Evaluation of the Thermic Efficiency of the Prototype at Scale of a Sustainable Housing that Uses Concrete with PET Fibers (CFP) and the Trombe System

B Dueñas¹, W Soto¹* and E Carrera¹

¹ Faculty of Engineering, Universidad Peruana de Ciencias Aplicadas, Prolongación Primavera, 2390, Lima, 15023

* u201403860@upc.edu.pe

Abstract. In the last century, climate change has been one of the most notorious consequences of global warming. These changes are manifested through extremely warm or icy temperatures. Being the latter, the one that affects Andean populations in diverse parts of the world. In view of this, many researchers propose various techniques or methods to improve the conditions of habitability and thermic comfort to confront these cold temperatures. This study conducts an experimental investigation of the improvement of thermic efficiency that reaches a prototype of housing to include polyethylene terephthalate (PET), as a component of the concrete mixture in the structural elements. For this purpose, studies were reviewed that allowed selecting the most optimal considerations, with respect to the elaboration and inclusion of PET in the mixture. In addition, the proposed technique includes an adaptation and innovation of the trombe system in the roof, in order to optimize the thermic properties. The results in the present study show that this combination has allowed us to considerably improve the thermal efficiency properties in the prototype of the housing, which is an indicator of its performance when it is applied to real scale housing.

1. Introduction

Global warming and its consequences is an issue of great concern to the world's population. The most notorious consequence is the climate change that occurs in diverse parts of the world through extremely warm or icy temperatures.

These changes have led to various techniques or methods being proposed to mitigate or relatively control extreme temperatures. Romero [1] proposes to implement a photovoltaic system on the roofs of the houses to use the excess of the energy reduction in the generation of cold or heat in the environment. Lizana [2] proposes the use of phase change materials (PCM) that allow the absorption of heat during the day and the release of this during the night. It is also mentioned the improvement of the thermomechanical properties (PTM) by including the glass fiber reinforced polymer (GFRP) in the production of adobe [3] and the plastic in the production of concrete [4].

For this reason, many authors propose plastic, specifically polyethylene terephthalate (PET), as a research material in the production of concrete. The use of this proposed material is given as an addition [5-6], a substitute for cement in the production of lightweight concrete [7] or as a replacement for aggregate [8]. Fraternali [5] concludes that the addition of PET allows for a decrease in the value of thermic conductivity (TC) and an increase in the resistance to compression (RC) in an 18% and 35.14%, respectively, with respect to conventional concrete. Pereira [6] mentions the influence of the
length and volume of PET in the improvement of the resistance to compression (CR) and tensile resistance (TR). Benosman [7] in his experimental research concludes that the inclusion of PET fibers in the cementitious matrix, allows reducing the ultrasonic pulse speed (UPV), thermic conductivity (TC) and absorption capacity (AC) of the compounds. Rodríguez [8] replaces in the concrete mixture to the fine aggregate with PET fibers in percentages of 0%, 4.5%, 5% and 5.5%. The tests performed allowed inferring that the thermal conductivity decreases, thus obtaining a greater degree of thermic insulation.

As a complement, this study carries out an experimental investigation of the influence of PET on the achievement of thermic comfort that can be obtained when combined with an innovative application of the use of the trombe system in the roof. In most of the studies, it is proven that the inclusion of PET allows to conclude indirectly the improvement of thermic insulation (TA). This study will assume the characteristics and volume of PET, which allow the most optimal thermo-mechanical properties (PTM), being these the ones that will be used in the concrete mixture. Likewise, it will be explained in detail how the concept of trombe walls was applied in the elaboration of the roof in a housing prototype. The innovative application of the trombe system includes Dong's proposal [9], which implies the partial use of an aluminium plate to replace the black paint to cover the surface that will capture the solar radiation. This will allow maintaining an adequate temperature for a longer period of time.

2. Methodology

2.1. Materials

The used materials in the present research conform the production of the reinforced concrete, the adaptation of the trombe system in the roof and the construction of the confined masonry system. The first one implies the use of cement (Portland type 1); the used standards for the validation of the used cement is the Peruvian Technical Standard 334.009 [10], which defines the performance requirements of Portland Cement. It also implies the elaboration of PET fibers, in the form of quadratic fractions of approximately 1 cm. The used aggregates in the mixture correspond to HUSO 6 and must comply with the requirements detailed in [11] because they will be exposed to a cold climate. The second one involves the use of a transparent sheet of glass, whose thickness for safety reasons was 8 mm. The black paint will be used on the roof after emptying the slab by capturing the solar radiation and allowing the functionality of the trombe system. In addition, an aluminium plate will be used, which is based on the study of [9]. Technopor cassettes will also be used as a replacement for the roofing brick, due to its contribution to thermic insulation and the ease it will provide us to implement the trombe system on the roof.

2.2. Mixture design

The resistance to be obtained corresponds to a value equal to or greater than 17.5 MPa, due to the fact that the concrete will be used in the confinement elements of the confined masonry system in the one-floor housing prototype. In addition, it is desired to obtain a 100 mm SLUMP to facilitate the workability of the concrete. The used method to perform the mixture design is the ACI method.

The inclusion of PET fibers in the mixture, as a replacement for fine aggregate, corresponds to a percentage of 4%. This percentage designated for the inclusion of PET is based on studies previously carried out; in which Rodríguez [8], when presenting a mixture design similar to ours, will guarantee the fulfillment of the minimum resistance considered in the design and an improvement in thermic insulation. The mixture design is shown in table 1, which shows the weight of each material for a cubic meter of concrete.
Table 1. Mixture design with PET fibers.

| Components of the mixture | Unit   | Added Sample |
|---------------------------|--------|--------------|
| Portland Cement I         | kg/m³  | 367          |
| PET fibers                | %      | 4            |
| Water                     | lt     | 177.3        |
| a/c ratio                 | -      | 0.50         |
| Sand                      | kg/m³  | 723.7        |
| Stone                     | kg/m³  | 834.1        |

The figure 1 shows the concrete mix reinforced with PET fibers, which will be used in the columns, beams and joists of the prototype.

![Concrete mix with PET fibers](image)

Figure 1. Concrete mix with PET fibers.

2.3. Prototype design

A design was made in the AutoCAD program to have a visualization in plant of the details to be considered in the prototype. The figure 2. presents the dimensions of the prototype and the location of the door and window.
Figure 2. Detail in plant of the housing prototype.

Figure 3 and Figure 4 show the considerations of the construction process of the lightened slab and implementation of the trombe system on the roof. The first one will consider making holes in the technopor cassettes and ensuring their continuity throughout the thickness of the roof. The second one will consider the painting of the surface after casting and the way the aluminium sheet will be used.

Figure 3. View in plant of pre-casting lightened roof.
2.4. Constructive process
Once the technical specifications that the housing prototype was going to present were detailed, we proceeded to build it, obtaining the prototype as shown in figure 5. Also, figure 6 allows visualizing the proposal to implement the trombe system on the roof.

Figure 4. View in plant of post-casting trombe roof.

Figure 5. Final physical prototype of the proposal.

Figure 6. Adaptation of the trombe system on the roof.
3. Results and discussion

3.1. Temperature

Figure 7 and Figure 8 show the temperature trend of a typical sunny and cloudy day, respectively, during the recording period. This will allow to visualize the differences that occur between the ambient temperature (AT) and the temperature inside the prototype of the housing (TP).

Figure 7. Temperature graph of a typical sunny day.

Figure 8. Temperature graph of a typical cloudy day.

On a cloudy day the greatest difference in temperature between the environment and the interior of the house was 4.6 °C, which occurred in the interval from 10 to 12 midnight. This means that the prototype has a temperature improvement of 27.5 % with respect to the environment. On a sunny day, the greatest difference in temperature between the environment and the interior of the housing was 6.5 °C, which occurred in the interval from 10 to 12 midnight. This means that the prototype has a temperature improvement of 36.1 % with respect to the environment. Likewise, it is inferred that this percentage will increase as the day presents more solar radiation.
3.2. Relative humidity

Figure 9 and Figure 10 show the trend in relative humidity on a typical sunny and cloudy day, respectively, during the recording period. This will allow to visualize the differences between the ambient humidity (HA) and the humidity inside the prototype of the housing (HP).

![Figure 9](image1)

**Figure 9.** Relative humidity graph of a typical sunny day.

![Figure 10](image2)

**Figure 10.** Relative humidity graph of a typical cloudy day.

The trend of the graphs that represent the relative humidities allows to infer that the variation of these parameters is inversely proportional to the variation of the temperatures.

3.3. CO₂ Reduction

Figure 11 contrasts the difference, in terms of CO₂ production, between reinforced concrete with PET fibers and the conventional concrete. This will highlight the importance of this type of reinforced concrete as a contribution to environmental impact.
Figure 11. CO₂ emission graph between PET concrete vs. conventional concrete.

The graph shows that using concrete with PET fibers benefits the environmental impact in a positive way, because with conventional concrete more sand and stone input is used and therefore the CO₂ emission increases. The relevance of the decrease in CO₂ will be considerable as the magnitude of the work increases. Although the replacement of aggregates contributes to this decrease, it is important to point out the new use that will be given to plastic bottles, which are currently the materials that produce the most environmental pollution.

4. Conclusions

Based on the obtained results in the experimental part of this study, the following conclusions are shown:

- It was demonstrated that the combination of the trombe system in the roof with the use of a reinforced concrete with PET fibers allowed to improve the thermic insulation in the prototype of the housing.
- On the cloudy day, the greatest difference in temperatures was 4.6 °C (27.5%), which occurred at midnight. It is inferred that the tempered air during the day is partially released during the night.
- On the sunny day, the largest temperature difference was 6.5 °C (36.1%), which occurred at midnight. It is inferred that this percentage will increase as the day presents more solar radiation.
- On average during the 8 a.m. span at 2 p.m., the temperature in the home increased as the ambient temperature reached its highest peak. After 2 p.m., the ambient temperature begins to drop rapidly. However, the temperature of the house still increased relatively until 4 p.m., from this time the temperature begins a decrease, not as abrupt as that of the environment. This difference in temperatures is conserved during the night and early the next day until 8 a.m., at which time the described cycle begins again.
- Although the aim was to demonstrate that the applied technique would allow the isolation of cold temperatures, it was demonstrated that it was also possible to isolate the high temperatures of the study area, generating percentage differences of up to 25.4%.
- The implementation of the aluminium plate, in conjunction with the black painted surfaces, made it possible to optimize solar capture and induce an improvement in the functioning of the trombe system on the roof.
- The use of reinforced concrete with PET fibers had an incidence in terms of environmental impact, because when carrying out an analysis, it was concluded that the use of this type of concrete reduced CO₂ emissions.
5. References

[1] Romero Rodríguez, L., Sánchez Ramos, J., Guerrero Delgado, M., Molina Félix, J., & Álvarez Domínguez, S. (2018). Mitigating energy poverty: Potential contributions of combining PV and building thermal mass storage in low-income households. *Energy Conversion and Management*, 173, 65-80.

[2] Lizana, J., de-Borja-Torrejon, M., Barrios-Padura, A., Auer, T., & Chacartegui, R. (11 de 2019). Passive cooling through phase change materials in buildings. A critical study of implementation alternatives. *Applied Energy*, 254, 113658.

[3] Gandia, R., Gomes, F., Corrêa, A., Rodrigues, M., & Mendes, R. (20 de 10 de 2019). Physical, mechanical and thermal behavior of adobe stabilized with glass fiber reinforced polymer waste. *Construction and Building Materials*, 222, 168-182.

[4] Záleská, M., Pavlíková, M., Pokorný, J., Jankovský, O., Pavlík, Z., & Černý, R. (2018). Structural, mechanical and hygrothermal properties of lightweight concrete based on the application of waste plastics. *Construction and Building Materials*, 180, 1-11.

[5] Fraternali, F., Ciancia, V., Chechile, R., Rizzano, G., Feo, L., & Incarnato, L. (2011). Experimental study of the thermo-mechanical properties of recycled PET fiber-reinforced concrete. *Composite Structures*, 93(9), 2368-2374.

[6] Pereira, E., de Oliveira Junior, A., & Fineza, A. (2017). Optimization of mechanical properties in concrete reinforced with fibers from solid urban waste (PET bottles) for the production of ecological concrete. *Construction and Building Materials*, 149, 837-848.

[7] Benosman, A., Mouli, M., Taibi, H., Belbachir, M., Senhadji, Y., Bahlouli, I., & Houivet, D. (2017). *CHEMICAL, MECHANICAL AND THERMAL PROPERTIES OF MORTAR COMPOSITES CONTAINING WASTE PET.*

[8] Rodrigues, N., Carvalho, M., Balbino, A., Vasconcelos,A. (2018). *PET FIBER IN CONCRETE PRODUCTION.*

[9] Dong, J., Chen, Z., Zhang, L., Cheng, Y., Sun, S., & Jie, J. (1 de 2 de 2019). Experimental investigation on the heating performance of a novel designed trombe wall. *Energy*, 728-736.

[10] NTP 334.009:2016, "CEMENTO. Cemento Portland requisitos", INACAL, Lima, 2016.

[11] NTP 400.012:2013, "AGREGADOS. Análisis granulométrico del agregado fino, grueso y global", INACAL, Lima, 2013.