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Experimental performance evaluation of solid concrete and dry insulation materials for passive buildings in hot and humid climatic conditions

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HIGHLIGHTS

- Experimental investigation of building insulation materials in UAE from 2012–2014.
- Four same calorimeters with different south walls were built in open air laboratory.
- Heat flux was reduced by 22–75% in steady state analysis during summer by insulation.
- Hence, energy consumption for cooling was reduced by an average 7.6–25.3%.
- Heat flow was steady in free floating analysis in winter through insulated walls.

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ABSTRACT

It is known that enhancement of building energy efficiency can help in reducing energy consumption. The use of the solar insulating materials are the most efficient and cost effective passive methods for reducing the cooling requirements of the buildings. Apart from theoretical studies, no detailed experimental studies were performed in the UAE on energy savings by using solar insulation materials on buildings. Four (3 m × 3 m × 3 m) solar calorimeters were built in RAK, UAE in order to perform an open air outdoor test for energy savings obtained with solar insulating materials. The design is aimed to determine the heat flux reduction and the energy savings achieved with and without different solar insulating materials, mounted at the south wall of solar calorimeters with similar indoor and ambient conditions. Experimental results are discussed to evaluate the thermal performance during high temperature conditions in summer's period when cooling demand of the building is at its peak and also in winters when there is no cooling demand. The test is from 2012 to 2014. The controlled-temperature experimental study at a set point of 24 °C showed that if the standard building material, i.e. solid concrete, is retrofitted with polyisocyanurate (PIR) and reflective coatings or completely replaced with energy-efficient dry insulation material walls such as exterior insulation finishing system (EIFS), energy savings up to an average of 7.6–25.3% can be achieved. This is due to the reduction of heat flux by an average of 22–75% at south wall during summer. Similarly, free floating analysis was done during winter and the measurements showed the behaviour of the heat flux flow and the variations in room temperature due to the variation of thermal mass caused by the difference in heat capacities of the façade with and without insulation. Heat flux and temperature variations were minimal in cases of insulated buildings when compared against a reference building in the winter free flow tests. The temperature variation is limited to 2 °C in case of insulated buildings compared to 6 °C in the reference case caused by high thermal inertia. Thus, insulation is essential in summer as well as in winter for the buildings in Middle East and North Africa (MENA). Overall, this paper provides a novel view on the most significant contributors to the thermal behaviour of the structure, and presents a methodology on the outdoor tests with various materials, that can significantly improve the thermal behaviour of the buildings in the extremely hot climate.

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Nomenclature

AC	air conditioner
AAC	autoclaved aerated concrete
CSEM	Centre Suisse d' electronique et de microtechnique
EIFS	exterior insulation finishing system
EPS	expanded polystyrene
L.L.C.	limited liability company
MENA	Middle East and North Africa
PIR	polyisocyanurate
PUR	polyurethane
R	resistance (m^2 K/W)
RAK	Ras Al Khaimah
RH	relative humidity
SOLAB	solar open air laboratory
UAE	United Arab Emirates
U	heat transfer coefficient (W/m^2 K)
XPS	extruded polystyrene

Greek notations

ά	absorption coefficient

1. Introduction

The electricity demands of urban areas have increased fivefold in the past two decades due to rapid industrialization and population growth [1]. Currently the electricity demand is mostly met by fossil fuels leading to emission of greenhouse gases thus causing global warming. Besides, the increasing energy costs and the adverse impacts on the environment by energy production plants, all contribute to the need to find means to substantially reduce energy consumption. Cooling and heating requirements of buildings are the major contributors to energy consumption worldwide. Around 30% of electricity consumption is attributed to building air conditioning [2] with significant peaks in summer months between June and August in hot climates [3]. Reducing the cooling load is one of the most effective energy conservation methods in buildings that can potentially be achieved with a combination of building design, thermal insulation and coatings [4]. The amount of energy used in buildings is mainly based on the variations related to weather, architectural design and the envelope features [5]. Thermal insulation are materials or combinations of materials that are used to provide resistance to heat flow, should have low conductivity for building application in order to reduce the cooling demand in hot climate and durability [6]. Early buildings were insulated with mineral wool, however in 1880 in United States of America and from 70s onwards more effective insulations materials have been discovered and analysed numerically which are used in building construction in the world [6]. In Europe, inorganic fibrous material, glass wool and stone wool account for 60% of the insulation materials while organic foamy materials, expanded and extruded polystyrene and to a lesser extent polyurethane accounts for some 27% [7].

Numerous studies have been done on insulation materials and their performance when used in buildings under various circumstances. Ozel [8] performed a mathematical study on the thermal performance of insulation thickness using XPS and EPS insulation on south wall made of concrete, brick, briquette, blokbims and AAC in climatic condition of Elazig, Turkey. Ucar and Figen [9] analysed numerically the optimum thickness of foam board, XPS and fibre glass insulation for an external wall in Turkey. Chirarattananona et al. [10] conducted a study in the tropical climate of Thailand and found that insulation of wall decreased the cooling load. Kawasaki and Kawai [11] have developed and build an alternative structural insulation composite for buildings, plywood faced sandwich panel with low density fibreboard core. Thermal conductivity and thermal diffusivity were measured in a laboratory and compared with samples of wood-based boards, solid wood and commercial insulators. Few publications showed the development of insulation systems with vacuum panels. This new panels has been developed since the end of the 1990s [12–15] and was known as vacuum insulation panels. The most appealing feature of these panels is their 5–10 times higher thermal resistivity for heat flow perpendicular to the main faces compared to conventional thermal insulation. Their cost and durability in the buildings are the main drawbacks. Nussbaumer et al. [12] performed experiments and numerical studies with a concrete wall externally insulated with expanded polystyrene boards containing vacuum insulation panels. Some authors have investigated the improvement of thermal inertia of the buildings by including phase change materials (PCM) in the envelopes and some directly in the insulation material [16–19]. Water vapour and humidity are important factor when selecting the insulation materials for the passive buildings. Karamanos et al. [20] worked exclusively on stone wool and presented experimental data that reaffirmed the sensitivity of stone wool when water vapour condenses in the material.

National renewable energy laboratory (NREL) in the USA has extensively examined green building design and energy efficiency in variety of climates [21]. Lundström and Wallin [22] computed heat demand profiles and annual electricity-to-heat factors of energy conservation measures in buildings and their impact on system efficiency and greenhouse gas emissions in Sweden. He identified that by improving the buildings' envelope insulation level and thereby, levelling out the heating heat load curve reduces greenhouse gas emissions and improves primary energy efficiency. Ihara et al. [23] studied, the effects of four fundamental facade properties related to the energy efficiency of office buildings in Tokyo, Japan, with the purpose of reducing the heating and cooling energy demands. Some fundamental design factors such as volume and shape were also considered. It was found that the reduction in both the solar heat gain coefficient and window heat transfer coefficient (*U*-value) and the increase in solar reflectance of the opaque parts are promising measures for reducing the energy demand. Therefore, the properties of facade material have to be studied under different circumstances and conditions to evaluate the performance of the buildings. Radhi [24] focused on buildings in Bahrain with dominant internal load and performed regression analysis on the existing building. Also, Radhi et al. simulated a series of residential building with the aim of analysing the thermal comfort characteristics of varying fenestration and insulation options, and thermal mass effects [25]. Using the climate data of Riyadh, Al-Sanea and Zedan [26] analysed dynamic thermal characterization of insulated building walls having same thermal mass and optimized insulating thickness under periodic conditions. Various layers of insulations were used by varying there arrangement in order to achieve the optimized performance. The best overall performance was achieved by a wall with three layers of insulation. Over the past few years, the development of concrete blocks with low thermal conductivity has been gaining interest in the research community. This can be observed in various research fields. For example, three types of concrete blocks were developed with low thermal conductivity [27]. These blocks were able to reduce the heat transfer and reduce cooling loads. More recently, the autoclaved aerated concrete (AAC) has been introduced as a