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ARTICLE

A Comparative Study of the Thermal Performance of Plastic Bottle Wall against Traditional Composite Brick Wall Typologies

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ABSTRACT

According to the container recycling institute, nearly a million plastic beverage bottles are sold every minute around the world. Plastic bottles are considered as an urban junk, however, it has shape characteristics which make them usable in construction in lieu of conventional bricks. This research promotes the use of recycled plastic bottles as eco-bricks by substituting it with the typical construction bricks. It evaluates the thermal performance of sand filled plastic bottle-walls in a comparative analysis with traditional composite brick walls. The thermal performance of the plastic bottle walls was evaluated through COMSOL® Multi-physics and the results are noted.

1. Introduction

According to Plastic Europe [1], plastic is a material that is essential is several industries. Plastic consumption has increased from 200 million tons/year in 2002 to 322 million tons in 2015 and is expected to reach 485 million tons in 2030 [1]. Plastic is a harmful material for the environment as it is considered non-biodegradable waste that causes levels of pollution as a result of its long-lasting existence to reach insolubility which is almost 300 years. Carbon monoxide and black smoke are primary causes of toxic pollution as a result of open burning of plastic, therefore, it is considered one of the primary environmental pollutants on the plant [2]. As shown in Figure (1), in the USA, the largest plastic disposing technique since 1960 was the landfilling technique followed with the combustion with energy recovery and then a small portion of plastic compared to the proportion of produced ones has been recycled. Due to the form and flexible nature of plastic bottles, an accumulation of it could require high storage areas and accordingly it assumes large spaces of sanitary landfill. Some plastic wastes were dumped into the shoreline or ocean up to 12.7 million metric tons in 2010 [3-4] and consequently affected the marine organisms [5].

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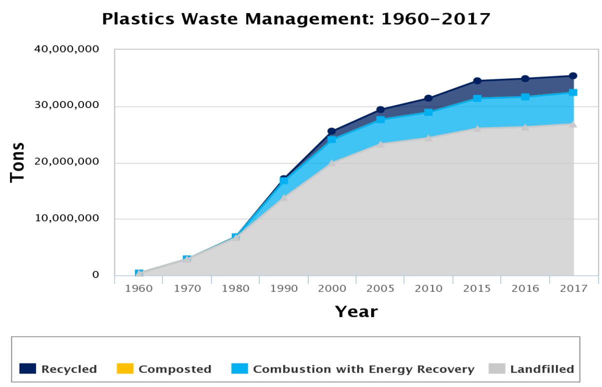

Figure 1. Different plastic waste management techniques in USA from 1960-2017 [12]

Accordingly, the reduction of plastic wastes, or plastic recycling, is the only option to reduce the environmental impacts caused by the prolonged impact of plastic waste. Plastic wastes were utilized through recycling and energy recovery (around 48-69%) in 2006 to 2014 [1]. In developing countries, the industry and rate of waste recycling is relatively low. Much of the problem lies in the improper waste management, collection practices and methods of plastic waste separation. In addition, much of the available techniques contribute to additional wastewater and air pollution and a substantial increase in the associated emissions from burning and transport. Hence, the best solution is reusing for which no additional addition to that, recycling needs additional energy to treat the materials for producing something usable and also, the process of recycling energy is required and does not contribute to pollution. Using filled plastic bottle in construction is one of the beneficial forms of plastic reusing. Plastic especially PET (polyethylene terephthalate) bottles, is a very difficult and costly process [6-9]. Moreover, the cost of construction using filled plastic bottles is lower than that of using conventional materials like brick. In addition, using local earth materials like local unprocessed sand ensures better thermal performance. Hence, the idea of using plastic wastes as a building material originated. The first bottle house was built using 10000 glass beer bottles by Wiliam F. peck in 1902 in Tonopha, Navada [10]. Afterwards, the newest building concepts have been using plastic bottles instead of glass in house construction. This idea of using plastic bottles in construction later grew because of the cost-efficient construction method especially in third-world countries, and the variety of solutions it provides utilizing the indecomposable plastic bottles. The first plastic bottles house in Africa was constructed in the village of Yelwa in Nigeria by Andreas Forese as shown in Figure 2. Forese used the plastic bottles instead of bricks, bound the bottles together with string and at the end applied the plaster [11]. Despite that building walls with plastic bottles instead of typical construction materials have been widely used in the past with success, both the industry and research focused on the investigation of the structural and thermal response of the plastic bottles were not taken seriously until couple of years ago.

Figure 2. The first two-bedroom bungalow made of entirely sand filled plastic bottles

A research study in 2015 focused on examining the thermal and structural response of walls using a comparative study of dry sand, saturated sand and empty plastic bottles. Brick work made of PET pieces were subjected to unconfined compressive stacking employing a compression machine of 3000 kN capacity and of an accuracy of 0.10 kN and after that the stacking was connected on the square in a way of the bottles laying evenly and subjected to a uniform compression mode, which simulates the way they are utilized in different wall typologies. In addition, the thermal examination was done by reenacting the simulated models of the three brick work squares on ECOTECT computer program. The results show that the impact of the infill fabric on the bulk unit weight and the compressive quality of the plastic bottle stone work pieces appeared slight effect of the utilized infill fabric on the quality. The gross strength of plastic bottles (670 kN/m^2) is much less than the traditional blocks (3670 kN/m^2), but the resulting data showed that the blocks of air-filled plastic bottles can still be used as suitable construction units for partition walls or as load-bearing walls for roof slab types. Thermally, plastic air-filled bottles show more improved thermal insulation characteristics than the traditional masonry construction, which could work as a thermal insulation material [13].

A similar study in Malaysia was published in which a comparison was performed between plastic bottle walls filled with brick and sand filled bottle walls. The strength of the walls filled with brick was three times stronger more than the sand filled bottle walls. However, the sand filled bottle wall system had an acceptable strength as it passed minimum permissible strength of Public Work Department (PWD) Standard Specification for Building Works (2008). Hence, the plastic bottle bricks had the capability to replace standard bricks in Malaysia's buildings in condition of thermal comfort [14]. A similar

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study focused on the thermal performance of sand filled plastic bottle walls was performed in Egypt, in which the researchers compared the traditional bricks and building with plastic bottle blocks utilizing energy simulation software on two sample rooms fitted with both materials. Onsite measurements for energy performance of the rooms were also taken. The results showed that the average temperature in brick room was higher than in the plastic bottles room. However, the relative humidity was higher in plastic bottles room [15]. Similar studies were performed in several other developing countries like Bangladesh, India and other Arabic countries. However, from the literature review, it is apparent that the thermal evaluation and its comparative performance against conventional wall typologies used in these counties is still not well investigated and was not focused on especially in developed countries which are the largest countries producing plastic wastes. The purpose of this research is to study the thermal performance of typical plastic bottles provided in the market as a municipal waste used in buildings in terms of calculating the thermal transmittance different material walls. It also intends to compare the characteristics of brick as a construction material with the bottle panels. The paper is organized as follows: Section 1 provides an introduction to the current research point and previews its importance. Section 2 describes in detail, the different wall systems we investigated. Section 3 discusses the results.

2. Materials and Methods

2.1 Typical "Conventional" Built Walls

Brick is a building material used to make walls, hard road surfaces and other elements in masonry construction. Usually, the term brick referred to a unit composed of clay, but it is now used to represent rectangular units made of clay-bearing soil, sand, and lime, or concrete materials. Brick has been used a lot in construction in the Middle East area and especially in Egypt. In our work, three walls representing the typical walls used in the Middle East area and Egypt were built and simulated on COMSOL [16] with the following specifications:

(1) Wall (T_1): 2.5 cm Plaster layer + 20 cm Brick layer + 5 cm Extruded polystyrene insulation layer2.5 cm + 1.3 Plaster Gypsum Wall Board (GWB) and Paint layer.

(2) Wall (T_2): 2.5 cm Plaster layer + 20 cm Brick layer + 2.5 cm Plaster layer.

(3) Wall (T_3): 2.5 cm Plaster layer + 10 cm Brick layer + 2.5 cm.

2.2 Plastic Bottles Wall

Building construction with plastic bottles is a low-cost and eco-friendly technique. The huge amount of packaging and plastic bottles is unlimited today and they comprise a large portion of the country waste which lead eventually to an increase in the greenhouse gasses worldwide. The reuse of plastic bottles is a more efficient solution than recycling. Nowadays, plastic bottles, can be utilized as a building block unit utilizing the plastic enclosure and sand fill to provide a building construction wall unit similar to bricks for small scale construction. Since walls built by bottles are lighter than the walls built by brick and block, this in turn, allow walls made of plastic bottles to be of a good response against earthquake activity. Due to the compaction of sand fill plastic bottles, the resistance of each bottle against the load is 20 times higher compared to brick. Since the plastic bottles are not fragile, they can be flexible and can tolerate sudden compressive loads without failure. This characteristic can also increase the building's bearing capacity against earthquakes. PET Bottles can be configured and joined to each other by several bonding techniques using a fish net or any equivalent tension and bracing technique. PET Bottles can be put in a vertical or horizontal configuration as illustrated in Figure 3. In our model, we used a vertical configuration as shown in Figures 4 were the bottles are plastered with mortar on each side. We performed our simulations by using two different volumes of water PET bottles; 0.75 L denoted as S-B wall and 1.5 L denoted as L-B wall and Figure 5 illustrates the dimension of both bottles.

Figure 3. Different bottle walls built in developing countries with various bottle configurations

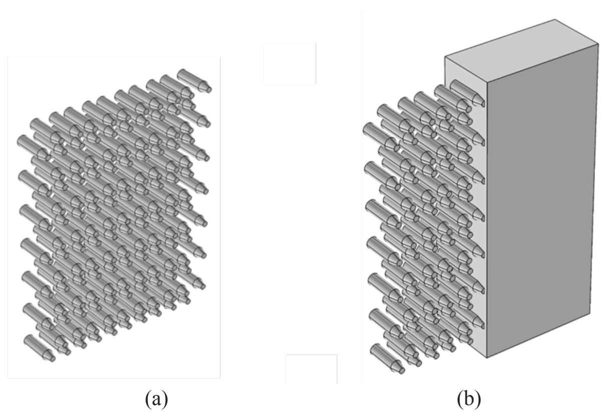

Figure 4. Illustration of a Cross-section of a plastic bottle wall: (a) Plastic Bottles (b) Plastic Bottles in Mortar layer

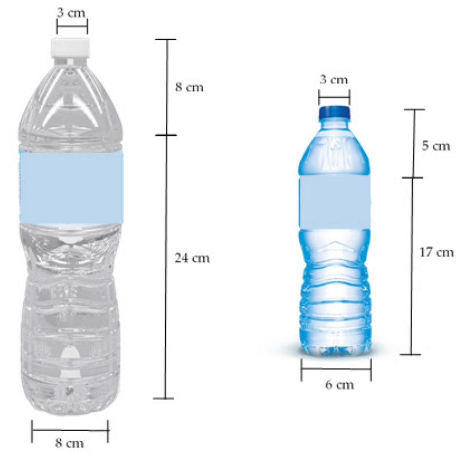

Figure 5. Dimensions of two water PET bottles used in our study

2.3 Simulation Model

COMSOL Multi-physics® is a cross-platform for finite element solver, analysis, and multi-physics simulations. It also allows conventional physics-based user interfaces and coupled systems of partial differential equations (PDEs). Heat flow and temperatures through our different walls system were measured and analyzed using COMSOL. COMSOL has been extensively used for studying several and different building related problems [17-19]; numerical results can be validated by comparison with various control systems such as thermo-flow meters, guarded hot boxes (as in the case under current analysis), and thermo-graphic techniques. The model on COMSOL is governed by three basic heat transfer equations. The heat transfers through solids, heat transfer by convection and the equation controlling the boundaries of the sample under adiabatic condition.

Heat equation of state:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u.\nabla T = \nabla.q + Q \tag{1}$$

Fourier's law of heat conduction:

$$q = -kA\ \Delta T \tag{2}$$

Newton's law of cooling controlling the hot and cold sides of the specimen's:

$$q = h(\ T_{ext} - T) \tag{3}$$

Adiabatic condition controlling through wall's boundaries:

$$-n.q = 0 \tag{4}$$

Where; q: Density of heat flow rate or heat flux (W/m^2), ρ: Density (Kg/m^3), C_p: Specific heat at constant pressure (J/kg K), k: Thermal conductivity [W/(m K)] and T: Temperature [K]. Figures 6 & 7 show the three typical walls & the two plastic walls system modeled in COMSOL; respectively. Table 1 illustrates the thermal and physical properties of the Brick, Concrete plaster, EPS and Gypsum wall board simulated in COMSOL. Table 2 illustrates the properties of Sand, PET and Plaster used to model the two different plastic bottle walls.

Table 1. Typical walls components specifications simulated in COMSOL

Material type	Brick	Concrete plaster	Extruded-Polystyrene board (EPS)	Gypsum wall board
Density (kg/m^3)	2000	2300	34	574
Thermal conductivity(W/mK)	0.5	1.8	0.041	0.28
Heat capacity (J/kg.K)	900	880	1450	1100

Table 2. Plastic bottle walls components specifications simulated in COMSOL

Material type	Sand	Concrete plaster	PET
Densit (kg/m^3)	1602	2400	1380
Thermal conductivity(W/mK)	2	1.8	0.4
Heat capacity(J/kg.K)	800	880	1030

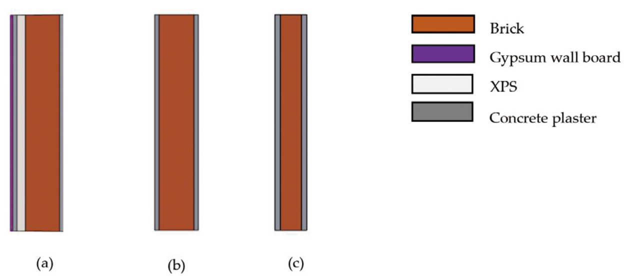

Figure 6. Illustration of typical wall systems used in Egypt residential construction in COMSOL: (a) Wall (), (b) Wall (), (c) Wall ()

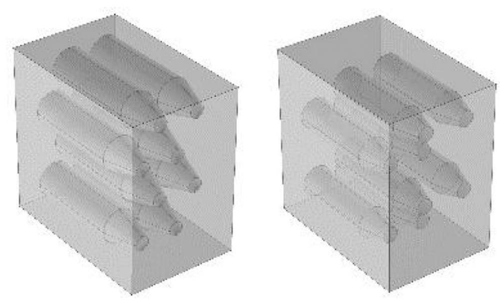

Figure 7. Illustration of two plastic bottle wall systems modeled in COMSOL: (a) Large bottle system; L-B wall, (b) Small bottle system; S-B wall

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3. Results

Protection from weather is a fundamental function of any building where mainly heat is lost and is also gained through the building envelope, i.e. walls, floors, doors, windows, ventilation and roofs. Consequently, it is important to study the thermal performance of the individual materials used in the construction of the building envelope and their resultant effect on thermal performance of the whole building. Heat flow can be measured and expressed, as "U - value" or "Thermal transmittance co - efficient". Thermal transmittance or the U-value, is the rate of transfer of heat through a structure divided by the difference in temperature across that structure. The U-value measures how effective a material is an insulator. In other words, U - values are generally used to describe the thermal performance of building elements, and also form part of the base data used to assess the energy performance of whole buildings. The U value is the reciprocal of the R-value, so it is calculated by the following equations:

$$\varnothing = A\ U.\Delta T \tag{5}$$

$$\therefore U = \frac{\varnothing}{A.\Delta T} \tag{6}$$

Where; $\varnothing$: heat flux (W), A: area of the specimen (m^2), U: thermal transmittance and : temperature different between both sides of the specimen. Another important property that influences the thermal performance of building envelopes is the "Thermal mass". Thermal mass is a property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations. Scientifically, thermal mass is equivalent to thermal capacitance or heat capacity, the ability of a body to store thermal energy. Therefore, concrete actually acts as a conductor of thermal energy and when it has a high thermal mass, it actually conducts thermal energy slower. The thermal energy transferred can be expressed as follows:

$$Q = mC_P\Delta T \tag{7}$$

Where; "Q" is the thermal energy transferred, "m" is the mass of the body, "C_p" is the isobaric specific heat capacity and ΔT is the change in temperature.

$$C_{th} = mC_P \tag{8}$$

Where; "C_{th}" is the thermal mass of the body.

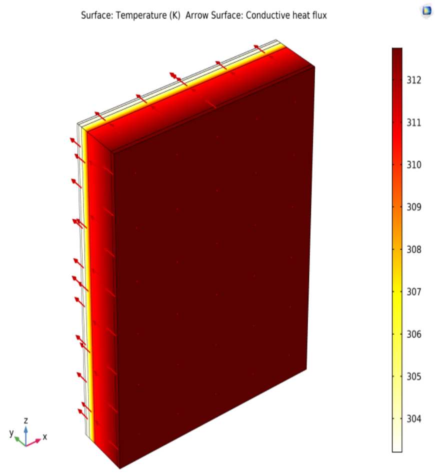


Figure 8. Illustration of temperature gradient on wall T_1 exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃

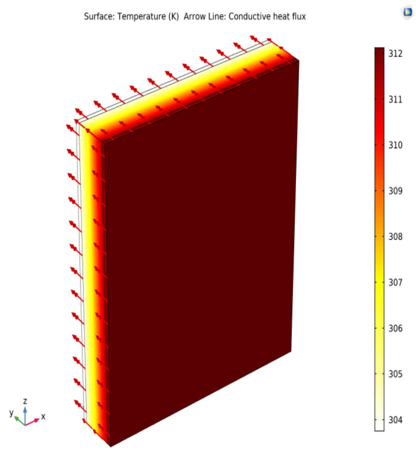


Figure 9. Illustration of temperature gradient on wall T_2 exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃

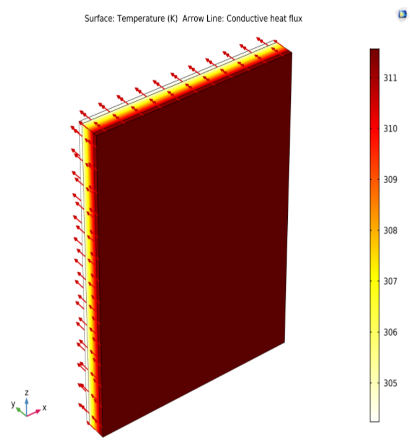


Figure 10. Illustration of temperature gradient on wall T_3 exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃

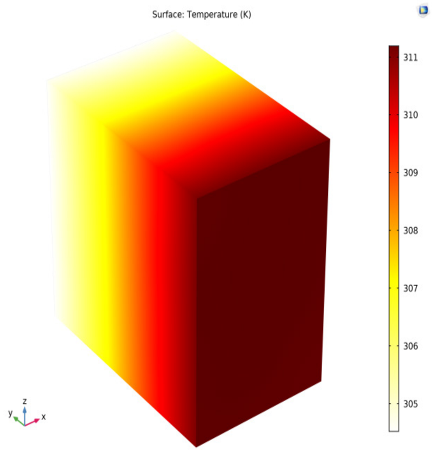


Figure 11. Illustration of temperature gradient on L-B wall exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃ .

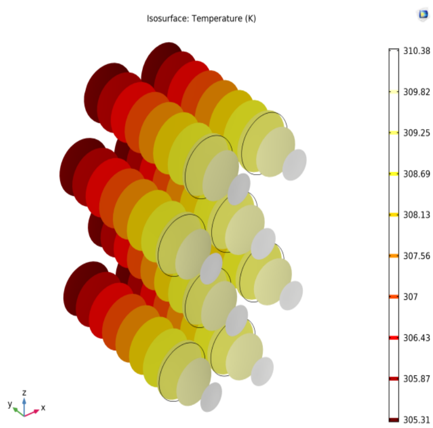


Figure 12. Illustration of temperature gradient on sand in L-B wall exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃

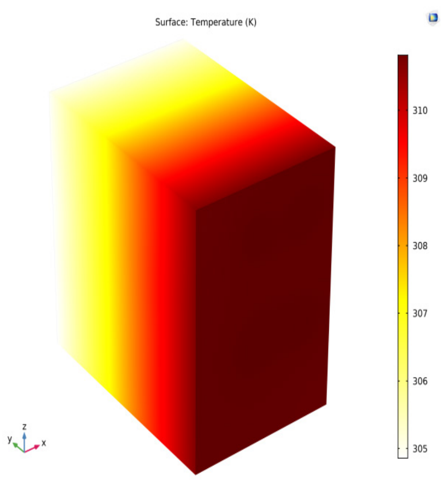


Figure 13. Illustration of temperature gradient on S-B wall exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃

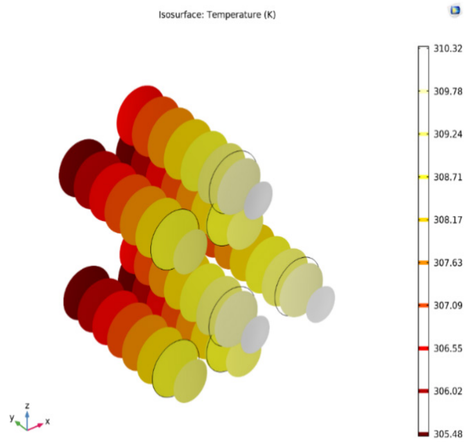
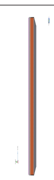
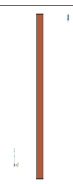
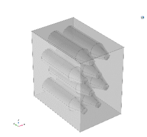
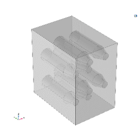


Figure 14. Illustration of temperature gradient on sand in S-B wall exposed to air flux of temperature 40℃ and internal air flux of temperature 30℃

Figures from 8 to 14 illustrates the temperature gradients in the five different wall system when exposed to hot air flux of 40 ℃ and cold air flux of 30 ℃ . Upon investigating the U-value of the five walls, results previewed that using conventional building materials with insulating layers as gypsum boards and XPS layers provide the better thermal insulation to buildings because of its high thermal mass of brick in addition to the excellent insulating characteristics of Gypsum board and XPS. However, sand contained in large plastic bottles showed a close thermal performance to Wall (T_2) and a better thermal transmittance than Wall (T_3). Small plastic bottle wall system showed the least insulation properties upon the other 4 walls. Table 3 illustrates the U-values of the five walls.

Table 3. U-value of the five wall samples

Property	Wall (T_1)	Wall (T_2)	Wall (T_3)	L-B Wall	S-B Wall
					
U-value	0.55585	1.957	3.2156	2.645	3.461

Respectively, upon increasing the outside's walls temperature from room temperature (25 °C) to (45 °C) gradually, the internal wall temperature of Wall () had the most stable temperature among the other four walls. While the large plastic wall system provided a cool internal wall temperature, but the outside wall temperature was highly affected by the external environmental temperature as shown in Figure 15.

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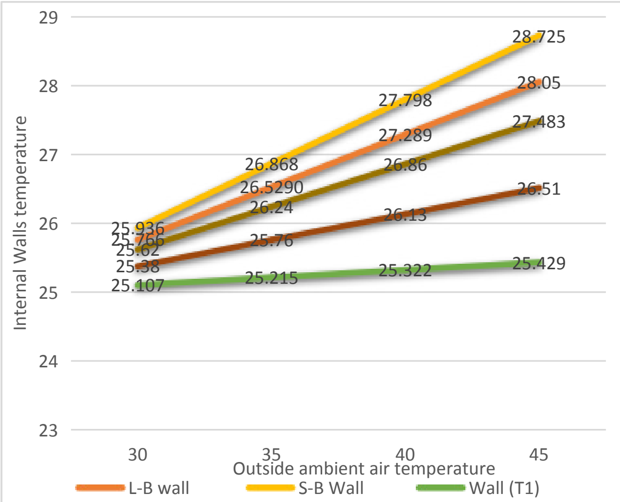

Figure 15. The change of the internal wall temperature due to the change of the outside ambient air temperature

4. Conclusion

Using Plastic bottles in construction has proved good thermal performance characteristics. Plastic bottle walls can replace brick walls as they are good insulators especially when using large bottles instead of small bottles to increase the thermal mass of the wall and still, they provide acceptable structural properties. Using large plastic bottles showed better thermal performance than brick wall type and a close performance to brick wall type The flexibility of using different glass bottle sizes and typologies, the workmanship challenges, and structural performance as a wall filler vs. a structural load bearing wall are yet issues that require further consideration. Based on the thermal performance alone, the PET bottle walls can replace traditional brick walls especially the traditional typologies formed of clay fired brick and plaster.

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Conflicts of Interest: The authors declare no conflict of interest.

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