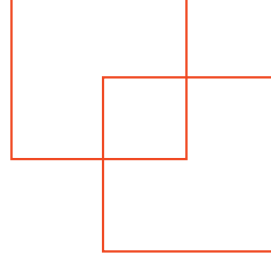
- desenvolvimento sustentável. São Paulo: Editora Senac, 2005.
- MANZINI, E; VEZZOLI, C. O desenvolvimento de produtos sustentáveis: os requisitos ambientais dos produtos industriais. São Paulo: Edusp, 2002.
- MARTINS, M. Poluição por plástico: A crise ambiental e as políticas europeias e nacionais. Orientador: Doutor José Eduardo Ventura. 202. 112 p. Tese (Mestrado). Gestão do Território - Faculdade de Ciências Sociais e Humanas, Universidade Nova de Lisboa. Lisboa, 2020.
- McDONOUGH, W; BRAUNGART, M. Cradle to cradle: criar e reciclar ilimitadamente. São Paulo: G.Gili, 2013
- PALOMBINI, F. L. et al. How sustainable is organic packaging? A design method for recyclability assessment via a social perspective: A case study of Porto Alegre city (Brazil). Journal of Cleaner Production, v. 142, p. 2593 – 2605, jan. 2017. DOI: <https://doi.org/10.1016/j.jclepro.2016.11.016>
- PALOMBINI, F. L. et al. Occurrence and recovery of small-sized plastic debris from a Brazilian beach: characterization, recycling, and mechanical analysis. Environmental Science and Pollution Research, v. 25, n. 26, p. 26218–26227, 5 set. 2018. DOI: <https://doi.org/10.1007/s11356-018-2678-7>
- PALOMBINI, F. L.; CIDADE, M. K. Lixo Invisível: Contribuição do Design para Recuperação de Materiais Problemáticos. MIX Sustentável, v. 9, n. 1, p. 17–26, 22 dez. 2022. DOI: <https://doi.org/10.29183/2447-3073.MIX2023.v9.n1.17-26>
- PICPLAST. 4ª Pesquisa Anual de índice de Reciclagem de Plástico no Brasil. 2022. Disponível em: www.abiplast.org.br/publicacoes/pesquisa_reciclagem_picplast. Acesso em 12 set. 2023.
- RYAN, P. A Brief History of Marine Litter Research. IN: BERGMANN, Melanie; GUTOW, Lars; KLAGES, Michael. Marine Anthropogenic Litter. Springer Open, 2015. p. 1–25.
- THE PEW CHARITABLE TRUSTS; SYSTEMIQ. Breaking the Plastic Wave: a comprehensive assessment of pathways towards stopping ocean plastic pollution. 2020
- UNEP - United Nations Environment Programme. From Pollution to Solution: A global assessment of marine litter and plastic pollution.



Nairobi: Synthesis, 2021.

VEZZOLI, C. A.; MANZINI, E. Design for Environmental Sustainability. London: Springer, 2008.

WWF - World Wide Fund for Nature. Impactos ambientais do petróleo pressionam o setor para a energia limpa. Disponível em: www.wwf.org.br/?84444/impactos-ambientais-do-petroleo-pressionam-o-setor-para-a-energia-limpa. Acesso em 12 set. 2023.



Tayná Steiger Mai

Undergraduate student in Industrial Design Course at UFSM. Academic Mobility in 2023 in the Art and Design course at the Polytechnic Institute of Bragança - IPB, Portugal. Conducts research in the areas of circular design and recycling of materials, with an emphasis on polymers.

MAI, T. S.; BERTONCELLO, V. B.; MANTOVANI, C.; GASPARETTO, D. A. Relatório de projeto história da arte na caixa de cereal. In: GASPARETTO, D. A. (Org.). História da Arte no Desenho Industrial - Imagens Fantasmas. Santa Maria: Facos UFSM, 2020.

MAI, T. S.; PALHANO, A. P.; PALOMBINI, F. L.; MELLO, C. I. de . Design and circular economy: studies and experiments with polymer recycling. In: SDS 2023 IX Simpósio De Design Sustentável, 2023, Florianópolis. ANAIS SDS 2023. p. 637-649.

<https://orcid.org/0009-0000-3950-8918>

Ana Paula Palhano

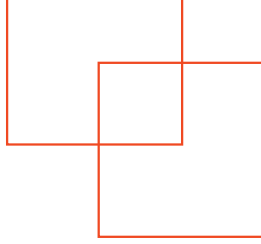
Undergraduate student in Industrial Design Course at UFSM. Technical degree in Integrated Furniture from the Farroupilha Federal Institute – Santa Rosa Campus (2016). Conducts research in the areas of sustainability, jewelry design, type design and typography.

PALHANO, A. P.; MELCHORS, A. ; CIDADE, MARIANA K. Processos criativos de repetição e combinações cromáticas aplicados no desenvolvimento de produtos sustentáveis. Revista Educação Gráfica, v. 25, p. 182-194, 2021.

MELCHORS, A.; PALHANO, A. P.; CIDADE, M. K. Estudo de reciclabilidade e reutilização de cápsulas poliméricas de café. Mix Sustentável (Online), v. 6, p. 93-104, 2020.

CIDADE, M. K.; PALOMBINI, F. L.; PALHANO, A. P.; MELCHORS, A. Experimental Study for the Valorization of Polymeric Coffee Capsules Waste by Mechanical Recycling and Application on Contemporary Jewelry Design. Kowloon: Springer Nature Singapore, 2021, v.1, p. 85-110.

<https://orcid.org/0000-0002-2822-5055>



Felipe Luis Palombini

Assistant Professor in the Department of Industrial Design at UFSM. Permanent Professor in the Graduate Program in Architecture, Urbanism and Landscaping (PPGAUP/UFSM). Researcher and Coordinator of the Innovation and Sustainability in Design Laboratory (NOVA Lab), in the area of 3D Technologies and Digital Fabrication. PhD (2020) and M.Sc. (2016) of Design, with an emphasis on Design and Technology, from the Graduate Program of Design at UFRGS, and a bachelor's degree in Product Design from the same university (2015). Post-Doc (2022) of Botany by the Graduate Program in Botany (PPGBot/UFRGS), and Post-Doct (2023) of Design (PGDesign/UFRGS), in the areas of Design, Sustainability, Materials, Biodiversity and 3D Technologies, with a scholarship from CNPq. Guest editor of the book series "Environmental Footprints and Eco-design of Products and Processes", published by Springer-Nature. Conducts research in the areas of Materials and Manufacturing Processes, Additive Manufacturing, Sustainability, Parametric Modeling and Generative Design, among others.

PALOMBINI, F. L.; NOGUEIRA, F. M. (Org.). Bamboo Science and Technology. Singapore: Springer-Nature, 2023. 428p.

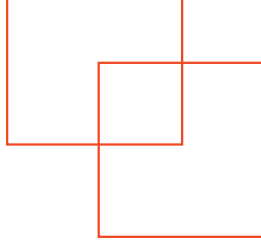
PALOMBINI, F. L.; NOGUEIRA, F. M. (Org.). Bamboo and Sustainable Construction. Singapore: Springer-Nature, 2023. 400p.

PALOMBINI, F. L.; MUTHU, S. S. (Org.). Bionics and Sustainable Design. Singapore: Springer-Nature, 2022. 448p.

<https://orcid.org/0000-0002-2112-6695>

Carolina Iuva de Mello

Associate Professor in the Department of Industrial Design at UFSM and leader of the GEPP Research Group (Product Design Study Group), registered with CNPq. Permanent Professor in the Graduate Program in Architecture, Urbanism and Landscaping (PPGAUP/UFSM), in the area of Planning, Design and Fundamentals. Bachelor's degree in Design (UFN, 2005), master's degree in Production Engineering (UFSM, 2008) and a PhD in Rural Extension (UFSM, 2016). Conducts research in the area of Product Design, mainly on the following topics: design and



territory, territorial identity, cultural heritage, handicrafts, social innovation and sustainability.

FROEHLICH, J. M. (Org.); MELLO, C. I. (Org.). Artesanato e identidade territorial: manifestações e estudos no Brasil meridional. Curitiba: Editora Appris, 2021. 219p.

MELLO, C. I.; FROEHLICH, J. M. Território feito à mão: o artesanato como expressão identitária em Comunidades Remanescentes Quilombolas. Tessituras: Revista de Antropologia e Arqueologia, v. 10, p. 73-96, 2022.

MORAES, R. E.; MELLO, C. I. Design no Esporte: Desenvolvimento de Utensílio para a Prática do Hipismo com Foco na Ergonomia. Human Factors in Design, v. 10, p. 3-22, 2021.

<https://orcid.org/0000-0003-0937-1230>

**Artigo selecionado para
publicação - SDS 2023.
Florianópolis - dez 2023.**