



Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings

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ABSTRACT

In hot dry climates, it is estimated that almost half the urban peak load of energy consumption is used to satisfy air-conditioning cooling demands in summer time. Since the urbanization rate in developing countries – like the case in Egypt – is rising rapidly, the pressure placed on energy resources to satisfy inhabitants' indoor comfort requirements is consequently increasing too. This paper introduces passive cool roof as a means of reducing energy cooling loads for satisfying human comfort requirements in a hot climate. A designed algorithmic hybrid matrix was used to simulate 37 roof design probabilities alternating roof shape, roof material and construction. The result of using a vault roof with high albedo coating shows a fall of 53% in discomfort hours and saves 826 kWh during the summer season compared to the base case of the conventional non insulated flat roof in a typical Cairo residential buildings. It is recommended that the selected cool roof solution be combined with natural ventilation to increase the indoor thermal comfort, and with passive heating strategies to compensate the increase in heating hours. The application is intended for low cost residential buildings in a hot dry climate.

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1. Introduction

Since the beginning of 2012, Egyptians have been experiencing unusual increase in electricity blackouts. During 2012–2013 there was a 8.6% deficit between electricity generation and electricity demand [1]. In the summer of 2013, the blackouts were at a rate of 1–2 h per day. The forecast blackout rate for the summer of 2014 was 4–6 h per day [1] while the number actually experienced was around six a day of up to 2 h at a time. The high annual rate of increase in electricity demand and the simultaneous increase in energy consumption per capita is likely to continue. There is a rapid increase in electricity-generating capacity to match demand where residential buildings account for 42.3% of total energy consumption in the country [2]. The energy supply deficit is expected to reach between 30 and 50 m.t.o.e between 2020 and 2050, which is 24–35% of demand [2]. This is because of a mounting increase in

demand for electricity in the summer due to the increased use of air conditioners [3].

Several research papers have concluded that one way of reducing energy generation is to reduce the demand for air conditioning [3–5]. Instead of relying entirely on mechanical means which are electricity dependent and generated mainly from fossil fuels, architects should invest time in researching passive strategies to reach the best possible combination of low energy and natural climatic control for their buildings [3]. Then mechanical and active systems can become supplementary aids.

Thermal comfort in the summer is always a main concern in hot climate regions like Egypt. Natural ventilation and passive cooling have traditionally been two important features in Egyptian vernacular architecture to achieve thermal indoor comfort [6]. It has been calculated that, in hot climate regions, from 70% to 80% of total energy consumption is used to operate mechanical cooling systems [7]. There are indications that this is not only the case in the hot regions: research shows that energy consumption related to cooling during the summer heat has been rising recently in the slightly cooler climates of southern Europe too [8].

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Cool roofs are one of the inexpensive passive strategies that are easy to install, reduce heat gain and improve indoor thermal comfort in hot climates [9,10]. Using cool roofs with good roof thermal properties during the initial design and construction of the building, or when retrofitting, are usually more cost effective on both the building and urban level, this can save a considerable amount of the energy that is consumed in cooling [7,9,11]. Unfortunately, Egyptian building regulations do not make it mandatory to install cool roofs despite this often being the least expensive option to achieve the required energy performance. From here comes the drive for this research: to focus on the cool roof as a solution to reduce the amount of energy used to satisfy cooling demands during the summer. Although the potential benefits of cool roofs has received considerable attention in the Middle East and North Africa region, little research on this topic has been carried out, and only on a limited scale, in Egypt.

This study will investigate several roof composition solutions as tools to reduce heat gain. The main idea is to enhance the performance of cool roof construction composition through an investigation of several alternatives and possibilities. In this paper we have combined the shape and the properties of the roof materials to reach maximum thermal comfort and energy saving. A lot of research has been conducted on the effectiveness of different types of roof sections in hot climates. However, some types do not conform to current conventional building techniques or they specify materials unavailable in Egypt [12–14]. These earlier studies suggest that better roof design, alone, is the way to reduce cooling loads or discomfort hours. Thus, this present research aims to evaluate a broader range of possible varieties of roof construction in terms of materials and shape; some elements of the research are based on literature review alone but this has made available a wider field for comparison and allows for better evaluation.

The range of this research covers roof solutions for low and medium rise residential buildings in Cairo, Egypt. The effect of natural ventilation as a supporting factor to enhance indoor thermal conditions was considered along with the proposed passive roof cooling techniques. The results of this research show a considerable reduction in cooling days and energy consumption can be effected when using low cost construction techniques available in the Egyptian building market. The paper offers recommendations for further research in combining cool roof techniques with energy efficient wall sections, and window to wall proportions together with glazing as a way of reducing thermal loads.

2. The concept of the cool roof

Based on Parker's [15] definition of what constitutes a cool roof, the technique is considered a passive solution and a building typology that assists in reducing the cooling loads and energy demands on a building's envelope. The same source specifies that cool roofs can be surfaces that reflect sunlight and emit heat more efficiently than other dark roofs. On a normal sunny day in a hot dry climatic zone, a typical roof surface can reach to 37 °C above the ambient temperature [16]. Research shows that roof surface temperature can exceed the temperature of the other surrounding surfaces covered with vegetation by 20 °C [10]. The actual benefits of a cool roof on any particular building will depend on several factors, including building type, load, season and most importantly the climatic zone. There are several environmental benefits to cool roofs. On the urban level, cool roofs can contribute in reducing urban air temperatures by decreasing the quantity of heat transferred from roofs to the urban environment [17,18]. This can be done by using, for example, retro-reflective materials and reflective coatings thus mitigating the urban heat island effect [19]. On the level of building, cool roof improves indoor thermal comfort [22]. Consequently, a cool roof

reduces energy bills by reducing the dependency on mechanical air conditioning systems [20]. A typical application for a cool roof will achieve a reduction of about 10% to 40% in air conditioning energy [21–23]. A further, long term, benefit is that a lower roof temperature reduces maintenance and, hence, extends the life of the roof [15].

Solar reflectance and thermal emittance are the two key material surface properties that determine the temperature of a roof [24]. An amount of solar radiation is reflected back towards the sky from the roof surface and the rest of the solar energy is absorbed at the surface. The higher the reflectance (albedo) of the surface the less energy will be absorbed. The energy balance of the roof surface can be expressed as (All units in W/m²):

$$R_n = Q_H + Q_E + Q_S \quad (1)$$

where R_n is the net absorbed short- and long-wave radiation, Q_H is the sensible heat which will be carried away from the roof through convection and radiation, Q_E is the latent heat from evaporation and Q_S is the heat that will be stored in the roof surface and transferred to the ceiling through conduction [7]. The amount of heat that reaches the inner space will be determined by the insulative properties of the roof materials. If the roof surface is dry, Q_E will be negligible.

Despite the fact that cool roofs are considered efficient solutions in reducing heat gain, there are drawbacks to their use. In general, they increase the need for heating in winter [25,26]. However, if the location has no or low heating needs, the cool roof solution is optimal. Another drawback is that the bright colours used in cool roofs cause glare and visual discomfort to neighbours in taller adjacent buildings. In this paper, in order to reduce heat gain we have tried to combine the conductivity of the roof, the reflective properties and the colour of the materials with the roof shape. We have also taken into consideration the number of heating days.

3. Structure, composition and material performance of the cool roof

A considerable number of experimental and field studies have been carried out to measure the energy efficiency of cool roofs and their effect in reducing cooling loads and energy consumption, especially in summer time [11,27,28]. Other researchers have conducted computational studies to demonstrate how a cool roof can help to reduce energy demands by cooling the effect of the dominant climate [15]. Some have carried out mathematical calculations to see the effect of a cool roof shape on indoor thermal comfort [29]. Another area of research has been to examine practical measures to reduce the heat island effect [30,31]. A recent review study on cool roofs and heat island mitigation shows that in hot climates, reflective cool roofs with high albedo present a much higher heat island mitigation potential than green roofs during the peak period [32]. Other studies show that cool roofs can save energy and reduce air pollutants [33,34]. In the following sections types of roof structure, composition and material performance which are relevant and applicable in the Egyptian context will be reviewed.

3.1. Evaporative cooling through roof ponds

Evaporative cooling has proved to be an effective passive cooling strategy for a hot arid climate. Site experiments by Al-Hemiddi in the hot arid climate of the city of Riyadh in Saudi Arabia in August have proved that an average reduction of 5 °C in indoor temperature can be achieved by using a roof with moist soil shaded by 10 cm of pebbles [12]. Kharrufa and Yahyah applied a roof pond cooling system with active methods using a fan to increase the efficiency of the roof pond [14]. Al-Hemiddi, in the research mentioned above, tested a walkable roof pond with night water circulation. The roof

pond was filled with pebbles, with an insulation layer on top of which thin tiles were placed over the insulation, acting as a roof top surface accessible for the building's occupants. This technique reduced the indoor temperature by 6 °C compared to the outdoor temperature when measured and tested in August [12]. However we believe it is not ideal to adopt this idea in the case of low cost housing in Egypt as it needs a special roof structure to stand the dead load of the water. In addition it needs regular maintenance. As Egypt suffers from water shortage, if a cool roof pond is used we recommend working with grey water instead of fresh water. Givoni adds that water leakage can be a huge problem as it is hard to locate cracks in a roof [35], which is also a point to consider given the inefficiency of workmanship in Egypt.

Ben Cheikh and Bouchair applied an evapo-reflective roof using water ponds, low emissivity surfaces and inserted rocks of high thermal capacity. They combined this cool roof system with natural night ventilation to improve space cooling in buildings in hot arid climates [13]. Their research was theoretically proved by dynamic mathematical models, which indicated that an evaporative reflective roof can reduce internal room air temperatures during the day by up to 8 °C. Another research project in Egypt used the passive cooling of water at night in an uninsulated open tank to indicate the effectiveness of the evapo-reflective roof when used through radiant ceiling cooling panel systems [36]. However this research result [36] cannot be considered significant as the only assessment of its viability was on a test cell box of a one square meter tank, where the water depth was 0.5 m, which is not feasible with residential roofs.

3.2. Solar reflection of the roof surface

Given that the thermal performance of a building is directly affected by the solar absorbance of the roof, it has been found that, in a clear sky situation, from 20% to 95% of solar radiation is typically absorbed by the roof surface [37]. The amount of absorption depends on the reflectivity (albedo) of the roof surface. The reflectivity varies from about 0.1 for a very black colours to 0.8 for a very white colour. Generally, the rejection of solar gain is the main goal of passive cooling strategies [38] especially in hot climates. Direct sunlight onto a roof not only affects the indoor thermal comfort; thermal radiation coming from the roof materials affects the micro climate around a building [5].

Akbari and his research colleagues proved in their research on hot climates that increasing the solar reflectance of a roof from 0.2% to 0.6% can reduce the cooling energy of a building by 20% [28]. A numerical study performed by Shariah [39] in the moderate climate of Amman and Aqaba, in Jordan, showed that by increasing the external reflectance of a roof from 0 to 1, the energy load was reduced by 32% in a non-insulated building and 26% in an insulated building.

Several studies have proved a significant difference in heat gain if light colours are used instead of dark colours [37]. Generally, the studies indicate that coating the roof with a cool heat reflective paint or using bright colours helps to maintain a lower temperature on the exterior roof surface, which consequently helps to reduce the indoor temperature [40,41]. White is the most effective colour for flat cool roofs as it reflects between 55% and 80% of incident sunlight [42]. For example, using numerical simulation, Suehrcke and his colleagues suggested that changing the colour of a galvanized corroded surface to white reduced the heat flow through a roof by 60% of peak value [37]. Despite all the research that supports the beneficial effect of roof surfaces with bright colours (high albedo); we should not forget that changing the paint and colour needs to be combined with a consideration of the thermal properties of the roof material itself [5].

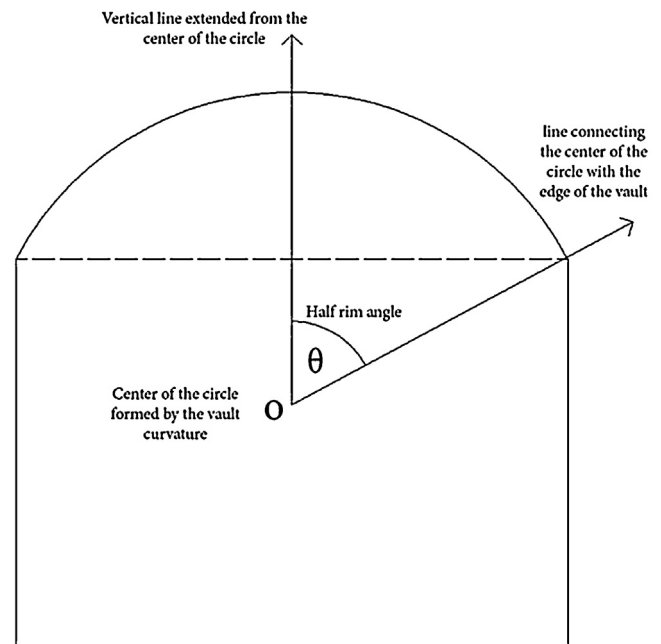


Fig. 1. Illustration for half rim angle.

3.3. Roof shape and form

When it comes to the roof shape, domed and vaulted roofs have been widely used in traditional and vernacular buildings in Egypt. As Koch-Nielsen stated, unlike the flat roof a rounded or curved roof is in the shade for part of the day [7]. It has hitherto generally been taken for-granted that rounded or curved roofs reduce the indoor temperature compared to flat roofs but a study carried out on the radiation absorbed by vaulted and domed roofs in a hot climate showed that domed roofs actually absorb less beam radiation than a corresponding flat roof but only during the hours around noon [29]. They actually absorb more beam radiation in the early morning and late afternoon. The study includes calculations which indicate that the absorbed radiation with of an east-west facing vaulted roof, when the half vault angle is less than 50°, approaches that absorbed by a corresponding flat roof [29]. This means that the smaller the area exposed to the sun, the smaller the amount of beam radiation. The study recommended the construction of domed roofs with more than 60° of half dome angle [29]. Other research has suggested that a vaulted roof with rim angles of less than 120° at night and in the early morning (see Fig. 1) has a lower heat flow than a flat roof [43]. The same research pointed out that the efficiency increases with higher rim angles [43]. In another study Tang et al. recommend a half rim angle for vaulted roofs of between 50° and 60° to satisfy the needs of both un-air-conditioned and air-conditioned buildings. They also recommend that the optimal orientation of the vault be north-south facing [44].

4. Methodology

The methodology implemented in this paper is based on an analytical literature study and comparative simulation work for different cool roof methods. The literature study was carried out to investigate and analyse possible roof solutions to suit Egypt's hot climate, with a focus on the climate in Cairo. There follows an experimental simulation study for one room in a typical residential apartment chosen to represent the common type of housing in Cairo (see Fig. 2), which was carried out by Attia et al. [45]. Drawing on the literature study, cool roof solutions were categorized

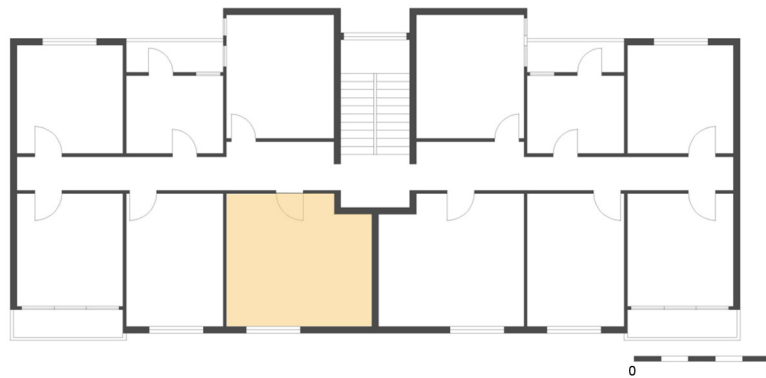


Fig. 2. Edited typical floor plan of a common typology apartment. The living room selected for the simulation test is highlighted in yellow. Illustration main source [45]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

according to previously tested strategies. They were compiled into one hybrid matrix (see Fig. 4) to produce different feasible alternatives for cool roof construction. Two main variables were chosen: roof shape and material. These were consecutively altered, which resulted in 37 different possibilities for roof construction. The aim was to evaluate a broad number of cool roof enhancements capable of extracting the most suitable energy efficient solutions in order to minimize heat transfer from the top roof to the building envelope with minimum cooling hours in the summer season. The efficiency of the 37 proposed cool roof solutions were simulated for the actual apartment chosen for the study and compared with its current conventional roof as a base case for the summer season (between 21 June and 12 September).

To calculate the thermal performance of the different roof sections, the building modelling simulation software DesignBuilder was used. Design Builder works with EnergyPlus as a simulation engine. This tool was developed by the US Department of Energy. EnergyPlus had been tested to comply with the industry needs and standard methods to produce a virus-free tool. The software passed three major tests: analytical, comparative and executable. It also passed the BESTest accuracy criteria [46].

4.1. Building typology and weather analysis

The aim was to choose a building type which was representative of the conventional construction techniques used in Cairo. Based on the GIS database at the Egyptian Ministry of Housing, Utilities and Urban Development, 80.47% of contemporary residential buildings in Cairo are constructed from concrete skeleton structures with brick infill, and with reinforced concrete flat roof. The modelled building prototype was based on a study on benchmarks of residential buildings in Egypt [45] and is located in Maadi in Cairo; latitude 30.05°N and longitude 31.23°E. The annual average high temperature in Cairo during summer ranges from 18.9°C to 35°C and average low temperature during winter from 9°C to 22°C. However, inside the city and due to the urban heat island, temperatures can reach 38.5°C in summer [47]. The annual average relative humidity is 57.75%, the maximum monthly average is 68% in January and the minimum monthly average is 44% in May [48]. Average wind speed in Cairo is 8 m/s [47]. The highest intensity for solar radiation in Cairo is in June, the lowest in January [49]. To put this in context, the global annual average daily radiation intensity is 5.03 kWh/m² [50].

According to the ASHRAE adaptive comfort model Standard [51], comfort levels in Cairo range between 19.6°C and 29.0°C (see Fig. 3). However, the comfort model used in this research is based on the Egyptian code of Energy Efficiency in Residential Buildings; the adaptive thermal comfort limits used in this research range

between 21.8°C and 30°C when humidity levels range between 20% and 50% and wind speed is 0.5 to 1.5 m/s [52].

The building studied is rectangular, 25 m × 11 m, consisting of six storeys, each 2.8 m high. Each storey consists of two identical apartments. The total volume of an apartment is 336 m³ with a floor area of 122 m².

The living room was chosen for the experiment as the most vital space inside an apartment. The room has one exterior façade with one window facing south. The extreme sun altitudes for the south façade is 83° at noon in summer and 36° in winter. The total floor area of the living room is 25 m²; window area 2.4 m². As this is a real case, not only the adjacent rooms were simulated for this study but the entire building the neighbouring buildings were modelled too and the heat transfer from the neighbouring rooms and buildings was considered. Table 1 shows the occupancy rate and occupancy schedule according to [45]. However, information regarding ventilation and when windows were opened were assumed by the authors as there was no reference to these factors in previous studies (Table 2).

4.2. The matrix

The Matrix, as shown in Fig. 4, is designed that the two main variables are alternated together. These two main variables are:

- Five roof shapes: flat roof, double roof, dome, vault and ventilated vault.
- Four cool roof material: insulation, albedo, an air gap and a water pond.

The matrix was designed in a simple mathematical way by which the two main variables match only once. The number of unique variables (M) are formed by a triangular matrix with identical input for head columns and head rows (m). The base case (C) was added to the number of variables as a constant. The number of incompatible roof composition (y) is subtracted from the total variables ($M - y$). Thus the total number of examined variables was calculated as follows:

$$m^2/2 + m/2 + C = M$$

$$16/2 + 2 + 1 = 11 \text{ roof layers variables}$$

$$(x1.M - y1) + (x2.M - y2) + \dots + (xn.M - yn) = \Sigma x.M - \Sigma y \text{ (that makes a total of 50 roof solutions)}$$

$$(1 \times 11 - 4) + (1 \times 11 - 7) + (1 \times 11 - 7) + (1 \times 11 - 0) + (1 \times 11 - 0)$$

$$5 \times 11 - 18 = 37 \text{ (total applicable variables).}$$

As shown in the equation above, the total number formed by this matrix was 50 roof sections. Theoretically, it is possible to simulate

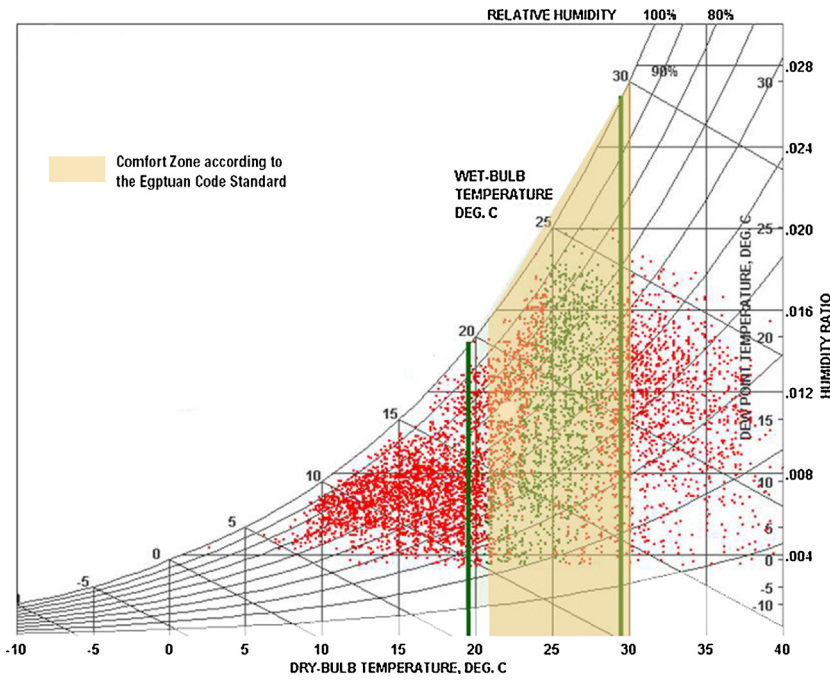


Fig. 3. Edited graph showing the Egyptian code comfort range on the psychrometric chart of the ASHREA adaptive comfort model Standard 55-2004. The upper and lower comfort ranges were used as set points in the simulation.

and examine all roof construction probabilities extracted from the matrix; however, in practice some probabilities are not applicable during construction, such as the water pond and the air gap layers with the dome, vault and the ventilated vault. Therefore, these were dismissed from the evaluation, resulting in only 37 examined roof sections. From the 37 we selected the most significant cases and their efficiency was compared, as shown in Section 5.

4.3. Cool roof material properties

There are four main material variables: high albedo paint, thermal insulation, air gap and water pond. Their thermal properties and description are given in Table 3.

4.4. Cool roof shape variables

In this study the flat roof, dome, vault, ventilated vault and flat double roof were tested. The cross section of the five different roof shape variables shown in Table 4 is the same as the conventional flat roof cross section in the Egyptian construction market, which is 15 cm of reinforced concrete, 2 cm of cement mortar and 1 cm tiling. The five different shapes of roof are shown in Table 4.

4.5. Materials' thermal properties

The thermal properties of the roof materials in addition to the materials used in the door and window are described in Table 5.

5. Results and discussion for findings

In this paper, the cool roof as a method to improve thermal conditions indoors is proposed, evaluated and simulated. Our proposed solution depends mainly on protecting the roof surface from direct solar radiation so as to reduce heat gain (thus reducing R_n in Eq. (1)) and allow for air movement to help in the cooling process. At the same time we tried to design the roof section in a way that would support reducing heating days as well, which appeared from our literature study to be a challenging compromise. Natural ventilation for the building itself was simulated and optimized. Temperature, heat gains and losses and U -values were parameters for evaluation for every case to obtain more detailed results, which were possible using the modelling process. The different roof proposals were compared with the base case, as shown in Fig. 5.

From Fig. 5, this study shows that the vault roof with rim angle of 70° and high albedo coating was the most effective cool roof solution, one capable of reducing cooling loads in Cairo compared to the conventional flat roof. Simulation tests and their analytical results in this study show that a vault roof with high albedo coating reduces cooling hours by 53%. This is 816 cooling hours compared to the 1735 h of the base case. Consequently, this solution will reduce the energy use for air conditioning, with savings of 826 kW h for the summer period. The vault high albedo roof section

Roof Shape					Roof Material	
Ventilated Vault	Vault	Dome	Double Roof	Flat Roof		
●	●	●	●	●		Base Case
●	●	●	●	●		Albedo
●	●	●	●	●		Insulation
○	○	○	●	●		Air Gap
○	○	○	●	●	Water Pond	

Applicable ● Not Applicable ○

Fig. 4. The matrix shows the combination of different probabilities for a roof section.

Table 1
The living room parameters, occupancy and window schedules.

Parameter	Description
Occupancy rate	0.25 person/m ²
Activity factor	0.9
Clothing value	Winter Clo: 0.9 Summer Clo: 0.5
Occupancy schedules	
Lighting	Incandescent lamps with average power intensity of 15 W/m ²
Window operability	
	<p>— Weekdays: Windows are only closed from 8:00 till 16:00</p> <p>— Weekends: Windows are only closed from 11:00 till 16:00</p>
Infiltration rates	0.7
Roof U-value	3.15 W/m ² K (15 cm reinforced concrete +7 cm of fresh soft sand, 2 cm of cement mortar + 1 cm tiling)
Wall U-value	2.13 W/m ² K (2 cm Mortar + 15 cm Egyptian Red Brick +2 cm Mortar)
Window U-value	5.89 W/m ² K (3 mm Clear Single Glaze)
Window SHGC	0.861

provides a net saving of 400 Egyptian pounds/m² throughout the whole summer season. The simulations suggest that, when combining the effects of natural ventilation and a cool roof, comfort conditions are 32% better than those achieved in the base case. The solution of the vault albedo roof is, therefore, recommended as it provides a large area for heat convection and heat exchange

where heat transfer occurs between the indoors and outdoors. The vault high albedo roof would also reduce heat gain during the day and increase heat release during the night. The simulation results indicate that increasing the height of the room can improve the indoor thermal comfort and accordingly reduce cooling demands.

Table 2
Calculated values for ventilation rates from Design Builder based on Cairo weather file.

Roof shape	Monthly ventilation rate schedule (ac/h)											
	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Flat roof, double roof, vault and dome	0.17	0.75	1.62	2.15	2.40	1.98	2.19	2.19	2.27	2.03	1.30	0.43
Ventilated vault	90.80	123.8	117.3	155.2	146.9	127.6	128.7	121.5	139.9	121.3	93.6	106

Table 3
Tested roof constructions (37 cases) and their U -value ($W/m^2 K$).

Material alternatives	Roof shape				
	Flat	Dome	Vault	Ventilated vault	Double flat roof
Bare roof	3.15	3.15	3.15	3.15	3.15
With high albedo coating	3.15	3.15	3.15	3.15	3.15
With insulation	0.361	0.361	0.361	0.361	0.361
With air gap	2.1	–	–	2.1	2.1
With water pond	2.5	–	–	–	2.5
With insulation & high albedo coating	0.361	0.361	0.361	0.361	0.361
With air-gap & high albedo coating	2.1	–	–	2.1	2.1
With water pond & high albedo coating	2.5	–	–	–	2.5
With insulation & air gap	0.26	–	–	0.26	0.26
With insulation & water pond	0.28	–	–	–	0.28
With air gap & water pond	0.821	–	–	–	0.821

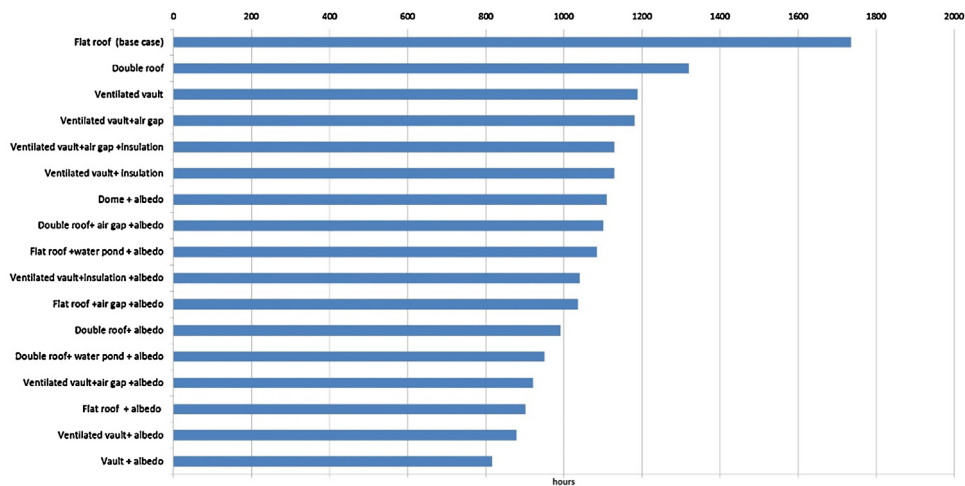


Fig. 5. Discomfort hours for the selected simulated roof alternatives, showing the most significant performance of cool roof solutions compared to the base case.

5.1. Roof geometry and heat gain

An analysis of the effect of the roof's geometry on the indoor thermal conditions yielded that:

- The total heat gain of the flat roof for the heat-stress months predefined is 414 kWh, with average indoor temperature in the month of August of 32.5 °C.
- In the case of the domed roof, heat gain decreased by 25% to reach a total of 310 kWh, with an average temperature in the month of August of 32.2 °C, despite the dome covering only 16 m² of the total roof area (25.32 m²).
- In the case of the vaulted roof, the decrease in roof gains is of greater value than with the domed roof, where the vaulted roof covers the entire 25 m² of the roof area. This leads to a decrease in the average indoor temperature in the month of August of close to 1.5 °C, reaching a value of 31 °C, as shown in Table 6.


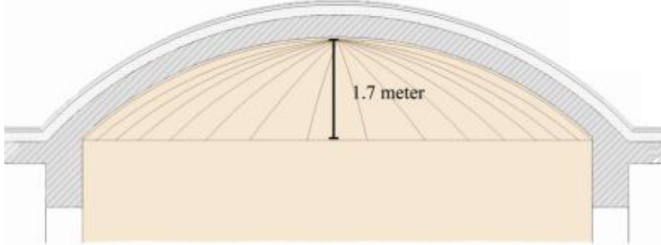
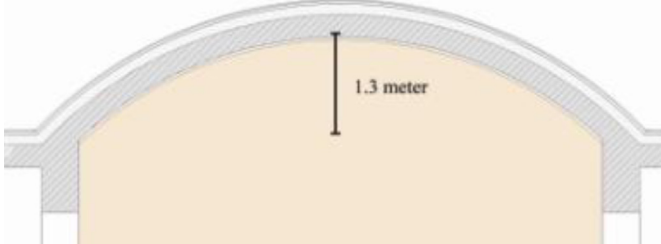
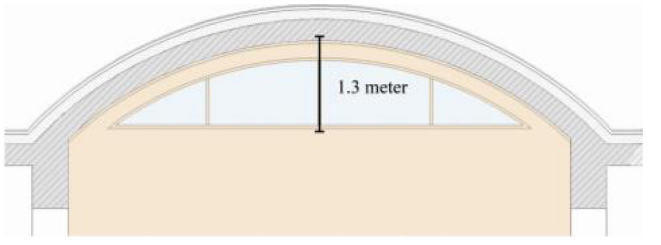

Generally a curved roof has a larger convection heat-transfer surface, allowing it to be more easily cooled. When air flows over a cylindrical or spherical object, the velocity of the air at the apex is increased and, as a consequence, the pressure at the apex is lowered [53]. In addition, when an air vent is added to the top of a curved ceiling, as in our ventilated vault case, it is rendered more effective. For the natural ventilation in the simulation, the wind velocity, frequency and direction were important to ensure correct behaviour. The most frequent direction of the cool prevailing wind in Cairo is

north–west, which was taken into consideration in the orientation of the vault.

In the flat roof section, adding a high albedo resulted in the fewest number of discomfort hours. In this case total heat gains from the roof are eliminated and heat loss through the roof section surpasses the heat gains to reach a total heat loss of (576 kWh) with an average indoor temperature of 30.4 °C in the month of August. This agrees with the work of Akbari and his research colleagues, where a high-albedo coating proved to be the most efficient cool roof approach, and albedo starts to pay for itself immediately through its direct effect [42]. Using high albedo or reflectance coating for roof materials is one of the variables that help in reducing heat gain [5]. In addition, a surface with raised albedo remains colder when exposed to direct solar radiation because it absorbs little and reflects more thermal radiation to the surrounding space [54]. As early as 1997, Simpson and McPherson had found that increased albedo roof heat gain is as effective as insulation in a hot climate and is a cost efficient solution. It is argued that the albedo effect of flat white roofs in cities with hot summers can offset the emission of CO₂, which in some cases reached the equivalent CO₂ emission over the life span of the roof [30,33,55].

Further on the flat roof insulated section (U value = 0.36), the total roof gains decrease by 90%, reaching a total of 48 kWh when the average indoor temperature in the month of August is 31.9 °C. The reason for the total decrease of heat is explained in other research work, which recommends that it is better to use a light roof colouring in combination with a reflective roof because that enhances the roof's reflecting qualities [34,56]. Other studies

Table 4
Roof shape alternatives.

Roof shape	Roof illustration	Rim angle
Flat roof		-
Dome		80°
Vault		70°
Ventilated vault		70°
Double roof 2.7 m roof height and extended two meters from the façade		-

confirm that using insulation alone may obstruct night-time cooling [37].

Consequently a flat roof with an air gap (U -value=2.1) yields poorer results due to the difference in the thermal conductance: in the month of August, the total heat gain through the roof can reach 360 kWh and an average indoor temperature of 32.1 °C. This is not the case in the flat roof water pond section (U value=2.5) where, although its total thermal resistance is less than the air gap section, the result is fewer indoor discomfort hours when the average indoor temperature in the month of August is 31.6 °C. That is because water has four times the thermal storage capacity of earth [7], which means that water will, therefore, experience a

lower range of temperature variations. In other studies, the water pond solution was combined with active electric fans, or a shaded pond was introduced to increase efficiency [57]. Nevertheless, the water pond is not recommended due to several significant concomitant limitations such as the contamination that is caused by standing water, the possibility of leakage, the cost of maintenance and its effect on heating hours. In addition, according to Vefik, a water pond should contain approximately 15–20 cm of water plus 4–8 cm of foam insulation. Although this construction appears capable of regulating the internal temperature to 18–21 °C [53], this is not feasible in the context of an Egyptian building.

Table 5
Thermal properties of materials used in the case study.

No.	Material	Density (kg/m ³)	Specific heat capacity (J/kg K)	Conductivity (W/m K)	Material thickness (cm)
1	Cement plaster with sand aggregate	1860	840	0.72	2
2	Fresh water	1000	4190	0.6	5
3	Dense reinforced concrete	2300	840	1.9	15
4	Fine sand	2240	840	1.74	7
5	Cement mortar	1650	920	0.72	2
6	Albedo bright white paint (0.1 visible absorptance)	2100	800	1.4	1
7	Cement roof tiles	2100	800	1.4	2
8	Polystyrene foam (low density)	38	1130	0.033	10
9	Bitumen impregnated sheet	1090	1000	0.06	0.1
10	Glass standard	2300	836.8	1.046	0.3
11	Wood, pine	550	2301	0.343	5
12	Air gap	–	–	Thermal resistance: 0.15 m ² K/W	10

5.2. The effect of material variables on heat gain

Solar protection measures e.g. roof shading or albedo, achieve a greater decrease in indoor discomfort hours than thermal protection measures such as decreasing the roof's *U*-value. As explained by Boixo and his research colleagues, the three main properties of a roof surface that affect heat gain and energy flux are solar reflectance and thermal insulation [9]. In the domed roof cases, increasing the albedo of the roof surface leads to heat loss through the roof of 520 kWh, and an average indoor temperature in the month of August of 30.8 °C. With added insulation to the roof section, the average indoor temperature in August reached 31.9 °C. In the vault roof, adding albedo led to a decrease of the average indoor temperature in the month of August to 30.2 °C, yet with added insulation the result was 32.2 °C. Inducing ventilation inside the vault by creating voids on both sides led to an indoor temperature of 31.6 °C. Hence the decrease in discomfort hours when combining induced ventilation and high albedo in the case of the vault decreased to 979 h only.

In the case of the total shading of the flat roof with an external shading device, the roof heat losses mark a value of 183 kWh. When compared to another solar control measure, such as adding albedo, the losses are about 30% of the albedo flat roof losses: this can be traced back to the explanation of Koch-Nielsen [7] mentioned in the section above. It is recommended that the roof be provided with shade: this is preferable done to using plantation because shade is proved to be viable and low cost. Roof planting is beneficial in many dry areas because the irrigation of the roof will cool the roof surface through evaporative cooling.

So a moist roof will lose at night the heat it absorbs during the day [53].

Cool roofing materials require an initial investment in bright materials, which turned out to be more effective in terms of life-cycle cost than the conventional dark alternatives. Usually, a lower life-cycle cost result from longer roof life and/or energy savings [42,58]. Insulation materials were also considered among the alternative solutions tested in this research. Generally insulating materials are very effective in saving energy, both for cooling and for heating, but their effectiveness normally depends on the properties of the insulation material used and its position in the roof sandwich structure. Cost is also an important factor in Egypt.

6. Limitations in applying the selected best case

One drawback of the vault albedo proposal is that it increases the initial cost of the roof construction by 3%; but the payback period is short. However if the vault is constructed from brick instead of reinforced concrete, that too eventually reduces the construction cost. If brick is to be used, the thermal properties of types of bricks and thickness need to be studied first. Cool roofs also have limitations in locations where both cooling and heating are required. In our study the base case annual heating hours was 2974 h, while the suggested vault high albedo roof heating hours was 3695 h. That is an approximate increase in time of 24%. A complementary passive heating solution is recommended to reduce the gap in heating hours load.

Table 6
Internal heat gains and losses compared to the external ones through the roof with the average operative temperature in the peak summer time in August.

Roof type	External gains + losses (W/m ²)	Internal gains + losses (W/m ²)	Total gains + losses (W/m ²)	gain through the roof (W/m ²)	Average temperature during the month of August (operative temperature) (°C)
Vault + high Albedo	–1143	402.1	–741	–1039	29.9
Vent vault + albedo + air	–1032.6	432.35	–600	–1383.9	30.22
Flat roof + albedo	–229.4	226.3	–3.1	–578	30.4
Double roof + air gap + albedo	51.6	–56.68	–5.08	–284	30.4
Double roof + albedo	–154.4	254.36	–0.04	–451	30.6
Double roof + water pond + albedo	136	–137.8	–1.8	–176	30.6
Flat roof + water pond + albedo	134.4	–135.8	–1.4	–262	30.6
Vent vault + albedo	–651.77	2002.2	–451.57	–199.12	30.6
Flat roof + air gap + albedo	–149	163	14.22	–189	30.7
Dome + albedo	–541.7	486.5	–55.2	–208	30.85
Vent vault + air + insulation	–1023.5	475.8	–547.7	132	30.9
Ventilated vault	–759.7	302.9	–456	1204.9	31
Vent vault + air gap	–854.56	365.8	–488.76	839	31.07
Double roof	–16.9	10.97	–5.93	–182	31.2
Vent vault + insulation + albedo	–182.7	–393.7	–576.4	–187.9	31.4
Vent vault + insulation	–1019.3	473.6	–545.7	139.1	31.4
Base case	290.5	–304.2	–13.7	414	32.4

It should be mentioned that not all roof materials are well adapted to high albedo painting. Although such materials could be specially designed to have a higher albedo, this would involve greater expense than using bright paint. To avoid this high-albedo alternative, we could instead turn to Egypt's vernacular building tradition and add a layer of lime with mineral granules or gravel as a final coating to conventional roofing materials, at little or no additional cost [59].

Additionally, to maintain a high albedo, roofs may need to be recoated or rewashed on a regular basis. In a dusty environment such as Cairo's, the cooling benefits of a cool roof surface with high reflectance changes with time due to dust and roof material ageing. Regular maintenance is required. A study on the cleaning of light coloured roofing indicated that maintaining them could restore their original reflectivity [60]. The cost of a regular maintenance programme should be always considered during the assessment.

7. Conclusion and recommendations for further research

Electricity demand has risen strongly in the last few years and high thermal loads in buildings has led to the need to increase the capacity of installations' electrical cooling equipment. The rise in energy consumption is likely to continue unless energy efficient and cost-effective measures are introduced. As discussed earlier, the roof is one of the most exposed parts of the building envelop to direct sun rays, and it is the most challenging to protect. Reduction in roof heat gain means reduction in cooling demands, using air-conditioning so as to increase human indoor thermal comfort levels. This also can have a positive impact on urban environmental quality. The performance of the roof depends mainly on its form, construction and materials. Generally when the roof surface is fully protected from the direct warming effect of solar rays, especially at noon, heat gain is minimal. This study proposes an affordable technique to reduce energy consumption through cool roofs, which it has been validated using simulation. Concrete as a conventional building material can be used in an effective form for passive cooling techniques, which can increase thermal comfort for the inhabitants with no energy burdens from HVAC systems.

This proposal is intended for low and medium rise residential buildings in hot climates where cooling systems are needed to achieve indoor thermal comfort. The results from this study can be applied in similar hot dry climates to Cairo's and the methodology is applicable for other climatic conditions. Other passive strategies are recommended for use with this proposed cool roof, such as thermal mass and solar shading for façades, together with double or triple glazing for windows with low U value. In addition, there should be a proper window-to-wall ratio. The building envelope and choice of materials, as well as natural ventilation, should all be considered when planning how to bring up a building's energy efficiency to optimum level, along with changes of life style on the part of the occupants such as adaptive clothing, electric equipment, the nature of their activities and their times of occupancy.

The results of the simulations shown in the paper provide an optimal solution for Egyptian hot weather conditions. However a prototype for the elected cool roof solution would need to be built to validate the results. The cost should be at a level to make its use affordable and low cost in comparison to other building cooling systems. Future work should also include passive heating strategies, and their efficiency measured against the cool roof solution to reduce the heating hours. We also recommend that applying cool roofs should be a mandatory item in the Egyptian code for energy efficiency for residential buildings.

We can conclude that, as cooling takes more energy than heating, the pressure on our energy resources to satisfy future cooling demands especially in urban areas will be huge unless effective passive cooling solutions are introduced.

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