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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 kW h 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.

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/m^2):

$$R_n = Q_H + Q_E + Q_S \tag{1}$$

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