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An Investigation on Using Passive Cooling Roofs Techniques for Improving Climatic Performance of Residential Buildings in Hot Arid Regions based on Post-Occupancy Evaluation of Inhabitants' Thermal Comfort Appreciations

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Abstract. In hot dry climates, employing passive cooling roofs systems can provide cooling needs with less amount of electrical energy. Furthermore, when focusing on living spaces in terms of indoor thermal comfort and energy performance issues, occupant's interaction with the building should not be underestimated. Recent studies with occupant-based focus have shown that human behaviour significantly impacts energy consumption, even more than building design. Likewise, understanding occupant's interactions within buildings plays a key role in enhancing the indoor environment performance. To examine the potential for cooling load reduction and thermal comfort enhancement by using cool roofs in residential buildings, a study was performed. Considering a sample of twelve multi-story houses located in the city of Biskra (southern Algeria), thermal comfort conditions were analysed on the basis of a post-occupancy evaluation (POE) survey and in situ recorded measurements campaign. The POE household survey indicated that out of 43 respondents, 54% perceive indoor thermal conditions as "hot" during summer period, while 79.33% of them operate HVAC device day and night. Using interviews, the study also explores social acceptability toward implementing passive roofing techniques. Results showed that cool roof and cool tiles were the best accepted systems with 100% and 90% voted strongly agree. Furthermore, the potential of thermal comfort and energy-efficiency improvements due to cool roofs was investigated through a dynamic simulation using TRNSYS software. Results indicated that air temperature was reduced by an average of 4.11°C to 3.28°C, and cooling loads have decreased to 508.60kWh/m² and 384.54kWh/m² respectively during the hottest period of summer. Therefore, user-centric satisfaction as a research method would enhance future buildings design.

Keywords: Post occupancy evaluation (POE), occupants' behaviour, energy consumption thermal comfort prediction, cool roofing techniques, social acceptability, hot arid climate.

1. Introduction

In Algeria, which is the focus of this study, the building sector's energy demand is huge. According to the APRUE (the Algerian national Agency for the Promotion and Rationalization of Energy Use), it corresponds to more than 41% of the national global energy consumption [1]. This excessive rate of energy demand is due, in part, to the social policy trends in Algeria where the energy use is subsidised. According to Kherfah et al. [2] the low cost of the energy bill and the lack of major financial constraints for energy supply have led to high energy consumption. Calling for a sustainable developmental strategy, the Algerian government has set a target to reduce buildings energy demand for heating and cooling by 40% by year 2030 [3]. This constitutes a major challenge, especially in view of the available building stock, which was not designed to achieve environmental performance. In southern Algeria where a hot and dry climate prevails, cooling living spaces is a basic need and a major priority for the residents. In these regions, where buildings are greatly dependent on air-conditioning to provide occupants with comfortable thermal conditions, cooling requirements reach peaks of consumption during the hot season from June to October.

Considering that people spend over 90% of their time in interior spaces, indoor thermal conditions significantly impact their health and wellbeing [4]. During the Covid-19 pandemic, time spent inside dwellings has increased, and this highlighted the importance of ensuring well-performing buildings that satisfy occupants' comfort demand/ needs, health and productivity [5]. In hot climates, the exterior envelope components are the most significant contributors to the comfort parameters and the energy performance of the buildings [6]. In this regard, terraces and roofs are considered to be the main sources of overheating inside spaces. Therefore, using efficient design strategies can lead to an increase in indoor thermal comfort and a consequent reduction in ambient air temperatures that in turn results in energy saving by reducing cooling loads. In particular, applying passive cooling strategies through rooftops proven to be very effective in maintaining indoor well-being, controlling heat dissipation, as well as reducing cooling demand [7].

This paper addressed the acceptability rate of using passive roofing techniques in their buildings as one of the important tasks of the optimisation process. The main goal of the study is to examine the potential for cooling load reduction and thermal comfort enhancement by using cool roofing techniques in residential buildings. Considering a sample of twelve multi-story houses located in the city of Biskra (southern Algeria), thermal comfort conditions were analysed on the basis of a post-occupancy evaluation (POE) survey and in situ recorded measurements campaign. Using interviews, the study also explores social acceptability toward implementing passive roofing techniques. Furthermore, the potential of thermal comfort and energy-efficiency improvements due to cool roofs was investigated through a dynamic simulation using TRNSYS software.

2. The potential of using passive roofs as a cooling strategy

Recently, passive cooling through rooftops has received increasing attention as an alternative to provide occupant's thermal comfort with ensuring energy efficiency of buildings during hot periods [8]. In this regard, a substantial amount of studies exploring various passive measures in the context of extreme climate conditions have been published. From the existent literature, authors have defined two passive cooling roof approaches: 1) radiative cooling, and 2) evaporative cooling. Furthermore, their applicability in the context of Biskra depends on climate conditions and roof shape of residential buildings. By referring to Parker et al. [9] a cool roof is both a passive solution and a building typology that assists in reducing the cooling loads and energy demands on a building's envelope. Accordingly, cool roofs can be surfaces

that reflect sunlight and emit heat more efficiently than other dark roofs. Consequently, using a high reflective roofs as a passive technique can be very effective in energy-efficiency; besides being low cost, easy to install and eco-friendly, it can also decrease discomfort hours by 9–100% and reduce cooling loads by 18–93% in different climate zones [10]. In a research conducted by Zinzi and Angoli (2012)[11] on two residential building typologies, it was established that applying cool roofing can reduce discomfort hours by more than 73%. In hot climate regions of Egypt, a study performed by Dabaeih et al. (2015) [12] demonstrated that solar shading devices help to block hot sunlight irradiations, and thus minimise surfaces heat flux. The study, also, displayed that using cool ventilated roof reduce discomfort hours by 32% better than those achieved in the base case. Considering hot and arid climatic conditions, evaporative cooling through pond roofs is the most efficient cooling technology [13]. In these regions, the pond roof technique reduce the indoor air temperature by 9°C [14]. Likewise, Almodovar and La Roche (2019) [15] evaluated two roof pond configurations built in a hot-dry climate. Through monitoring campaign, authors found out that indoor temperature stayed below 24°C when outdoor air temperature was above 35°C.

Residential building stock represents a significant potential in tackling both worldwide energy and thermal built environment challenges. Actually, beside building itself, the biggest energy consumers are the inhabitants [16]. Simply put, the way of occupying a building, humans' habits and activities explain differences between the estimated and real energy consumptions [17]. Consequently, the human's dimension is a key factor to be addressed when it comes to assess indoor environment quality and building energy performance [18,19]. Inhabitant-dwellings interactions topic, subjective post occupancy evaluation (POE) surveys together with objective building features can help in assessing indoor thermal comfort and thus building energy performance. In this regard, it is important to monitor occupant satisfaction to provide measures that can determine building performance. POE surveys seek occupant satisfaction feedback regarding their indoor environment which can help in enhancing design expertise, satisfies users' requirements and promote retrofitting process [20]. POE approaches include two complementary methods; subjective method using survey questionnaires to indicate occupant's perception in their built environment and objective method using in-situ physical measurements [1].

From the available literature, six passive cooling roof techniques as the most suitable, low cost and easy to install on existing roof in Biskra's climate, Algeria. However, besides their high thermal-energy feasibility, social acceptability of such techniques is among the main criteria taken into consideration to achieve its requisite success on a large scale application. Thus, it is important to evaluate the social acceptance and users' awareness to understand the social perceptions of owners regarding passive techniques application on bare concrete roofs [21].

3. Materials and method

The primary purpose of the present study is to assess the occupant behaviour and thermal sensations perceptions of the indoor environment in conjunction with building energy performance (behavioural adjustments) with a subjective and objective post-occupancy evaluation data. In addition, the research aims to examine the potential for cooling load reduction and thermal comfort enhancement by using cool roofs in residential buildings. Therefore, the adopted investigation combines between a post-occupancy evaluation survey and a numerical simulation approach. This investigation will be described through the in-situ interviews and the numerical simulation results. Accordingly, to analyse the interactions

between inhabitants-dwellings and their energy use, twelve (12) different multi-story houses were selected in the city of Biskra as a hot and dry region.

The figure below illustrates the research methodology adopted in the study (figure 1).

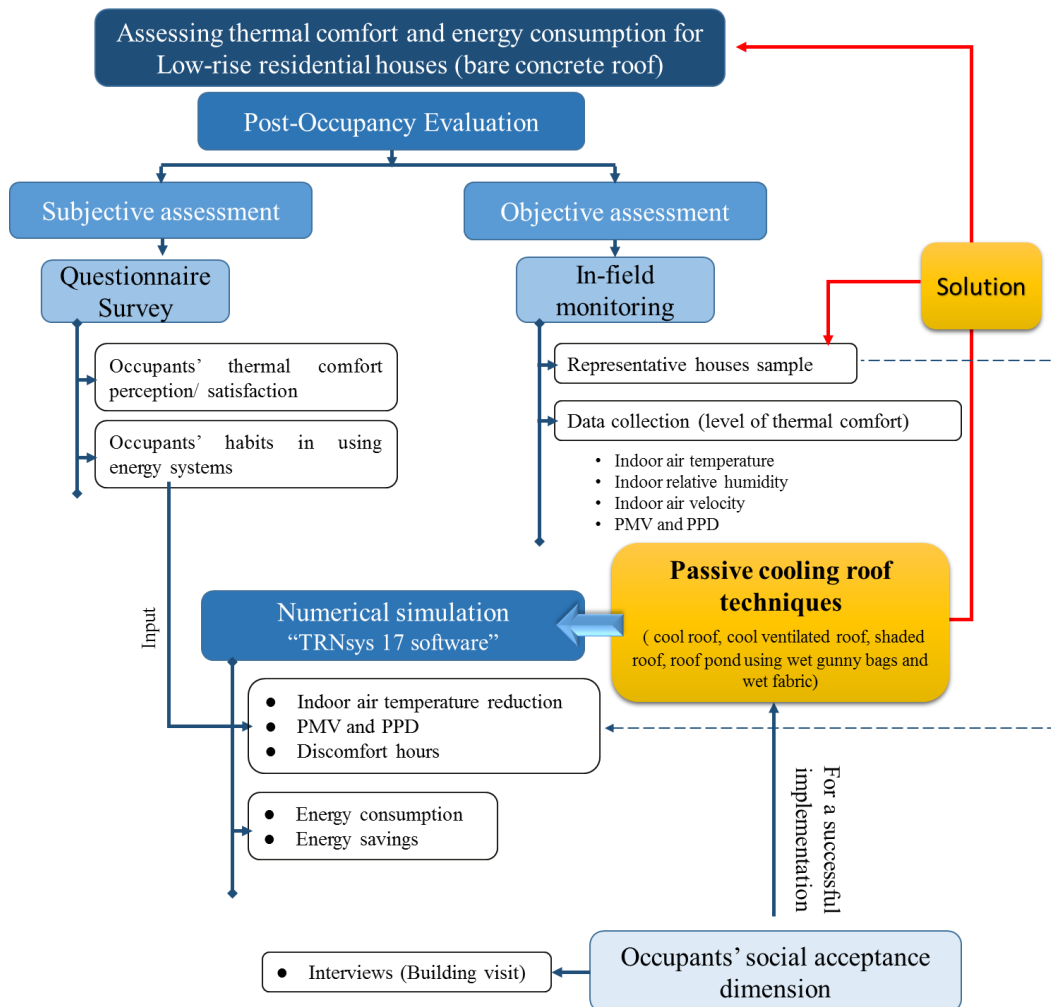


Figure 1. The conceptual framework of the study

3.1. Case study area and selected houses description

The study was conducted in the city of Biskra (34.8° N, 5.73° E and 87m) located in southeast Algeria. Based on the Köppen climate classification, Biskra's climate falls in zone BW_h, thus, it is characterised by hot and dry weather conditions. Summers are extremely hot, temperatures can range from 38°C to 48°C with 2mm average rainfall during July (the hottest month of the year); whilst, winters are relatively cold. In these severe climatic conditions, the hot season is quite lengthy and occurs from June to October. According to the psychometric chart analysis and by referring to the prevailing climatic conditions in the studied region, the comfort zone ranges from 23°C to 27°C; whereas, relative humidity percentage ranges from 40% to 60%.

This research has adopted a case study research method approach. Accordingly, the study was carried out on twelve (12) individual multi-story buildings selected from residential districts in Biskra (Figure 2). These case studies are representative of the most common and wide-spread housing type in Biskra. All the selected houses use the same structural system,

i.e. frame reinforced cement concrete structure, as well as the same combination of construction and finishing materials. The roofing system is on hollow bloc concrete with no external protection as the most common multi-story houses in Biskra.

In each house, we selected a room that is in direct contact to outdoors where all family gathers to run the physical measurements and questionnaires campaign. Table 1 presents the thermal proprieties of the selected building samples.

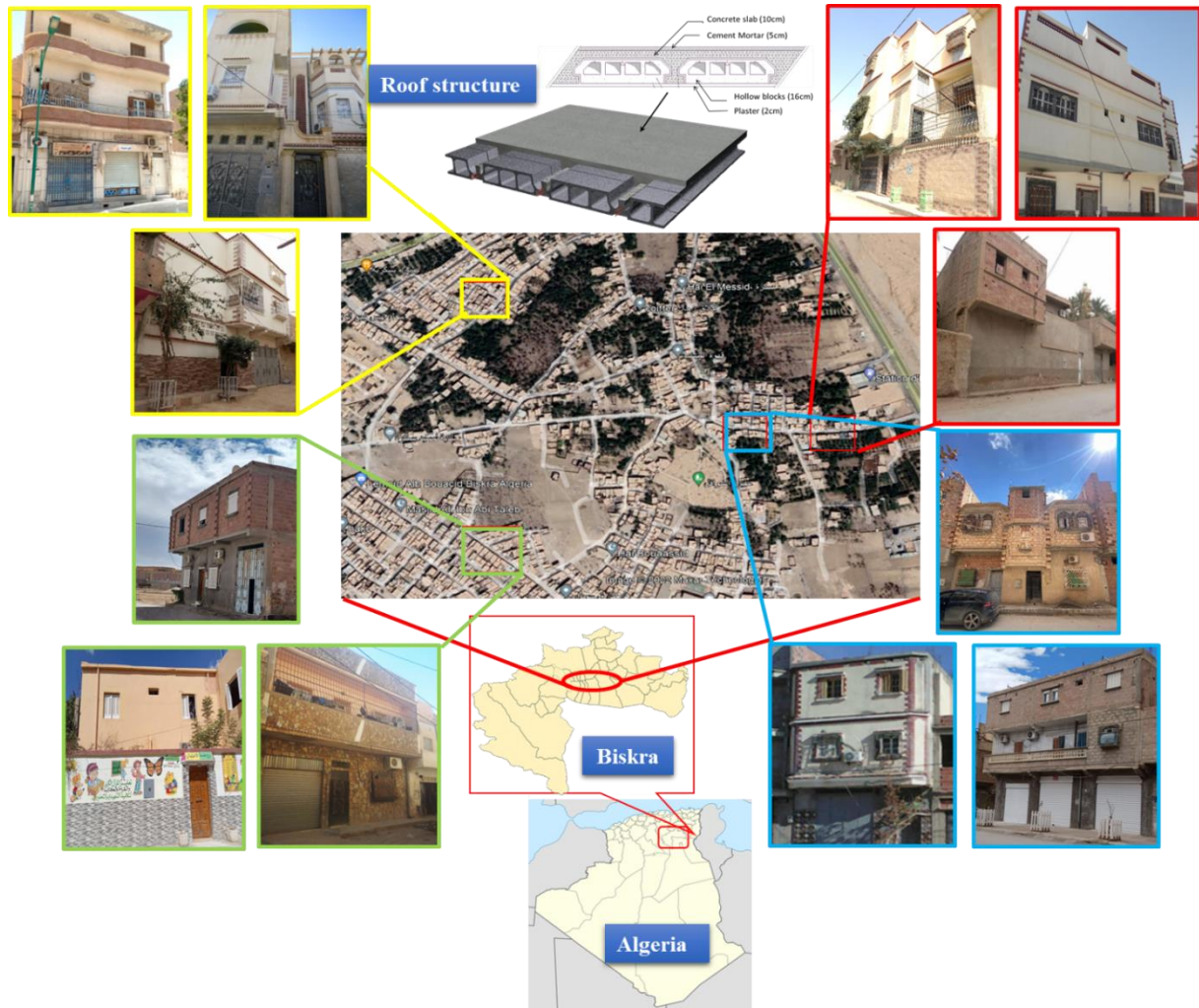


Figure 2. The study area and some examples of the multi-story houses selected for study in Biskra

3.2. Post occupancy evaluation and field measurement data

3.2.1. Objective assessment: on site monitoring and thermal comfort evaluation

This study focuses on thermal comfort evaluation. In this regard, the most commonly used model for the indoor assessment is the predicted mean vote (PMV) and percentage of unsatisfied persons (PPD). Many factors affect PMV indicator including indoor air temperature, indoor air velocity and relative humidity, and therefore these data have been

measured. Metabolic rate (met) and occupant clothing insulation (Clo) are included in evaluation [22].

The measurements were carried out in the twelve selected individual multi-story houses during the hottest week in the hottest month of the year from 7th to 10th July. Using a thermo-hygrometer sensor “Testo 480”, measurements (thermal, humidity and ventilation) were collected from each case study. Measuring instruments were installed in non-conditioned rooms situated in the last floor to assess the direct impact of heat gains coming from roof surfaces. Measurements were collected from 9am -12pm and 2pm - 6pm (as allowed by the homeowners) (Table 2).

Table 1. Materials characteristics of the selected houses [23]

Building element	Thickness (m)	Thermal conductivity (W/m.K)	Density (Kg/m ³)	Specific heat capacity (KJ/kg.K)	U- value (W.m ² .K)	
Roof	Mortar	0.04	1.15	1900	1.08	
	Concrete slab including Hollow blocks	0.20	1.45	1450	1.08	2.49
	Plaster	0.02	0.35	800	0.93	
Walls	Mortar	0.04	1.15	1900	1.08	
	Hollow brick	0.15	0.48	900	0.93	
	Air cavity	0.05	0.024	1.22	1.00	1.12
	Hollow brick	0.02	0.35	800	0.93	
	Plaster	0.02	0.35	800	0.93	
Window	Simple glazing	U= 5.74 W/(m ² .K)				

3.2.2. Subjective assessment: Occupant Survey/questionnaires

The main aim of the questionnaire survey is to investigate occupants’ indoor sensation/satisfaction and their habits/behaviour regarding HVAC systems use. Even though 50 questionnaires were distributed, only 43 were reliable questionnaires for further treatment with a percentage of 86 % (incomplete questionnaires were eliminated). The formulated questions were short and direct with simple and precise expressions in Arabic (native language of respondents). In addition, the questionnaire is made up of closed-ended questions such as multiple-choice questions. Furthermore, to ensure the results reliability, authors made a pre-questionnaire study to a small sample size in order to check the clarity and understanding of questions.

This questionnaire was divided into three sections; it includes 1) General information about the respondents (age and gender); 2) Information about occupants’ thermal sensation and acceptability rating as well as their appreciation about indoor relative humidity and airflow highlighting strengths and weaknesses on the thermal condition. A 7-point ASHRAE rating scale hot (+3), warm (+2), quite warm (+1), neutral (0), quite cool (1), cool (2) and cold (3) was used for the study as the commonly involved psychometric scale in this kind of studies; 3) Information about energy efficiency investigating the habits used to improve thermal comfort, average daily time and duration of running air conditioner and satisfaction with indoor air quality and energy bills.

3.3. Exploring social acceptability of cool roofing

As mentioned before, social acceptability is a widely assumed factor for the successful real-scale implementation of effective passive roofing. In this regard, structured interviews with homeowners were carried out (including a house visit). This part attempt to provide an in-depth insight of users' awareness and acceptance toward the proposed solutions revealing factors of selection of each system. We should mention that the interviewed occupants sample earn about 170 € to 350€ per month.

The interview started by giving a clear insight about each system presenting; definitions, thermal-energy effectiveness, investment costs, the level of maintenance, technical challenges and risks. Thereafter, questions focused on: 1) Roof existing protection, condition and occupancy during summer time; 2) Rating acceptance/decline toward each roof technique; 3) Factors affecting their choice; 4) Willingness for implementation.

3.4. Energy consumption and indoor thermal comfort analysis: the simulation process

This part of research focussed on modelling occupant's interaction with the building (windows opening/closing scenarios, occupancy time, lighting, and activities) and their interaction with cooling appliances (thermostats and ventilation regulation, manner of use and duration) as input data to assess how building's performance is affected by the occupants behaviour.

A representative building was chosen as most common housing widely constructed in Biskra (figure 3). The investigated living room is located in the second floor with direct contact to outdoor. The roof is a hollow concrete blocks slab covered with a layer of plaster in the inside face, but without protection or coating on the outside. Energy consumption was examined through cooling energy reduction and savings, while thermal comfort of the occupants was analysed in terms of air temperature, PMV and PPD reduction over a time period of 31 days (744h) of July with a time step of 1 h.

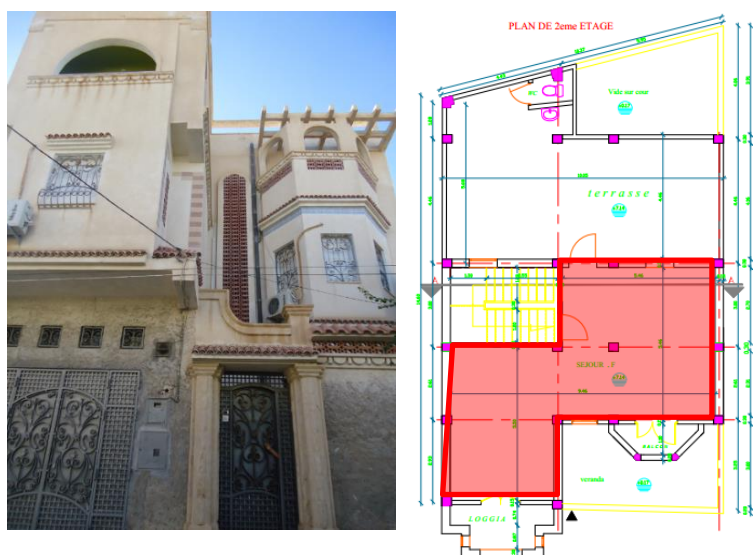


Figure 3. The house used as case study for the simulation; exterior view and 2nd floor plan showing the investigated living room.

4. Results and discussion

4.1. POE survey regarding indoor thermal comfort

Table 2 presents the average recorded measurements in twelve houses under natural conditions from 7th to 10th of July. Measurements show high air temperatures above the thermal comfort zone ranged between a maximum average of 34.96°C in mornings to 40.43°C in the afternoons with a stable air velocity (0 to 0.15 m/s). Relative humidity ranged between 27.57% to 34.66% in the morning while afternoons ranged from 19.65% to 23.6%. Considering the comfortable range of relative humidity for human ranges from 40 to 70%, the obtained values confirmed the dryness of the climate.

Table 2. The average recorded measurements in twelve houses during July (7th to 10th)

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	
9am-12pm	T°C	36.45	35.9	36.35	37.65	37.46	36.68	36.37	36.33	34.96	36.05	36.56	37.15
	RH%	31.45	37.45	30.53	28.5	28.98	30.4	29.2	28.45	30.66	34.2	27.57	29.15
	V m/s	0.1-0.15											
	PMV	2.89	2.75	2.64	3.23	3.23	3.19	3.05	2.7	2.34	2.56	2.73	3.24
	PPD	98.5	97.4	95.7	99.7	99.7	99.7	99.3	96.8	89.3	94.6	97.1	99.8
2pm-6pm	T°C	38.06	37.98	37.88	39.63	39.1	39.8	39.85	38.55	38.17	40.3	40.27	41.63
	RH%	20.55	23.2	23.6	20.4	22.6	19.35	21.9	20.65	27.75	19.98	22.18	19.65
	V m/s	0-0.1											
	PMV	2.98	3.28	3.24	3.49	3.39	3.85	3.65	3.25	3.12	3.92	3.91	4.16
	PPD	99	99.8	99.8	100	99.9	100	100	99.8	99.5	100	100	100

The recorded PMV average values were 2.87 with 97.3% of dissatisfaction from 9am to 12pm, while from 2pm to 6pm a 99.81% (3.52) of dissatisfaction toward indoor thermal conditions. Overall, readings indicated that buildings did not fulfil comfort level mainly due to high temperature fluctuation. The survey deals with a total of 41 respondents with a percentage of 86%. Analysing the collected data, out of 30 (60%) of them were women, and 13 (26%) were men. Moreover, 56% of the questioned people were between 25-45 years old. Clothing insulation level was determined by 0.4 CLO meanwhile, metabolic rate for home activities was estimated as 1 met (sitting, quiet, light movements).

Figure 4 presents users' thermal sensation votes during July. The responses varied between "warm" and "hot". During summer mornings (8am to 11am) the majority of the respondents in the different houses voted for a "warm" (+2) and "hot" (+3) sensation with percentages between 40 % to 24 %. Only 6% who had a comfortable sensation and 16% who had a "slightly warm" (+1) feeling. However, during the afternoon no person presented comfortable sensation while 72% voted "hot" (+3) and 14% voted "warm" (+2). During the night, votes were 52% for a "hot" sensation. The Overall voted thermal sensation of the users was "hot" during the summer period with an average percentage of 59% presenting 74% of "very unsatisfied" occupants affirming that air temperatures are the main cause of discomfort feeling.

Figure 5 presents the correlation degree between the measured and voted PMV. We can deduce a good correlation ($r^2= 0.69$) between the measured air temperatures and the voted thermal sensations. This correlation confirms the validity of the results obtained by the questionnaire.

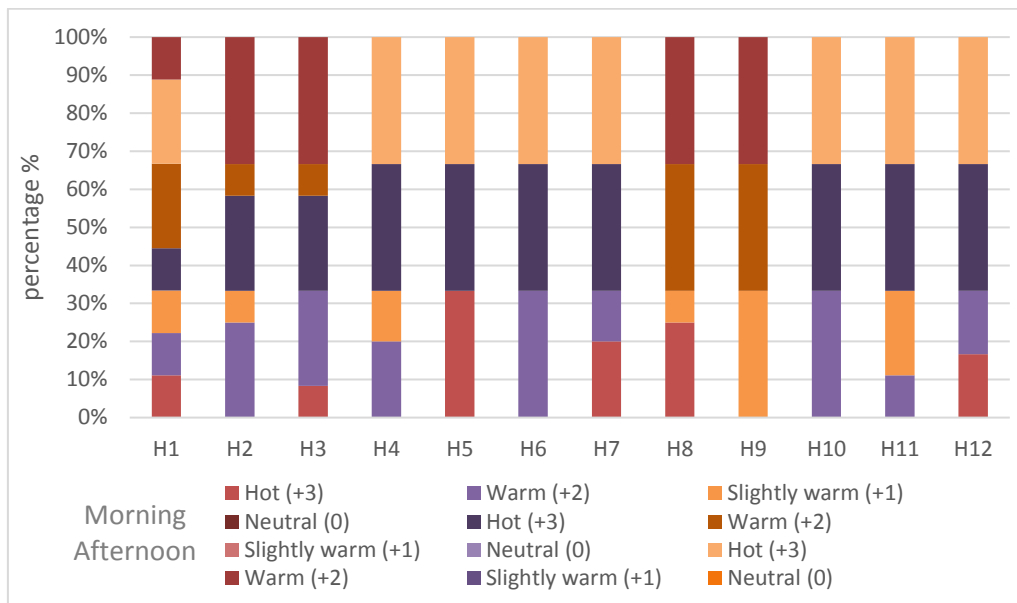


Figure 4. Thermal sensation of occupants during the hottest month “July”

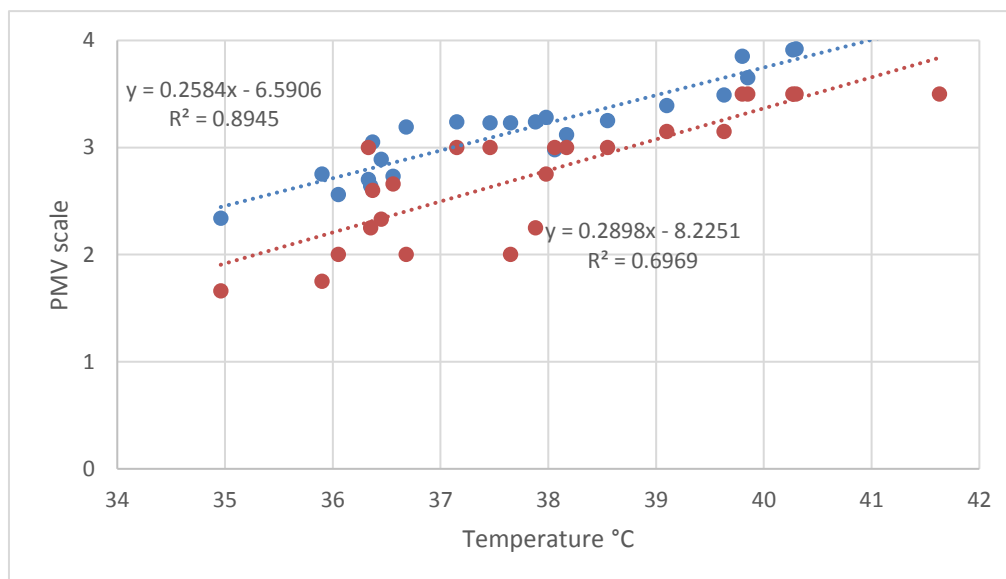


Figure 5. Linear regression of measured and voted PMV with the measured temperatures.

Facing discomfort situation, occupants’ thermal comfort adjustments and energy use behaviours has been identified. During the morning, 74% of users open their windows “always” and 12% open it “sometimes” while, 80% never open their windows during the afternoon. Occupants declared that opening windows were generally to get some fresh air because some days temperatures were high in the morning which do not help in enhancing indoor temperature.

Since residents confirmed that air conditioner is the only energy-device used to generate cooling needs, the questionnaire investigated their behaviour toward its use.

According to results, all users (86%) operate “always” the systems during the afternoon and nights while 66% operate it during the morning. These percentages confirm again the weakness of buildings envelope to offer thermal comfort for inhabitants. With the existence of cooling device, 56 % of people rated the environment as “acceptable” and 20 % rated as “satisfied” sensation while 10% presented “unsatisfied” sensation mainly due to health problem.

It is clear that electricity bills are the most worrying factor for residents during summer period where, 66% rated their energy consumption as “very high”, 14% rated it as “high” and 6% rated by “acceptable”. This situation is due to the daily use of air-condition that exceeds 10 hours per day especially during the month of June, July and August. In addition, some houses presented more than one installed device. This large use of air conditioning for long periods affects directly health and productivity of occupants and the energy performance of buildings. Respondents declared that the use of air-conditioners is not optional, but rather obligatory to overcome the high temperature fluctuations. They included their willingness to find solutions that would reduce at least the duration of operating.

4.2. Social acceptability regarding passive cooling roof

Given the structured interview that was carried out with 30 persons (who accepted to be investigated), user’s perception and degree of acceptability to apply passive cooling roof techniques on houses rooftops was revealed. The interview started by evaluating occupant’s awareness about roof high contribution in indoors overheating risks. Furthermore, 60% users do not occupy roofs during summer due to high surface temperature. Then, a clear insight about the selected techniques was presented using also illustrating pictures.

From figure 6, it can be seen that regardless the high feasibility, evaporative cooling system using roof pond wet gunny bags was not accepted at all from home owners affirming that will never install such protection on roofs. The most accepted systems were cool tiles and cool roof with 100% and 90% respectively voted “Strongly agree” to install. Cool ventilated roof was accepted by 40% that voted “agree”, however 43.33% was “disagree” for wide-scale installation.

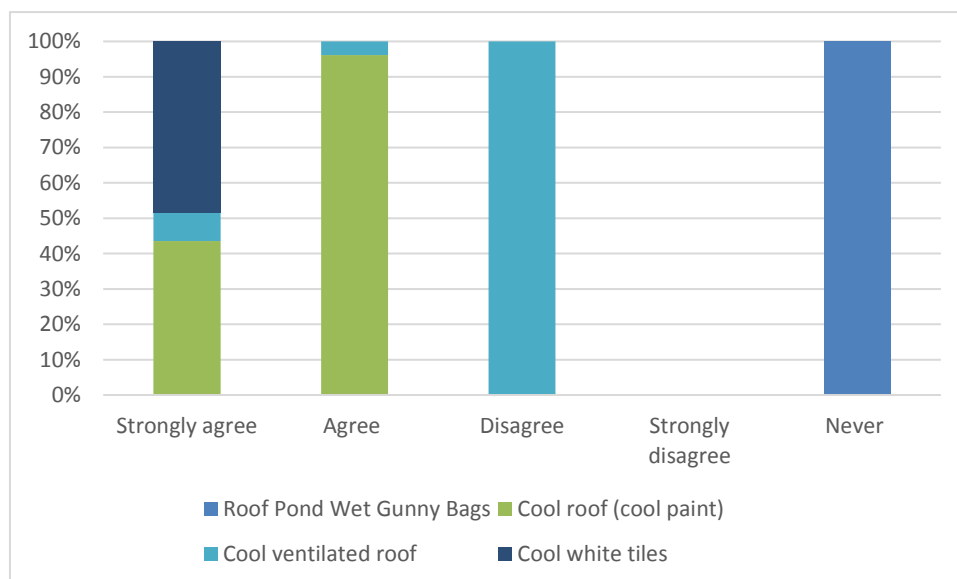


Figure 6. Social acceptability degree regarding each passive roof system.

Considering the refusal and approval factors influencing owner's choice, for evaporative system, water leakage risk and high requirement for water especially for Biskra where water availability is limited for the residents. Besides, high investment cost strongly involves in declining the adoption of this system. In addition, occupants were conscious regarding mosquitos spread that will cause dangerous diseases. From this part, it can be concluded that technical viability, economic viability and maintenance process are the main contributor for social acceptability.

4.3. Energy consumption and indoor thermal comfort simulation

Figure 7 shows average indoor air temperatures during the hottest month of summer. It can be seen that air temperature in the reference building ranged above thermal comfort zone from 33.55°C to 36.15°C. Applying cool paint reduced air temperature by an average of 4.14°C compared to the base case during daytime, meanwhile, using low-cost, local reflective tiles reduces the average daily indoor temperature by 3.28°C.

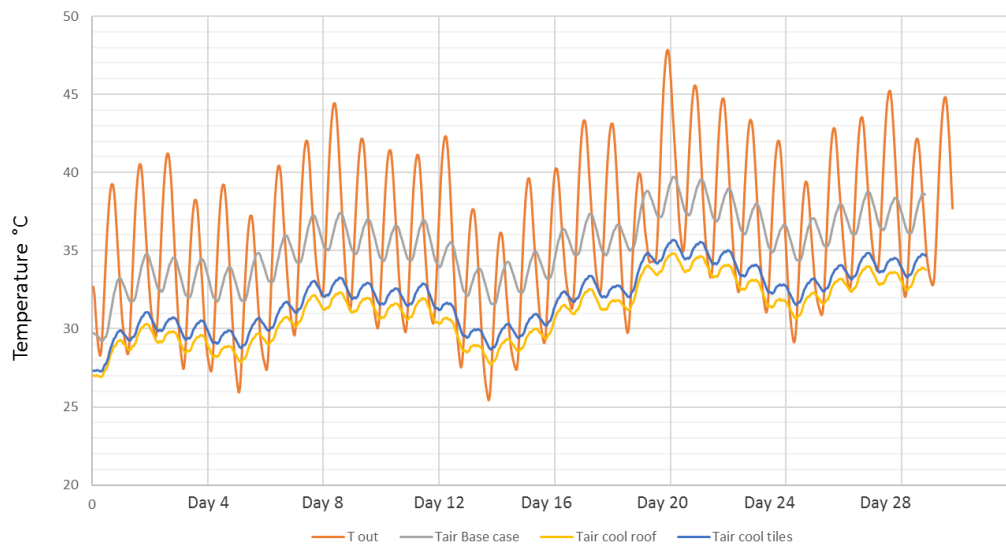


Figure 7. Indoor air temperature profiles for cool roof and cool tiles compared to reference case during July

The results indicate that due to the optical proprieties of the roof exterior surface (high solar reflectance and high emissivity) solar radiations have been removed which leads to lowering heat gains transfer through the roof, and consequently, thermal discomfort was attenuated. In addition, the predicted mean vote (PMV) was reduced to 1.57 and 1.86, consequently the predicted percentage of dissatisfied (PPD) has fallen back to 56.67% and 67.11% for cool roof and cool tiles respectively.

Figure 8 shows building energy consumption and saving during the month of July. Electrical energy consumption of the reference building to fulfil cooling needs reached 1121.91 kWh/m². Cool roof application recognized as a potential energy saving strategy provides a significant decrease accounts for 508.60 kWh/m², while cool tiles by 417.75kWh/m².

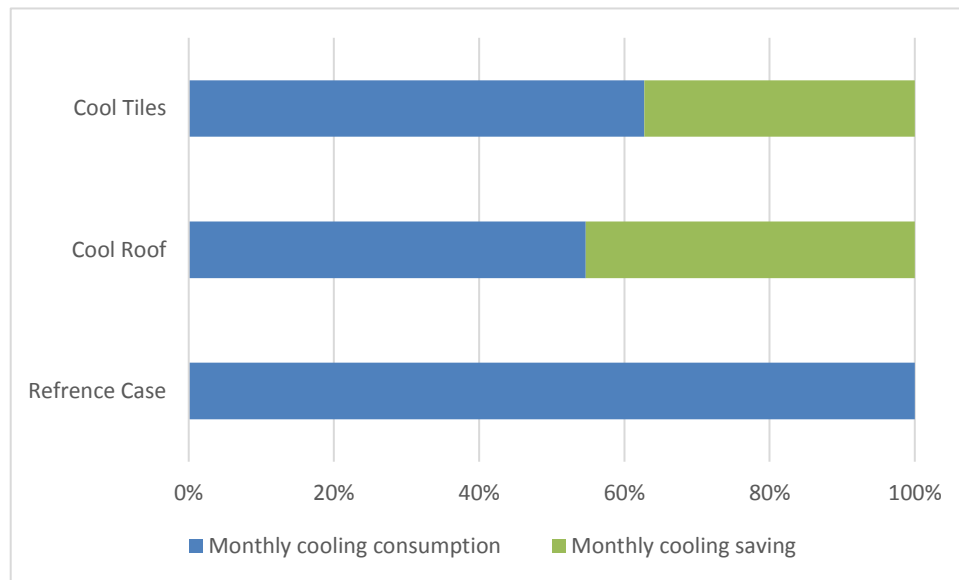


Figure 8. Average monthly cooling energy consumption and saving compared to reference case.

5. Conclusion

A POE study was conducted via recorded hygro-thermal measurements and questionnaire surveys to assess thermal comfort appreciations in 12 contemporary houses located in Biskra where a hot dry climate prevails. Furthermore, the paper discusses the energy saving achieved by applying passive cooling through rooftops since this technique represents an eco-sustainable measure to tackle high energy consumption and indoor thermal discomfort. In addition, cool roofs are relatively low-cost strategies and easy to install, either during the initial design and construction of the building, or when retrofitting. In this regard, by performing a dynamic numerical simulation, several roof composition solutions were investigated as tools to reduce heat gain. Besides, as households behavior is a key factor that can be targeted to help reduce energy consumption, the study investigated the satisfaction of the occupants regarding indoor thermal comfort conditions to provide orientations for improving building performance. Using interviews, the study also explores social acceptability toward implementing passive roofing techniques. Finally, the main findings of this study can be summarized as follows:

- According to physical measurement (objective assessment), the indoor thermal environment was above limits of the comfort zone; temperatures varied from 34.96°C

to 41.63% with high percentage of dissatisfaction; in the range of 89.3% to 100% during peak summer days.

- Subjective assessment (questionnaire survey) indicated that 54% of people as not satisfied toward indoor thermal comfort level for the whole day, consequently 76% operated air conditioner more than 10 hours per day complaining about the high energy bills. A strong linear relationship was identified between the measured data and thermal sensation votes. Physical variable like indoor relative humidity levels and air velocity were not as important as temperature regarding the occupant's perception.
- In-situ interviews reveal high acceptability rate to the application of cool roof and cool tiles on existing concrete roof. Technical viability and systems' affordability are the main factors affecting inhabitant's selection process.
- Through numerical simulation, cool roof using white reflective paint registered best reduction in term of indoor air temperature by an average of 4.14 °C with 56.67% of dissatisfaction percentage (PPD) compared to reference case (PPD=100%). Energy consumption has been decreased, by 613 kWh/m² for the hottest month of the year.

The outcome of this study reinforces the importance of designing efficient space through the adoption of passive cooling roof strategies in dwelling. The findings can assist building designers at implementing energy efficiency measures based on user-centric satisfaction.

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