Energy for Sustainable Development 24 (2015) 79–85

Contents lists available at ScienceDirect

Energy for Sustainable Development

Reusing waste plastic bottles as an alternative sustainable building material

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ARTICLE INFO

Article history:
Received 5 March 2014
Revised 2 November 2014
Accepted 5 November 2014
Available online xxxx

Keywords:
Waste reuse/recycling
Renewable energy
Sustainable construction
Thermal insulation
Plastic bottles

ABSTRACT

Plastic bottles (PET) are examined both structurally and thermally to be utilized as building units, replacing traditional concrete blocks. Tests were conducted after filling the bottles with either dry sand, saturated sand, or air, bound by cement mortar to produce stable masonry walls of reduced thermal conductivity.
The effect of the infill material on the bulk unit weight and the compressive strength of the plastic bottle masonry blocks showed slight effect of the used infill material on the strength. Although the gross strength of these plastic bottles is much less than the traditional blocks, 670 kN/m^2 compared to 3670 kN/m^2, but calculations showed that the blocks of air filled bottles still can be used as suitable construction units for partition walls or as bearing walls for one roof slab.
Thermal wise, air filled bottles showed better thermal insulation than the tradition block construction, which could act as thermal insulation material.

Introduction

Industrialization, economic development and population growth, have led to an increase in, and diversification of waste disposal. Most are disposed of at dump-sites leading to environmental issues that are both cumulative and disruptive to the ecological structure. For centuries, waste was considered as an unavoidable consequence of materialism that had to be collected, and buried. Basically, out of sight, was out of mind. Disposal has made way, where possible, to recycling and reuse. There is a need to close the material cycle loop by transforming waste into a material resource (Fischer-Kowalski, 1998).

Waste management that optimizes waste streams and material flows challenges sustainable urban development where there is a growing consensus that waste should be regarded as a valuable resource. It has been argued that the concept of 'waste' should be substituted by the concept of 'resource', and Braungart and McDonough point out that the practice of dumping waste into landfill is indicative of a failure to design recyclable, sustainable products and processes. All eco-cities have to embed zero-waste concepts as part of their holistic, circular approach to material flows (Braungart and McDonough, 2002).

According to Abou Elseoud (2008), GCC (2004), and EMEA (2007), Plastic wastes account for 12% to 16% of the waste in the Arab countries. Thousands of plastic materials, particularly plastic bottles, are improperly disposed of each day resulting in large volumes of plastic waste accumulating in the natural environment, dumped in rivers, buried, and burned, releasing toxic contaminants into the environment. This has become a solid waste management challenge in most countries (Abou Elseoud, 2008).

Recycling technology has been the solution of choice in many cases but it may not always be economically viable, and for this reason the research embarked on utilizing plastic bottles as an alternative building material. Accordingly, this paper will examine the use of plastic bottles in construction, both structurally and thermally as an architecturally innovative sustainable building approach.

Background

Several references reviewed the waste management practices and discussed building with recycled plastic bottles. Katdare (2011), demonstrated that environmental concerns prompt many of us to seek environmentally friendly alternatives, as we explore green alternatives, and seek to respect our ecology by utilizing plastic bottles as a building material. Alvarado (2010) also discussed building with recycled materials that, apart from plastic bottles, involve other recyclable material s, including expired powder milk and even horse manure. See Fig. 1.

Some solid waste materials are non-perishable, however, if they are reused or recycled as a building material, they would become an effective solution, responding effectively to the requirement to consider nature. Such alternative construction materials could also be an effective

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http://dx.doi.org/10.1016/j.esd.2014.11.001
0973-0826/

Fig. 1. Use of plastic bottles wastes in building (Katdare, 2011; Alvarado, 2010).

thermal insulator especially for harsh climates as the arid ones. This study offers the dual advantage of disposal of such waste materials without damage to the environment and also for the thermal enhancement of structures built with such waste materials. Consequently, it is important to examine the structural durability of these waste bottles and their thermal behavior.

Material and methods

Masonry polyethylene terephthalate (PET) plastic bottles block specimens of an average length, diameter and capacity of 30 cm, 9 cm and 1.5 l respectively were used. The mean shell (skin) thickness of the bottles is 0.5 mm plastic. The average weight of the air filled bottle is 0.33 N, while the weight of the bottle filled with dry sand, and saturated sand is 22.45 N and 32.54 N respectively.

Testing specimen preparation

The work was conducted by preparing masonry bottle blocks with 10 mm vertical and horizontal bonds of mortar as a binder, using block manufacturing facilities at the engineering material testing laboratory at the University of Nizwa. For each bottle infill type (dry sand, saturated sand and air) at least three block samples were prepared. Each sample has been constructed by eight plastic bottles and configured as interlocking pieces, as shown in Fig. 2.

Subsequently, a wooden mold was prepared and the bottles have been located and bound by a 10 mm mortar bond. For the mortar, prescribed portions of cement and sand were weighed out in a metal pan and a specific amount of water was added in the proportions of: 1:2:0.54, sand: cement: water. Then the blocks of 300 × 300 × 300 mm were molded, and the block samples were left in the molds for 24 h at laboratory temperature (20 ± 2 °C), then removed from the molds and cured by immersion in a water tank for an additional 27 days.

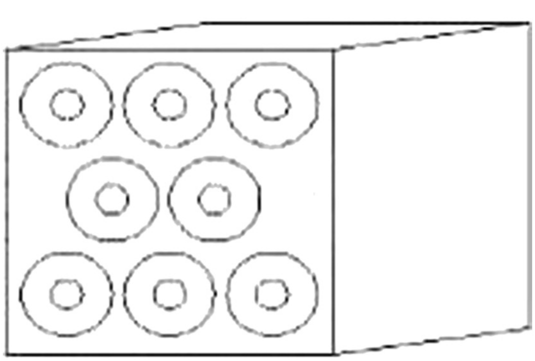

Fig. 2. Arrangement of bottles per each block sample.

The arrangement of bottles, casting of the cement mortar, shapes of the testing samples and the curing process are shown in Fig. 3.

So as to check the increase of strength of the blocks, some bottle samples have been perforated. The idea was to increase the friction between the bond and bottles. The perforated dry bottles blocks were casted in similar way to all previous blocks and the strength determined for 28 day curing.

Strength study

The masonry blocks were subjected to unconfined compressive loading using a compression machine of 3000 kN capacity and of an accuracy of 0.10 kN. The loading was applied on the block in a manner of the bottles laying horizontally and subjected to a diametric compression mode, which simulates the way they are used in wall construction. The compressive strength of the blocks was determined as: $_c = P/A$.

Where,

$_c$ is compressive strength,
P is load at failure and
A is cross sectional area

In addition, the wet bulk unit weight of the masonry blocks was determined at the time of testing for all types of blocks. Fig. 4 shows the mode of testing in the laboratory.

Thermal study

The thermal study was calculated for the chosen three bottle block samples with different bottle infill; dry sand, saturated sand and air filled bottles. Accordingly, a model has been simulated with a building simulation software to examine the thermal performance for plastic bottles constructed room versus a traditionally built one.

Thermal resistance calculations

The thermal resistance was calculated according the following equation:$R = L/kA$

Where;

R is the thermal resistance (°C/W)
L is the wall thickness (m)
K is the thermal conductivity (W/m°C) and
A is the area (m^2)

Building thermal simulation

Energy simulation software tools are an important support used for building designers to reduce the cost of energy in buildings. Energy simulation software tools are an important support used for building designers to reduce the cost of energy in buildings (Sousa, 2012).

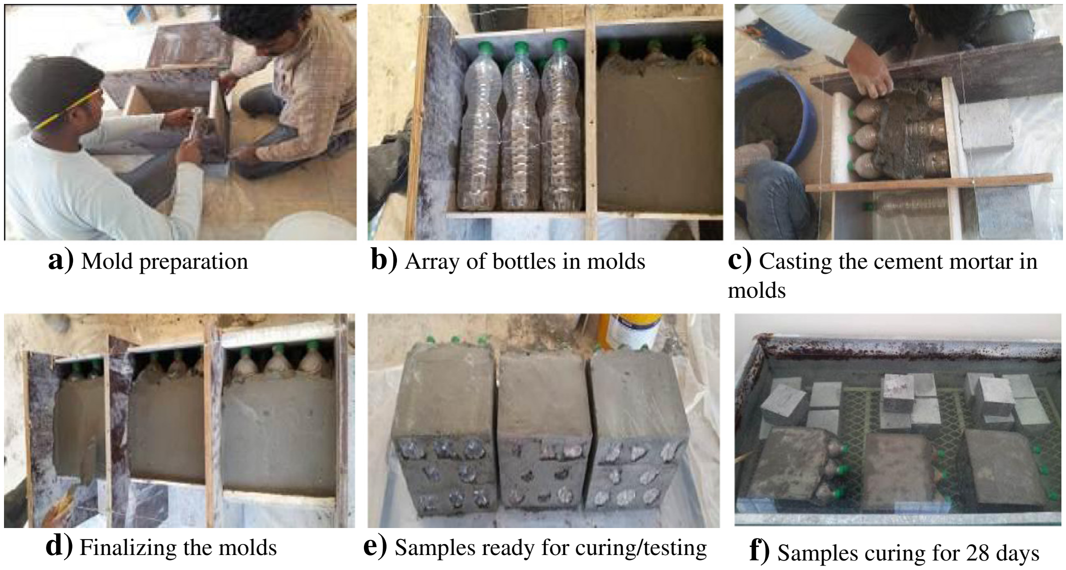

Fig. 3. Preparation of samples.

Accordingly, a proposed room model has been simulated by the aid of ECOTECHT[1] computer software so as to examine the behavior of the room built by the air filled plastic bottles verses a room built by traditional common cement blocks.

Accordingly a room has been modeled as one zone which describes enclosed and individual space. The proposed room dimensions are 2.5 m × 2.5 m with a height of 3 m. The model is built up to have a solid glass window opening 1 m × 1 m and a door 1 × 2.2 m facing the exact north. The east, west and south walls have no openings. (See Fig. 5.)

The inputs are shown in Table 1

A weather file for Abu Dhabi was chosen for simulation as an example for an arid region. The walls have been modeled with two material types' air filled plastic bottles with mortar and traditional common used blocks. The thickness of the walls for both materials has been set as 300 mm. The thermal resistance for both wall types has been assumed as calculated above; $R_{(\text{air filled bottle block})} = 18.967$ °C/W while $R_{(\text{common blocks})} = 4.63$ °C/W For both 'traditional blocks' and 'plastic bottles' constructed rooms, simulation was run for three dates of the year; the 22nd of July, the 22nd of December and the 15th of September. The indoor temperature was plotted versus the outdoor temperature for both rooms.

Results and discussion of results

Structural study results

Both Table 2 and Fig. 6 show the effect of the infill material on the bulk unit weight and the compressive strength of the plastic bottle masonry blocks. As shown, there is a slight effect of the used infill material on the strength.

A similar mode of cracking was obtained for all samples regardless of infill materials. The cracks started as a vertical cleavage from the top layer of the mortar down through the vertical bond between bottles, with single or multiple crack patterns. See Fig. 7. A possible explanation is that tensile stresses created inside the specimen were due to a considerable difference between the modulus of elasticity of the mortar and bottles. This happened in all the types of blocks. Blocks of air filled bottles showed a relative higher strength.

Perforation effect on the air filled bottles blocks strength

The results of strength for perforated bottles are given in Table 3. It can be concluded that the perforation led to decrease the strength rather than increase. This may be attributed to the fact that the bearing strength of the bottles lowered due to increase in compressibility of the perforated bottles.

Structural check for plastic bottle wall stability

To check stability, an assumed wall of 3 m high and 300 mm thick, constructed of air filled bottle blocks, considering the obtained unit weight and height, the load subjected by the wall = height × width × unit weight × 1 m = 3 × 0.3 × 11.02 × 1 = 9.92 kN/m .

The strength of the blocks wall per meter run = width × strength of blocks × 1 = 0.3 × 670 × 1 = 201 kN/m .

The strength of the constructed wall is assumed to be less than that of the individual block, due to block interlocking mortar strength and the wall height effect. Accordingly the value will be estimated as 50% of the individual block. Therefore the factor of safety equals strength of the wall/load exposed = 201/9.92 = 20.2

Fig. 4. Compression test in progress.

[1] ECOTECHT is a complete environmental analysis design tool which couples an intuitive 3D modeling interface withextensive solar, thermal, lighting, acoustic and cost analysis functions. It allows designers to simulate building performance right from the earliest stages of conceptual design. It combines a wide array of detailed analysis functions with a highly visual and interactive display that presents analytical results directly within the context of the building model, enabling it to communicate complex concepts and extensive datasets in surprisingly intuitive and effective ways. An engagement with simulation and analysis at a time when the design is sufficiently 'plastic' and able to respond is critical to achieving the high levels of performance being demanded of modern buildings.

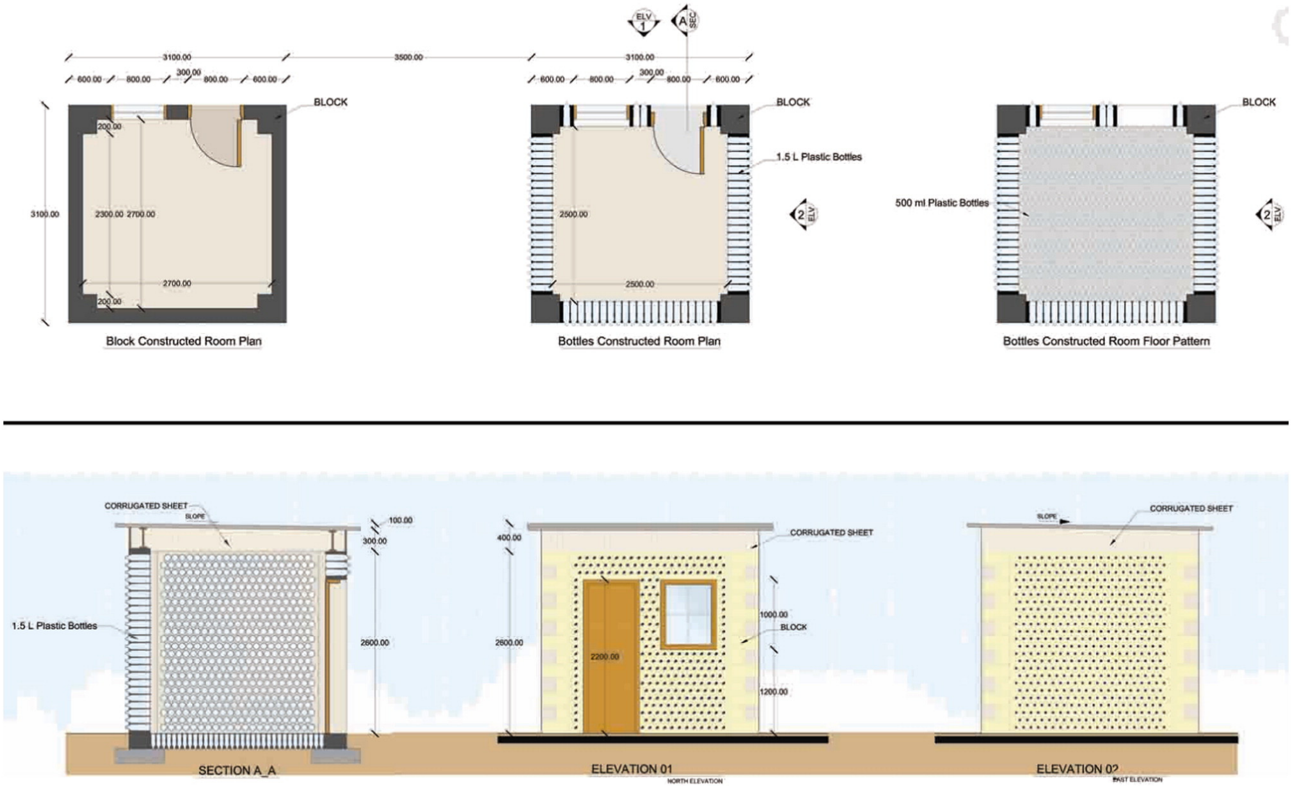

Fig. 5. Architectural drawings for the proposed simulated rooms.

Considering a slab of 4 m span, with thickness of 0.15 m, the unit weight of concrete = 24 kN/m^3

Load from the slab = $2 \times 1 \times 0.15 \times 24 = 7.2$ kN/m .

The total load from (slab = wall) = $9.92 + 7.2 = 17.12$ kN/m .

Hence the factor of safety considering 50% of the wall strength equals $201/17.12 \times 50\% = 5.87$.

Comparison with traditional blocks

The traditional block used in the region is the hollow concrete block having dimensions of $390 \times 190 \times 190$ mm. The volume of voids in such block is about 31% of its total volume. The blocks are casted with well graded coarse and fine aggregates, well vibrated and cured for 28 days.

It has been tested at the engineering material testing laboratory at the University of Nizwa, so as to compare it with the blocks under study.

The gross strength of these blocks is 3670 kN/m^2 (average of 30 specimens). This type of block is used for either partition wall or for bearing wall of construction up to three story building high, considering both live load and dead load.

Thermal study results

According to Cengel (2006), $K_{air} = 0.027$ W/m·°C, $K_{dry\ sand} = 0.27$ W/m·°C, $K_{saturated\ sand} = 2$ W/m·°C while $K_{mortar} = 0.72$ W/m·°C.

1- Regarding the air filled bottle block sample, the air inside the bottles is non moving air, thus there is no heat transfer by convection. Area

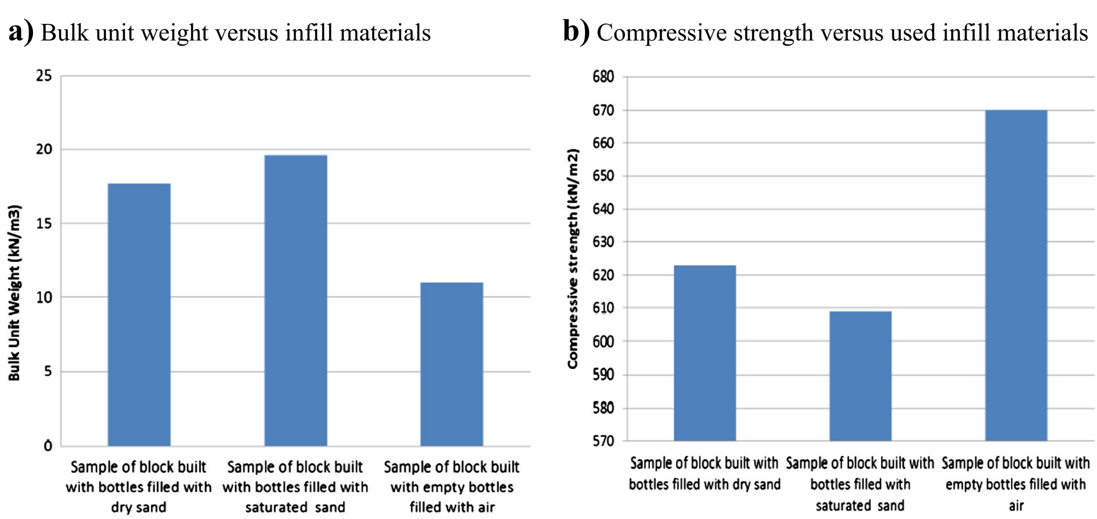

Fig. 6. Effect of infill materials on the bulk unit weight and compressive strength of block sample.

a) Sample of block built with bottles filled with dry sand	b) Sample of block built with bottles filled with saturated sand	c) Sample of block built with air filled bottles	d) Sample of block built with air filled Perforated bottles

Fig. 7. Mode of cracking for the different samples.

of the bottles cross section equals $\pi r^2 = 0.007854\ m^2 \times 9$ bottles $= 0.07\ m^2$, while the area of the mortar cross section equals $0.3 \times 0.3 - (9 \times 0.007854) = 0.019314\ m^2$. Hence, as per the above equation, $R_{(air\ filled\ bottles)}$ equals $0.3/0.027 \times (9 \times 0.007854) = 157.19$ °C/W and $R_{(mortar)}$ equals $0.3/0.72 \times 0.019314 = 21.57$ °C/W.
Therefore, the *overall heat transfer coefficient for the air filled bottles wall* $= 1/R_{(air\ filled\ bottles)} + 1/R_{(mortar)} = 1/157.19 + 1/21.57 = 0.052722$ W/°C. Accordingly $R_{(air\ filled\ bottle\ block)}$ equals 18.967 °C/W.

2- Regarding the dry sand filled bottle block, $R_{(dry\ sand)}$ equals $0.3/0.27 \times 0.007854 \times 9 = 15.719$ °C/W, while $R_{(mortar)}$ equals 21.57 °C/W. Therefore $R_{(dry\ sand\ infill\ bottle\ block)}$ equals 9.093 °C/W.
3- Regarding the saturated sand filled bottle block, $R_{(saturated\ sand)}$ equals $0.3/2 \times 0.007854 \times 9 = 2.122$ °C/W and the $R_{(mortar)}$ equals 21.57 °C/W. Therefore: $R_{(saturated\ sand\ bottle\ infill\ bottle\ block)}$ equals1.932 °C/W.

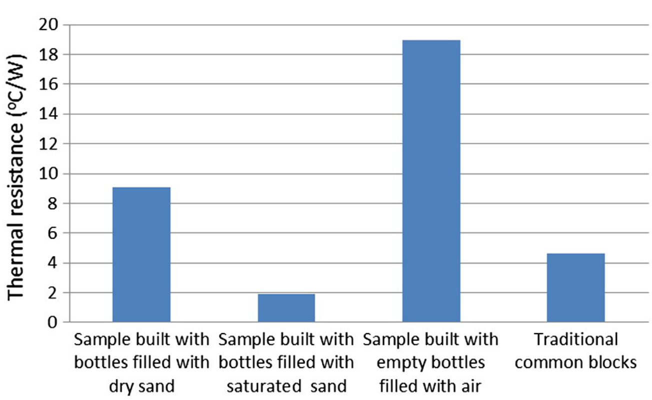

Fig. 8. Thermal resistance for three bottle blocks and the traditional common cement blocks.

Comparing the results with the traditional common blocks construction, it was found that the $R_{(common\ blocks)}$ equals $0.3/0.72\ (0.3 \times 0.3) = 4.63$ °C/W.

Fig. 8 shows that the air filled bottles has the best thermal resistance.

Thermal output results

The thermal simulation output in Fig. 9 showed that the air filled plastic bottles room indicated better and stable thermal performance in summer, winter and autumn, than the traditional blocks one.

The software output graphs indicated the effect of thermal stability, in the air filled plastic bottle room according to the high thermal resistance value for the air filled plastic bottle walls. Accordingly, this material could act as a thermal insulation. This proves that building with the air filled plastic bottles has much better thermal insulation properties than the traditional block construction.

Conclusions

The following conclusions can be drawn:

The block of air filled bottles showed slightly higher strength than the different types of bottle filling, and has proved to have structural stability with a high factor of safety.

The block of air filled bottles can be used for construction as either a partition (in a multi-story building) or a bearing wall for a roof slab, with a factor of safety of. 5.8 in one story building.

The infill materials have also been examined according to their thermal properties. In addition, a proposed room model has been simulated by the aid of ECOTECH computer software so as to examine the behavior of the room built by the air filled plastic bottles verses a room built by traditional blocks. The simulated air filled plastic bottles construction model showed much better thermal insulation properties than the tradition block construction.

Table 1
Input values for the model for the simulation software.

Variable	Base case study (room built with common concrete blocks)	Modified case study (room built with air filled plastic bottles with mortar)
Zones	One	One
Room dimensions	2.5 m × 2.5 m with a height of 3 m	2.5 m × 2.5 m with a height of 3 m
Openings	solid glass window opening 1 m × 1 m and a door 1 × 2.2 m facing the exact north	solid glass window opening 1 m × 1 m and a door 1 × 2.2 m facing the exact north
Infiltration	No indoor air circulation considered	No indoor air circulation considered
Wall material	Common concrete blocks	Air filled plastic bottles with mortar
Wall thickness	300 mm	300 mm
Wall R value	$R_{(common\ blocks)} = 4.63$ °C/W	$R_{(air\ filled\ bottle\ block)} = 18.967$ °C/W
Roof material	Concrete	Concrete
Roof thickness	150 mm	150 mm
Roof R value	2.31 °C/W	2.31 °C/W

Table 2
Results of compressive strength and bulk unit weight.

Sample description	Compressive strength (kN/m^2)[a]	Bulk unit weight (kN/m^3)[a]
Bottles blocks filled with dry sand sample	623	17.67
Bottles blocks filled with saturated sand sample	609	19.59
Air filled bottles blocks sample	670	11.02

[a] Each value represents an average of at least three specimens.

Table 3
Results of compressive strength and bulk unit weight for both perforated and non-perforated bottles samples.

Sample description	Compressive strength (kN/m^2)[a]	Bulk unit weight (kN/m^3)[a]
Non-perforated bottles block sample	670	11.02
Perforated air filled bottles block sample	560	11.02

[a] Each value represents an average of five specimens.

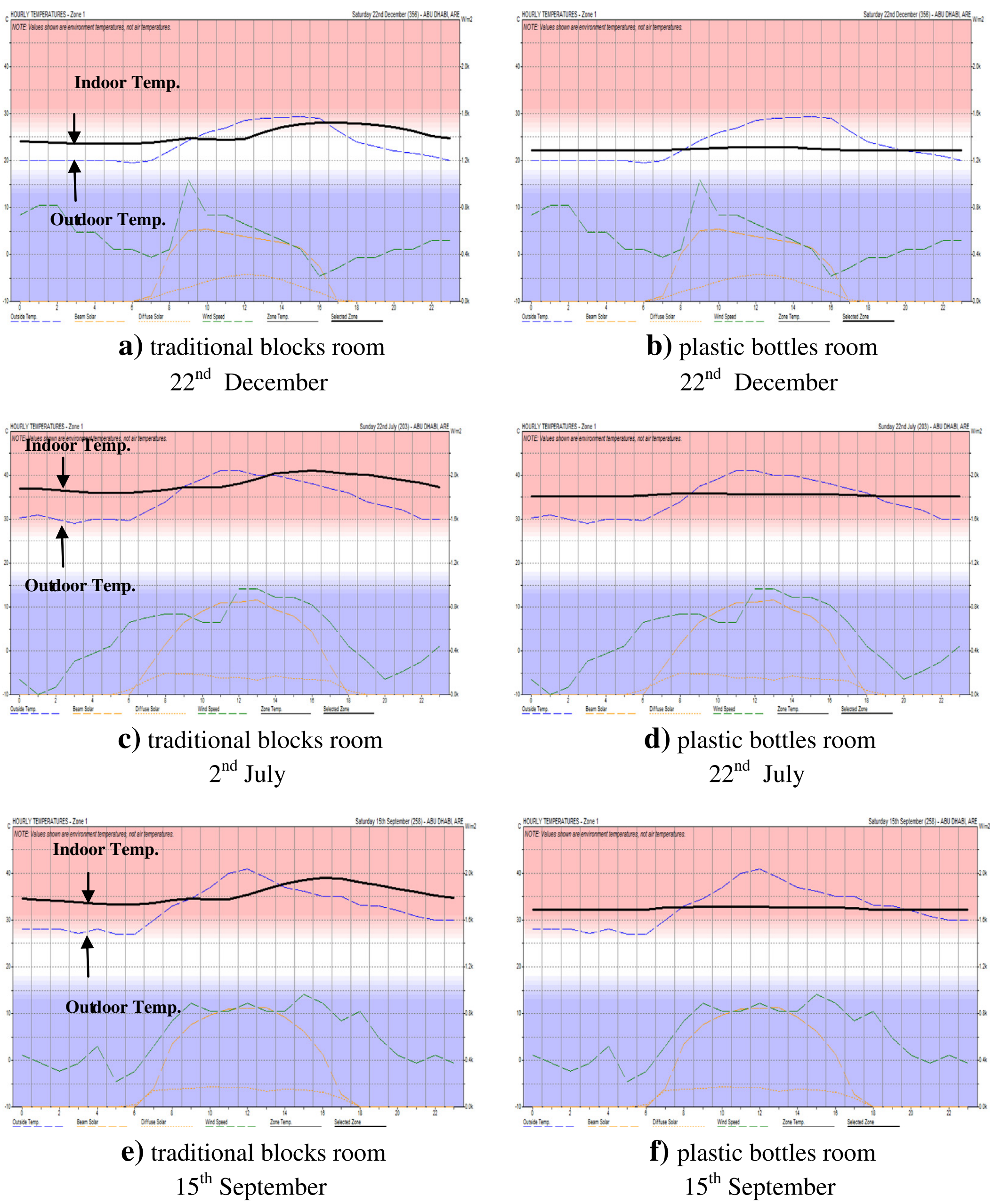

Fig. 9. Indoor temperature thermal simulation output for both rooms.

Therefore, using plastic bottles as an infill building material, not only relieves the burden of their waste disposal, but is considered an acceptable thermal insulation material, that is structurally stable and achieves environmental awareness.

Acknowledgments

The authors wish to acknowledge University of Nizwa, Oman (A/12-13-UoN/04/CE&A/IF), for its funding and contribution for this paper. Many thanks to both Dr. Isam H. Aljundi and Mr. Wael A. Khudhayer, University of Nizwa, for their contribution and assistance in the paper. The authors also express their appreciation and gratitude to Mr. Raymond Petersen; the Quality Assurance and English language lecturer, of the Foundation Institute of the University of Nizwa for his role in editing the paper.

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