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Household waste as a low-tech thermal insulation for roofs

A vernacular approach to climate change mitigation and adaptation strategies for vulnerable communities in Egypt

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ABSTRACT: A gradual increase in earth's temperature is becoming a reality faced nowadays. Communities in informal settlements or deprived neighbourhoods living in buildings of poor quality are the most vulnerable to indoor heat stresses. Six test cubes were constructed on the rooftop of a residential building in Cairo, Egypt. Ten different thermal roof insulation ideas were tested and experimented in an urban living lab setting under real climate conditions. The 10 solutions were tested during peak summer hours and their efficiency was monitored along two consequent time intervals, where 5 solutions were monitored at a time. The two best solutions were tested again in winter. This experimental study showed that using reed mats and reed crate with wet burlap can reduce temperatures up to 3.5 degrees compared to conventional roof construction methods. The feasibility of the proposed solutions, their cost efficiency and their maintenance were discussed. We hope this experimental study can be scaled up to help vulnerable groups in informal or deprived areas to reduce their level of suffering from indoor heat stress. Low-tech and low-cost roof insulation can offer adequate thermal comfort for marginalized populations.

KEYWORDS: low-tech; vernacular solutions; climate change; urban living lab; municipal waste

1. Introduction

1.1 Study background and problem definition

It is a known fact that buildings account for 40 percent of global energy consumption [1]. Existing solutions such as energy-efficient windows, insulation, heat regulators, efficient pumps, smart meters and intelligent management systems can reduce energy consumption by at least 50 percent [2]. But how about the majority suffering in many cities in the global south? Their shelters are structurally insecure with poor to no insulation - not even offering minimal levels of indoor thermal comfort. Mortality levels especially in the global south are increasing due to indoor heat stress [3,4]. Both mortality rates and levels of suffering will continue to rise with the increasing frequency and impact of extreme climate change events.

In Egypt, 40 % of residential areas are informal and is around 60 % of Cairo's residential stock [5,6]. Horizontal flat roof with no thermal insulation is the typical roof system in Cairo's residential buildings, contribute to the increase of heat gains in buildings. During hot summer days, flat roofs receive 1.5 times the solar radiation that vertical west-facing façades receive, and 4 times more than what vertical south-facing façades receive [7,8]. Previous research has shown that flat roofs in single story buildings can account for ± 50 % of total daytime heat gains [9,10]. Treatments to roofs can contribute to reducing the cooling loads and the need for air-conditioning systems in hot climates [11]. Several studies have shown diverse techniques and solutions for passive cooling in buildings [12]. Some focused on low-tech approaches [11] and some mainly looked at high-tech solutions like aerogels [13]. Experimental test cells were used as a methodological approach in real climates to test the performance of several roof solutions in several studies [14]. The same approach has also been used extensively in hot climates [15,16].

After conducting a review of the available discourse and literature, we can deduce that there is still no focus on low cost and low-tech thermal insulation solutions for vulnerable groups who cannot afford to pay for standard insulation. The aim of this paper is to introduce passive and low-tech thermal insulation proposals for roofs that are almost zero cost through the use of mainly household waste. The goal is to come up with solutions that should be easy to implement, require little maintenance and are easy to replace when needed. Ten alternatives were tested in a real environment on the rooftop of an apartment building in Cairo, Egypt as a proof of concept. The test cubes were built, and the 10 solutions were tried out and monitored for 10 days in summertime and 10 days in wintertime. The outcome of the monitoring revealed that the proposed passive low-tech solutions have a direct impact on the heat flux from the roof to the inner space of the test cubes. Thus, affecting the indoor temperature and thermal comfort levels.

This research has a social dimension in addition to the environmental and economic ones. We hope that we can contribute in reducing the knowledge gap by conducting this research, which we hope will be followed by more in-depth testing and wider application on full scale residential units. The outcome was mainly aimed at targeting people in informal areas earning little to no income. However, there is a potential for wider applicability of the outcomes of this research in other low-income areas in hot climate zones.

2. METHODOLOGY

2.1 Experimental set up for the urban living lab and text cubes

First the test cubes were modelled using Autodesk Revit software and a shadow study was performed for the summer and winter seasons. This was to make sure that the test cubes would not drop shade on each other. Also, to avoid any shadows from neighbouring buildings or the roof's fence. Then the test cubes were constructed using reclaimed mud bricks from construction rubble in the same neighbourhood. All the test cubes were covered with the same reinforced concrete flat roof, which is how typical roofs for residential buildings are constructed in Cairo. One cube was used as a base, or "control" case to resemble a typical residential unit. The other 5 were used to try out different passive cooling solutions for roofs. Prior to installing the different roof solutions, a test trial was conducted to check that all the test cubes had the same thermal behaviours and no air that could affect monitoring results was infiltrating. All the loggers were calibrated at that stage as well.

The proposed passive cooling solutions mainly relate to coating shading strategies. Materials were mainly sourced from household waste, like Tetra Pak juice containers, toilet paper tubes, EPS (foam) plates filled with white Styrofoam, transparent plastic bottles filled with Styrofoam and egg cardboard cartons. Other vernacular inspired solutions were also tested – for example, reed mats, cactus as green roof solution, reed crates[1] covered with wet burlap[2] (jute cloth), and broken pottery pieces and sand. Addition, one test cube was painted with white lime wash paint. Thermal performance was assessed over 10 days in summertime and 10 days in wintertime. The measurements were made in comparison to the bare roof test cube (the base case). Local climate parameters were recorded during monitoring using an outdoor home weather station. Recorded measurements from the weather station were compared to a reference meteorological year in Cairo – 2018.

2.2 Building process for the different roof solutions

Six identical text cubes were constructed with the dimensions 60 cm * 60 cm * 72 cm. The test cubes were built from mud bricks composed of construction waste in order to resemble the poor quality of wall construction materials and techniques that compose the majority of informal residential units in Cairo. Test cube roofs were constructed from 10 cm of reinforced concrete, which also resembles standard roofing solutions. The test cubes were then left to dry. After the first 5 solutions were tested which include those with broken pottery and sand, plastic bottles with Styrofoam filling, egg cartons, EPS (foam plates) and white lime wash paint. Then, reed mats and juice carton packs, empty toilet paper roll, palm reeds crate with burlap, together with Cactus plants and soil. All were tested for another 10 days. The most efficient solutions from the first and the second rounds of monitoring were compared to the base case and monitored for another 10 days in winter. The solutions are shown in (Fig. 1).

2.3 Monitoring process

The monitoring was done using Easy Loggers. (Fig. 2) depicts the location of the data loggers hung in the centre of the test cubes. The test cubes were monitored in 10-minute intervals with an accuracy of +/- 0.5 °C and +/- 3 % humidity. The 10 different thermal roof solutions were monitored over two phases. The first 5 solutions were monitored for 10 days, from the 3rd of August to the 13th of August 2019. The second 5 solutions were monitored for 10 days, from the 30th of August to the 9th of September 2019. The two solutions that should best thermal performance and least reduction in indoor temperature from each phase were monitored against the base case from the 21st of February to the 2nd of March 2020. The outcome of the monitoring was analysed and synthesized based on the understating of the thermal performance and heat gains in addition to the proposed solutions behaviour in relation to the material properties of each of the roof insulation alternative.

[1] Crate is a wooden container used for transporting goods, in Egypt it's used to make from palm tree wood.

[2] Burlap is a fabric rough closes made from jute, it's often used for packing and shipping bulk goods and cotton in Egypt.

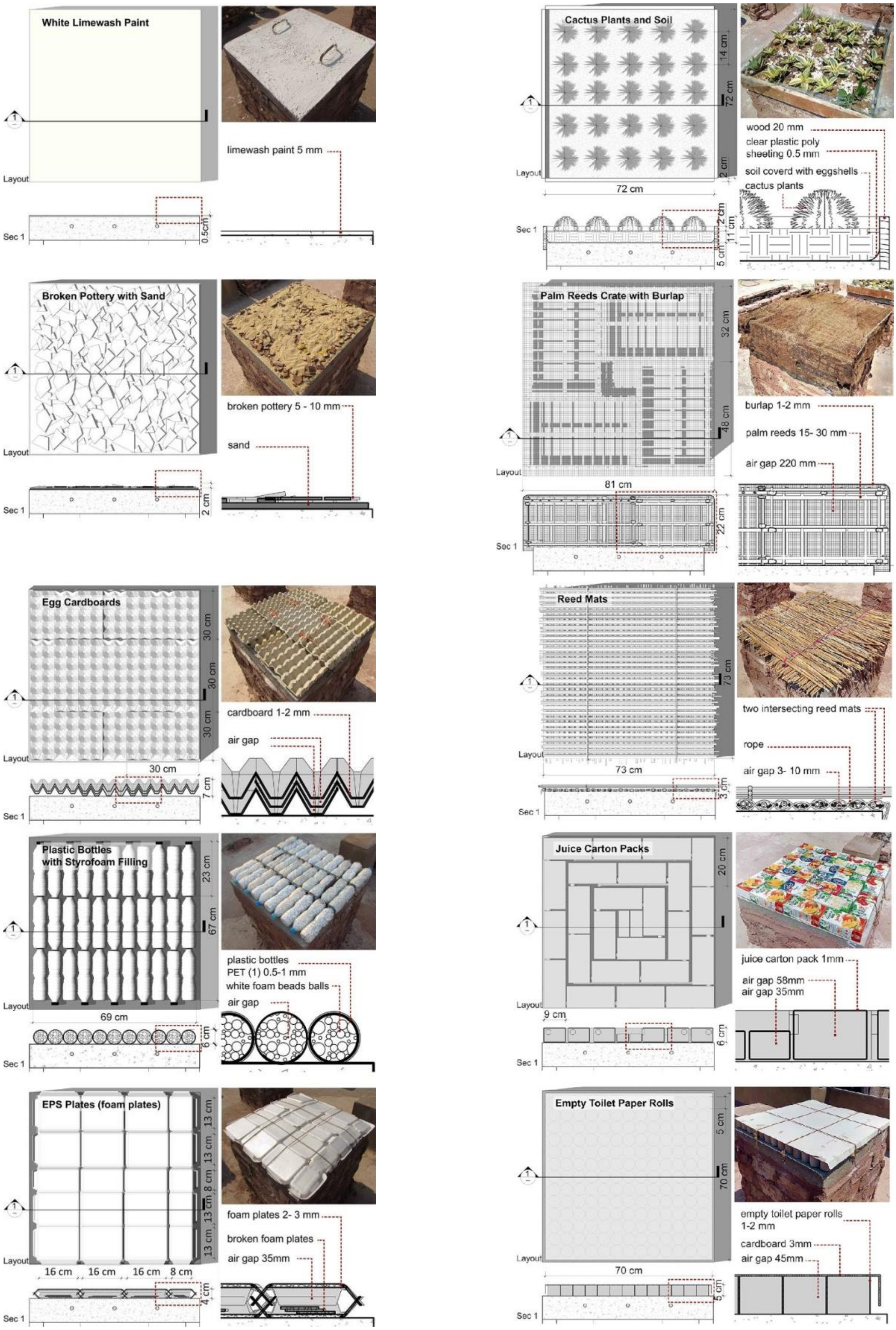

Figure 1: Detailed drawings and real shots for the 10 solutions that were tested, to the left (round 1) August 03-13, and to the right (round 2) August 30 to September 09.

Figure 2. The logger hung in the middle of the test cell during monitoring.

2.4 Comparative analysis for insulation performance and cost

The outcome of the thermal performance of the 10 different solution were compared to the base case to define the most effective one in terms of reduction in heat gains on the roof surface and indoor temperature. Also, the initial costs of each solution were compared to each other to define the most cost-efficient ones. In addition, the two best solutions from each monitoring interval were kept for the rest of the summer and winter seasons to observe their durability and maintenance. The strategy was to see if these solutions would deteriorate over summer or winter from the strong radiation of the sun, or rain and wind, respectively.

3. RESULTS AND DISCUSSION

3.1 Temperature and humidity monitoring

The majority of the solutions proposed resemble a typical shading strategy commonly used to reduce heat gains through the roofs of buildings. Results differed in regard to the air gap buffer between the roof and the insulation material or in between the insulation solution different layers. Also differ based on the material with high thermal properties like foam or material with high reflectivity as white lime paint. White lime wash paint and egg cartoon holders resulted in the best outcomes during the first round of temperature monitoring in summer. The paint and the cartoon reduced heat gains from the roof so consequently managed to reduce the indoor temperature by 3 °C to 2.5 °C compared to the trials with broken pottery pieces and sand, plastic bottles and EPS plates. The second monitoring round showed that the solutions using reed mats, cardboard, and burlap and wet crate cloth were the best solutions in reducing the heat gains which reduced the indoor temperature by 3.0 °C to 3.5 °C compared to the base case. Minimal to negligible differences in humidity were measured. This is most likely due to the fact that the climate in Cairo is relatively dry. Monitoring results are shown in (Fig. 3, 4 & 5).

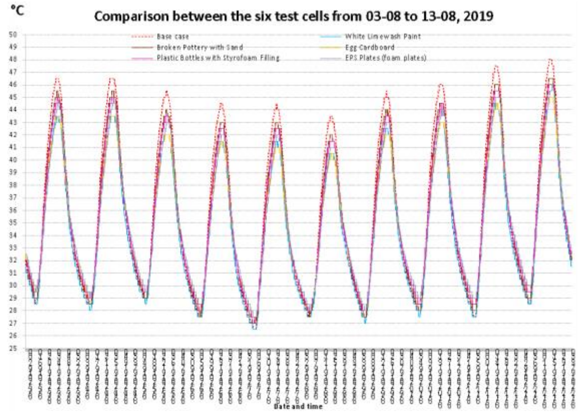

Figure 3: Monitoring results for the first 5 roof solutions compared to the base case and the outdoor temperature over summer.

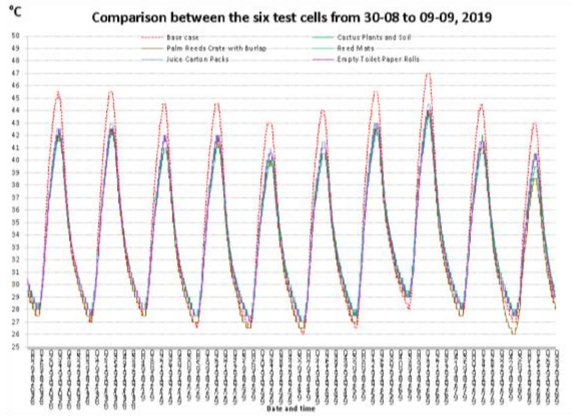

Figure 4: The monitoring results for the second 5 roof solutions compared to the base case and the outdoor temperature over summer.

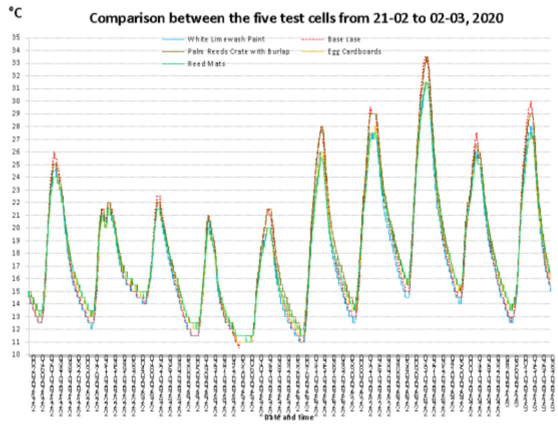

Figure 5: Monitoring results for the 4 best roof solutions compared to the base case and the outdoor temperature over winter.

The efficiency of reeds is expected to be connected to their U-value and their ability to retain heat for a long time before it is transmitted to the surface of the roof and then to the indoor space [17]. Reeds also have hollow stems which act as air gaps and increase the time lag for heat transfer [18]. While the burlap and crate create a fairly large shaded space allowing for air to pass underneath the burlap in between the crate hollow box like shape. The burlap was also

sprayed with water early in the morning, adding to its capacity to reduce heat gains through evaporative cooling. This explains why this solution was one of the most effective.
The solutions with high reflectivity like the white lime paint, transparent plastic bottles with Styrofoam and the EPS white foam plates also performed well, with an average 2°C difference from the base case. However, the white paint was more effective as it acted as an albedo material - proving in several studies to be an effective passive cooling solution [10,11].

The solutions with air gaps like the toilet paper tube, and Tetra Pak reduced indoor readings in the test cubes to a good degree, lowering the temperature by 3°C and 2.5°C, respectively. These results were quite close to the those of burlap and crate in the second monitoring round. It is assumed that if the paper tubes and Tetra Pak were thicker, their respective performances would have been even better, reducing the time of heat absorption and transmission from each material's surface to the air gap. One way to enhance the performance of these two solutions would be to fill them with foam. This could have increased the time lag for the heat to transfer from the tubes or the bottles to the roof's surface.

The green roof was expected to perform better. As normally planting vegetation in a soil layer combines three different roof cooling strategies which are; surface shading from the vegetation, earth covering form soil and evaporative cooling from the irrigation water [12]. Although green roofs are known to reduce the heat island effect and sequester carbon, the monitoring results for the solution tested here showed that the thermal reduction effect was not very high. The thickness of the soil, the types of plants used (in this case cactus) and the amount of water used for irrigation which helps in evaporative cooling, all play a role. Plants also transpire, which also helps to reduce indoor temperatures. Yet since the cacti were small, no plant canopy was created. It is also presumed that the dark brown colour of the soil, which was partially exposed to the sun, might have increased heat gains. While it has been suggested to cover the soil's surface with dry mulch (i.e. gravel) or light sand, or to use vegetation that needs water daily [19], these are not practical solutions for the hot, dry and water-scarce climate of Cairo.
In winter, comparing the egg carton, the burlap with crate, the reed mats and white paint it revealed that the reeds together with the burlap and crate proved to be the most efficient in keeping the indoor temperature warmer with an average gain of 2.5°C. Comparing results of the four solutions that were tested both in summer and winter, the reeds together with the burlap and crate was the most effective method for thermal roof insulation in both seasons.

We want to re-emphasize that only the top two efficient solutions were carried over to the winter tests because thermal comfort in summer was more important; otherwise, there might have been other materials that didn't perform best in summer, but performed better winter than the best-performing case in summer. It should be stressed here that the test cubes' indoor air temperature and humidity readings don't reflect their full-scale performance if applied in normal residential buildings. This is due to the small size of the test cubes and their lack of windows. Here, the experiment shows the difference in performance as it is useful for comparative purposes.

3.2 Durability and waterproofing of the proposed solutions

On roofs, the materials tested could be affected by sun, rain, wind, dust, birds, rodents or tiny reptiles. None of the materials are waterproof; however, some were more affected by rain than others. The solutions can be categorized into four typologies. First are the materials which were damaged and need to be replaced every summer like burlap and EPS plates (foam plates). The second typology consists of the materials that were affected but not damaged and can be used for another summer like white lime paint and Tetra Pak. The third category wouldn't need to be change – this includes the plastic bottles filled with Styrofoam, the reed mats, the broken pottery with sand and the egg cartons and empty toilet paper rolls. The fourth category are the solutions that need year-round care, like the cacti, which need to be watered on a weekly basis.

3.3 Cost efficiency and maintenance

The cost associated with the majority of the solutions is minimal. Tetra Pak, egg cartons, EPS plates and burlap with crate are all typical household waste materials. Even if they deteriorate every season, the cost of replacing toilet paper and egg cartons is almost zero as they are typically readily available as household waste as long as a storage area is available. While it can be tiresome to replace these materials as roofing insulation every season, the payoffs in their insulation capacities make the time spent worth it. Reed mats, while not free, are still cheaper than lime paint and might be available from agricultural waste for no cost. Nevertheless, transportation costs should be factored in as well as the time it takes to weave the reeds together as mats.
The white lime wash and cacti would could be cost-prohibitive to low-income communities. However,

the white lime paint is economical in the long run as it performs well and showed effective reduction in indoor temperature. In addition, it can last for a couple years before it needs another coat or to be re-painted. Previous research also shows that white lime paint's efficiency is also reduced if dirt accumulates on the roof's surface, meaning that regular cleaning would be needed in combination with this solution [11]. As the cactus proved to be the least efficient solution, the investment is not advisable.

4. CONCLUSION

This study is an experimental monitoring test for test cubes in urban living labs. The aim is to construct test cubes and add different passive cooling roof solutions. The solutions were monitored for their performance in a real environment – on the rooftop of a residential apartment building in a dense neighbourhood in Cairo. It is considered a trial for a proof of concept for testing different low-tech cool roof solutions. In this study, 10 passive low-tech solutions for thermal insulation and solar protection were tested. Low-tech roof insulation solutions using household waste and vernacular inspired passive strategies proved to improve the indoor temperature. The solutions suggested are almost zero cost solutions with thermal efficiency up to 3.5 degrees difference in indoor temperature compared to outdoor. The study concluded that reed mats together with the burlap and crate are considered the best two solutions in terms of durability, efficiency, maintenance and cost.
We hope that the outcome of this paper will help relieve the extreme heat conditions often born by vulnerable communities in the global south. The solutions have wider applicability in areas with similar building structures and climate conditions. We also hope this paper will inspire researchers and architect practitioners and most importantly homeowners to follow the same low-tech solutions. Heatwaves are now more frequent and increasingly long summer periods are inevitable. A popular science description and short film are also available so that the cool roof strategy can be more easily applied through this link.

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