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Technical Properties of Constructive Boards Made from Tetrabrik Waste

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Abstract

This study aims to determine the physical and mechanical properties of boards developed at the Centro Experimental de la Vivienda Económica (CEVE, Experimental Center for Economic Housing) from unshredded Tetrabrik waste. The boards were produced via thermo-compaction, using the polyethylene from the outer layers of Tetrabrik containers as a binder. Their intended application is as wall panels for social housing. The performance of these new boards was compared with that of conventional market-available boards of similar use - specifically, particleboard and OSB- in terms of flexural strength, water absorption, and fire resistance. The Tetrabrik specimens were molded at 110°C, 140°C, and 200°C. The best overall performance was achieved at 140°C. In flexural strength, boards pressed at 140°C reached 27 MPa, outperforming the best traditional board tested, which reached 16 MPa. In water absorption, the 140°C Tetrabrik boards absorbed 32% less water than particleboard and 69% less than OSB. In fire resistance testing, the Tetrabrik boards performed well thanks to their multilayered composition, in which the aluminum layer acts as a flame-retardant. These results demonstrate that it is possible to produce a construction material made entirely from Tetrabrik waste, offering clear technical advantages over the conventional boards studied.

Keywords
Tetra Brik; Tetra Pak; social economy; waste valorization; boards; social housing; recycling

1. Introduction

In Argentina, 55630 t of municipal solid waste (MSW) are generated daily, averaging 1.21 kg per person per day. More than 45% is improperly treated and disposed of, causing serious damage to public health and the environment. This is a growing problem, as it is estimated that the generation of MSW in Argentina in 2027 will be 63000 tons daily [1, 2].

In this context, a difficult-to-recycle MSW type is Tetrabrik packaging, one of the most widely used packaging types in the world. According to data from Tetra Pak Company, in 2023, it sold 179 billion Tetrabrik-type packages worldwide. Tetrabrik is a multilayer material composed of 75% cardboard, 20% polyethylene, and 5% aluminum. The separation of these materials for their recycling requires high-cost technologies, resulting in a low recycling rate, as these packages are generally thrown into landfills or incinerated. As a consequence, the company Tetra Pak promotes improvement initiatives to manage this MSW, and although it recovers nearly 50 billion packages per year, this represents only 28% in the total production [3].

However, ongoing research and technological innovations offer promising solutions to improve the recyclability of multilayer packaging [4]. One of these is upcycling, which involves converting waste materials into higher-value products, thereby extending their useful life and reducing waste. Unlike traditional recycling, which often degrades materials, upcycling enhances their utility or aesthetics by creating more valuable items from discarded materials. Successful examples include transforming packaging into furniture or construction materials. These initiatives not only reduce waste sendt to ending up in landfills but also conserve resources and promote sustainability [5].

Currently, there are different upcycling alternatives for Tetrabrik waste, some of which are already available on the market, while others are still in the experimental phase. Regarding the commercial alternatives, the principal ones are: the fabrication of sheets of Polyaluminum, using a Hidropulper machine, which separates the cellulose fibers, polyethylene, and aluminum. This material can be used to manufacture corrugated sheets via a thermal process or converted into pellets [6, 7].

Another commercial proposal is the production of boards composed of Tetrabrik packaging crushed into particles from 1 to 5 mm, which are hot-pressed; additives that serve as binders are generally added. These boards can be used as non-load-bearing enclosures and for furniture manufacturing. In the last 30 years, many factories have been built around the world, mostly small-scale, to manufacture panels from crushed Tetrabrik packaging, with brands such as T-PLAK® in Argentina, Reciplak® in Brazil, Tetrabuild® in Chile, Chiptec in China, Ecoplak® in Colombia, Novapak and PackWall in the Czech Republic, Greenpak in Ecuador, Ecolink in India, Lamiboard in Kenya, saveBOARD in New Zealand, Green Board in Pakistan and Thailand, TeRO® in Poland, Tetra K1® in Slovakia, Maplar® in Spain, Yekpan in Turkey, and Everboard and Kelly Green Products in the U.S. Some process only Tetrabrik packaging, while others also include plastic-coated paper products, such as cups [8, 9].

Some proposals in the experimental phase share the common goal of producing non-load-bearing insulating boards for construction: the report by Yilgor *et al.*, on boards composed of crushed Tetrabrik packaging produced by hot pressing and then cooled at room temperature. The dimensions of the manufactured boards were 5 × 5 × 1.8 cm. The research demonstrated that the cellulose and LDPE fractions present in composite panels manufactured from discarded Tetrabrik packaging exhibit distinct responses to fungal attack and photo-degradation. Surface deterioration due to light exposure was limited to the outer layers of the samples, whereas biological degradation extended throughout the entire thickness of the material. The degradation mechanisms were analyzed using FT-IR ATR spectroscopy. Additionally, the study evaluated the incorporation of 1-10% zinc borate (ZnB) into the panels to enhance resistance to fungal decay and improve fire performance. Fire testing results indicated that ZnB contents above 10% are required to achieve satisfactory fire resistance. Because untreated panels show limited resistance to fungi and significant water absorption, their use is more appropriate for indoor environments. The authors suggest that adding 1% ZnB can improve durability when these materials are intended for outdoor applications [10]. Tetrabrik cartons, both with and without aluminum layers, were mechanically recycled to produce thermoplastic composites composed of recycled polyethylene and ground Tetrabrik in proportions ranging from 20 to 90 wt%. The study examined how varying the formulation influenced the material's morphology, thermal performance, mechanical behavior, and water absorption. Results showed that when the Tetrabrik content exceeded 80 wt%, the fibrous character of the filler became the dominant factor governing the composite properties. Maleated polyethylene was incorporated as a compatibilizing agent, and its positive effect on enhancing the mechanical performance of composites containing up to 60 wt% Tetrabrik was demonstrated. Overall, the mechanical response of the developed materials spanned from values typical of lightly filled polymer/wood or polymer/cellulose systems to those characteristic of highly fibrous products (such as particleboards and fiberboards) at the highest Tetrabrik loadings (80-90 wt%) [11]. Sandwich panels with aluminum face sheets were produced using two different core materials: one composed of polyethylene, aluminum, and cellulose derived from recycled Tetrabrik and HDPE containers; the other core made exclusively from recycled Tetrabrik. Mechanical testing showed a similar tensile stiffness. Under flexural loading, both systems behaved similarly, with the response mainly governed by the aluminum face sheets. From a thermal perspective, the polyethylene, aluminum, and cellulose core displayed lower thermal conductivity, attributed to its higher cellulose content [12]. More recently, this Tetrabrik-based composite was assessed at full scale for use as a structural building component. The seismic behavior of a complete moment-resisting frame housing unit, fabricated entirely from recycled Tetrabrik panels, was experimentally investigated. This work proposes an innovative strategy for incorporating waste-derived materials into structural systems, highlighting the lightweight and modular characteristics nature of the construction. The findings demonstrated a strong seismic response of the housing system. A key contribution of the study lies in being among the first to conduct shaking table tests on a full-scale residential module made from recycled materials, specifically subjected to biaxial excitations. This approach enabled a distinctive assessment of the structure's performance under multidirectional seismic loading conditions [13].

On the other hand, laminated boards manufactured from Tetrabrik containers represent an alternative strategy for producing construction components from this recyclable waste. However, only a limited number of scientific studies have addressed this approach. In this sense, a work reported by Antón *et al.*, who manufactured specimens of 4 × 10 cm composed of between 6 and 10 polylaminated packaging. The production method involves joining multiple layers through the sequential application of heat and pressure, allowing the polyethylene to melt and act as the bonding agent, without incorporating additional adhesives. The study examines how factors such as temperature, applied pressure, processing duration, and the number of layers influence the material's mechanical performance. Reliability was assessed using Weibull analysis, applying with different failure estimators to identify the most suitable materials. The findings indicate that the mechanical behavior of this material is comparable to that of wood-based products [14]. It is also worth highlighting the research by Macías Gallego *et al.*, in which the mechanical properties of three types of specimens composed of 15 Tetrabrik packages of different dimensions: 18.5 × 9 mm, 5 × 5 mm, and 10 × 5 mm. The findings indicated that tensile strength ranged from 9.5 MPa to 37.4 MPa. Based on the mechanical characterization, the authors determined that this material is suitable for non-load-bearing applications within the construction sector. Examination of the fracture behavior revealed that the predominant failure modes were fiber pull-out and layer separation, with rupture occurring through a progressive sequence of intralaminar cracking [15]. Bonocore and De Luca studied a thermal method for producing boards composed solely of Tetrabrik packaging. The dimensions of the specimens were 5 × 5 × 1 cm. The thermal manufacturing process was optimized by adjusting variables such as time, temperature, pressure, and the number of polylaminate layers. The results indicate that this method produces panels suitable for sustainable construction. A key advantage is that it requires no chemical adhesives, using only recycled polylaminate sheets as raw material. The panels showed low thermal conductivity, providing insulation performance approximately twice that of polyethylene and three times that of chipboard at equal thickness. In fire tests, combustion was slow and limited to the flame contact area. Unlike polyethylene or chipboard, which burn within seconds, the polylaminate panel remained largely intact even after 300 seconds of exposure. After one hour of water immersion, no significant changes were observed, indicating slow water penetration, a property that can be further improved with waterproof coatings. For industrial-scale production, proper sheet overlapping and control of surface discontinuities between layers are key factors to consider [16]. Recently, this strategy for post-consumer multilayer packaging was also proposed by Morales *et al*., in which the laminated structure of rigid and flexible containers was preserved instead of separating their individual components. The resulting composite boards exhibited mechanical properties and moisture resistance comparable to those of commercial particleboards, while the manufacturing process required neither solvents nor sophisticated equipment. In addition, the effects of processing temperature, pressure, and the proportion of flexible packaging on board performance were investigated, demonstrating the potential of preserving the multilayer structure as an alternative route for producing sustainable construction materials [17].

Following this research line, we propose an alternative strategy for valorizing MSW by developing boards from uncrushed Tetrabrik packaging. The boards are manufactured by a thermo-compaction process in which heat and pressure are simultaneously applied using a hot-plate press, allowing the melted polyethylene layers to act as a natural binder. By eliminating the grinding stage, the process reduces both production time and costs. The resulting panels are intended for use in building enclosures for social housing. The objective of this study is to determine and analyze the mechanical and physical properties of the developed boards and to compare their performance with that of commercially available boards used for similar applications.

2. Materials and Methods

2.1 Production of the Boards

Methodologically, it is an experimental procedure, where the development and subsequent study of a new material composed entirely of Tetrabrik packaging waste are proposed. The process of the board's production consists of the following consecutive steps:

Acquisition of the MSW and preparation: The waste of Tetrabrik packaging was obtained from municipalities in Córdoba, Argentina, which provided the material free of charge, as they currently have no destination for it. Although the stock is variable, availability is constant because it is a type of MSW with low or no local valorization alternatives. The packaging is mainly from milk and wine; both are manufactured by the Tetra Pak company and are generally in good condition with prior rinsing.

The preparation of the MSW is carried out by cutting the upper and lower ends of the packaging and performing a crosswise cut, obtaining a poly-laminated sheet of 30 × 25 cm, as shown in Figure 1. After that, these sheets are washed in concrete mixers in batches of 200 units, to remove the dirt they might still have. Finally, they are dried with air and at room temperature.

Figure 1 Preparation of Tetrabrik packaging.

Manufacturing of the board: For pressing the boards, a hydraulic press was used, with a metallic mold of 30 × 30 cm; inside, a steel plate with thermal insulation and a release agent for plastics was placed. Then, 1 kg of Tetrabrik packaging (40 sheets) was evenly distributed with the aluminum sides facing outward. Finally, another metal plate with release oil was placed, and the mold was sealed with cast iron plates. Between the plates, a 23 Ω resistor connected to a power regulator was placed, to apply heat in a controlled manner, while the material was being compacted. To achieve a uniform temperature distribution, a 5 mm-thick iron plate and a 1 mm-thick stainless-steel plate were placed between the electrical heating elements and the specimen surfaces. In addition, three thermocouples connected in parallel were used to monitor temperatures at three different locations on each plate and to control the electrical heaters through a feedback control system. This procedure can be seen in Figure 2.

Figure 2 Manufacturing process of the boards.

The boards were pressed at different temperatures to establish how this parameter influences their mechanical properties. The set temperatures were higher than the melting point of the polyethylene present in the material [18], up to the maximum temperature that the press was designed to reach, 110°C, 140°C, and 200°C. To achieve these temperatures, the power regulator was set to 50 V for 110°C, 60 V for 140°C, and 100 V for 200°C. Once the desired temperature was reached, the pressing was maintained for 1 hour in all cases. Subsequently, they were cooled and removed from the press.

The selected pressing time was 1 hour under a pressure of 9 kg/cm^2. The amount of packaging used varies according to the desired thickness; in this case, the 40 sheets that make up the board are equivalent to a thickness of 1.8 cm (a thickness commonly used in commercial boards).

Preparation of specimens for tests: Once the material was demolded, the burrs were removed, obtaining boards of 25 × 25 × 1.8 cm. To determine and analyze their mechanical and physical properties, they were cut into specimens with dimensions specified by the corresponding standards, to be subjected to various tests: flexural strength [19], water absorption [20], fire resistance (glow wire test) [21, 22], and determination of density [23]. Specimens were conditioned under laboratory environmental conditions before testing (20-25°C and approximately 40-60% relative humidity). The dimensions of the specimens are shown in Figure 3.

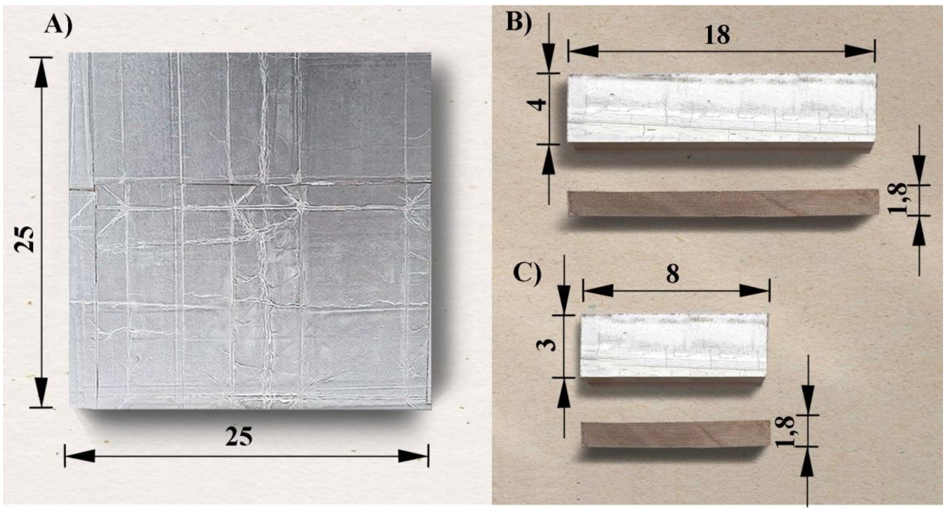

Figure 3 Dimensions in cm of specimens: (A) Resulting board, (B) Specimens for flexural strength test, (C) Specimens for water absorption and fire resistance test.

2.2 Physical and Mechanical Properties

In order to study the properties of the material and comparatively evaluate its performance, specimens of the same dimensions were cut from commercial boards with similar uses: Oriented Standard Boards (OSB), wood particleboard, Polyaluminum, and T-PLAK boards. These specimens were subjected to the tests described below.

2.2.1 Density (ρ)

To determine the density of the boards, the procedure specified in IRAM 9705 was followed [23]. The dimensions of each specimen (length, width, and thickness) were measured to calculate its volume (V, m^3), and its mass (m, kg) was determined. The density was then calculated using the following equation:

$$\rho = \frac{m}{V}$$

After that, the averages for each material were established, along with their corresponding standard deviations and coefficients of variation. The reported values are the mean of five measurements, with the corresponding standard deviation.

2.2.2 Three-Point Flexural Strength Test

The boards were cut into specimens of 18 × 4 × 1.8 cm according to standard ASTM D790-10 [19] and tested in a Shimadzu Autograph® AGS-X 50 kN press (Figure 4). The tests were carried out at a speed of 4 N/s with a maximum displacement of 10 mm. After conducting the test, the Tetrabrik specimens were analyzed with a Binocular Magnifying Glass with a 4× objective lens calibrated to observe the cracks that occurred in them; the apparatus is equipped with a Moticam 1SP camera, which allowed capturing the images. The reported values are the mean of five measurements, with the corresponding standard deviation.

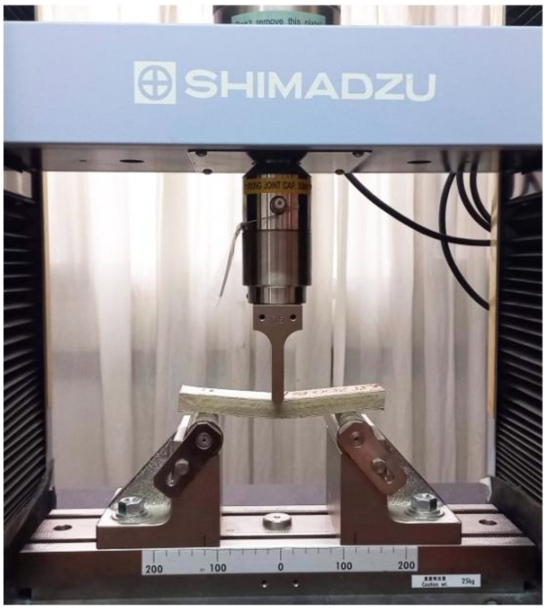

Figure 4 Tetrabrik Specimen subjected to flexural strength test in Shimadzu Press.

2.2.3 Water Absorption Test

The boards were cut into specimens of 8 × 3 × 1.8 cm according to standard ASTM D570-22 [20]. To perform this test, the dimensions of the specimens were measured, and after that, they were placed in an oven at 50°C for 24 hours, removing any excess moisture. Next, their weight was determined, and they were placed in glass jars with distilled water inside. At intervals of 24, 48, 72, 168, and 336 hours, specimens were surface-dried, and the weight was recorded, determining the percentage of water absorption (Figure 5). The reported values are the mean of five measurements, with the corresponding standard deviation.

Figure 5 Water absorption test procedure.

2.2.4 Glow Wire Test

The glow wire test was performed according to standard IEC 60695-2-10 [21]. The temperature range in which this test can be performed is 500°C to 960°C; the initial test temperature is considered just high enough to cause ignition, as defined in IEC 60695-2-13 [22]. Since all the specimens ignited at 700°C, this was the selected temperature. The test begins when the incandescent filament comes into contact with the specimens, which must be maintained for 30 seconds and then removed; within this period, it is observed whether ignition begins in the specimens and whether the fire self-extinguishes (Figure 6). The reported values are the mean of five measurements, with the corresponding standard deviation.

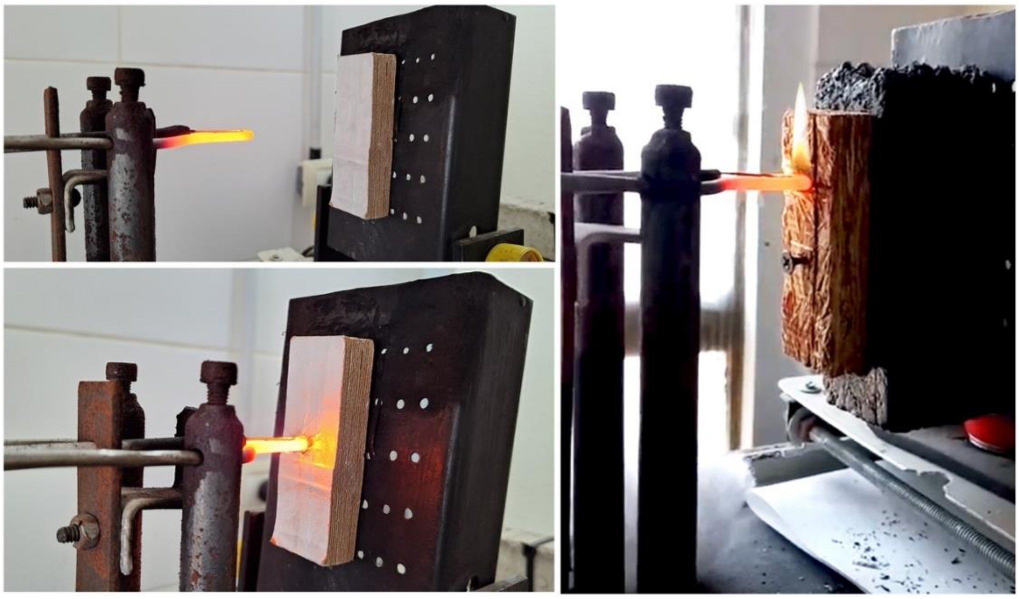

Figure 6 Glow wire test applied over Tetrabrik specimens and OSB specimens.

This test considers the following parameters:

Ignition time (tI): Time from the beginning of the test to the start of the longest-lasting flame event. Measured value. Extinction time (tE): Time from the beginning of the test to the end of the longest-lasting flame event. Measured value. Total flame event time (tT): Duration of the longest-lasting flame event. Calculated value using the following formula:

$$tT = tE - tI$$

Flame time after removal (tR): Time elapsed from the removal of the glowing filament tip from the test specimen to the end of the longest-lasting persistent flame event. Calculated value using the following formula:

$$tR = tE - 30s$$

Flame time during application (tB): Duration of the longest-lasting flame event while the tip of the glowing filament is in contact with the test specimen. Calculated value using the following formula:

$$tB = tT - tR$$

In addition, the flammability classification serves as a reference point to evaluate the fire resistance of materials:

Class V-0: Materials that extinguish quickly, do not allow flame propagation, and do not produce flammable drips.

Class V-1: Materials with a higher tendency to burn, but that self-extinguish within a controlled time and do not produce flammable drips.

Class V-2: Materials that allow flame propagation and/or produce flammable drips.

3. Results and Discussion

3.1 Physical and Mechanical Properties

3.1.1 Density Determination (ρ)

Table 1 shows the averages of the densities of the different specimens, along with their corresponding standard deviation and coefficient of variation.

Table 1 Density of the different boards studied. [a]

Board	ρ (kg/m^3)	Coefficient of variation
Tetrabrik 110°C	(826 ± 2)	0.3%
Tetrabrik 140°C	(847 ± 3)	0.4%
Tetrabrik 200°C	(882 ± 7)	1%
OSB	(664 ± 6)	1%
Particleboard	(756 ± 7)	1%
Polyaluminum	(818 ± 8)	1%
T-PLAK	(906 ± 9)	1%

[a] Values are the mean of five measurements.

As can be observed, the densities of the Tetrabrik specimens increase as the compression temperature rises, with a ρ of 826 kg/m^3 for the specimens pressed at 110°C, 847 kg/m^3 at 140°C, and 882 kg/m^3 at 200°C. In coincidence with the conclusions of the work by Antón *et al.*, it can be deduced that a higher degree of compression is achieved at the highest temperature, producing a reduction in volume due to the compacting of the cardboard layers, which have high porosity, and the possible infiltration of the polyethylene into the cellulose layer [14].

3.1.2 Three-Point Flexural Strength Test

The Tetrabrik specimens, as well as those of Polyaluminum and T-PLAK, behaved elastically, without showing cracks perpendicular to the applied stress, returning to their original shape after the test was completed. This did not occur in the Particleboard and OSB specimens, which cracked, as can be observed in Figure 7.

Figure 7 Particleboard and Tetrabrik specimens after being tested in flexion.

A behavior observed in the Tetrabrik specimens is that, as deformation increases, the specimen begins to fail in a stepwise manner, leading to progressive delamination without abrupt breaking. This behavior was also reported by Macías Gallego *et al.* in laminated Tetrabrik board specimens composed of only five layers [15].

In this regard, it is important to note that an accumulation of porosity (due to variations in the application of pressure during processing) can induce premature delamination under higher loads. The failure occurs more due to the greater number of contact interfaces (PE–PE, PE + cardboard–cardboard) than due to porosity itself [14]. Figure 8 shows the average curve resulting from this test on Tetrabrik specimens, which evidences such behavior; each peak represents the moment when a layer yields under the bending stress. The results of the bending strength test of the studied boards are detailed below in Table 2.

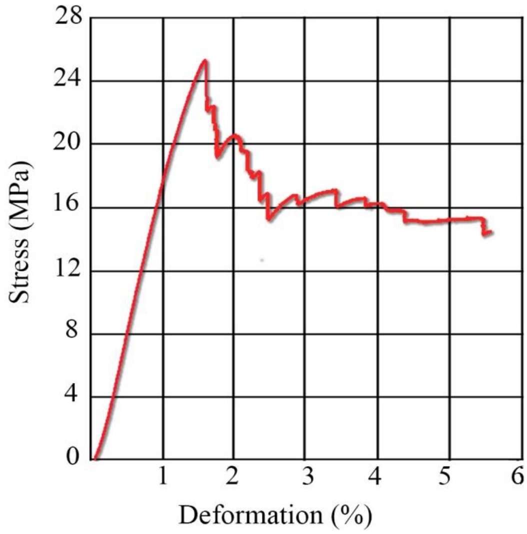

Figure 8 Average curve resulting from the three-point flexural strength test.

Table 2 Comparison of results, bending strength tests. [a]

Board	Bending Strength (MPa)	Coefficient of variation	Elastic Modulus (MPa)
Tetrabrik 110°C	(15 ± 1)	8%	(1.00 ± 0.08)
Tetrabrik 140°C	(27 ± 1)	3%	(2.20 ± 0.01)
Tetrabrik 200°C	(30 ± 1)	3%	(2.50 ± 0.04)
OSB	(16 ± 1)	4%	(1.40 ± 0.05)
T-PLAK	(14 ± 1)	4%	(0.80 ± 0.05)
Particleboard	(14 ± 1)	9%	(2.0 ± 0.2)
Polyaluminum	(10 ± 1)	10%	(0.7 ± 0.1)

[a] Values are the mean of five measurements.

The obtained data shows that as the pressing temperature increases, so does the flexural strength of the Tetrabrik boards, with specimens pressed at 110°C resisting 15 MPa, at 140°C 27 MPa, and at 200°C 30 MPa. In comparison, the OSB specimens had a lower strength with 16 MPa, the Particleboard and T-PLAK specimens 14 MPa, and the Polyaluminum specimens 10 MPa.

On the other hand, as the pressing temperature increases, the elastic modulus also increases. The higher the modulus, the stiffer the material, meaning less elastic deformation occurs under a given stress [24]. Thus, the specimens compressed at 110°C have an elastic modulus of 1 MPa, those at 140°C an elastic modulus of 2.2 MPa, and those at 200°C an elastic modulus of 2.5 MPa. This behavior is evident in Figure 9, which shows the average curves obtained from this test.

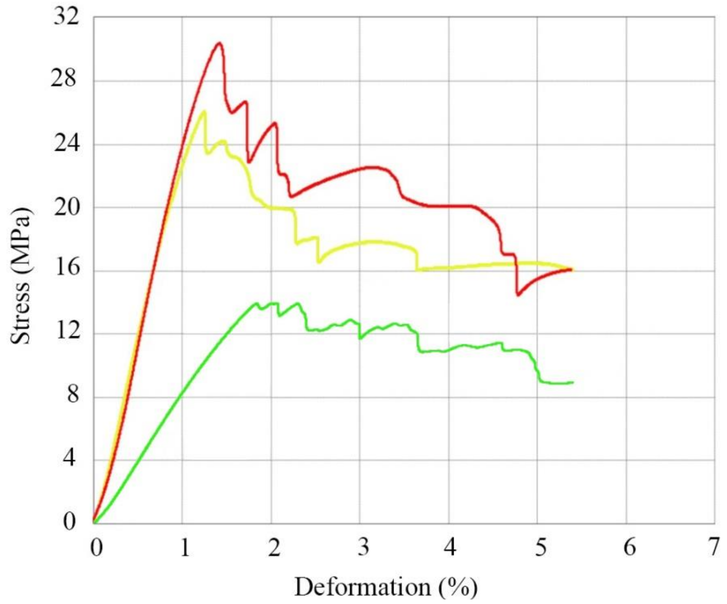

Figure 9 Average flexural strength test curves. Red: 200°C, yellow: 140°C, and green: 110°C.

The Tetrabrik specimens pressed at 140°C showed the fewest fissures and the highest elastic behavior compared to those pressed at 110°C and 200°C. This led us to conclude that at 110°C, the polyethylene does not melt sufficiently to cover all layers, resulting in greater delamination and making the specimens less resistant to bending. In turn, the specimens pressed at 200°C exhibited the greatest number of fissures and the lowest elastic behavior. This is because, as temperature increases, polyethylene becomes more flexible, but upon cooling, it may crystallize, leading to increased stiffness and decreased ductility [25]. The tested Tetrabrik specimens were analyzed using a binocular stereoscopic magnifying glass with a 4× objective, in order to observe in which layer the crack occurs. Figure 10 shows a Tetrabrik specimen manufactured at 110°C during a flexural test, with the corresponding cracks marked by red circles.

Figure 10 Crack in the cardboard layer; Tetrabrik specimen manufactured at 110°C during a flexural test.

The images obtained with the magnifying glass show the irregularity of the layers that make up the specimens, which prevents the cracks from being clearly distinguished; in addition, torn cardboard fibers from the saw used to cut them can be observed. In Figure 11, a specimen pressed at 140°C is shown. The fissures generated in these specimens are imperceptible to the naked eye. Still, under a magnifying glass, the layers of the different materials that compose them could be clearly seen, and the failure occurs in the cardboard layer in all cases. Finally, as can be seen in Figure 12, the specimens pressed at 200°C show cracks that can be noticed with the naked eye, and when analyzed under the magnifying glass, it is observed that they also occurred in the cardboard layer.

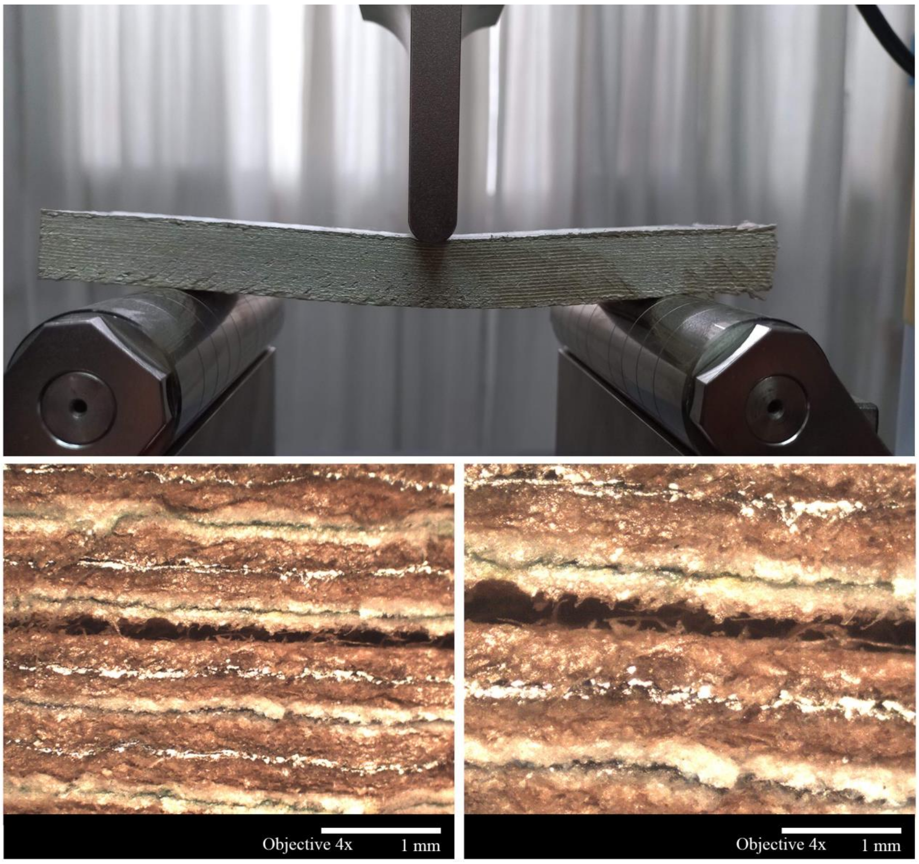

Figure 11 Tetrabrik specimen manufactured at 140°C during a flexural test.

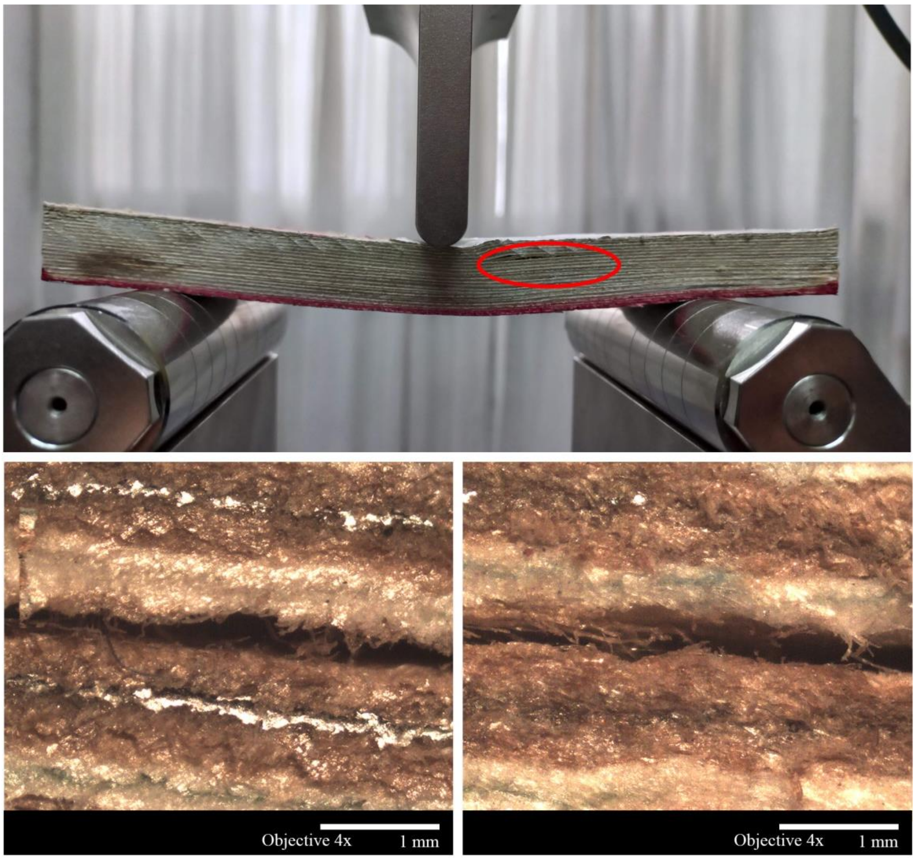

Figure 12 Tetrabrik specimen manufactured at 200°C during a flexural test.

3.1.3 Water Absorption Test

Once the test was completed, the curves for the percentage of water absorption over time during submersion were established (Figure 13). As can be seen, the specimens absorbed water quickly during the first 48 hours; then the curves increased in a linear fashion until reaching equilibrium after 300 hours of immersion. A similar behavior was observed in the work of Yilgor [10].

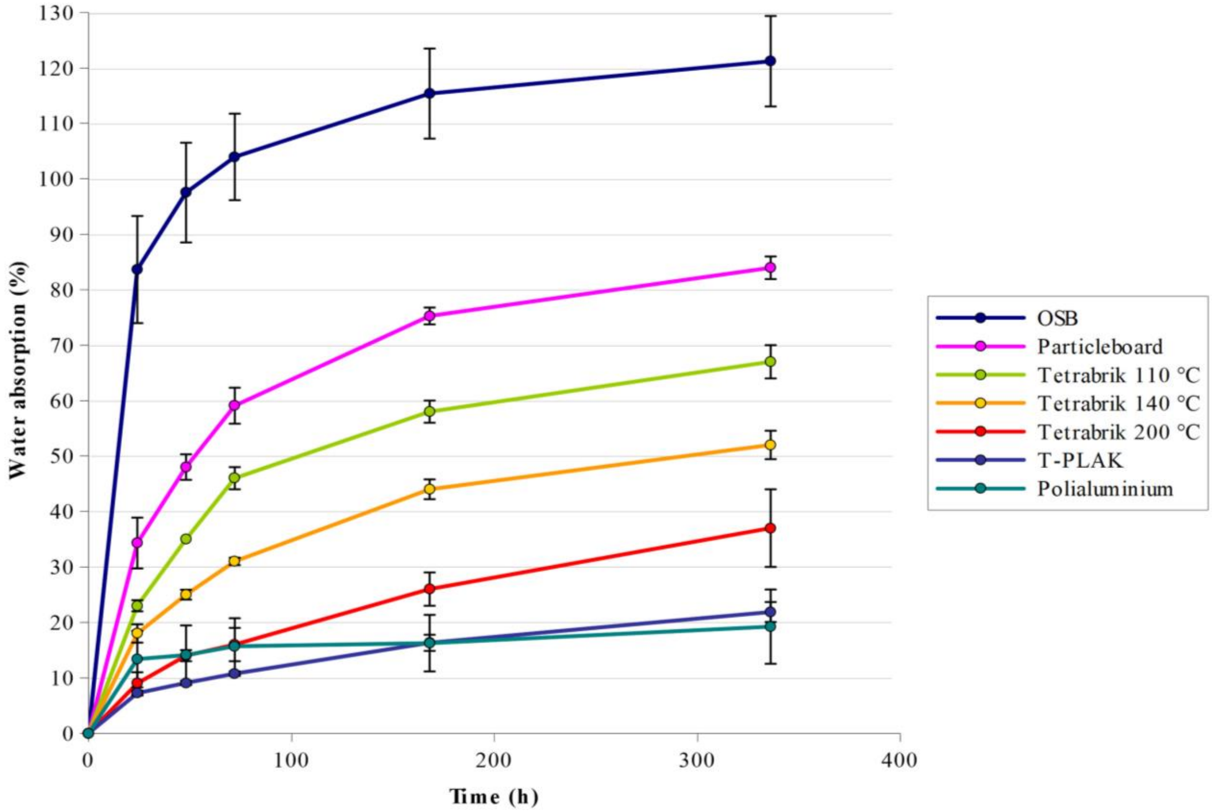

Figure 13 Result curves, water absorption test.

The data obtained indicate that the percentage of water absorption of the Tetrabrik specimens decreases as the pressing temperature increases, absorbing 67% of water at 110°C, at 140°C, 52%, and at 200°C, 37%. These absorption percentages are low compared to those of the wood chip boards studied, which absorb 84% in the case of particleboard and 121% in the case of OSB, these presenting leachate, staining the water, as can be observed in Figure 14.

Figure 14 Specimens of OSB, particleboard, and Tetrabrik submerged in water.

On the other hand, the Polyaluminum specimens absorbed 19% and the T-PLAK specimens 22%. The relatively low absorption of the latter two materials can be attributed to the absence of cellulose in the Polyaluminum composition, and, in the case of the T-PLAK boards, this behavior indicates the presence of a water-repellent component.

Another aspect to highlight is that during the test, the Tetrabrik specimens, regardless of the pressing temperature, increased their thickness by 5 mm. Still, once the specimens dried (in air), they remained 2 mm above their original thickness without showing material detachment or deformation, as shown in Figure 15. The fact that after air drying, the boards do not completely recover their original shape, maintaining a residual swelling, is due to the hydrophilic nature of the cellulose fibers present in the cardboard, which absorb water and experience structural changes that are not fully reversed upon drying [10].

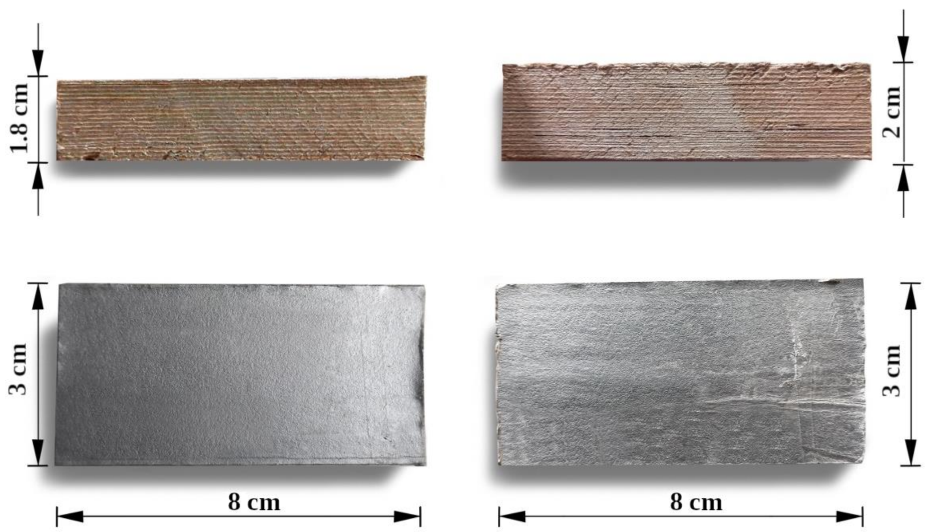

Figure 15 Dried Tetrabrik specimens before and after water absorption test, dimensions in cm.

To further investigate this aspect, thickness swelling after 24 hours of water immersion was evaluated in accordance with the procedures specified in ISO 16983 [26]. The boards' performance was classified according to ISO 16894 [27], which establishes the maximum allowable thickness swelling after 24 hours of water immersion for OSB panels. The obtained values and the corresponding classification are presented in Table 3.

Table 3 Thickness swelling after 24 hours of water immersion. [a]

Board	Swelling in thickness (%)	Classificacion ISO 16894 [27] [b]
Tetrabrik 110°C	(28 ± 2)	NC
Tetrabrik 140°C	(29 ± 1)	NC
Tetrabrik 200°C	(17 ± 1)	LB-REG
OSB	(35 ± 2)	NC
Particleboard	(15 ± 2)	LB-REG
T-PLAK	(0 ± 0)	HLB-MR
Polyaluminum	(0 ± 0)	HLB-MR

[a] Values are the mean of five measurements.

[b] NC: no classified; GP-REG: general purpose non-load-bearing board for interior fitments for use in dry conditions (swelling in thickness <25%); LB-REG: load-bearing board for use in dry conditions (swelling in thickness <20%); LB-MR: load-bearing board for use in humid conditions (swelling in thickness <15%); HLB-MR: heavy duty load-bearing board for use in humid conditions (swelling in thickness <12%).

As shown in Table 3, the Tetrabrik boards processed at 110°C and 140°C, as well as the commercial OSB, do not meet the classification requirements, as their thickness swelling after 24 hours of water immersion exceeds the 25% limit specified by the standard. Nevertheless, the Tetrabrik boards exhibited significantly lower thickness swelling than the reference OSB, demonstrating superior dimensional stability under water immersion. On the other hand, increasing the processing temperature to 200°C reduced thickness swelling to 17%, a value very close to that of the commercial particleboard used as the reference.

3.1.4 Glow Wire Test

In Table 4 are presented the average values with their corresponding standard deviation of the results obtained from the glow wire test. This test was carried out in a comparative manner, so the Glow-Wire Flammability Index (GWFI) and the Glow-Wire Ignition Temperature (GWIT) were not determined.

Table 4 Glow wire test times for all boards (IEC 60695-2-10). [a]

Board	tI (s)	tE (s)	tT (s)[b]	tR (s)[c]	tB (s)[d]	Class[e]
Tetrabrik 110°C	(2 ± 2)	(8 ± 2)	(6 ± 2)	---	(6 ± 2)	V0
Tetrabrik 140°C	(13 ± 1)	(16 ± 1)	(3 ± 1)	---	(3 ± 1)	V0
Tetrabrik 200°C	(4 ± 2)	(9 ± 2)	(5 ± 2)	---	(5 ± 2)	V0
OSB	(0 ± 0)	(33 ± 2)	(33 ± 2)	(3 ± 2)	(30 ± 0)	V1
Particleboard	(0 ± 0)	(33 ± 1)	(33 ± 1)	(3 ± 1)	(30 ± 0)	V1
T-PLAK	(0 ± 0)	(116 ± 50)	(116 ± 50)[f]	(86 ± 40)	(30 ± 0)	V2
Polyaluminum	(5 ± 2)	(18 ± 18)	(15 ± 15)	(3 ± 5)	(10 ± 11)	V0

[a] Values are the mean of five measurements. The testing temperature was 700°C.

[b] tT = (tE − tI)

[c] tR = (tE − 30)

[d] tB = (tT − tR)

[e] Class V0: Materials that extinguish quickly, do not allow flame propagation, and do not produce flammable drips. Class V1: Materials with a higher tendency to burn, but that self-extinguish within a controlled time and do not produce flammable drips. Class V2: Materials that allow flame propagation and/or produce flammable drips.

[f] Some specimens had to be extinguished manually to prevent complete combustion of the sample.

The observations that could be made after finishing the test were as follows: In the case of the OSB and Particleboard specimens, ignition began upon contact with the filament (tI =0 s) and self-extinguished 3 s after it was removed (tE = 33 s). These are materials that tend to burn but self-extinguish without dripping flaming droplets; they are within class V1. On the other hand, the T-PLAK specimens also ignited immediately upon contact with the glow wire (0 s). However, after the glow wire was removed, the flames did not self-extinguish, resulting in the longest flame persistence time (tR = 86 s). Consequently, this commercial Tetrabrik–based board is classified as V2. The high measurement standard deviation is related to the variability observed in the flame persistence time. In some cases, the specimens had to be extinguished manually to prevent complete combustion. In the case of the Polyaluminum board, a slight delay in ignition was observed (tI = 5 s). The flame remained small and did not propagate across the specimen. Moreover, the flame self-extinguished while the specimen was still in contact with the glow wire (tE = 15 s). However, considerable variability was observed among the specimens (see Table 4 for the standard deviation for tE). This behavior can be attributed to the board's composition, which consists of polyethylene and aluminum, two materials that respond differently to fire. While polyethylene is combustible, the aluminum phase is non-combustible and acts as a barrier to flame propagation. Consequently, the Polyaluminum board was classified as V0.

Finally, all the Tetrabrik specimens exhibited distinctive behavior due to their multilayered composition. Some specimens did not ignite, and others began to ignite a few seconds after contact with the filament. Still, when the flame reached the aluminum layer, it self-extinguished (tT = 3 s to 6 s), even while contact was maintained, lasting only 3 to 6 s.

The tT values obtained for the Tetrabrik boards processed at the three different temperatures were not significantly different, indicating that the fire behavior of the laminated Tetrabrik boards is independent of the processing temperature evaluated in this study and is primarily governed by their multilayer structure. These results suggest that the aluminum layer acts as an effective flame-retardant barrier. This was also observed in the work by Bonocore and De Luca, in which the behavior of the specimens under direct fire was evaluated. They determined that flame resistance was also favored by the high compacting of the material, which, unlike other materials such as particleboard, which is very porous, favors flame propagation [16].

In Figure 16, it can be observed that the mark left by the flame on the OSB, T-PLAK, and particleboard specimens is considerably greater in relation to the mark on the Polyaluminum and Tetrabrik specimens. This is due to the presence of aluminum in the latter materials.

Figure 16 Flame mark on specimens: OSB, T-PLAK, Particleboard, Polyaluminum, and Tetrabrik.

3.2 Energy Cost Analysis

The main energy cost associated with the manufacture of the Tetrabrik boards is the electricity required to power the heating elements used to achieve the desired processing temperature. Each heating plate was equipped with a 23 Ω electrical resistor, which operated at different power levels depending on the target processing temperature. At 110°C, the electrical power supplied to each resistor was 111 W. Since the hot-pressing process lasted 1 hour, the total electrical energy consumed to manufacture one 30 cm × 30 cm Tetrabrik board was 222 Wh (800 kJ). This corresponds to an energy consumption of approximately 8888 kJ per square meter of Tetrabrik board produced at 110°C. For processing at 140°C, the electrical power supplied to each resistor was 157 W. Using the same calculation described above, the energy consumption required to produce one square meter of Tetrabrik board at this temperature was 12556 kJ. Similarly, at a processing temperature of 200°C, the energy consumption increased to 34800 kJ/m^2.

The differences in energy consumption among the three processing temperatures are evident. At 200°C, the energy consumption was approximately 3.9 and 2.8 times higher than that at 110°C and 140°C, respectively. Therefore, considering the balance between the physical and mechanical performance of the boards and the associated energy consumption, a processing temperature of 140°C appears to be the most suitable for manufacturing Tetrabrik boards.

4. Conclusions

The analysis of the data obtained indicates that the production of a construction-grade material from Tetrabrik waste is feasible. The main advantages of the Tetrabrik boards compared to the conventional particleboards studied are their higher flexural strength, lower water absorption, and greater fire resistance. The test results showed that the higher the pressing temperature, the better the mechanical properties of the Tetrabrik boards, as they withstood more flexural stress and absorbed less water. The Tetrabrik boards compacted at 140°C had a flexural strength of 27 MPa, indicating better performance compared to the other agglomerated boards studied, whose highest value was 16 MPa. Although at 200°C the Tetrabrik specimens withstood 30 MPa, as previously mentioned, the energy expenditure required to manufacture boards at this temperature is not justified. Moreover, at 140°C, the specimens demonstrated greater elastic behavior, presenting fewer fissures under flexural stress. Regarding water absorption, as the pressing temperature increases, the polyethylene present in the Tetrabrik flows more, infiltrating all the layers of the material, making it more impermeable and therefore less absorbent. Consequently, depending on the pressing temperature, the Tetrabrik boards absorb relatively between 17% and 47% less water than the wood chip particleboards and between 54% and 84% less than OSB. Like the boards that contain Tetrabrik, those made of Polyaluminum absorbed 19% of water, and those of T-PLAK 22%. However, it should be considered in this comparison that Polyaluminum does not contain cellulose in its composition and is a board that requires the separation of all the materials that make up the Tetrabrik, eliminating the cardboard, which requires expensive machinery. On the other hand, T-PLAK boards are composed of shredded Tetrabrik, with a water-repellent material added to improve the adhesion of the layers, which entails higher cost and manufacturing time, unlike the proposed Tetrabrik boards, which use the material entirety, without shredding and without additives, overcoming the main difficulty of recycling this MSW. On the other hand, the proposed Tetrabrik boards, regardless of the pressing temperature, showed good performance in terms of fire resistance; the aluminum present in their composition acts as a flame retardant, causing the fire to self-extinguish even while in contact with the filament; in fact, some specimens did not present ignition. This does not happen with the other boards studied, in which the flame only self-extinguishes once the contact with the filament is removed. In addition, the flame left a considerably smaller mark on the proposed Tetrabrik boards than on the specimens of the other boards.

Based on the obtained results, it is inferred that it is possible to scale up the production of this material by manufacturing boards of larger dimensions. Future work will focus on scaling up the manufacturing process by designing and constructing a hot press capable of producing boards up to 1.20 × 0.65 m. This stage of the project is being carried out in collaboration with a cooperative specializing in the collection and recycling of post-consumer packaging waste, to assess the technical feasibility of large-scale production under realistic operating conditions. In parallel, long-term durability studies, including resistance to UV exposure, weathering, fungal attack, and biological degradation, as well as a comprehensive life cycle assessment and techno-economic analysis, will be conducted to further evaluate the suitability of the developed Tetrabrik boards for building applications.

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Author Contributions

María Laura Gaetan: conceptualization, data curation, writing – original draft, investigation, visualization. Lucas Ernesto Peisino: conceptualization, data curation, methodology, writing – original draft, writing – review & editing. Rosana Gaggino: conceptualization, funding acquisition, methodology, project administration, resources, writing – review & editing.

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Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

Data are contained within the article.

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