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Assessment of Utilizing Hard-to-Recycle Plastic Waste from the Packaging Sector in Architectural Design—Case Study for Experimental Building Material

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Abstract: The environmental impact of plastic waste has become a significant concern worldwide, prompting innovative approaches to address sustainability challenges, particularly within architectural design. This research paper delves into assessing the environmental impact and sustainability implications of using hard-to-recycle plastic packaging waste in architectural design practices. This study aims to evaluate the feasibility, challenges, and potential benefits of repurposing hard-to-recycle plastic packaging waste as building materials in an architectural context. The paper presents a compelling case study showcasing innovative architectural projects that have successfully integrated hard-to-recycle plastic waste. It offers recommendations for future research directions and policy interventions to promote the adoption of hard-to-recycle plastics in environmentally conscious architecture, thereby advancing sustainability goals and fostering a circular economy paradigm within the construction industry. The research paper also highlights a specific experiment conducted using hard-to-recycle plastic waste, illustrating the potential for creative solutions in sustainable architectural design. This study provides valuable insights into the environmental impact and feasibility of repurposing hard-to-recycle plastics as building materials, contributing to ongoing efforts to address sustainability challenges.

Keywords: circular economy; plastic waste management; sustainable architecture; hard-to-recycle plastics; sustainable construction; plastic packaging waste

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1. Introduction

Plastic waste has become a pervasive environmental crisis of our time, posing significant challenges to ecosystems, public health, and the global economy [1–3]. Every year, millions of tons of plastic end up in landfills and oceans, causing severe harm to the environment [4–6]. Based on research conducted by PlasticsEurope, it can be seen that, as of 2018, plastic production continues to increase globally. In 2022, it was 400.3 Mt (million tons), of which PP turned out to be the most popular polymer produced (18.9%), with PE-LD, PE-LLD (14.1%), and PVC (12.7%) following [7]. In addition, statistics also show how much plastic was recycled. In 2022, global production of recycled plastics continued to grow, reaching 35.5 Mt, accounting for an 8.9% share of total global plastics production [7]. This number is growing every year, but it is still essential to take immediate action to reduce the adverse effects of plastic waste and work towards a more sustainable future [8–11]. The quest for innovative solutions to mitigate plastic waste has gained momentum within the architectural sphere, where materials and design choices profoundly shape the built environment [12]. Plastic production and consumption growth have worsened environmental degradation, leading to widespread pollution and ecological harm [13,14]. Hard-to-recycle plastics, in particular, present a formidable challenge due to their persistence in the environment and limited avenues for disposal [15,16]. As such, there is a pressing need to explore alternative strategies for managing plastic waste, especially in architectural design and construction [17,18]. Within architectural design, the principles of the circular economy advocate for repurposing hard-to-recycle plastic waste as viable building materials, thereby closing the loop on the plastic waste stream and reducing environmental harm [19,20]. By embracing sustainability and resource efficiency, architects and designers can be pivotal in reshaping the built environment towards a more circular and resilient model [21,22].

Furthermore, the concept of sustainable development, as outlined by the United Nations Sustainable Development Goals (SDGs), provides a comprehensive framework for addressing environmental, social, and economic challenges [23–25]. Sustainable Development Goal 12 (SDG 12) specifically targets responsible consumption and production patterns, urging industries and consumers to adopt more sustainable practices [26,27]. Architects, engineers, and researchers are increasingly exploring alternative materials and methodologies to address sustainability challenges [28–31].

As people become more aware of the detrimental effects of plastic waste on the environment, innovative ideas have surfaced in foreign nations to repurpose used plastics into furniture, sculptures, or construction materials [32–34]. However, the abovementioned ideas often only encompass some types of plastic, selected groups that can be recycled without any reservations. Plastics are usually classified based on their recycling process [35,36]. Depending on their internal structure, plastics can be classified as thermoplastics, thermosets, or elastomers, although the main types of plastics are characterized by different degrees of recyclability. The Society of Plastics Industry established a classification system to facilitate proper segregation and disposal of plastic waste [37]. Based on this program, plastics numbered 01–07 are distinguished [38–40]. PET (01) is primarily plastic beverage bottles; HDPE (02) and PP (05) are most often used to produce containers and food packaging; PVC (03) and PS (06) are most commonly used in the construction industry; and LDPE (04) is used in the packaging industry, i.e., bags, commercials, or films. The last group is OTHER plastics (07), which contains a mix of plastics that do not qualify for the previously mentioned categories. Examples of products in this group are food storage containers, inner parts of food and beverage cans, or plastic parts of pacifiers. These products accompany us most in our everyday lives.

Moreover, plastics can also be divided into recyclable and hard-to-recycle plastics. Recyclable plastics are plastic wastes from which new materials can be produced and transformed into new products. Plastic items identified with the numbers 01 and 02 are primarily processed without any problems. Examples of recyclable products from groups 01 and 02 are beverage bottles, shampoo bottles, or plastic storage containers. In contrast, the remaining ones, characterized by numbers from 03 to 07, are recycled under certain conditions or not recycled at all due to their minimal or negative processing value. Such products include packaging film, baby bottles, or plastic CDs. The recyclability of the plastics mentioned above is also based on aspects that can be considered regarding thermal properties, economic viability, recycling policy, or the effectiveness of separation methods in the recycling process [41]. This results in a growing amount of waste in the ecosystem, which, given its properties, can only accumulate and degrade the environment. Therefore, solutions for developing technologies that use hard-to-recycle materials to produce products with a longer life, such as construction materials, are highly desirable [42]. In addition, a gap in the modern approach to recycling is the need for an innovative methodology for disposing of plastic waste, which could translate into shaping new solutions using recycled materials. This study aims to identify the possibilities of using hard-to-recycle plastic packaging waste to create diverse or surprising architectural arrangements. In the scope of the research topic, an experiment was conducted involving creating a prototype construction material composed entirely of hard-to-recycle plastic packaging waste. The entire process was performed according to the pre-established framework, significantly aiding the intricate research process [43].

Employing blocks crafted from this material presents a promising substitute for conventional design approaches, streamlining construction processes and cutting down on investment expenses [44–46]. Applying plastic waste to facades and structural components is anticipated to significantly limit construction projects' carbon footprint [47–49]. Furthermore, producing blocks out of hard-to-recycle materials contributes to advancing sustainable development objectives.

This research paper builds upon the theoretical underpinnings of the circular economy and sustainable development to assess the environmental impact and sustainability implications of utilizing hard-to-recycle plastic packaging waste plastics in architectural design practices. This study evaluates the feasibility, challenges, and potential benefits of integrating hard-to-recycle plastic waste into architectural projects. By scrutinizing case studies showcasing innovative architectural endeavors that have successfully incorporated hard-to-recycle plastics, researchers aim to glean insights into design considerations, construction techniques, and environmental performance metrics associated with plastic-based architectural solutions. By providing suggestions for future research and policy changes, stakeholders can work together to promote environmentally friendly architectural practices and create a more resilient and sustainable built environment. Through thorough investigation and collaboration across disciplines, this study aims to pave the way for a future where plastic waste is repurposed, resources are preserved, and the built environment sets an example of sustainability for future generations.

2. Materials and Methods

The research paper discusses one of the methods of using hard-to-recycle plastic packaging waste, which aims to minimize the accumulation of pollutants in the ecosystem and encourages experimentation with secondary materials in various scientific disciplines, including architecture and urban planning. The primary objective is to use hard-to-recycle plastic packaging waste, after appropriate processing, as a new construction material. This novel approach to environmental conservation is a viable alternative to traditional design and implementation elements in building structures. The entire research process (Figure 1) consists of several key stages that are necessary for the execution of the discussed study.

The first step involved conducting a detailed literature review that presented current issues related to plastic waste pollution as well as the possibilities of environmental conservation, ranging from basic recycling activities to approaches involving the utilization of waste in architectural and urban design. Based on the literature study, much valuable information was gathered, including existing methods and tools used in the processing concepts for this type of object. This information contributes to establishing fundamental design decisions.

Next, the study involved a comprehensive analysis of recyclable and hard-to-recycle plastics to better understand their properties, potential uses, and associated challenges. All cases selected for comparison were characterized by their presence and assistance to users in their daily functioning. Based on the analysis conducted, appropriate groups of plastics were selected. The limitation of further research regarding the selection of plastic waste that is not easily subject to recycling processes was also based on studies related to pollution, which showed that the most frequently persistent waste is hard-to-recycle plastics.

Simultaneously, a thorough examination of the possibilities for transforming plastic waste in different scientific disciplines and methods of converting used materials was conducted. Excessive waste production necessitates their reuse due to the increasing area of landfills and environmental protection against pollution. Such actions are significant in the case of a large amount of hard-to-recycle plastic, whose life cycle usually ends in landfills. Furthermore, solutions utilizing plastic waste have yet to be widely implemented, so processing possibilities have to be carefully verified. This analysis aimed to identify the everyday use of worn-out plastics while examining how collected materials are transformed. Through this analysis, it is possible to determine the domains in which there is a need for innovative solutions utilizing plastic waste.

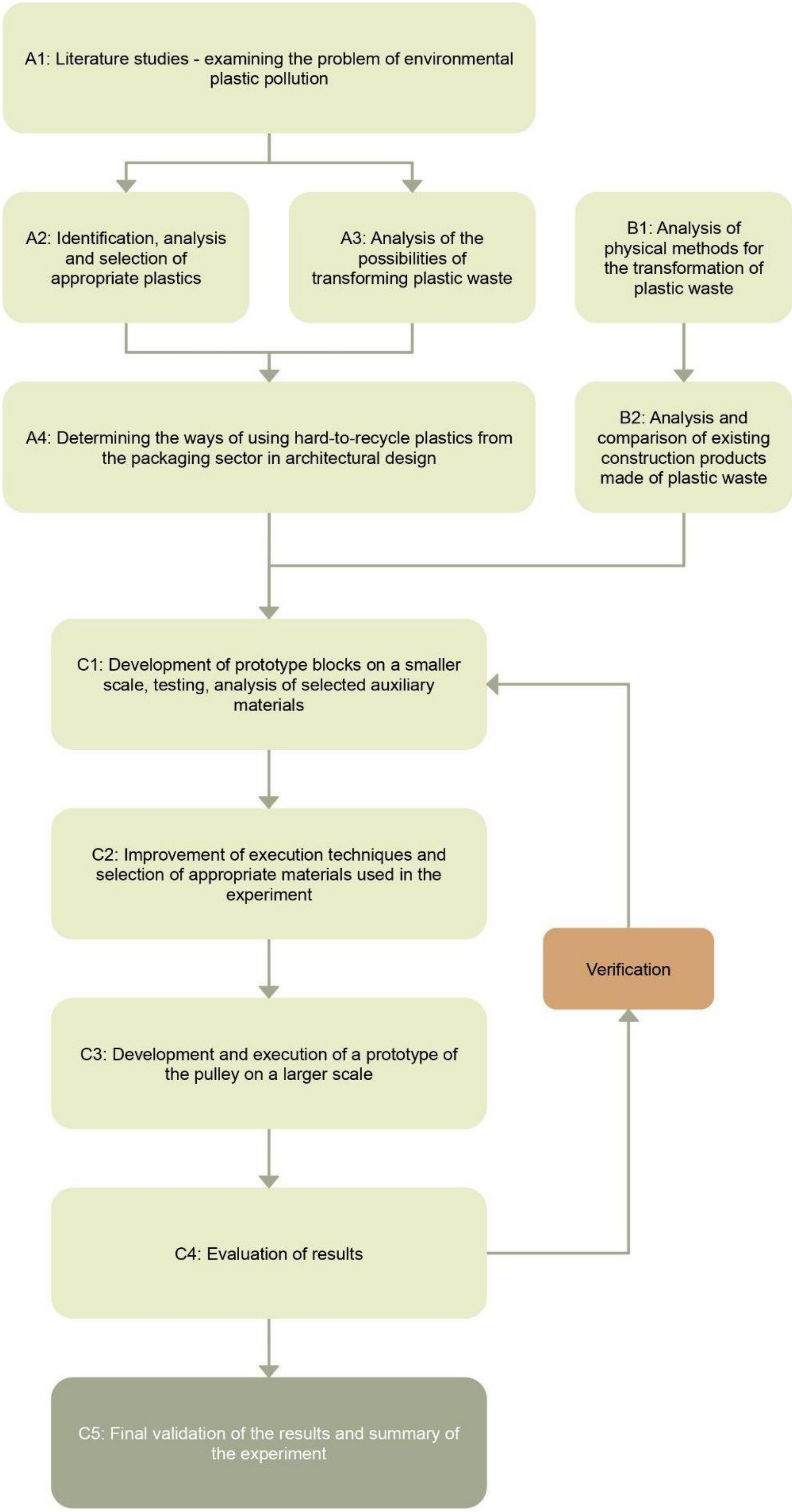

Figure 1. Research design—method explanation diagram.

The next stage in the research process was determining how to use hard-to-recycle plastic packaging waste in architectural design and analyzing existing construction products made from this material. There is growing interest in architecture and construction using hard-to-recycle plastic waste as a building material. One way to use hard-to-recycle plastic packaging waste in architectural projects is to incorporate it into building materials such as bricks, insulation, and cladding. Currently, only some products on the construction market are made from hard-to-recycle plastic waste. Analysis and comparison of existing construction products made from plastics provided valuable information on the potential uses of hard-to-recycle plastic packaging waste in architectural design. By examining these products' characteristics, performance, and environmental impact, information was obtained on innovatively using plastic waste.

The last step focused on improving the study's design, materials, and manufacturing techniques. The concept is still being developed to optimize the entire manufacturing process as effectively as possible. Next, the effectiveness and efficiency of the experimental method, tools, techniques, and materials were evaluated and compared with the manufacturing methods of existing plastic construction products. Currently, the research is focused on analyzing the obtained results. In the case of negative results, a procedure has been implemented to reanalyze and improve the production part of the research process.

The final phase of the study validated the results obtained, culminating in a concise summary that facilitates the identification of the assumptions made and the presentation of innovative directions in the design of alternative building materials and related elements. The research aims to create a new building material from plastic waste and effectively generate various design options while reducing environmental pollution. The experiment has the potential for innovative structural elements and significant reduction, primarily in accumulating hard-to-recycle plastic waste and severely degrading ecosystems.

2.1. Materials

The prototypes used only hard-to-recycle plastic packaging waste, so items characterized by more difficult biodegradation were collected: 03 (PVC), 05 (PP), and 07 (OTHER). Due to the lack of an official model for dealing with hard-to-recycle materials, the presented plastics pose the most significant environmental threat. There are exceptions where some companies reuse the mentioned plastics, but some factors still determine that they mainly belong to the group of hard-to-recycle plastics.

In the case of PVC, most products are hard to recycle due to the high chlorine content and high levels of hazardous substances added to the polymer [50,51]. In contrast, as with other homogeneous polymers [52], the main problems with recycling PP arise from its easy degradation during its lifespan and processing. Heat, radiation, and mechanical stresses strongly modify the structure and, thus, the properties of polypropylene (PP) [53]. Furthermore, the smell of the product that the recycled PP housed in its first life is difficult and expensive to remove. Some odors, such as gasoline or moldy food, are particularly repulsive. The last group of materials used to create the prototypes are plastics marked 07. Since they are combined with other types of plastics that do not qualify for the previous six categories and also often contain residues, such as foils or food contamination, they are almost impossible to recycle. The process is also hampered by the content of the toxic chemical compound BPA (Bisphenol A), which cannot be verified by the label on the packaging alone [54]. Attempting to recycle this type of low-quality plastic is a costly procedure that yields materials of lower value than initially, so recycling them is probably not cost-effective.

The collection of suitable plastics, which was the first step in the entire production process (Figure 2), required accumulating many plastic samples with predefined specifications. Based on the identification code located on a given product, it was possible to check whether the item met the research requirements. PVC, PP, and OTHER samples, which are plastic packaging intended for consumer purposes, were obtained from the post-consumer polymer waste stream from private entities in Poland. With the help of private entities and their contributions, about 50 kg of plastic was obtained as packaging from various food or beverage corporations. Due to their ubiquity, these products are much easier to obtain and are the most common items littering the environment. Then, the collected materials were properly prepared to be as suitable as possible for thermal processing. It is recommended to thoroughly clean all products of dirt and additional substances such as foil, paper prints on packaging, or other materials that do not fit the characteristics of the study.

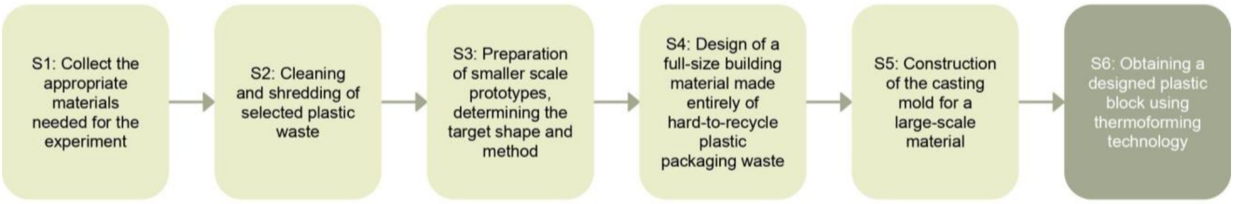

Figure 2. The production process of the experiment—individual stages explanation diagram.

In addition, various material options were considered in the prototype manufacturing process to design the casting mold in which the large-scale block was to be made. Alternatives to steel were considered to provide greater design flexibility and reduce production costs, among other things. The considered materials included substances with lower thermal conductivity and lower combustion points, i.e., wood or wood-based materials. However, after a thorough analysis, it was decided to reject these options due to their limitations. Materials with organic thermal conductivity or low combustion temperatures may not meet expectations regarding strength, durability, and safety. Ultimately, metal materials were chosen for their adequate thermal strength, stability, and other necessary properties like uniform heat conduction and resistance to mechanical damage, regardless of material costs and available production technologies.

2.2. Sample Preparation

In the initial phase of the study, smaller prototypes were created using various sets of material tools. Small samples were preferred due to lower material costs and reduced energy consumption during testing. The research attempted to use a material other than steel for the mold to provide greater design flexibility and cost reduction. Unfortunately, the alternative materials were rejected due to organic thermal conductivity or low melting temperatures.

Sample number 1 (Figure 3) utilizes finely crushed pieces of plastic packaging waste and a wooden casting mold to give it a cylindrical shape. The sorted plastic materials were mechanically shredded into small fragments, i.e., avg. 1.5 × 1.5 cm, and the wooden mold was lined with a thin piece of parchment paper coated with grease. This procedure prevents the plastic pieces from sticking to the walls. Then the model was filled with crushed plastic fragments and placed in a laboratory chamber furnace type FCF 57 heated to 250 °C. The first attempt resulted in a cylindrical prototype with a diameter of 10 cm and a height of 3 cm.

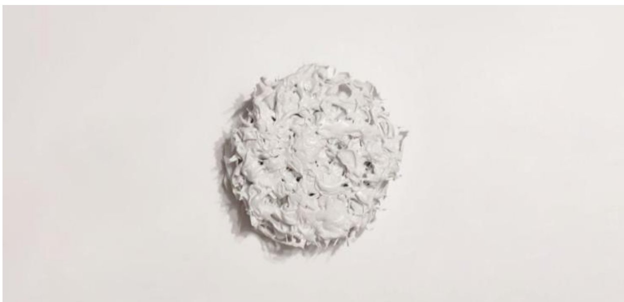

Figure 3. The first attempt at making a product from hard-to-recycle plastics from the packaging sector, formed in a wooden mold.

In sample number 2 (Figure 4), shredded pieces of plastic packaging waste were still used, only in a larger format (avg. 3 × 3 cm), along with a metal mold. The significant difference in preparing this sample was the method of arranging the chopped plastics. Instead of filling the entire mold with plastic at once, a layered approach was adopted. This involved adding another layer of plastic waste immediately after melting the previous layer. The process's remaining steps matched the process for sample number 1. As a result of the second test, a plastic cuboid was obtained with a length of 22 cm, a width of 9 cm, and a height of 3 cm.

Figure 4. A sample product from hard-to-recycle plastics formed in a steel mold.

Both mixtures from hard-to-recycle plastic packaging waste were melted at 250–300 °C. The selected temperatures allow for the desired physical properties, i.e., sufficient plasticity to ensure their re-formability, because the chosen values are classified in the range of their melting or degradation points. Additionally, the processing temperatures enable the appropriate viscosity of the individual fragments, which is necessary for their homogeneous fusion. Higher temperatures would destroy the test material due to thermal degradation, while lower temperatures would reduce the strength of the material caused by the incomplete fusion of the shredded plastics. For polypropylene, liquefaction of the material occurs at 160 °C, and complete thermal degradation occurs at 345–493 °C [55]. For PVC, the melting value is 150–220 °C, and the total degradation of the material practically occurs after exceeding 360 °C [56,57]. However, these are generally accepted temperatures; in reality, the melting point may vary due to the composition of the plastic waste used. The presence of various additives, such as stabilizers or fillers, can affect the temperature resistance of the product.

When working with a material such as plastic, it is essential to be mindful of the risk of volatilizing hazardous chemicals produced by burning plastic materials. It is worth noting that both the sampling stage and the actual experiment consisted solely of melting the previously prepared fragments so that they could stick together. Furthermore, the entire research was conducted in a secluded room with special equipment to minimize the risk. The room was equipped with local exhaust ventilation (LEV), which ensures adequate toxic air ventilation, and extraction filters using activated carbon (ACFs). Thanks to the active carbon content, ACFs can easily remove the following unpleasant volatile organic compounds (VOCs): toluene, xylene, styrene, alcohol, benzene, decane, ethylbenzene, heptane, and octane, and the following gases: pentane, acetone, and hexane [58].

Based on the results obtained from the initial prototypes, the next stage of the study was improving production techniques, selecting appropriate materials used in the experiment, and creating a prototype on a larger scale. Before starting production, the final shape of the block was developed using the industry-standard AutoCad design software (version: S.51.0.0). The target structure of the block (Figure 5), due to its decorative function, is characterized by a simple geometric shape with a variety in the form of a centrally located triangular opening, which changes its size depending on the direction of view. The front of the solid is based on a 35 × 35 cm square, while the thickness is set at 15 cm. In the case of the centrally located opening, the larger triangle on one side has perpendiculars of

25 cm. At the same time, the smaller one is determined by the ratio 3:2. In both cases, the hypotenuse results from the assumed perpendiculars.

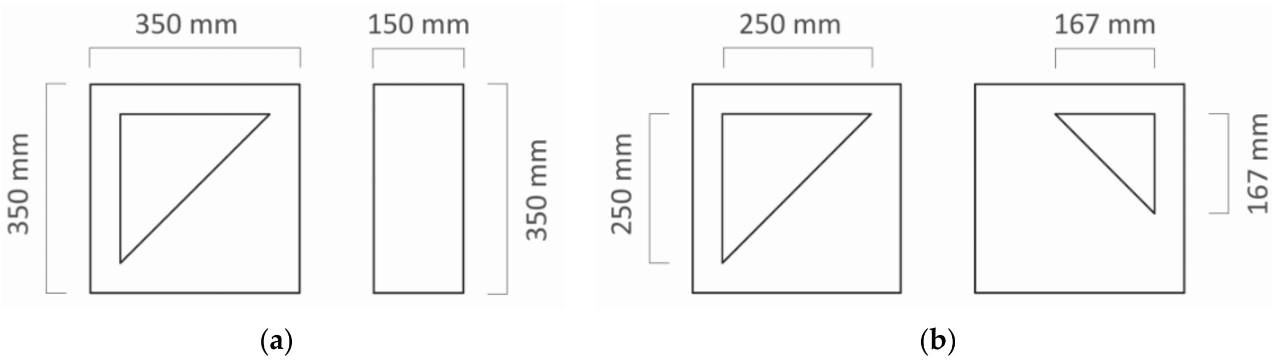

Figure 5. Dimensions of individual block design elements: (**a**) main dimensions; (**b**) dimensions of the designed opening.

After designing the model, the production process began. The previously cleaned plastic packaging waste was shredded into pieces of relatively similar sizes to those used for sample number 2. It is not recommended to use plastics in their original shape or in huge fragments due to the uneven melting of the element. Moreover, it is not advisable to combine various polymers due to their different chemical or electronegative properties. However, this does not pose a significant threat to their correct integration since the plastics used have different percentages in the composition of the prototype. The dominant polymer forming the base of both the smaller samples and the full-size prototype was polypropylene (PP), which accounts for about 60–65% of the total given sample. The remainder comprises PVC (03) and OTHER (07) plastic admixtures.

Then, based on the model developed in the AutoCad program, each component was thoroughly analyzed, and the dimensions of the parts needed to construct the casting mold were determined on a metal plate. The samples showed that wood is unsuitable for heat treatment experiments due to its low thermal conductivity. Metal melts plastic waste inside the mold faster due to its lower resistance to high temperatures. The designated parts were cut from galvanized steel sheets, cleaned, and joined together by welding the individual edges. The constructed design (Figure 6) was then polished. This action reduces the risk of damaging the mass from the inside and eliminates the rough surface, ensuring safety for users.

Figure 6. A steel casting mold made to produce a full-size prototype.

The final step of this research phase was to create the designed block using the previously prepared components. Before filling the mold with pieces of hard-to-recycle plastic from the packaging sector, it was adequately protected with previously tested greased paper to prevent damage to the poured material. Paper is an excellent alternative to greasing emulsions such as oil, grease, or protective accessories (aluminum foil). The actual experiment was then conducted. Since the chosen technique involves thermoforming, the prototype was made in a laboratory chamber furnace type FCF 57 with low energy consumption at a temperature of 250–300 °C. Once the device reached the specified temperature, the first layer of shredded plastic waste was placed on the protected structure. After melting the first layer, the next layer was added to the top. This process was repeated until the designed dimensions were achieved, especially the specified thickness. The layering method allowed for the even distribution of plastic waste and precise melting, forming smooth, solid outer walls of the developed block. After melting the final layer, the entire block was exposed outside to cool down. Once the sample was cooled and removed from the mold, it was cleaned of any unnecessary residues.

Manufacturing the plastic block into a full-size building material took about 6 h, or statistically, about 10–15 min for each layer to melt. In addition, from the collected and sorted 50 kg of hard-to-recycle plastic packaging waste, about 18 kg of finely cut plastic fragments were enough to construct a larger-scale prototype. Except for the preparation stage of the collected waste, which required accurate precision, the production process proceeded without any problems.

Because the study focused on producing facade blocks, examining how the individual blocks would connect was essential. As the survey required a single full-sized prototype, no proposals for combining blocks were suggested. Nonetheless, several methods were presented to implement different structural systems. One of the methods of joining given facade blocks made of hard-to-recycle plastics from the packaging sector is the use of adhesive. The process would involve applying solid glue or resin to the edges of the blocks and then pressing them together to create a secure connection. Another method is welding, which involves melting the edges of the blocks with a heat gun and pressing them together to achieve a uniform fusion. This method creates a combination resistant to weather conditions and can help create a more cohesive facade. The last proposal is possibly connecting the individual facade blocks using mechanical fasteners, which involve using screws, bolts, or other types of steel elements to secure the blocks together. This method tends to be more labor-intensive, but it can provide the most robust and durable connection. In general, how individual facade blocks made of plastic waste are joined together will depend on the specific requirements of the project and the desired aesthetic effect. Choosing a method that ensures a safe and durable connection is essential, considering factors such as weather resistance and ease of assembly.

3. Results

This study aimed to develop and evaluate a new building material made entirely from hard-to-recycle plastic materials from the packaging sector, which could effectively serve as an alternative to traditional construction methods or structural elements. One of the most severe problems facing modern civilization is environmental pollution and poorly organized waste management in some countries. Therefore, the proposed product was intended to minimize plastic waste in nature, especially that which is not easily subject to recycling processes, by using them to produce the concept presented in this article or another design variant.

3.1. Appearance of the Obtained Material

The thermoforming process resulted in a full-size product (Figure 7), consistent with the samples' results and the previously established design assumptions. The block consisted solely of waste unsuitable for recycling, utilizing waste identified under numbers 03, 05, and 07. From the beginning, the designed block was intended to serve a function related to architectural detail. Therefore, the dimensions and appearance replicate an actual construction module, emphasizing its practical usefulness.

(**a**) (**b**) (**c**)

Figure 7. The full-size prototype view: (**a**) bottom surface under pressure; (**b**) side; and (**c**) top surface uncompressed.

The block is a rectangular solid with 35 × 35 × 15 cm dimensions. A characteristic feature is the internal triangular hole, which, depending on the viewing direction, is larger from one side and proportionally smaller from the other. This procedure gives the prototype a certain dynamism and emphasizes its three-dimensionality or originality compared to other materials of similar origin. In addition, the designed opening and color scheme allow for shaping compositional arrangements such as walls, fences, or other objects. Due to the high production flexibility in the design and colors, these blocks can be customized according to the user's preferences and material resources.

3.2. Block's Physical Properties

When expressing the intention to introduce the designed construction product to the service market, conducting a series of specialized tests is necessary to obtain the appropriate technical documents. One such certificate confirms whether the product is suitable for use during construction work in a manner corresponding to its functional properties and purpose. It is important that the functional properties of materials implemented in the building have a decisive impact on ensuring the basic requirements for safety, construction, and use within and through it.

Due to the inability to conduct specialized strength or chemical tests, the sample underwent examination for fundamental material properties such as weight, odor, absorbability of the first contact with water, and reaction to fire. Compared to traditional construction blocks such as concrete blocks, the full-size conglomerate is characterized by a low weight of about 11 kg. This lightweight feature is unlikely to present any issues during construction activities. Subsequently, the sample was assessed for odor, considering that plastic melting can produce an unpleasant smell. The thermoforming process in preparing raw materials may occasionally generate an unpleasant odor, though it was not intense or irritating enough to disrupt the experiment. The unpleasant odor dissipated only after the completion of the research process and the cooling of the sample. The absence of odor emitted from the block would not impact the perception of the space in which it is installed.

Water absorption refers to a material's ability to absorb moisture from its surroundings and is an essential aspect in the processing of thermoplastics. Plastics generally have a limited ability to absorb water, with the extent of absorption influenced by factors such as the material type and environmental conditions like temperature, humidity, and the duration of liquid contact. Polymers such as PEEK, PPS, PSU, PPSU, PEI, PVDF, PET, PVC, PP, and PE demonstrate low water absorption [59]. Conversely, polystyrene (PS) and polycarbonate (PC) exhibit a considerably higher level of absorbency, leading to an increase in their overall mass. Semi-crystalline plastics, such as POM, PA, PET, and PBT, have better properties than amorphous materials, but due to their hydrophilic properties, they can absorb water into the structure [59,60].

Given that the block comprises various polymers and functions as a conglomerate of hard-to-recycle plastic waste, determining its water absorption level definitively from a chemical standpoint is challenging. Since the composition of the full-size prototype is dominated by a plastic marked PP and the rest is present as admixtures, it can be assumed that the block is characterized by low water absorption. To confirm the high water impermeability, a small test was performed to evaluate the prototype's direct response to water. The fabricated block was placed in a container filled with water and then left for a full day. When the sample was removed the next day, it was weighed, and its weight was compared to the original to see what percentage of its weight had increased. The weight of the material before the test was 11 kg, while after the experiment its weight increased by about 1 g, which indicates the block absorbed less than 0.01% of its weight in water during the 24-h immersion test.

In the case of a temperature test involving exposing the material to everyday temperatures on a hot, sunny day, the prototype did not experience any material losses in the form of deformations. A different reaction occurs when the product is exposed to fire or temperatures exceeding 300 °C. The surface layers slowly deform due to the melting effect. When a flame is applied directly to a sample fragment, it only takes a few seconds to see the first effects of localized material softening. In addition to rapid melting, the material may be slightly charred due to the progressing combustion reaction. On the other hand, very low temperatures do not significantly affect the shape, structure, or level of deformation of the obtained sample.

In the experiment's next stage, several specialized tests should be performed to check the block's physical, mechanical, and chemical properties. Regarding physical properties, it is important to check water absorption, hygroscopicity, frost resistance, and thermal expansion. This will allow us to determine the capabilities of the manufactured prototype, especially during extreme weather conditions. Then, strength tests should be performed, which are necessary to determine the mechanical characteristics. Compression, tension, and bending will decide whether or not it is resistant to destruction under external forces. The last tests necessary for the further development of the research process are chemical tests. Determining the features in terms of chemical composition will check the material's resistance to fire or loss of original material properties, known as aging resistance. This article focuses on the research part related only to constructing a facade block made of hard-to-recycle plastic packaging waste, so no specialized tests were carried out at this stage, which translates into a lack of data in the context of technical characteristics. However, to decide whether the manufactured prototype is suitable for construction use, further research will be conducted to check its strength and plastic properties.

3.3. Comparison with Other Similar Products

Despite being just a prototype, the research defining the characteristics of the decorative block showcases a commendable blend of building function, environmental aspects, and aesthetic appeal. When compared to other materials fashioned from varying degrees of recycled plastic waste, it becomes evident that the designed block encounters significant competition, particularly on a global scale. Among the most notable patented products are the Silica Plastic Block (Rhino Machines and R+D Studio, Anand, India), Gjenge (Gjenge Makers, Nairobi, Kenya), and ByBlock (ByFusion, Los Angeles, CA, USA). The Silica Plastic Block, for instance, is an eco-friendly building brick composed of 80% construction waste like sand, dust, and small rubble fractions and 20% mixed plastic waste. Its production involves crushing collected plastic waste and blending it with dust in specific proportions before passing the mixture through an extruder to form a compact and sturdy mass.

Another noteworthy product is the Gjenge brick, crafted from a mixture of sand and plastics categorized as HDPE (number 02) and LDPE (number 04). The production entails gathering suitable plastic waste, employing cutting-edge technologies for processing, and blending it with sand to attain the desired shape. These bricks are primarily designed for road infrastructure purposes. ByBlock represents another innovative building product in the construction industry. Its production occurs in three stages. Initially, used waste, predominantly sourced from aquatic environments, is collected, encompassing items like plastic bags (LDPE), water bottles (PET), paper, cardboard, fishing nets, rubble, and marine debris. The collected raw materials are then crushed and shaped into blocks using a compressing machine. The final blocks share similar dimensions to standard concrete blocks, approximately 40 × 20 × 20 cm.

Each product mentioned above has unique characteristics, presenting opportunities and potential challenges. The block developed through this research stands out primarily due to its composition, which exclusively incorporates used plastic packaging waste that is not easily subjected to recycling processes. Additionally, it offers high flexibility, allowing for the selection of colors and textures. The chosen thermoforming technique enables block customization according to individual preferences, requiring carefully selected raw materials, desired forms, and cooling methods. This adaptability renders the block suitable for various applications such as partition walls, retaining walls, facade enhancements, or urban furniture (Figure 8). These distinctive properties underscore the differences between the prototype created during the research and existing patented products.

Figure 8. Example application of the block made from hard-to-recycle plastic waste from the packaging sector in the form of architectural detail—visualization by Klaudia Kropisz.

4. Discussion

Analyzing the blocks made regarding strength tests is necessary in the next stage. This aspect of the blocks is related to fire resistance, load-bearing capacity, and obtaining approval for their use in construction. However, this is a further path, and the current experiment aims to create a proof-of-concept solution—using secondary material or achieving an attractive contemporary aesthetic. The findings presented in this research paper underscore the significance of integrating hard-to-recycle plastic waste into architectural design practices to address the pressing environmental challenges associated with plastic waste. Several key insights have emerged through a comprehensive examination of the ecological implications and sustainability considerations of utilizing hard-to-recycle packaging plastics.

Firstly, the analysis reveals that repurposing hard-to-recycle plastic waste from the packaging sector as building materials offers a viable solution to mitigate the adverse impacts of plastic waste on the environment. By diverting these materials from landfills and oceans, architects and designers can contribute to reducing the overall burden of plastic pollution while promoting resource efficiency and circular economy principles within the construction industry. Moreover, the study highlights the importance of interdisciplinary collaboration and knowledge exchange in advancing sustainable architectural practices. By fostering dialogue between architects, engineers, environmental scientists, and policymakers, stakeholders can collectively identify opportunities and address challenges associated with integrating hard-to-recycle plastics in architectural projects.

Furthermore, the study emphasizes the need for innovative design strategies and construction techniques to optimize the environmental performance and longevity of plastic-based architectural solutions. By prioritizing durability, recyclability, and lifecycle considerations in the design process, architects can ensure that plastic-based building materials contribute to a more sustainable built environment over the long term. Additionally, the study underscores the role of policy interventions and regulatory frameworks in incentivizing the adoption of environmentally conscious architectural practices. By implementing measures such as tax incentives, green building certifications, and waste management regulations, policymakers can create an enabling environment for the widespread adoption of plastic waste reduction strategies in the construction sector.

Finally, the study acknowledges the importance of ongoing research and continuous improvement in refining plastic waste management techniques and advancing sustainable architectural design practices. By embracing a culture of innovation and learning, stakeholders can remain at the forefront of sustainable development efforts and contribute to shaping a more resilient and sustainable built environment for future generations. Due to their ease of use, blocks made from hard-to-recycle plastic packaging waste may gain attention as a potential alternative to traditional building materials. However, several doubts should be addressed before the construction market accepts the block.

One of the main problems with using plastic blocks is the chance of creating micro- and nanoplastics. Since the manufactured prototype is ultimately intended for use outdoors, fine plastic particles can form under heavy stress, such as wind, weather, or temperature changes. While there is a significant chance that no additional substances will come out of the block, this requires further testing. In turn, if this type of situation occurs, additional outer layers may need to be added to prevent the release of microplastics, or the block's manufacturing process may need to be adjusted. At this point, these are only suggested solutions to the potential problem. However, to more accurately determine the possibilities, such an experiment should also be included in the next research stage.

Its fire resistance is another problem when building various self-supporting structures from the abovementioned material. Plastics are highly flammable, and their use in construction can pose a severe threat to the environment and users in the event of a fire outbreak. In this case, adding appropriate flame retardant additives to the plastic blocks during thermoforming or applying appropriate fire retardant paints to the finished product would significantly increase their fire resistance and meet safety standards. Load-bearing capacity is another essential factor when evaluating the suitability of blocks made from hard-to-recycle plastics in the construction industry. Although plastic blocks are relatively light and easy to install, they may need more structural strength to support heavy loads acting on the building. Detailed tests and analyses should be conducted to determine the maximum weight the blocks can bear.

Moreover, in addition to their fire resistance and load-bearing capacity, the approval of blocks made of hard-to-recycle packaging plastics for construction depends on their environmental impact. Sustainable development is becoming the top priority in the construction industry, so the benefits and drawbacks of using these materials must be carefully considered along with regulatory compliance and the consequences of production or disposal. Although hard-to-recycle plastic blocks offer promising benefits as building materials, several key issues must be resolved before their widespread introduction into the construction market. Fire resistance, load-bearing capacity, and some environmental considerations are critical factors that should be further analyzed in ongoing research to address concerns about their environmental impact and general approval for construction use. By solving these problems, developers can make informed decisions about using hard-to-recycle plastic blocks as an alternative option in the construction industry.

5. Conclusions

In conclusion, utilizing hard-to-recycle plastic waste from the packaging sector in architectural design offers a concrete solution to mitigating plastic pollution while advancing sustainability in construction. Research shows that repurposing these plastics can reduce waste and enhance resource efficiency. Specifically, plastic-based building materials provide notable advantages in durability, lightweight properties, and ease of transport and installation, making them cost-effective and practical alternatives to traditional materials.

However, addressing fire resistance, load-bearing capacity, and regulatory approval remain essential to fully integrating these materials into construction practices. Fire resistance is critical to ensuring the safety and longevity of structures. Thus, future research should focus on developing and testing fire-retardant treatments for plastic-based materials. Similarly, understanding and enhancing the load-bearing capacity of these materials is crucial to ensuring they meet the structural requirements for various construction applications. Regulatory approval processes must be streamlined, with clear guidelines and standards established to facilitate the adoption of plastic-based materials in the industry. Despite these challenges, the study demonstrates that using plastic waste blocks in structural elements can significantly cut construction costs and complexity, offering a promising outlook for the industry. These blocks are not only lightweight and durable but also reduce transportation and installation expenses, leading to increased efficiency and productivity, especially in large projects with stringent time and budget constraints. For instance, the ease of handling and quicker installation times can help meet tight project deadlines and reduce labor costs. The economic benefits extend beyond initial cost savings. Unlike traditional materials such as wood and metal, plastic-based materials can have lower long-term maintenance and lifecycle costs due to their resistance to corrosion and degradation. This makes them a sustainable choice for various climatic conditions and environments, potentially reducing the overall environmental impact of construction projects.

Further research on the life cycle analysis of plastic blocks is crucial to establishing their viability in green building practices. This involves assessing their environmental impact from production to disposal and exploring their potential for recycling at the end of their lifecycle. Understanding the complete environmental footprint of these materials will help optimize their design and usage, making them an integral part of sustainable building strategies. It is also important for stakeholders to recognize their role in advocating for policy interventions and regulatory frameworks that promote environmentally conscious architecture. Measures such as tax incentives for using sustainable materials, green building certifications that recognize innovative uses of plastic waste, and enhanced waste management regulations that encourage recycling and repurposing are critical. Policymakers need to create an enabling environment that supports the widespread adoption of plastic waste reduction strategies in construction. Collaboration between industry, government, and research institutions is essential to solving these changes and ensuring that regulatory frameworks keep pace with technological advancements. By actively participating in these discussions and advocating for change, stakeholders can play a significant role in shaping the future of sustainable construction.

In summary, integrating hard-to-recycle packaging plastics into architectural design is a viable and promising approach to building a more sustainable and resilient environment. Through continued innovation, collaboration, and research, the construction industry can significantly reduce plastic waste, conserve resources, and align architectural practices with sustainability and environmental stewardship principles. By embracing these strategies, we can move towards a future where plastic waste is effectively repurposed, leading to ecological, economic, and social benefits. This holistic approach is essential for creating a built environment that is resilient, efficient, and sustainable for future generations.

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