Comparison of Hygrothermal Comfort and Life Cycle Between Recycled Plastic Block and Concrete Blocks in a Social Housing in The City of Cuenca

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Abstract. The qualitative and quantitative housing deficit in the city of Cuenca Ecuador is high, to provide help to the homeless, the Ecuadorian government decreed “Casa Para Todos” project in 2018. This type of housing focuses on providing an accessible alternative for people with limited resources, however, the type of housing that is granted does not comply with the conditions and materials that guarantee the comfort of the users. Additionally, there is a large percentage of plastic garbage that is collected every day by the city's cleaning system, part of it is recycled and another part is deposited in sanitary landfills due to poor handling within the recycling chain and process. The main objective of this research is to determine the hygrothermal comfort and life cycle of a housing prototype with recycled and processed plastic material for the manufacture of modules that together form the walls of the proposed houses. To achieve the proposed objective, traditional concrete block systems are compared to recycled plastic (polyethylene and polypropylene) walls, using the K coefficient (thermal conductivity) in the Desing Builder software, obtaining simulations of hygrothermal comfort and relative humidity. As a complement to the research, the analysis of the life cycle and environmental impact was carried out with the SimaPro software. As result of the simulations, it was obtained that the relative humidity in the analyzed environments, parents' bedroom, and living room, has a value of between 40 and 60% in the two construction systems, being within the comfort ranges. The internal temperature in the concrete block system fluctuates between 15 to 20 °C while with the recycled block it is in the ranges of 17 to 20 °C, which allows evidence that the house made up of recycled blocks has higher thermal gain in prolonged periods during the day and that the concrete block house has great heat losses due to the porosity of the material, so the use of recycled plastic blocks is recommended; deepen research on the life cycle and its environmental impact, as the results indicate that the recycled plastic block has a greater environmental impact in its life cycle than the concrete block.

1. Introduction
In Ecuador according to the latest census carried out by the National Institute of Statistics and Censuses (INEC) [1] there are 17.08 millions of inhabitants, of which 70% live in urban areas, this massive flow of people to the cities causes an increase in the demand for housing that urban areas cannot supply. Currently, according to government policies, citizens have a constitutional right to housing, however, in
2018 a housing deficit of more than 12.4% was reported, representing 573,000 homes. Similarly, one of the most important cities in Ecuador and with the highest traffic of inhabitants of rural areas to its center is the city of Cuenca, that in the last decades expanded inefficiently and generated an urban footprint not very compact and low density [2].

In addition, the increase in demand and the lack of free space in the city for the creation of new homes raised the cost of land that people with average resources and low cannot pay. This situation, added to the fact that Cuenca is expanding towards its periphery and that due to its geographical location the living space is limited generates that a part of the population migrates to sites that do not have minimum standards of habitability. To the exposed, the city has a poverty index of 19% who live in vulnerable socio-economic realities that must seek alternative solutions in informality to build rooms in unsuitable places and with inefficient materials that do not provide the basic comforts for their habitants [3].

In an effort to provide help to people with housing problems, the Ecuadorian government decreed in 2018 the project Casa Para Todos, a plan that proposed to build 350,000 social type housing until the 2021. This type of housing refers to those homes whose prices are not governed by the values of the real estate market and, for the contrary, adapts to economic capacity of the possible tenants, since it is focused on helping people with economic crisis who cannot afford a traditional home. However, by various economic factors in the country reduced this amount to 140,000 namely, 210,000 families that will not gain access to decent housing, this open a huge socioeconomic gap between people who can afford a residence and those who cannot, and contributes to continuous decline in the standard of living of the vulnerable population of Ecuador, especially in Cuenca.

According to the latest report by the United Nations Organization (ONU) [4], the consumption and use of plastic packaging in the world has increased alarmingly during the year 2020 and the first months of 2021. Despite efforts and campaigns for the efficient use of resources and decrease in plastic containers (polyethylene and polypropylene) single use only, the social reality that the planet is going through as a consequence of the Covid – 19 in recent years the demand for online shopping has increased and caused food and other products to be packaged in plastic container for easy transportation. Only in Ecuador, they generate 531,461 annual tons of plastic waste of which 260,000 tons correspond to plastics single use only [5]. However, of this percentage, actually they are only recycled 11,200 tons, what causes that 248,800 tons of usable plastic are discarded by different means if no viable alternative is found for these wastes.

An alternative to take advantage of plastic waste caused by the massive consumption of packaging polyethylene is the recycling and transformation of these remains into new materials that can be used for different purposes. A material that is causing a lot of expectation, is the transformation of plastic waste into building blocks that can be used to make homes for people with vulnerable socio-economic realities, how is the case of the houses of social interest. In this way, recycled blocks offer a great alternative for its thermal characteristic, mechanical strength, moisture absorption among others, also, the raw material is obtained from the waste generated by the same population, which reduces the environmental impact of plastic waste in the environment and help people in need of housing to improve their quality of life. But some aspect must be taken into account to analyze the feasibility of using plastic as a viable construction element in this type of residence. [6].

First, the life cycle of blocks made of plastic waste must be analyzed to ensure permanence and construction stability over time, for this, a comparative analysis should be carried out between a construction made with this material and another that uses traditional concrete materials. The second aspect is the thermal comfort offered by plastic waste blocks, this is achieved by calculating the thermal transmittance of the material or also known as U factor to ensure the thermal comfort of the habitants.
Consequently, this project arises: generate a comparison of thermal comfort and life cycle between plastic blocks and concrete blocks in a social housing in the city of Cuenca. To achieve the aforementioned, it begins with the investigation of theoretical efferent to determine the K factors (thermal conductivity) of building blocks made from recycled plastic. On the other hand, we proceed to determine the U factor of a social housing in the city of Cuenca to check the thermal comfort it offers. Finally, the thermal comfort offered by a conventional social housing is compared with a social housing built with plastic blocks.

2. Theoretical framework
2.1. Application of plastic waste as a construction material

Currently, polyethylene terephthalate, also known as PET, dominates the market for the manufacture of packaging for mass consumer products, especially for food and medicine for to its thermoforming properties, low density, high elastic limit and the innocuousness of its chemical composition that does not represent a danger to the health of consumers [7]. Another relevant factor that diversified its use in the industrial field globally is the reuse property it possesses. In the present, one of the most avant-garde applications is the implementation of recycling for the manufacture of constructive elements such as bricks or prefabricated plates for the construction of social housing. To carry out this process it is necessary to start with the choice of raw material and define the recycling processes before thermoforming each block. The reference [8] mentions that containers and bags made of plastic go through a series of processes before being recycled.

The first process is classification and refers to the categorization of containers by color and other characteristics that can be identified with the naked eye, since a change in the chemical composition of the plastic as a colorant or an agent that was added to improve its molding at the factory, can change its properties significantly, it is for this reason that it is necessary for the recycled material to have the same characteristics to obtain a homogeneous result. Subsequently after the classification of the containers it is necessary to remove labels and other components outside the containers to prevent them from contaminating the final product. To the exposed, once the raw material has been classified and the pollutants have been removed various recycling methods can be applied to transform the packaging into a product suitable for reuse. The reference [9] mentions that there are two basic methods to performs this task such as; mechanical recycling, and chemical. On the other hand, as the reference mentions [10], despite the fact that Ecuador does not currently have regulations in force regulating the manufacture of plastic blocks or bricks, there is research that supports the use of this material to build social housing. Research such as that of the Experimental Center for Economic Housing (CEVE) [11] in Argentina, use machinery to process and convert raw material derived from PET containers into particles for the manufacture of low-density plastic bricks. For the actual manufacture of the products, techniques similar to the manufacture of conventional bricks were used, but the aggregate components were replaced with recycled material [12].

2.2. Comparison of hygrothermal comfort in homes built with recycled blocks and concrete blocks.

The concept of hygrothermal comfort refers to an absence of discomfort or thermal discomfort that people perceive within an environment [13]. In this way, buildings must ensure that outside temperature changes do not negatively influence the ideal temperature of the human body, it is for this reason, that houses must consider some factors in the elements used for construction to ensure correct temperature regulation and humidity of the environment to which users will be exposed, since, as mentioned in the reference [14] buildings exchange heat with the environment through various means that affect their internal temperature such as solar radiation, the conduction between the floor of the house and the ground, the speed of the outside air, the radiation and the ventilation that it has. All these aspects have a direct and indirect impact on the change in temperatures and the thermal comfort that the home can provide.
According to what the reference mentions [15] the user is another factor to consider in the hygrometric behavior of a home since the human body generates steam in the environment through the skin and for this reason it contributes to the increase in humidity in buildings, especially in houses with little volume. There for, the ability to transmit heat from building materials are key to ensuring thermal comfort. This ability to transmit heat energy is defined as thermal transmittance or U factor (W/m²K).

The Ecuadorian Construction Standard (NEC) defines it as: Heat transmission per unit of time through a material or through a constructive element and air film/barriers, induced by a temperature difference between the environment in both sides of the considered elements” [16]. Likewise, the thermal comfort of a structure is closely linked to this factor and the lower its value, the greater its ability to thermally insulate a wall. [6]. The formula to calculate this factor is determined by Fourier’s Law: $Q=K.a.t.ΔT/b$ Where: $Q$ = amount of heat; $t$ = time; $a$ = area; $ΔT$ = temperature variation; $K$=constant thermal conductivity; $b$ = thickness (measured in the direction of heat flow)

Given this, plastic materials such as PET, polyethylene and polypropylene, for his crystalline structure, low density and insulating properties, seem suitable materials for the formation of coatings intended for thermal comfort, but you have to have some considerations. As a first instance, the determination of the U factor of the plastic is different since its structure and crystallinity is affected after thermoforming, in this way, the U factor of virgin polyethylene Will not be the same as recycled polyethylene especially if this material is mixed with other components such as cement, water and additives. For this reason, obtaining a constant value of thermal transmittance for all blocks made with this material is impossible. However, the investigations of various authors such as those shown in Table 1 and Table 2, can provide some referential data on this value and can be compared to data obtained from other common construction materials such as concrete blocks.

### Table 1. Reference values of thermal conductivity from various authors, concrete Block.

| Source | Components | Thermal Conductivity (W/K.m) | Dimension |
|--------|------------|-----------------------------|-----------|
| Universidad Nacional de Córdoba y del INTI en Capital Federal | Lightweight concrete block masonry | 0.38 – 0.72 | 40x20x15 |
| Blanco, Fróméte & Madrid | Cement, sand, limestone (sawdust) | 0.60 – 0.69 | 40x20x15 |
| Ahmed, Baghabra, Omar, Mohammed & Mohamed | Cement, sand, limestone | 0.46 | 40x20x20 |
| Majid, Syafawati, Abdul, Salleh, & Jamellodin | Mix of lightweight concrete with clay, cement, sand and Glycol (Solid block) | 0.36 | 40x25x10 |
| Bustamante, Martínez, & Macías | Mix of cement, gravel, sand, baked clay, pumice stone, split stone, volcanic granules (INEN 638) | 0.56 | 40X20X20 |

### Table 2. Reference values of thermal conductivity from various authors, Block with recycled material.

| Source | Components | Thermal Conductivity (W/K.m) | Dimension |
|--------|------------|-----------------------------|-----------|
| Gaggino | Indeterminate mixture o PET, LDPE, BOPP, PVC, inks, aluminum powder. | 0.15 – 0.18 | 39x19x19 |
| Tolozano | Mix of cement, water and recycled PET | 0.15 | 40x19x7 |
| Ampuero | Cement, sand, water and recycled PET | 0.153 – 0.3 | 40x20x20,5 |
| Sulaiman, Gaggino, Kreiker, Peisino, & González | Mix of cement, water and recycled PET | 0.15 | 40X20X15 |
3. Methodological framework

The methodology of the present investigation is of a quasi-experimental type since there is no control over the variables that intervene in the context of the investigation. In this regard, the reference [17] mentions that the study subjects in this type of research are not randomly assigned and, on the contrary, it is derived from other experimental studies to obtain conclusions. The phases of the investigation are presented in Figure 1.

![Figure 1. Research methodology.](image)

As shown in the previous figure, the research started from the review of the existing literature on the properties of plastics and their potential use as a constructive element, in addition, investigations were addressed on the manufacture of blocks with bottle waste and other single use containers derived from Polyethylene focused on the construction of social type houses and their application as a regulator of hygrothermal comfort in homes. This section was based primarily on research conducted by [9], [11] y [18].

Also, the thermal conductivity factor (k) of the blocks manufactured base on recycling was estimated and it was compared with the values found in different compositions of concrete masonry to contrast the thermal insulation of both elements. To carry out the aforementioned, relevant investigations were investigated that experimentally determine this factor under similar conditions. The criteria to determine the validity of the investigated data are based on the composition of the masonry mixture, the volume of the block and the similarity in the data determined by the experimental phase.

Subsequently, an analysis of the life cycle of the building blocks based on recycling and the concrete blocks was carried out. For this, the SIMAPRO software was used to carry out a comparative simulation between these two elements and to verify the technical feasibility of the recycled plastic blocks. To obtain a point of comparison and base the simulation on a real building, the prototype of social housing built with blocks of polyethylene and recycled polypropylene from the Catholic University of Cuenca located in the Luis Cordero ranch was taken as a reference. It began with the determination of the area subject to an analysis, in this case a square meter of masonry for both concrete and plastic, then the materials available in the program that most closely resemble the building blocks used in Cuenca were chosen, in this case, dry lightweight concrete block. The list of subjects is shown in Table 3.

| Table 3. Materials chosen for the analysis that are available in SIMAPROs. |
|-----------------------------------------------|-------------------------------|
| Concrete Block Masonry                        | Recycled Pet Block Masonry    |
| Lightweight concrete block, expanded clay {RoW}| production | Cut-off, S (del Proyecto Ecoinvent 3 - allocation, cut-off by classification - system) |
| Cement mortar {RoW} | cement mortar production, hand-mixed, on-site | Cut-off, S (del Proyecto Ecoinvent 3 - allocation, cut-off by classification - system) |
| Cement, Portland {RoW} | production | Cut-off, S (del Proyecto Ecoinvent 3 - allocation, cut-off by classification - system) |
| Tap water {RoW} | tap water production, conventional treatment | Cut-off, S (del Proyecto Ecoinvent 3 - allocation, cut-off by classification - system) |
| Waste polyethylene terephthalate, for recycling, sorted {RoW} | treatment of waste polyethylene terephthalate, for recycling, unsorted, sorting | Cut-off, S (del Proyecto Ecoinvent 3 - allocation, cut-off by classification - system) |
After this, the total weight values were entered for each element that makes up the masonry of the concrete and plastic blocks, which were 134.40 kg and 24 kg respectively. In the same way, the analysis method called “Base Line” was entered and began with the life cycle and environmental impact analyzes of the two elements. Finally, an analysis of hygrothermal comfort was carried out through simulation for constructions with recycled base blocks. For this, the factor “u” (Thermal transmittance) is calculated using the references values “k” found in phase two of this investigation, which corresponds to 0.72 for concrete and 0.15 for recycled plastic blocks. These values were obtained by the simulation of the prototypes in the Desing Builder software. To determine the other factors such as temperature variation, air speed, solar radiation among others, a strategic location was selected in the city of Cuenca.

The Project is located in the city of Cuenca, more specifically, in the rural parish Chiquintad located 12 km from the urban area. According to the NEC – HS – EE, the city is in Climate Zone 3 – Continental Rainy.

![Figure 2. Type of Housing Analyzed.](image)

To carry out the simulation, the climate file has been used with the information collected from the meteorological station closest to the sector. This information can be obtained on the web platform: “http://climate.onebuilding.org/”. The city has average monthly minimum temperatures that range between 7 – 10 degrees Celsius and average maximums between 15 – 18 degrees Celsius. For the present analysis by simulation, a period of 3 months between July and September has been chosen, since, according to the climatic data obtained, lower temperatures were determined in this period. In turn, an energy model of the house was made using the Design Builder software, which uses the energy plus motor for its calculations. Finally, the data collected by a previous investigation of the source was used [19] which addresses the same construction used in this study in the Chiquintad area in which, it was found that the bedrooms and the area belonging to the living room are the rooms with the highest concentration of cold in the year, especially in the hours of 21 pm - 07 am and 18-21 pm respectively, it is for this reason that the analyzes Will focus on these spaces at the mentioned time.

4. Result and Discussion

4.1. Analysis of environmental impact and life cycle of concrete blocks and plastic blocks.

The result determined with the SIGMAPRO software, show that the manufacture of concrete block masonry greatly influences global warming since it registers a value of 65,65 kg CO2 while the plastic block has a value of 13,43 kg CO2 (Figure 3).

Along the same lines, Figure 4, the emissions produced by the life cycle of concrete masonry were determined in terms of the manufacturing processes of its constituent elements, among which they can be mentioned; the heat produced by the industrial districts both base on coal and in coal furnaces, mining exploitation, Clinker production, heat produced by the burning of oils in industrial furnaces, among others.
Figure 3. Comparison of environmental impact between concrete and plastic masonry.

Figure 4. CO2 emissions from concrete masonry, according to life cycle.

As can be seen in the previous figure, the processes with more carbon emissions in the environment correspond to the industrial district that reach 33 kg of Co2, since they use the burning of coal, Clinker, and petroleum derivatives to treat the raw material that makes up the concrete. In the figure 5 shows the result of the emissions produced by the life cycle of the recycled plastic blocks corresponding to; emissions from transport of the material, the processing of urban solid waste and its treatment for sanitary landfill, pig iron production, emissions from diesel production, refinery operation and processing for the manufacture of ethylene, among others.

Figure 5. Co2 Emissions from recycled PET masonry, according to life cycle.

As can be seen in the previous figure, the emissions produced by the life cycle of the constituent elements of the plastic block do not exceed 2.5 kg of Co2.

4.2. Hygrothermal comfort analysis with concrete blocks.
The analysis of the results began with room 1 and continued with the other rooms following the same procedural schemes. First, the analysis of the Envelope Thermal Behavior (ACTE) of the simulation, shows daily indoor temperatures with fluctuations that are generally between 16 and 21 degrees Celsius.
When analyzing the heat balance graph, it can be identified that the greatest amount of thermal gains occurs in the Windows, in turn, it was possible to identify that there are significant heat losses in the walls formed by the concrete block.

In addition, the Hygrothermal Comfort Analysis (ACH) with the hourly data in the period of one week, it was identified that this space has significant temperature fluctuations and is most of the day outside the comfort range, that is, between 21°C and 25°C, even having periods in which the interior temperature registers a minimum of 15°C. In addition, the same them can be identified by analyzing the graph with hourly data in the entire analyzed period of 3 months.

As for the Relative Humidity (RH), it is in acceptable ranges, that is, in prolonged periods of time it is within optimal values (40% - 60% of relative humidity). However, this data alone does not imply that there is hygrothermal comfort since the aforementioned interior operating temperature must be taken into consideration. When analyzing these two parameters, it was identified that this space, for most of the day, is outside the comfort range. In addition, it was identified that relative humidity has the same behavior in all bedrooms, which is why it has only been analyzed in this room. Shown in Figure 6.

The previous analysis was applied to all the spaces of the house, both for the concrete blocks and for the blocks made with recycled plastic material. The results are show in Table 4.
Table 4. Temperature (TE) and relative humidity (HR) fluctuations in homes with two types of block.

| Housing block | Concrete block | PET Block |
|---------------|----------------|-----------|
|               | ACTE (°C)      | ACH (°C)  | RH (%)  | ACTE (°C) | ACH (°C) | RH (%) |
| Bedroom 1     | 16-21          | 15-20     | 40-60   | 16-22     | 17-20    | 40-60   |
| Bedroom 2     | 16-19          | 15-20     | 40-60   | 16-20     | 15-20    | 40-60   |
| Bedroom 3     | 16-20          | 16-20     | 40-60   | 16-20     | 16-23    | 40-60   |
| Dining room,  |               |           |         |           |          |         |
| living room   | 16-20          | 15-20     | 40-80   | 16-20     | 20-24    | 40-75   |
| kitchen       |               |           |         |           |          |         |

On the other hand, the range of hours that the housing blocks remain in the thermal comfort zone between 20°C and 25°C in the months of July and September was determined, since they are the months with the lowest reported temperature. It is shown in Table 5.

Table 5. Average hours that living spaces remain in the comfort zone.

| Housing block | Concrete block (hour) | Pet block (hour) |
|---------------|-----------------------|------------------|
| Bedroom 1     | 6.57                  | 12.42            |
| Bedroom 2     | 1.14                  | 11.42            |
| Bedroom 3     | 6.57                  | 12.85            |
| Dining room,  | 3.85                  | 17.85            |
| living room   |                       |                  |
| Kitchen       |                       |                  |
| Average       | 4.53                  | 13.64            |

As shown in the previous tables, despite the fact that both simulations have similar fluctuations in temperature and relative humidity, table 5 shows that the recycled plastic block remains in the comfort zone for longer. These results agree with the data obtained by the investigations of [11], [21] and [22], since the thermal conductivity of the plastic blocks reported by the researchers ranges between 0.15 W/K.m and 0.18 W/K.m while, for his porosity of the concrete, it fluctuates between 0.36 W/K.m and 0.72 W/K.m.

5. Conclusions
According to the hygrothermal comfort analysis in the simulated house, it could be determined that both masonries have similar fluctuations, that is, they maintain values that range between 15 °C - 21 °C for traditional blocks and 15 °C - 24 °C for recycled plastic blocks. In the same way, the relative humidity is kept in the comfort zone, with identical values for the two elements (40% y 60%) with the exception of the living room-kitchen-dining room area. However, although the values of the fluctuations are similar, it was shown that the house that uses plastic masonry remains a much longer percentage of time in the comfort zone than traditional blocks since, on average, the house with Concrete masonry stays in the comfort zone for 4.53 hours while recycled blocks stay for 13.64 hours.

In the same way, it was determined that concrete block masonry has a much greater environmental impact on the planet than plastic blocks since, according to simulations, the manufacturing processes of traditional blocks generate emissions that exceed 65,65 kg of CO2 for each square meter of material, while plastic masonry generates only a fraction, which corresponds to 13,43 kg of CO2. Through the life cycle analysis of the building blocks it was shown that the use of recycled plastic as a construction material is a more ecological option since it generates 2.5 Kg of Co2 while concrete reports 33 kg of Co2.
Base on the data previously exposed, it can be concluded that recycled plastic masonry is a more suitable option for the construction of social housing in Cuenca than concrete blocks, for his hygrothermal conditions that it offers in a longer time of comfort, the environmental impact and decreased Co2 emissions of its manufacturing process and the contribution to the recycling of single use plastic packages in the city.

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