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Experimental assessment of thermal performance of three passive cooling techniques for roofs in a semi-arid climate

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ABSTRACT

Three passive techniques for air cooling in buildings are tested in the real conditions of Marrakech (Morocco) whose climate is hot semi-arid (BSh type according to the Köppen–Geiger climate classification). The passive techniques, that are white painting, shading and thermal insulation, are applied to the roofs of three outdoor test cells. Thermal performance of these techniques are assessed simultaneously via a 29 summer days monitoring of four test cells, including a reference cell with bare roof. Measurements concerned the cells indoor air temperature, the roof slab inside (ceiling) and outside surface temperature, as well as the heat flux through the roof slab. Moreover, all the local climate parameters were recorded by means of a weather station installed near the test cells. The results show that the studied passive techniques have a significant impact on the heat flux through the roof and consequently on the cells ceiling and indoor air temperature. The white painted roof has the highest thermal performance as it lowers the ceiling temperature by up to 13.0 °C relatively to the reference cell; while this temperature reduction was always less than 9.9 °C and 8.9 °C respectively for the thermally insulated and the shaded roofs. Moreover, the white painted roof reduced the heat flux through the roof slab by up to 66%.

1. Introduction

Building's sector is one of the most energy consuming and greenhouse gases emitting sectors all over the world. That's true in Morocco, as the building's sector account for 25% of the total energy at national scale [1]. The new Moroccan construction thermal regulation (RTCM) aims to introduce energy-efficient practices in the buildings [2]. Furthermore, energy consumption for air cooling represents a major issue for hot climate areas and it is increasing as a consequence of global warming [3]. In these areas, air conditioning in the building sector could be drastically reduced by the use of passive cooling techniques. It is known that horizontal roof contributes by large amount to the accumulation of heat in a building, especially in locations with huge solar radiation. Indeed, in summer and on a daily basis, the horizontal roof receives around 1.5 times of solar radiation than a west facing wall and about four times than the south facing wall [4]. There are several passive techniques for building's roof that improve indoor thermal comfort and reduce energy consumption for air conditioning [5–8]. Passive cooling may be classified in three categories: heat and solar protection, heat dissipation and heat modulation [9]. In the present paper, three passive cooling techniques for heat and solar protection of the roofs are experimentally evaluated under real climate conditions of Marrakech (Morocco).

Several researchers [8,10–13] performed a review of different passive cooling and heating techniques in buildings. One of the most important technique for cooling is that concerning heat and solar protection of buildings' roof. This technique has been experimentally tested in real climate conditions in the literature using outdoor test cells [4,14–18]. Nahar et al. [14] conducted a comparative study of four passive cooling techniques for the roof. The authors assessed the thermal performance of these techniques in the hot and arid climate of Jodhpur (India) by means of metallic outdoor test cells. The roofs of three cells (also made of metallic sheets) were treated by the studied techniques while the fourth cell's roof is bare. The latter, taken as a reference, was used to calculate the reduction in the indoor air and the ceiling surface temperature during hot summer days. The authors compared the performance of the following techniques: i/ white painted roof, ii/ 4 cm layer of thermal insulation below the metallic roof, iii/ 10 cm thick shallow pond on the roof with movable thermal protection and iv/ Gunny bags on the roof continuously soaked with water (evaporative cooling). The best results are obtained by the tech-

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nique of evaporative cooling. However, this system requires significant amount of water. Thus, it may be not suitable for arid climate. Furthermore, the authors results show that the white painting technique performed well, as it provides high reduction in the ceiling surface temperature especially during night-time. Hamdan et al. [15] conducted a comparative experimental study involving several passive cooling techniques. Four structures of $0.6 \times 1 \times 1\ m^3$, each equipped with a passive cooling technique were monitored during a summer day of 2010 in Amman (Jordan). These techniques are as follows: A/ Standard roof (reference prototype) made of concrete with a thickness of 8 cm, B/ Roof A covered with a thin layer of white cement, C/ Roof A with broken pieces of white glazed stuck on it, D/ Roof A covered with a 3 cm thickness layer of clay. The authors showed that the technique D is the best one that leads to good air cooling in the hot and arid climate of Amman. The authors also showed that the cooling efficiency of the clay layer increases with its thickness, which optimum thickness was determined to be approximately 5 cm. Amer [4] studied experimentally the effect of several passive cooling techniques for the roof including: i/ white painting, ii/ 5 cm of glass wool thermal insulation, iii/ solar chimney and iv/ evaporative cooling through a series of PVC pipes equipped with sprinklers that keep the roof constantly wet. Two cubical cabinets made of galvanized iron sheets with steel frame (including the roof) were built by the author for the test purposes. The studied techniques were introduced to the roof of one of the cabinets (test cell), one at time, while the second cabinet's (reference cell) roof was kept bare. Thus, the author conducted the experiments for each technique by comparing the average indoor air temperature in the test cell to the one measured inside the reference cell. These experiments were performed during summer with high global solar radiation that may reach 1100 W/m². The authors' results show that the daily average difference in indoor air temperature between the test cells and the reference one reached: 6.5 °C for the white painted roof, 7 °C for the insulated roof, 8.5 °C for the solar chimney and 9.8 °C for the evaporative cooled roof. It is important to mention that these reductions should not be compared as the weather conditions were quite different during the experiments. However, the author's results are similar to the ones found in other studies, especially for the white painting technique [15,16] and the thermal insulation [14,16]. These authors conducted an experimental study on similar techniques as in [4] in the arid climate of Jodhpur in India. However, the authors' experiments were performed simultaneously for all the techniques contrary to Amer [4]. These experiments were realized using similar test cells as in [14] with concrete slab roof instead of metallic one. The results obtained by the authors show that during a typical summer day, the average difference in temperature between the various test cells equipped with passive techniques and the control cell is: 5.4 °C for the white painted roof, 3.4 °C to 5.8 °C for the insulated roof (according to the type of insulation), 13.2 °C for the evaporative cooled roof and 11.2 °C for the roof with white glazed tiles glued on it. The authors concluded that the evaporative cooling is the best passive technique; however it requires a huge amount of water (about 50 l/m² of water per day). The authors therefore recommend the white glazed tiles that are durable. Furthermore, the authors carried out investigation for thermal performance in winter. The results show that water pond with movable insulation is the unique technique that performs well either in summer and winter. Indeed, this technique provides the highest increase in indoor air temperature with an average of 2.6 °C. Another interesting experimental study on horizontal roofs was conducted by Pearlmutter and Rosenfeld [17]. This study was carried out with two identical 8 m^3 test cells made from insulated concrete blocks for the walls and concrete slab without any thermal insulation for the roof. The cells' roofs were covered by 16 cm layer of soil. This layer of soil in one of the cells was continuously watered and shaded successively by a shading mesh and a layer of gravel. The authors assessed the thermal performances of these techniques by means of summer and winter monitoring campaigns in the hot arid climate of the Negev desert. The measurements concerned the indoor air temperature as well as the heat flux through the roof. The results show substantial effect of the dry soil layer in terms of temperature stabilization and time lag. However, the dry soil does not provide any cooling effect which was achieved by the watered soil that lowers the ceiling temperature by 4 °C with daily water consumption of 8 l/m². Adding the 6 cm layer of gravel on the watered soil, results in high test room's ceiling temperature stability. Moreover, the shading mesh provides slightly lower ceiling temperature. Furthermore, the authors concluded that the gravel has the advantage to reduce highly water consumption for the soil irrigation. It should be mentioned that the authors performed comparison analysis of their techniques using a so-called "normalized temperature" obtained from the measured temperature at a given day and the ratio of the average reference cell temperature, during the whole test days, to the reference cell temperature for the given day. Recently, Sabzi et al. [18] carried out a numerical and experimental investigation of three passive cooling techniques for the roof. The studied techniques are: water pond, water bags and shading. These techniques were applied on the roof of an outdoor test cell built in Shiraz (Iran) which climate is very hot and dry in summer. The experimental results, for the indoor air temperature measured in summer, were used for the validation of a numerical code whose results show that maximum energy saving, in terms of diurnal cooling, was achieved through the water pond. Moreover, the authors found that the energy performance of the shading was close to that of the water pond except in the afternoon over which water evaporation provides extra cooling of the roof. An interesting cooling technique for the roof is the so-called "cool roof". This technique, which aims at reducing solar radiation absorption of the roof and enhancing its emissivity for night cooling, was extensively studied in different climates [19–21]. Garg et al. [19] conducted a comparative experimental study on un-conditioned classrooms with the same size and similar occupancy in Hyderabad and Nagpur areas in India. One of the classrooms' roof was coated with high albedo coating (polymer-acrylic blended ceramic) and the other was untreated. The authors' spring monitoring results show that the reduction in the average temperature of indoor air, ceiling surface and roof surface was 2.1 °C, 5 °C and 12.3 °C respectively in Hyderabad, while it was 1.5 °C, 4 °C and 9.5 °C respectively in Nagpur. Synnefa et al. [20] performed an experimental and numerical study to examine the impact of a cool roof coating on thermal behavior of a school building in Athens, Greece. The initial roof surface was grey with a solar reflectance of 0.2. The authors showed that the application of white elastomeric cool coating, with solar reflectance of 0.89, reduced the building's indoor air temperature by 1.5–2 °C and 0.5 °C, respectively in summer and winter. Moreover, the numerical results showed that the considered cool roof technique reduces the building's cooling load by 40% while it slightly increases its heating load by 10%. Romeo et al. [21] conducted a measurement campaign on un-conditioned building in Trapani (Sicily), to assess the impact of white double layer paint with solar reflectance of 0.88. The authors' results show that this technique reduced the roof surface temperature by up to 20 °C and allowed an average reduction of 2.3 °C of the indoor operative temperature. Moreover, the authors' numerical study registered 54% reduction of the cooling energy demand.

In the light of our literature review it can be deduced that the assessment of thermal performance of passive techniques for building's roof is still worthy of investigation. Indeed, these techniques performance is climate-dependent and should be explored in real climate conditions. Furthermore, even though many of these techniques were widely studied in the literature, the measure-