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Passive cooling roof design under Jordanian climate

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ABSTRACT

Four identical test structures each having dimensions 1 m × 0.6 m × l m have been fabricated. All the four sides of the test structure were made by using mild steel angle and galvanized steel sheet. A 0.08 m layer thickness of reinforced cement concrete CRCC roof was casted over each one. Different passive techniques were used over the roof for cooling the environment inside test structure; these techniques are painting of roof with white cement, pieces of glass and clay layer. One of the four structures is without any material over the cement concrete roof which is to be a reference one to compare other system results with it. The four structures were constructed, and installed next to each other so that they may be tested simultaneously. Under local climate the test procedure was casted out by measuring the inside, outside, wet and dry temperatures and also by measuring the relative humidity. The structure with clay on top of the concrete was found to be the most efficient structure for cooling purpose. Finally the thickness of clay layer was varied so as to find optimum layer thickness for cooling purpose. It was found that the cooling efficiency of the clay structure increases with thickness up to 0.05 m, beyond which the inside temperature remains constant.

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1. Introduction

Passive cooling is the removal of heat from the building to the ambient by the natural processes of convection, radiation and evaporation or to the adjacent earth by conduction and convection. This involves designing buildings and selecting construction materials in a way that reduces heat absorption and conduction through the roof and walls. Passive cooling systems are associated with minimum use of mechanical air conditioning systems to decrease energy consumption. Agrawal (1989) has postulated that by using proper passive design concepts at least 2.35% of the world energy consumption could be avoided.

Several passive cooling studies have been conducted over the years, with a focus on roofs. Meng and Hu (2005) studied roof cooling effects due to a humid porous medium, which made use of water evaporation. Their results showed that the outer and inner surface roof temperatures were reduced significantly. Several studies compared various passive cooling strategies (Amer, 2006; Kumar, 1994; Nahar, Sharma, & Purohit, 1999; Nahar, Sharma, & Purohit, 2003; Tiwari, Upadhyay, & Rai, 1994) which ranged from painting roofs with white ceramic paint, installing thermal insulation above and underneath roofs, installing shallow water ponds, and incorporating air cavities in walls. Each study determined that evaporative cooling was the best method for lowering the roof temperature and inside air temperature.

Raeissi and Taheri (2000) demonstrated that the Skytherm method of covering roofs with water filled plastic bags and using moveable insulation could reduce both cooling and heating loads of buildings in regions with large solar irradiation. Cheikh and Bouchar (2004) investigated the use of an evapo-reflective roof for hot and dry climates, and showed that cooling inside buildings could be reduced by up to 8 °C compared to a bare roof. The system was composed of an aluminum plate with white titanium based paint, which reflected solar radiation, while water vapor inside the roof condensed and fell due to gravity. This system created a heat pipe effect, which removed heat from the roof. Kharrufa and Adil (2008) found that a roof pond, in conjunction with mechanical forced ventilation, could reduce the cooling load by approximately 29% when compared to a bare roof. The main disadvantage of the evaporative cooling, Skytherm, and evapo-reflective methods is the need for water, which could be a problem in arid regions or other places where water is not readily available in enough quantities during specific times of the year. Nahar et al. (2003) estimated that for evaporative cooling to be effective, 50 L/m^2 of water per day would be needed. In humid regions, such passive cooling systems are less effective given the lower potential for evaporation at higher relative humidity levels.

Nahar et al. (1999) fabricated five identical test structures or studying passive techniques for better comfort conditioning in

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arid areas. They found that the fall in roof and ambient temperatures inside the test structures were in increasing order for roofs treated with thermal insulation, painted with white paint, shallow pond with movable thermal insulation and evaporative cooling. Alvarado, Terrell, and Johnson (2009) investigated the thermal effects of newly designed passive cooling systems on concrete roofs in existing buildings. Each tested passive cooling system consists of a combination of materials that can reduce net heat load in buildings. Commercially available materials such as aluminum 1100 and galvanized steel were used as radiation reflectors; and polyurethane, polystyrene, polyethylene, and an air gap were used as insulation. Experimental results based on laboratory-scale prototypes show that the radiation reflector shape as well as the material selection of each passive cooling system led to reductions in heat conduction between 65 and 88% when compared to a control prototype. Each passive cooling system showed a slow thermal time response when compared to a plain concrete roof, which is a desirable characteristic for controlling thermal fluctuations when heat conduction is also reduced simultaneously. Transient empirical models to predict accurately the midpoint temperature of a cement roof were formulated with and without passive cooling systems in use.

Alvarado and Martinez (2008) tested a simple and inexpensive passive cooling design for concrete roofs, and demonstrated that the implementation of the design could result in a considerable drop in roof temperature. Their design is composed of an insulating layer topped by a triangular-shaped reflector, which casts shadows on itself and promotes the formation of cooler spots resulting in better natural convection. Their study focused on a single geometry and two orientations of the reflector, and did not consider alternate materials for either the insulating layer or the reflector, or other alternate geometries for the reflector. The purpose of the current study is to extend the analysis of Alvarado and Martinez (2008) by testing the performance of similar passive cooling systems but considering various geometries for the reflectors, and different reflector and insulation materials. These systems have been devised taking into account the temperature range that is usually encountered in subtropical and tropical climates. Such systems could be of special benefit as a low cost retrofit solution for individuals who cannot afford air conditioning systems and the associated energy costs in tropical regions. Material selection for each passive cooling system considered thermal properties such as thermal conductivity, solar reflectivity, ease of maintenance, ease of installation and low capital cost. Materials were selected with the goal of achieving low heat absorption and low heat conduction.

Alvarado and Martinez (2008) investigated the impact of a newly designed passive cooling system which can minimize heat transfer through concrete roofs. The passive cooling system consists of a corrugated aluminum sheet with a unique orientation to promote heat dissipation. A layer polyurethane is also used to minimize heat transfer. Experimental results based on lab-scale prototypes show that the well-designed roof insulation system can reduce the typical thermal load by over 70%.

Several laboratory sized units of passive roof designs were constructed and tested side-by-side under outdoor conditions to obtain temperature data of the roof, attic and ceiling in order to compare their performances (Ong, 2011). It was found that the bare metal roof with insulation underneath resulted in the highest roof temperature. The roof solar collector design resulted in the coolest attic, the solar collector roof provided the coolest ceiling and finally insulation under the tile is preferred to above the ceiling.

The effects of over insulation on the thermal performance of roofs in summer were investigated by D'Orazioa, Di Pernab, and Di Giuseppea (2010), by analyzing experimental data from monitoring a full-scale mock-up in Italy. Results show how an increase in insulation thickness reduces the effectiveness of traditional passive cooling strategies, as an effect of the thermal decoupling between the interior and the upper layers of the roofs.

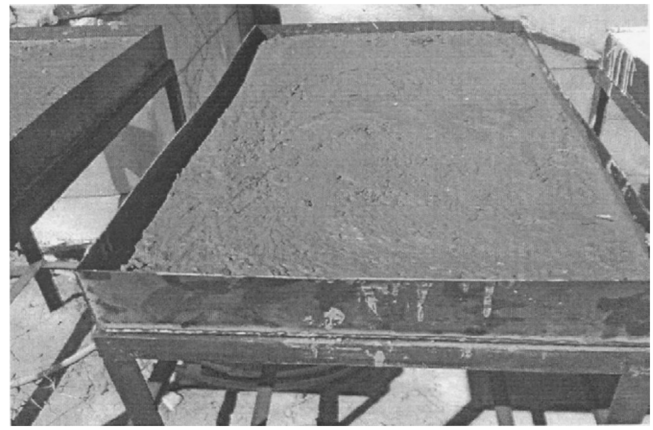

Fig. 1. Controlled unit without any treatment (structure A).

The purpose of this study is to reduce heat load from the roof by identifying suitable passive techniques for cooling of building with RCC roof as major heat load in the buildings is only from roof. This is achieved by testing four different roof structures; the first one is widely used in Jordan, which is of concrete structure. The other three structures consist of adding materials to the concrete structure type, these added materials are locally available at a very low cost and hence the total cost of the structure is not affected.

2. Experimental setup

Four identical test structures, each having dimensions 0.6 m × 1.0 m, have been fabricated. All the four sides of the test structure were made by using mild steel angle and galvanized steel sheet. Roof of 0.08 m thickness has been casted over the test structure. Since the major portion of heating load in building is from the roof, reduction of the heating load from the roof was studied.

As shown in Fig. 1 all sides of the test structures are closed by polystyrene sheets and no ventilation has been provided so that only treatment on the roof can be compared.

These four different types of structures are as follows.

2.1. Test structure (A) – controlled unit without any treatment

As shown in Fig. 1, this structure is without any treatment. It is made up of pure concrete material which is used in almost all buildings in Jordan. This structure is used as a reference one.

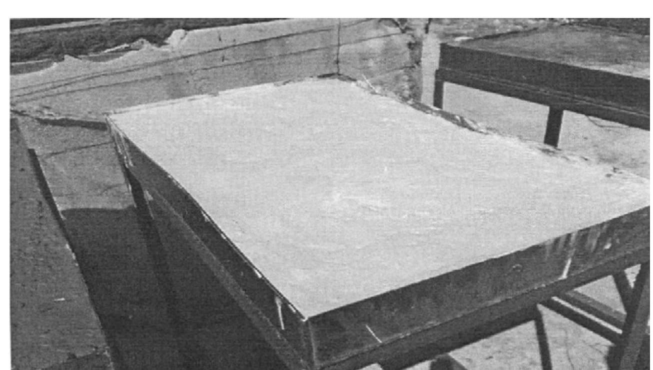

Fig. 2. Covered by white cement test structure (structure B).

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