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Experimental performance evaluation of solid concrete and dry insulation materials for passive buildings in hot and humid climatic conditions[1]

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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 (3mx3mx3m) 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 ^{o}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 ^{o}C in case of insulated buildings compared to 6 ^{o}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.

Keywords: UAE buildings; Solar calorimeter; Insulation materials; Experimental analysis; Heat flux reduction; Energy efficiency

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^2K/W)
RAK	Ras Al Khaimah
RH	Relative humidity
SOLAB	Solar open air laboratory
UAE	United Arab Emirates
U	Heat transfer coefficient (W/m^2K)
XPS	Extruded polystyrene

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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] [13] [14] [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] [17] [18] [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]. Lukas et al [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. Takeshi 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, Sami A.Al-Sanea et al. [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 green masonry material. It was found that considerable reduction in heat gain and cooling load could be achieved when the AAC was used instead of cement blocks, which are very commonly used in buildings in UAE [28]. Radhi [29] did a simulation study on AAC building material and showed that it can alone provide up to 7% of energy reduction if used in Emirates. The AAC blocks were able to provide thermal comfort inside the buildings without the use of thermal insulation [30]. However, the classical wall built from cement blocks with an insulation layer was found to provide more energy savings [31]. Radhi [32] analysed insulation of residential villa in Al Ain, UAE. He did simulation study on a typical Al-Ain villa and during his work he applied uniform resistance (R-value) on the walls. Friess, Rakhshan et al. [33] did modelling on thermal bridge and its effect on building energy consumption in Dubai. The results showed that 30% of the energy consumption can be reduced by retrofitting existing buildings. Thermal insulation was found to be effective in skin load dominated buildings because of small internal heat gains. The useful electrical savings in residential sector could exceed 50% of the total energy consumption [34] [35]. Based on this, an attempt was made to optimize the thickness of insulation material with consideration to electricity tariff [36]. In addition to thickness, the placement of insulation material does also have an impact of heat load reduction. Eben Saleh [37] evaluated thermal performance of different arrangements, types and thicknesses of insulation materials in buildings. A better performance was achieved when insulation was located on the outer side of building envelope. Similar conclusions were obtained by Al Nafeez et al. [38] who evaluated insulation materials on basis of time lag, decrement factor, cost and R-value, keeping overall thickness and U-value constant of a three layered building envelope.

Kossecka et al. [39] carried out energy analysis on the whole-building and concluded that material configuration of exterior wall could significantly affect annual thermal performance. However, this effect depends upon the type of climate conditions. Therefore, real open air experimentations are necessary to validate the building insulation performance under specific climatic condition. Experimental study was done on insulation materials in Mediterranean ambient conditions by Cabeza et al. [40]. The thermal performance of the reference building (2.4m x 2.4m x 2.4m) made of hollow and perforated bricks walls were compared with the thermal performance of similar building with, added PUR, mineral wool or XPS insulation materials respectively. It was identified that up to 64% energy use can be reduced in summer and 37% in winter by using insulations. Soubdhan et al. [41] also constructed four small scale test cells (1.22m x 1.22m x 0.5m) to test heat transfer via roof only in tropical climate. The walls were insulated with polystyrene and four different scenarios were tested on the roof (having polystyrene, radiant barrier or fibre glass insulations or no insulation). Swinton et al. [42] performed experiments on insulation specimen of XPS, PUR foam, mineral fibre or glass fibres on the external east and west walls in Ottawa, Canada for two years. Thermal mass, in combination with night-time ventilation strategies for cooling load reduction for Hong Kong building was discussed by Yang and Li [43]. Experimental study was done by Ibrahim [44] for six months in UAE for thermal behaviour of insulated building (5m x 5m x2.8m) by XPS foam. The testing was done on east, west walls and roof. Initial results showed a reduction in inside wall temperature. Only room temperature behaviour was observed during the test. More recently, Mattias et al. [47] identified and carried out experimental analysis on the simple automated ventilation system of the buildings as it can have large energy savings potential. The building controller was assessed for indoor climate control by automating the ventilation flow rate during a typical office working day. Experiments were conducted in two different office sites, as well as during two weather seasons of Swedish summer and winter. From the investigation, it was concluded that despite of using a simple controller, it could save between 12% and 19% of energy compared to a system of common practice while maintaining the quality of indoor climate. José et al. [48] carried out experimental analysis, in order to determine the characteristic curves for total cooling capacity, sensible cooling capacity and energy efficiency ratio of two room units. It was performed to improve the modelling of air conditioning system in building simulation tools. Sami et al [49] investigated the effects on dynamic heat-transfer characteristics of insulated building walls by varying amount and location of thermal mass with same nominal resistance (R-value) under steady periodic conditions using climatic data of Riyadh. It was found that maximum savings in yearly cooling and heating transmission loads were about 17% and 35%, respectively, as a result of optimized thermal mass for same R-value. It was recommended that building walls should have insulation placed on outside for applications with continuously operating year-round air conditioner (AC) [49]. Thermal mass location in the envelope plays a significant role on the overall energy consumption of the building. Danielle at al [50]provided fundamental insight into configuring wall layers for improved insulating performance. Thirty-three different walls were evaluated based on four primary configurations with fixed volumes of insulation and thermal mass. Only the layer distribution was varied. Because the total volume of each material was fixed, the overall thermal resistance and capacitance were equivalent for all configurations studied. The best insulating performance was achieved when insulation layers were positioned as close as possible to the inside and outside layers of the wall (i.e., near the indoor and outdoor environments). In addition, optimal results occurred when both the insulation and thermal mass were distributed evenly throughout the wall.

Reflectivity of roof has also become an inexpensive method in reducing energy usage in warm climates. The surface absorptivity also affects the building energy consumption profile. Sami et al [51] studied the effects of type of masonry material and the surface absorptivity to solar radiation on critical thermal mass thickness in insulated building walls for a fixed wall nominal thermal resistance (R_n-value). The results showed that for a given critical thermal mass thickness, higher energy savings potential were obtained with walls with solid concrete blocks and walls with lower surface absorptivity.

Synnefa et al. [45] and Bhatia [46] studied that by increasing roof reflectivity, the energy usage can be decreased in warm climate.

Several studies found that insulation towards the outside (with thermal mass towards the inside) provides better thermal performance than insulation towards the inside [52], [53], [54], [55], [56] and [49], and most agree that, generally, more thermal mass yields lower peak loads, a lower decrement factor, and a larger time lag [53], [55] and [57]. Insulation materials, while they increase *R*-value, are not commonly been looked upon as elements that can increase time lag; these are usually associated with thermal mass. On the other hand, thermal masses, while they increase energy storage capability, are not commonly been looked upon as materials that can effect substantial reduction in daily transmission load; the latter is commonly associated with thermal insulation. These common beliefs are based upon facts that increasing amount of mass would not much increase the *R*-value and increasing amount of insulation would not much increase energy storage capability. This view is simply based upon thermal properties and behaviour of building and insulation materials under static (steady state) conditions. Studies under dynamic conditions have shown that these issues are rather complicated and interactive; both insulation and thermal mass have wider effects on thermal characteristics than commonly believed [49].

The hot and humid climate in UAE is one of the harshest in the world, and it presents several barriers to technologies for reducing the energy consumption. The passive design is valid in general terms for any hot and humid climate in the word. The current energy system model is changing worldwide as well as in UAE; several sectors in government, industry and society are more aware of the negative effects of greenhouse gases emissions and economical risks associated on dependence on fossil fuels for coming years. Also, they are aware of the business opportunities associated with a sustainable and green buildings tendency. Recently, there has been a consensus to legislate for energy efficiency in the UAE. A major share has been given to the building sector with special focus on the important role that efficiency codes and green materials play in reducing energy consumption and CO2 emissions [58].In UAE the energy required for buildings is higher 45%, since during summer up to 70% of that energy is used for air conditioning [59]. UAE has experienced a boom in its building industry in the last years, which has caused an increase in the energy demand. UAE is ranked among the highest energy consumers per capita in the world in 2012 [60]. In addition, real estate buildings has become a core business in Dubai and other UAE regions, the rate of growth in residential villas from 2000 to 2010 in Dubai was about 300%, from 200 000 villas to 600 000 approximately [33].Buildings are not only important energy consumers, but they are the place when we spent most of our time, therefore, comfort conditions cannot be compromised to save energy. Those facts are the motivation for this project, which has a general aim to contribute with the reduction of carbon footprint in residential sector. Therefore, energy efficiency in buildings is of prime importance for energy policy. As a part of building energy efficiency research, research centre is working on passive cooling by reducing the solar thermal heat load of buildings in parallel to developing active cooling solutions. Taking advantage of available building material manufactured by local industries such as polystyrene, polyurethane, ceramic, cement, and glass, research centre can develop or test thermal insulating material and solar reflective coatings in real environment. The location of Ras al Khaimah (RAK), UAE was chosen because it was planned to build a model passive building in Al-Hamra village townhouse, located in RAK, UAE. The initiative here was to provide detailed experimental base study for low cost solutions to reduce the cooling demand and energy consumption, for new and existing buildings in UAE. Presently, different insulation materials are available in the market. Usually, they are compared by their thermal conductivity and with theoretical calculations, but there were no experimental comparisons available, where the behaviour of such insulation materials in a building was compared over time as it is important to study effects of R-value and the thermal mass together under real conditions as both are important to understand the behaviour of a building. Therefore two important issues must be dealt with; firstly, means of increasing the *R*-value usually by adding thermal insulation, and secondly, means of increasing thermal energy storage capability. Using heavy thermal masses in building walls is well known in moderate climates (e.g. Mediterranean climate) as means of regulating indoor temperature through night-time natural ventilation [40]. However, such an advantage cannot be utilized in dusty climates in which reliance is made on the AC equipment (for cooling and heating) for almost all days of the year. For this purpose four solar calorimeters were designed and validated previously [4] In UAE the concept of passive design of the buildings and its research are at preliminary stages. Insulated building walls are integrated parts of a building envelope. They protect the inner space from extreme weather conditions and damp down large fluctuations in temperature. As such, the building envelope should provide the necessary thermal comfort for the occupants as well as reduce energy consumption requirements for cooling. This is usually done through increasing thermal resistance (*R*-value) of envelope and, hence, reducing transmission loads. Therefore, addition of thermal insulation is important, particularly in regions with extreme climates. It is also importance to provide means to increase time lag factor by increasing thermal energy storage capability. The latter is usually regulated through thermal mass in the building envelope [38]and [49].

The calorimeters were designed to provide passive design for zero energy buildings for the houses. Therefore, a comparison between typically constructed *solid (concrete)* walls and a relatively new concept of *dry (EIFS)* walls in the market was done to evaluate the performance and behaviour of these two concepts of construction in hot climate of UAE. It will provide beneficial experimental study in order to propagate building efficiency in the local market of UAE and at the same time provide useful practical data to the manufacturer to assess and improve the manufacturing of these insulation materials as per the local environmental conditions. For this purpose detailed experimental design, monitoring and investigation with different materials and methods are presented. The thermal and energy performance of three different conditions are presented. In first condition, since surface absorptivity plays an important role in energy savings [51] therefore reflective coating as retrofit material was used on the south façade of one of the calorimeter. In second condition, PIR insulation was added as a retrofit material on the south façade of one of the calorimeter instead of coating. PIR insulation was used instead of PUR because it is moisture resistant and has better mechanical properties [61]. Lastly, a new dry wall technology of EIFS was used on the south façade of the calorimeter instead of retrofitting the existing solid concrete façade, it was commercially available product and was provided by German company, BASF and used as build [62]. The experiments were carried out in open air and then results of the above described cases were compared against the reference concrete calorimeter (typical UAE construction). Summers test with controlled-temperature and winters test with free floating conditions were analysed and discussed. Summers experiments with control temperature conditions were performed when the cooling demands of the buildings are the highest. Controlled-temperature conditions were reached after a sufficiently long time from start of AC operation and when initial transient effects subside. Thermal characteristics and roles played by insulation and thermal mass are so much dependent on climatic conditions and operating conditions of AC equipment [49]. While free floating experiments were performed and analysed for winters and being presented to evaluate the performance of the insulation materials in humid conditions. The main objective of the present study is to investigate effects of thermal mass on transmission loads, and time lag, in building walls and at the same study the effect of R-value and the interaction.

2. Experimental setup

The design of calorimeter was aimed to compare two buildings being tested under exactly same conditions. The first one acted as a reference; the testing façade of this building was made with typically used building materials in UAE. The next two buildings testing facades were made exactly identical to that of reference building wall furthermore they were retrofitted by adding reflective coating and insulating material respectively. The fourth building testing surface was made with a relatively new technology i.e. dry wall instead of a typical solid concrete wall. Comparing the insulated or coated building with un-insulated one gave the effect of that solar insulating material on the heat flux reduction. The south wall and the roof (the two main insolated surfaces) were less insulated, while the rest of the surfaces were heavily insulated. Simulations were carried out to estimate cooling load of a 1 m^3 cube building, with no internal heat gains or infiltrations. Every side of the cube was oriented as (North, South, East, West or horizontal) with reference to sun. It was observed that the roof and south façade played a major role in cooling load contribution to the building. The heat flow through the roof was around 31% followed by the south facade which was around 20.5% [63] and [64] . The heat flow through the north, east and west was around 11.5%, 18.5% and 18.5% respectively. Therefore it was decided to choose the roof and south façade as testing surfaces.

Tests were done on vertical south facing surfaces and are presented in this paper. However, the test on roof (horizontal surface) is not presented in this paper and will be done in future work. Calorimeters as shown in Fig.1 are located in RAK, UAE (Al Jazeera Al Hamra, RAK, UAE Latitude: 25° 5' N | Longitude: 55° 5' E, GMT+4) and built in 2011-2012 [4]. The design of four calorimeters and their sizing were validated previously [4]. The size of the calorimeter was optimized in order to detect the apparent heat gain and temperature changes between the reference calorimeter and the calorimeter being tested.

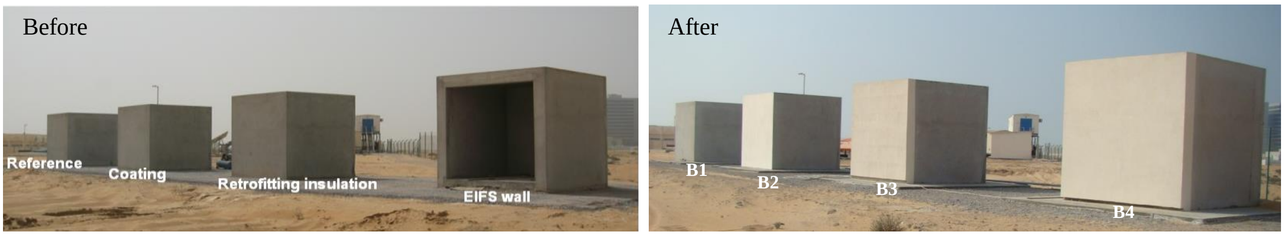

Fig.1. Four cubical calorimeter at site with different south wall configuration [Volume = 3 x 3 x 3 meter each]

The structure of the four calorimeters (3m x 3m x 3m) for this study were made of four pillars (25cm x 40cm x 300cm) with reinforcing bars at each corner of the cubical. The configuration of calorimeter north, west, east surfaces were of AAC blocks with thickness 25cm and wall area of 3m x 3m (R=2.11 m^2K/W) [65]. Roof was made using concrete precast beams (25cm x 30cm x 300cm) at each corner with 15cm thick concrete slab resting on beams and 2cm thick plaster on each side of the slab (R=0.18 m^2K/W) [65]. Area of the base was 3m x 3m and it was filled with crushed gravel, 5cm thick XPS and concrete slab 15cm thick (R=1.687 m^2K/W) [65]. There are no windows and only one door at the north facing facade of the building, which was kept, closed during the experiments. No internal heat sources were kept inside the buildings except for the identical recording instruments. The doors were properly sealed to prevent infiltrations and buildings were unoccupied during experiments.

The distance between each calorimeter building is 6m. The south wall of the first three buildings are solid-concrete and it was made of 15cm thick concrete with 2cm thick plaster on each side and the fourth one was made of dry composite wall instead of solid concrete wall, that is known as EIFS. Area of each wall surface is 3m x 3m. Three calorimeters with various insulation methods and materials on south wall were compared against a reference calorimeter with no insulation. The configuration of south walls from inside to outside of each calorimeter is shown in Table 1.

Table 1. South surface configuration from inside to outside for each calorimeter [65]

Construction type	Buildings	South surface configuration (inside to outside)	R(m^2K/W)	U($W/(m^2K)$)
Solid Concrete facade	Reference- (B1) *typical concrete construction*	Plaster(2cm)+Concrete(15cm)+Plaster(2cm)	0.308	3.25
	Coating retrofit- (B2) *on typical concrete construction*	Plaster(2cm)+Concrete(15cm)+Plaster(2cm)+Coating(ά=0.16)	0.308	3.25
	PIR retrofit-(B3) *on typical concrete construction*	Plaster (2cm)+Concrete(15cm)+ Plaster (2cm)+PIR (5cm)	2.56	0.391
Dry Composite facade	EIFS-(B4) *as provided by BASF*	Gypsum(2.4cm)+Mineral wool(10cm)+Cement board(0.9cm)+ EPS board(10cm)	5.7	0.175

Table 2 shows the material physical properties of the construction material. PIR used on building B3 as retrofit has higher specific heat capacity. Whereas, for building B4 the EPS and mineral wool has higher specific heat capacity and being used with higher thickness. Therefore, according to Table 2 it is being expected that the building B3 and B4 will have better thermal mass properties compared to building B1 and B2.

Table 2. Physical properties of the materials used on south façade of the calorimeters [66] [67] [68] [69]

Building material	Thickness (cm)	Density (kg/m^3)	Specific heat capacity (KJ/ (kg. K)
Plaster	2	1860	0.72
Concrete	15	1920	0.88
PIR	5	30	1.5
Gypsum board	2.4	600	1
Mineral Wool	10	64	1.03
Cement board	0.9	1350	1
EPS	10	35	1.5

Fig.2 and Fig.3 shows the calorimeter dimension in meters when viewed from east surface (side view) and different stages of the construction process of the calorimeter.

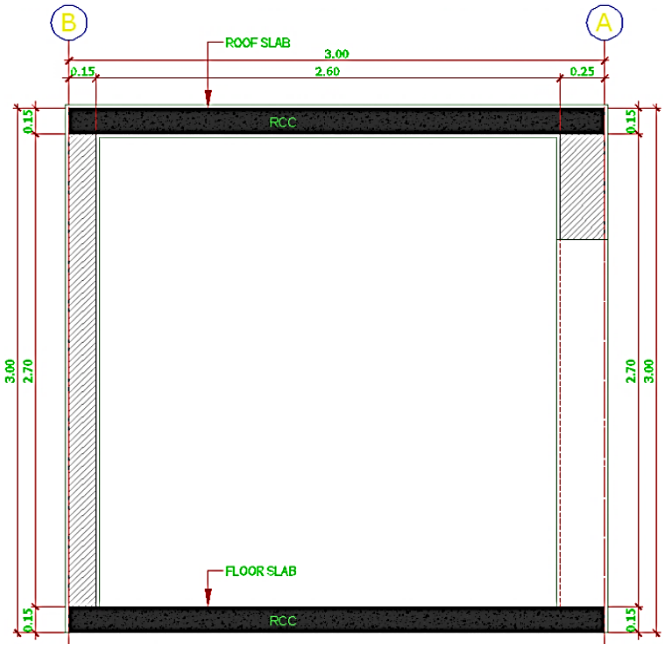

Fig. 2. and Fig.3. Dimension of calorimeter in meters (m) and the construction of calorimeter with different south wall configuration [65]

All the four buildings were calibrated at a set point of 24 ^{o}C for heat flux and energy consumption before adding any insulation or coating to the testing surface. In order to calibrate the buildings, building energy consumption and heat flux was measured for a week at a set point of 24 ^{o}C. The difference in energy and heat flux consumption was measured and differences of all buildings were comparted with that of the reference. Percentage change or correction factor compared to the reference were added to other buildings during measurements. During the experiments the data was sensed and it was recorded at 1 second interval via ADAM module for the heat flux through the south walls, external and internal room temperatures and energy consumption.

Details of instrumentations used to collect data during the experiments in the calorimeters along with its accuracies are as follows:

- External and internal room temperature and humidity: E+E Elektronik- EE08, accuracy 2% for RH and ±0.5^{o}C for temperature. Room temperature was measured from the middle of the room approximately 1.5m above the floor. The outside air temperature was measured approximately 5m above the ground level.
- Heat flux through south wall (inside): Hukseflux heat flux sensor –HFP01, accuracy of 3%. It was fixed on the inside at the middle of the south wall surface (1.5m above ground and 1.5m from the adjacent walls).
- Electric consumption: Kamstrup energy meter-KM162L, accuracy of ±1%.
- Solar radiation: Vantage Pro 2, accuracy of 0 to 1800W/m^{2} with ± 5 % of full scale accuracy.

The experimental setup enabled to provide the possibility to perform two kinds of test:

- Summer:
  - ➢ Controlled temperature-set point 24 ^{o}C: Air conditioner was used to control the room temperature at 24 ^{o}C during the duration of the test in summers. The average heat flux and the energy consumption of the calorimeters were compared with the reference. The experiments were initiated once the temperature of all the calorimeters was at 24 ^{o}C.
- Winter:
  - ➢ Free floating test: Temperature inside the room was not controlled and no cooling or heating system was used. Heat flux flow through south walls and room temperatures were measured continually to determine the effect of R-value and thermal mass of insulation materials. This experiment was performed in winters.

3. Results and discussion

The experiments were carried out from 2012 to 2014. The tests were run simultaneously in all four buildings to measure the performance of each building at same time. Here, one week of hot summer and cold winter season has been selected and the results obtained are presented and discussed in paper, in order to describe the behaviour of the calorimeter under different ambient conditions.

3.1 Summer results

3.1.1 Controlled temperature-set point 24 °C

The indoor temperature was maintained at set point of 24 °C (±0.5 °C) all time during tests with the help of 1 ton$_{thermal}$ air conditioner in controlled temperature experiments. Summer temperature reached around 35-45 °C at peak time. Fig.4. shows the average daily temperature inside the room as measured during the experiments, the average temperature for the duration of the experiments was approximately 24 °C in all four buildings. Fig.5 gives the average heat flux measured on the south walls of the calorimeters. The heat flux through the reference building (B1) south wall was much higher than that of B2, B3 or B4. The heat flux through the dry wall (EIFS) B4 was the lowest as compared to the solid concrete wall B1.

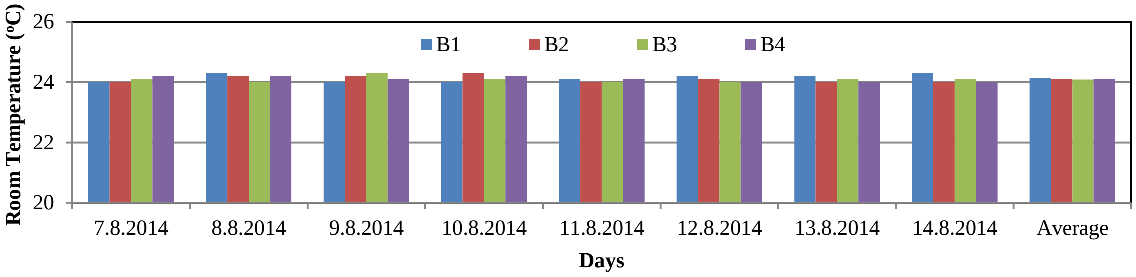

Fig. 4. Average daily temperature inside the room as measured during the experiments

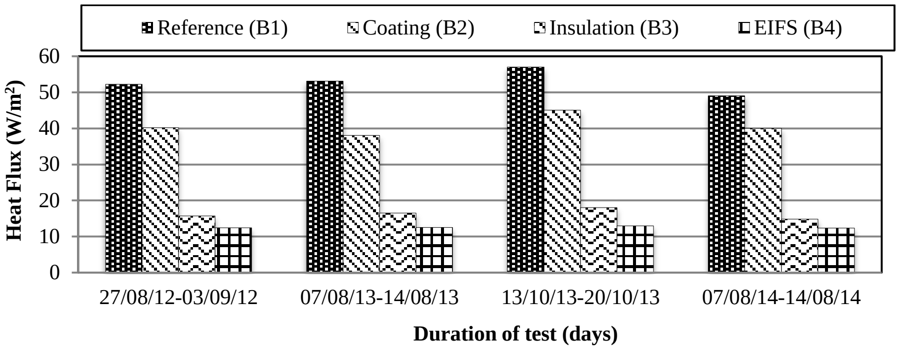

Fig. 5. Average heat flux measured through south wall during steady state tests in summers

The average reduction in heat flux by reflective coating retrofitting on B2 south wall was around 22% due to the reflection of the solar radiation from the surface coating. The average reduction in heat flux increased by 69% by retrofitting the south wall with PIR board of 5cm on B3 and by using the EIFS south wall on B4 reduction of heat flux was 75% compared to the B1. It was caused due to the increase in the R-value of the south facade of B3 and B4 calorimeters, hence providing a resistance to the heat flow inside the calorimeters. It is shown in Fig.6.

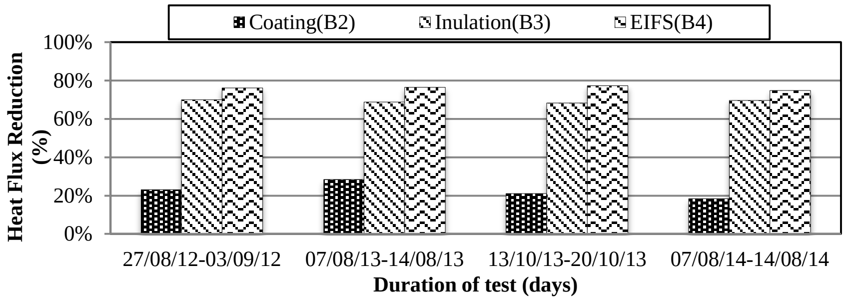

Fig. 6. Average percentage reduction of heat flux through south wall compared to reference building (B1)

Another week of August (August 7th to 13th, 2014) is presented in Fig.7, in order to show the measured accumulated electrical consumption profile of air conditioner. The set point of the air conditioner system was set at 24 °C and the average temperatures inside all the calorimeters were always within the range 24 °C ±5 °C. The energy used to cool the reference calorimeter is much higher than that of the other calorimeters. Using reflective coating as retrofit in B2 the energy consumption reduced by 7.6% compared to reference B1. With 5cm PIR insulation on B3 energy saving has increased by 23% followed by EIFS dry wall on B4, as it has increased the savings by 25.3% against reference B1 due to reduction of heat flux at south façade.

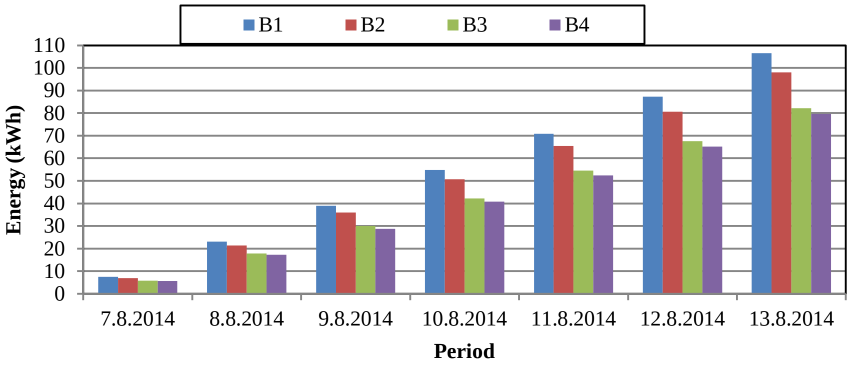

Fig. 7. Accumulated energy consumption of the air conditioner (AC), during 7/08/14-14/08/14

3.2 Winter results

3.2.1 Free floating experiments

The results considered in this case were from weeks in December 2014 which has been selected and discussed. Temperatures are typically low variating from 15-27 °C as compared to summer. The humidity during the week also remains on an average by 70%. Fig.8 shows the hourly average heat flux measured in December via south wall inside buildings B1, B2, B3 and B4 and ambient temperature. The pattern shows that the heat flux fluctuation in building B1 was high as compared to the other buildings. The heat flux variation in coated building B2 followed the same trend as that of building B1 but the magnitude was less as the coating was reflecting the radiations. Whereas, in the insulated buildings B3 and B4, the heat flux magnitude were not only less but very steady. Due to the high thermal resistance of the insulated walls of buildings B3 and B4, the peak of the heat flux has reduced when compared to the peak of building B1 and B2. Also, due to higher specific heat capacity of the insulated buildings B3 and B4, as shown in Table 2 the peak of the heat flux has shifted right when compared to the peak of the building B1 and B2 as shown in Fig. 8.Hence it takes longer time for the heat to travel inside the rooms through B3 and B4l therefore, it allowed to maintain the room temperature at a certain value for longer time.

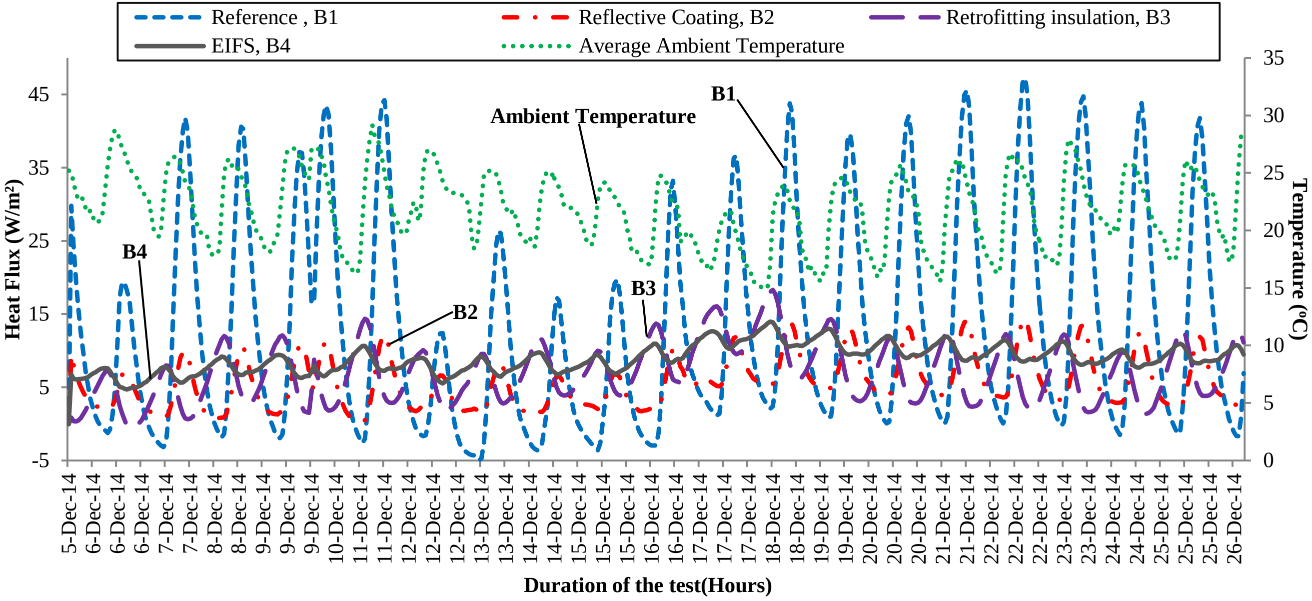

Fig. 8. Hourly average heat flux and ambient temperature measured through south wall during free floating tests during December 2014

In order to analyse the heat flux behaviour in detail, two days that is from 19 December 2014 to 20 December 2014 were selected from Fig.8. Fig.9 shows the instantaneous heat flux profile during the selected days in December and the corresponding ambient temperature profile as measured without using hourly average of the measured data. It shows that the heat flux through the testing surface in B1 and B2 followed similar trend but different in magnitude as coating reflects some of the irradiance falling on the surface. Heat flux increased with increase in the ambient temperature with time lag of 4hrs approximately from sunrise to noon. Heat flux through B3 and B4 was rather steady compared to reference due to high thermal resistance, thus avoiding any thermal inertia effect. The heat flux trend in insulated buildings B3 and B4 were inverse to that of B1 during the whole day. Hence, heat flux pattern illustrates that insulation is essential in winter as well as in summers to maintain the temperature inside the room stable with less fluctuations during the whole day.

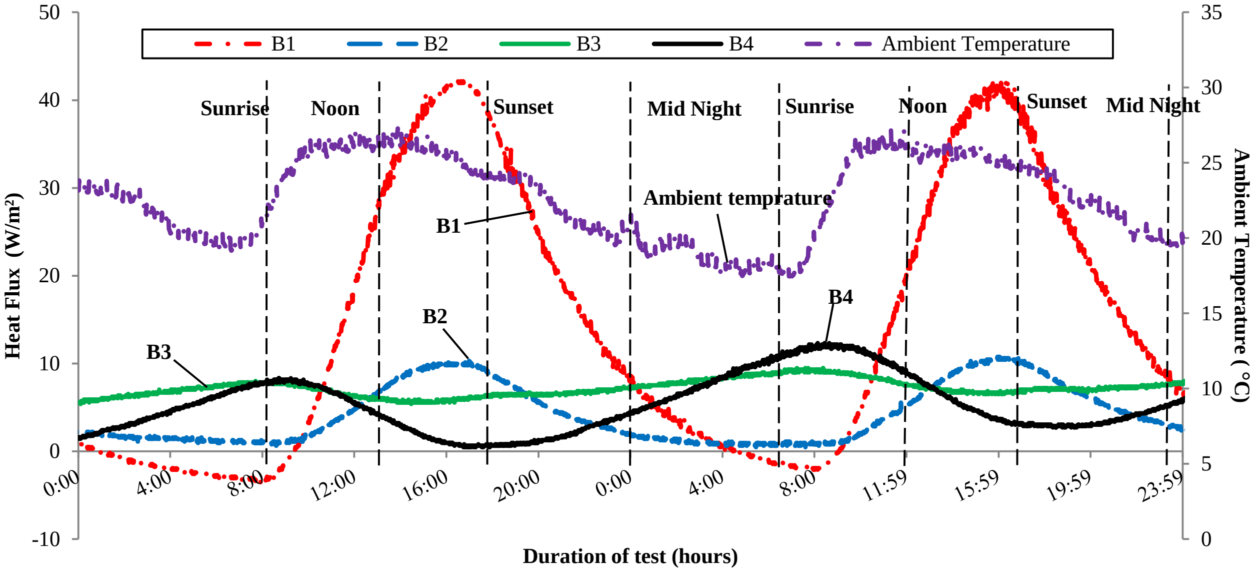

Fig. 9. Free floating heat flux variation measured each second through south wall during 19/12/14-20/12/14 and corresponding ambient temperature

Fig.10 shows the temperature inside the calorimeters and compared against the ambient temperature. The values of the interior temperatures experience soft fluctuations during the week due to relatively high thermal inertia of all the calorimeters. But the temperature in the reference building B1 has a larger daily oscillation compared to the insulated buildings. The indoor temperature shows that the fluctuations in temperature was limited to 2 ^{o}C average in case of insulated and coated buildings (B2,B3,B4), compared to average 6 ^{o}C in reference. Also the reference building was more sensitive to the outside temperature decrease that occurs on the last four days of the week. Among the insulated buildings their differences are minimal as the three of them showed the same trend. In insulated buildings the fluctuation between the highest and lowest temperature peak is less as they provide the resistance of heat movement between the indoor and outdoor environment. It can also be observed that due to the heat capacity of the tested walls in all buildings (B1, B2, B3 and B4) there is a delay in time, when the indoor temperature reaches its peak both during the day and at night when compared against the ambient temperature peaks.

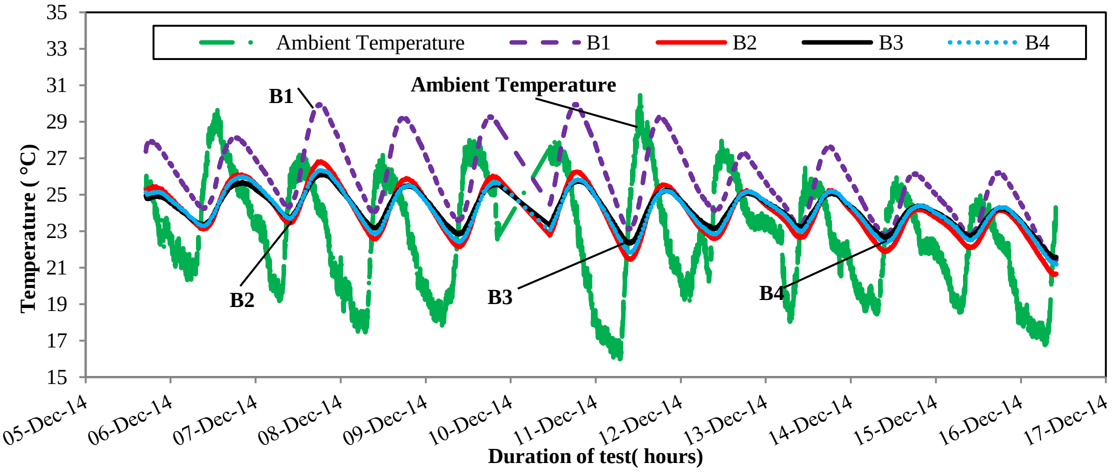

Fig. 10. Measured ambient temperature and calorimeters room temperature during free floating test in winters

7. Conclusions

The experimental study was done to evaluate the influence of retrofit on typical solid concrete walls and new insulation techniques practically in buildings. Four calorimeters were constructed in RAK, UAE. It was observed that, heat flux reduced by an average of 22% with reflective coating on B2 and with PIR board (5cm) by 69% on B3 when existing solid concrete construction was retrofitted. With dry wall EIFS, heat flux reduced by 75% on B4 when compared to the solid concrete reference building B1. Based on reduction of the heat flux through south wall, the average energy consumption measured was reduced, by 7.6% in building B2, 23% in building B3 and 25.3% in building B4 compared to reference building B1.The reduction in heat flux through south wall and increase in overall energy saving in the calorimeter was due to high thermal resistance (R-Value) of the material and also by reflecting the solar radiation with coating. The results during summer testing showed that the room temperature of building B3 and B4 were well maintained while using less energy. The free floating test during winters showed that building insulation proved to be vital in winter as well. It has a great impact on the thermal inertia caused by thermal mass and heat capacity of the wall. Thermal mass or heat capacity effect was evident in B3 and B4 in free floating experiments, as it acts as thermal storage element which helped to shift time of occurrence of peak heat load and also helped to reduce the temperature fluctuations. The reduction and shift of peak heat flux are quite important: firstly it evens out the large demand on the electricity grid during peak hours; secondly, by reducing peak heat load and flux, smaller capacity air conditioner equipment would be required. As larger capacity air conditioners would operate most of the time at part load in insulated buildings, which makes them less efficient and would also incur increased capital and maintenance costs. Thirdly thermal mass shifted the peak load to the later part of the day and it would assist in reducing the burden on the grid during peak load hours and lastly, it would increase the energy efficiency of overall system. Therefore, it is recommended to use dry wall technology i.e. EIFS for improved energy performance of buildings in hot climates instead of conventional solid concrete buildings. However, the cost effective method is to retrofit the existing solid concrete walls with reflective coating for immediate solutions. Retrofitting insulation (PIR-5cm) also showed promising results and it can be used as immediate solution to existing villas in UAE and MENA region. The façade with the combination of higher R-value and higher thermal mass performed better than the wall with less R-Value and relatively high thermal mass. The effect of thermal mass and the R-Value are important to select the building envelop and this study can be used to measure and analyse the effect of these two factors for selecting the material for building envelope. The experiment showed the methodology and the interaction between R-value and thermal mass in real application. There exist a huge potential to reduce the CO_2 emissions from MENA region if passive methods for energy saving are used and applied in real applications in MENA region. The study is valid for hot and humid climate region, like MENA where this climate persists for a longer duration of the year. The investigation will be continued to evaluate the thermal transmittance of the walls and insulations in order to test if aging of the insulation, humidity and dust accumulation has any effect on the thermal properties, heat flux and energy consumption. Since manufacturers do not consider any degradation of the thermal properties of the insulation materials with time, which may occur in real buildings. This degradation can be detected by utilizing such calorimeters. To better understand the thermal comfort inside the building, it is being planned to measure the air velocity inside the room along with the room temperature. This experimental setup and procedure can be used as it is in different climatic conditions. It will be interesting to perform similar test in Nordic countries where climate is extremely cold for longer periods in a year and there is relatively larger heating demand in the buildings instead of cooling demand as in this case.

This facility is open to industrial cooperation and to academic research and development projects. It will be highly beneficial for the manufacturers in performance evaluation of solar insulating materials in UAE climatic conditions. They can also benefit by developing new or modifying existing insulating materials based on the experimental results in order to earn market shares in the Middle East region. It is also advised that the government policies for buildings have to be reformed in order to promote and incorporate these designs in new and existing buildings to support sustainable development in building sector. This study can also be helpful for the government in order to formulate comprehensive building policies and standards which can be followed by the construction companies for future buildings construction in real applications.

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Conflicts of Interest

The authors declare no conflict of interest.

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