Thermal Insulating Panels Based on Recycled Tetra-Pak® Packaging Materials

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Abstract. This article introduces a novel approach for repurposing Tetra-Pak® residues as raw materials for the manufacturing of insulating panels for dwelling frameworks. This new development is intended as affordable insulation systems for emergency and permanent social housing. The three proposed panels were designed, manufactured, and tested, and showed similar or better thermal properties than traditional insulators available in the local market. To benchmark the design embodiments, custom apparatuses and dedicated sensing instruments were also developed.

1. Introduction

Chile is a country constantly stricken by natural disasters as well as other calamities caused by human action, which usually produce a massive destruction of homes. In general, the reconstruction or new construction of the affected homes was carried out with very low material standards, where most of persistent deficiency is the lack of thermal comfort [1].

In the 2014 fires that affected the city of Valparaíso, 2975 homes were destroyed and, 17 months later, 73% of them had been replaced or completely repaired. Of those, 53% of the reconstructed houses were built precariously, which, two years after the event, have been converted into definitive homes [1].

On the other hand, the accumulation of garbage in the urban space increases unsustainably in municipal and private landfills, even having to close some of them due to lack of capacity [2]. In this context of continuous calamities and extreme garbage accumulation, the present project aims to create an insulator material, by recycling an abundant source of garbage that can improve the thermal quality of emergency homes or any other type of partition-based construction: The Tetra-Pak® containers. Previous successful recycling approaches for Tetra-Pak® can be separated into two groups. Approaches that use the whole Tetra-Pak® material as it is, and the ones that rely on hydropulping as the first step, separating cellulose fiber from PE-Al laminate [3]. The present project focuses on the first group, offering three design embodiments that were built and tested.

2. Background

Thermal insulation materials are poor temperature conductors, which means they have a low heat transfer index [4]. These materials are generally used within frames of linear elements - such as the partition walls - where the space between studs is usually filled to generate the thermal envelope [5]. In order to meet cost requirements, typical Chilean emergency dwellings are built of very simple, inexpensive components, both in their structure and envelope. They have lateral partitions of half-timbered pine wood in dimensions 2x2”; usually enclosed externally by OSB (Oriented strand board) boards. The floor sits on a pine wood wrap with plywood plates and the roofs have a pine wood structure with corrugated zinc sheets [6]. In the entire dwelling, thermal
insulation or any other type of barrier against moisture are normally not considered. (Figure 1)

Tetra Pak packaging are made of three key components: 75% Cellulose fibers, 20% Low-density polyethylene and 5% Aluminum. Paper material used in Tetra Pak packaging is unbleached sulfate (Kraft) and CTMP (chemi-thermo-mechanical process) pulp [7] (Figure 2). The boxes are designed to store and maintain food, thus achieving a very good insulation with a low material thickness. Because of this property, various attempts have been made [3] to produce recycled materials that can potentially improve basic homes thermal behavior using a filling made from crushed Tetra-Pak® containers inside a dwelling wooden structure. Furthermore, fiber Recycling or Re-Pulping processes led to the development of cardboard, paper towels, notebooks and other new paper products [8]. Another approach is the PolyAl Recycling method, where LDPE and Aluminum in Tetra Pak packages are used, either together or separately, to conform a raw material for its potential use as insulation [7]. In addition, Full Carton Recycling, methods are found in literature, where packages with no process of separation cellulose fibers, LDPE and Aluminum showed positive structural and insulating ratings [3]. For instance, in the Eee project [9], randomly tested samples with different insulation materials (Figure 3A). Those samples coated with Tetra-Pak® boxes achieved a substantial advantage in thermal insulation, and a better overall structural performance, when compared with other studied materials and techniques (Figure 3B).

Figure 1. Typical emergency house. Figure 2. Layers of a Tetra-Pak® container.

Figure 3. A. Tetra-Pak® containers placed randomly, B. Tetra-Pak® panels as cladding
Another approach previously explored [10], is the use of Tetra-Pak containers as inner and outer lining of overlapping tiles (Figure 4A). Also, this approach was studied to make blocks filled with polymers. A third similar approach [11] proposed to work on an empty containers stack that relies on the thermal insulation provided by a sealed air chamber (Figure 4B). All these research projects have shown promising results, although they lack of published tests to support them.

![Figure 4. A. Overlapping containers as cladding. B. Filled and empty containers as filling.](image)

3. Proposed Insulation Panels

As a response to the evident issues described in the introduction section, regarding excessive Tetra-Pack® waste and the need of an affordable insulating material, three new uses for Tetra-Pak® insulating materials were designed, produced, and tested. These prototypes are characterized by being insulating, self-supporting and multilayer panels, composed entirely of Tetra-Pak® containers, thermofused by mechanical means. These boards offer the possibility of being used as an insulator and - at the same time - as a lining boards that prevent thermal bridges. Their insulating capabilities are possible because the panels have flaps on their four sides. This means, the panels remain above the structure of the partition, overlapping with the neighboring panel. Thus, the panels create a continuous and practically smooth covering, with only slightly noticeable seams.

3.1 Design concepts

In order to create design embodiments for the three proposals, existing thermal insulator approaches are being considered. For example, the least-used home insulator materials, which are highly efficient and commonly found in industry applications, are reflective sheets. These materials work reflecting the heat transmitted by radiation thanks to thin metal layers, which prevent any energy loss [4]. However, the most common insulating materials in partition walls are wool: minerals, glass, cellulose, polyester, and expanded polystyrene. All these materials, by having a low thermal transmittance, generate an insulating layer inside the partition wall that prevents heat exchange [5]. Another concept considered in the present proposal is the airtight chamber. If the air is still, there is no heat transfer. Therefore, the concept of insulated sealed chambers increases the potential for a thermal insulator.

By combining the conceptual ideas previously described, it is established that the three proposals should have external metal faces to create a reflective layer, and they should produce a waterproof airtight chamber. Finally, the low thermal transmittance of the panels will be ensured by its predominant material (75% of a Tetra-Pak® box): Cardboard.
To define the final design, the proposed modularity will follow the basic type used in most of the framework-based constructions, i.e. a grid of 60x60 cm. These dimensions correspond to the boards used commercially for cladding (Figure 5). The use of this grid configuration leads to the use of a second grid starting one-inch inwards. Therefore, this second grid is generated at a 2” thickness in the edge of the classic stud used in wooden frameworks, e.g. 2x3”, 2x4” or 2x2” for the case of emergency houses, achieving a series of 55 cm squares in which the proposed insulators can be arranged.

3.2 Gathering and preparation of the Tetra-Pak® containers

The stages for collecting and preparing the containers are crucial. Nowadays, there is a limited number of organizations that collect this type of waste, and most of them lack advanced or industrialized logistics. However, agreements and networks could be generated to facilitate the gathering of this raw material, at least at local level. Due to this reality, the proposed preparation technique is developed in a simplistic, manual way, within the reach of any organized neighborhood or community (Figure 6).

Once the Tetra-Pak® containers have been collected, it is very important to wash them thoroughly, otherwise, the fusing step will not be effective. After having the raw material in optimal conditions, it is necessary to open the containers by means of guillotines or paper cutters to obtain proper cuts that facilitate producing the insulating panels (Figure 7).
3.3 ‘Flat board’

The ‘flat board’, the first and simplest of the three proposed designs. It can be considered as the base module for the following two types. As the name implies, it consists of a flat and thin board composed of three layers of Tetra-Pak® containers arranged in an overlapping manner. The two exterior faces have reflective appearance, achieved by exposing the aluminum side of the containers. The core of the panel consists of unopened containers, arranged edge to edge, minimizing the preparation steps by omitting cutting them (Figure 8).

3.4 ‘Colmepack’

The second proposal is called ‘Colmepack’ based on the honeycomb-style shape of its central layer, which is attached to two cover boards. In this embodiment, the first layer corresponds to a ‘flat board’ followed by a central core consisting of a series of prisms, formed by Tetra-Pak® containers transversely cut and arranged next to each other, perpendicular to the base. Finally, another ‘flat board’ that closes and forms the final insulation panel is added. This arrangement seeks to limit the air movement within the cylinders and generates reflection on both aluminum faces (Figure 9).

Figure 7. Proposed guillotine cuts.

Figure 8. Schematic of a ‘flat board’ panel with its constitutive layers.
3.5 ‘Corrupak’

The third design embodiment consists of a ‘flat board’ as first layer, followed by a core based on a wavy ‘flat board’ created via thermoforming, and another ‘flat board’ layer. The wavy board is pressed into a mold made of angled steel profiles, which are welded together by their edges (Figure 10). Because of its grooved intermediate layer, as in the Spanish “Corrugado” it is called ‘Corrupack’. This design - like the previous one - seeks to improve insulation via; (1) trapping air in the space between the flat and the wavy sheets, and (2) reflecting heat by means of its outer aluminum faces (Figure 11).
3.6 Preparation of the base module
In order to manufacture the base module, the so called ‘flat board’, an oven is required. This oven should be able to reach 150°C and have an internal capacity of at least 60x60 cm of area. It is also required to have a press with a minimum area of 60x60 cm and a load capacity of 20 tons. To develop the proposed panel, a custom oven with temperature control was built, and a press with steel profiles was manufactured using an automotive heavy-duty hydraulic jack. After the required equipment is built and the Tetra-Pak® containers are properly prepared, the manufacturing process starts. This begins by applying new motor oil as a release agent on the zinc covers, which act as separator between different units of flat boards. Open containers are then arranged with their aluminum face towards the zinc mold in an overlapping manner. Later, a central layer of unopened containers is placed. Subsequently, a second layer of open containers is distributed with its aluminum face facing up. This process is duplicated, using another zinc cover as a separator, and adding again the release agent on both sides. Due to the temperature and pressure limitations of custom-made equipment, which lacked the power to achieve a larger production, a maximum of five ‘flat boards’ could be manufactured at a time.

The heating step should last an hour and a half at 120°C, and the molding should be turned over at the 45 minutes mark. Once the outer polyethylene face melts, the containers can be removed from the oven and placed in the press, applying all available pressure to ensure a uniform weld of the different layers. The pressing stage continues until the melted polyethylene cools down and solidifies, ensuring a proper thermo fusion of the three layers. For the manufacture of the wavy plate, necessary for the "Corrupak", a similar process is conducted. However, a wavy mold is required.
3.7 Manufacturing of "Colmepak" and "Corrupak"
Panels that consider still air in their core must be assembled in cool temperature, and between oiled zinc sheets. These panels should be heated inside the oven and then pressed. Extreme care must be taken to avoid crushing the cylinders in the case of the "Colmepak" or the wavy board in the case of "Corrupak" due to overpressure.

3.8 Production costs
A cost estimation of each insulated panel type was performed considering collection and preparation steps, payback of equipment, manufacturing, supplies, labor, and general expenses. The main outcome of this cost estimation suggests that the ‘flat board’ panel has a unit value of USD$2.40, the “Colmepak” panel USD$7.00 CLP and the “Corrupak” USD$11.20, being “Corrupak” the most expensive due to the longer manufacturing time required to produce the wavy structure. For all cases, approximately 70% of the cost corresponds to labor. This is due to the lack of mass production methods during manufacturing.

4. Installation
The proposed panels are installed by positioning them between studs and noggings, leaving the overlapping flap on the edge of the framework structure. The panels should be fixed by means of nails, staples or screws. The joint between adjacent panel flaps, separated by a stud or noggings, is sealed with an aluminum foil tape (Figure 13).
5. Benchmarking

The three proposed design embodiments were benchmarked among them, and with other insulators available in the market. To do this, seven prototypes were built, applying the same construction methods used in emergency houses. Therefore, each prototype framework was made using 2x2” pine wood components and covering its six outer faces with 11.1 mm OSB boards painted with two coatings of water-based paint (Figure 14, Figure 15). A wooden truss structure was installed on top each prototype with a “5V” metal roof as a cover, while leaving a ventilated ceiling.

Each prototype was insulated differently. A prototype without insulation was used as base or reference point. Three were insulated with traditional materials: mineral wool, glass wool and expanded polystyrene. The remaining three prototypes were insulated using the ‘flat board’, ‘Colmepak’ and ‘Corrupak’ panels. Each prototype was evaluated by installing a temperature and humidity sensor on a support positioned exactly in the center of the interior volume (Figure 16). All sensors were calibrated within the same range to ensure proper data collection and test validation. In total, eight sensors were used, one for each prototype and one to measure environmental conditions.
Figure 15. Testing prototypes

Figure 16. Cross section of the base module and sensor position.

By following the methodology described above, it was possible to generate a database registered in microSD cards, connected to an Arduino® system specially programmed for the tests (Figure 17).
Of all tests carried out, a representative day was selected for display as can be seen in Figures 18 (overall data), 19 (high temperatures range) and 20 (low temperatures range).

### 5.1 Complementary tests

Qualitative complementary tests using the ‘flat board’ were carried out exposing this prototype to two controlled tests: (1) fire resistance test and (2) water resistance and shape stability test. The first test, fire resistance, involved placing the plate directly to the flame of a hand torch. The results suggest that the ‘flat board’ panels last longer when compared with mineral wool, glass wool and - undoubtedly – much longer than expanded polystyrene. The second tests, water resistance and shape stability, consisted on immersing a piece of “flat board” for 30 days in a water container. The ‘flat board’ presented a minimum increase in thickness, millimetric, and did not generate detachment of its components or any noticeable deformations in its global composition.
Figure 19. Zoom of figure 18 to display high temperatures.

Figure 20. Zoom of figure 19 to display low temperatures.

6. Conclusions
Overall, the proposed panel manufacturing process is easy to implement when considering the required raw materials, supplies and production steps. Its low cost and simple labor training suggest an economic and sustainable feasibility. Comparatively, the cost of these insulation panels is greater than the available commercial options. The cost difference is driven by the extensive manual labor required due to the one-at-the-time approach. Mass production approaches could reduce up to 70% of the panel production cost, making them competitive in the market.

The temperature measurements taken from the seven prototypes suggested that, at the maximum ambient temperatures recorded during the month of July 2018 in the area of Villa Alemana, Chile (33.0476° S, 71.3734° W), the proposed panels prevent core temperatures from exceeding 25°C. Furthermore, the measurements stayed within comfort zone, which starts at 18°C.
With respect to the stability and time spent in the comfort zone, glass wool and mineral wool were more efficient in keeping temperatures stable and for a longer time. However, the "Colmepak" and "Corrupak" panels scored close. These four prototypes kept temperatures for more than 6 hours within the desired range.

As it can be seen in Figure 18, when ambient temperatures declines, the proposed insulators have the lowest temperature drop, indicating that the temperature of these prototypes drops at a lower rate than traditional insulators. In fact, they almost double the heat retention time.

When looking at the minimum temperatures recorded during the test period (Figure 19), the proposed non-traditional insulators stood out once more. The three of the insulators composed by Tetra-Pak® containers ranked within the four highest recorded interior temperatures. The only drawback with these panels is that gaining heat from environment is a slow process, thus, requiring a longer time to reach thermal comfort when compared with its commercial competitors.

When analyzing the relative humidity tests, Tetra-Pak® insulators showed a greater resistance to moisture penetration, either from the outside or from the inside, generating a strong moisture barrier, practically impermeable. Therefore, when implementing these insulators, a proper ventilation design is required.

Finally, when comparing the three proposed insulating panels from the thermal point of view, it was observed that the “Corrupak” is slightly more efficient, followed by the ‘Colmepak’ and finally by the ‘flat board’. The collected evidence indicates that the three proposed panels can compete on equal terms with mineral and glass wools, two of the traditional insulators of moderate price and high performance available in the market.

7. Further Recommendations

- **Modularity and installation method improvement.** For example, make larger panels, replace installation flaps or generate tie systems between panels.
- **Manufacturing automation.** For example, generate a mechanized system to arrange containers according to size, imitating the operation of the machinery used in the manufacture of plywood plates or OSB plates.
- **Craft press systems with variable temperature.** Use of thermal fluids for heating and cooling during the press step for temperature control in order to avoid the baking and cooling processes of the panels.

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