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Contribution of compressed stabilized earth bricks (CSEB) to the control of indoor air quality in buildings: case study of Algeria

Fezzioui Naïma [1], Miloudi Yassine [1], Roulet Claude-Alain [2]

[1] Laboratory of Mechanical and structures L.M.S., Tahri Mohamed University Institute.
BT214, Bechar, Algeria
E-mail: naifez@gmail.com, miloudi.yacine@hotmail.fr

[2] École Polytechnique Fédérale de Lausanne
CH-1015 EPFL; City: Lausanne; Country: Switzerland
E-mail: claude.roulet@epfl.ch

Abstract. *The aim of this work is to examine the thermohydric behavior of a building made of compressed stabilized earth bricks (CSEB), by testing its effectiveness in stabilizing the quality of indoor air, compared to four conventional materials. The study is carried out using TRNSYS-COMIS software with its Buffer Storage Humidity Model for three types of climates: desert, Mediterranean, and dry and cold semi-arid climate. The results highlight the contribution of the CSEB material in regulating the indoor relative humidity of buildings, also in limiting the effects of condensation thanks to its adsorption effect.*

Keywords: Indoor air quality, condensation, compressed stabilized earth bricks, simulation, hygrothermal behavior.

1. Introduction

The transport of heat and moisture in building materials has a direct impact on air quality, mold development, temperature fluctuation and thermal comfort, and therefore on the reduction of energy consumption, in addition to their direct impact on the sustainability of the building [1-3]. The indoor air quality of buildings has itself a direct impact on the health of occupants and their thermal comfort; it is managed by certain parameters linked to habitable environments[4]. Humidity is an intrinsic parameter in buildings, and its excess can increase the prevalence of certain pathologies, and cause moisture condensation, mold growth, insulation failure and degradation of materials, etc [5]. Too dry air favors the irritation of mucous membranes. In addition, experimental studies on airborne-transmitted infectious bacteria and viruses [34] have shown that the survival or infectivity of these organisms is minimized by exposure to relative humidity between 40 and 70%.

Earth blocks and other naturally based hygroscopic materials have become a promising new way of achieving a sustainable and ecological building. Globally, about a third of the human population resides in earth shelters. In developing countries, this number is estimated at 50% [6]. According to several studies, the earth material has a good ability to regulate and stabilize internal humidity [7, 8] and thus contributes to the creation of a healthy and comfortable atmosphere in buildings. Some research has shown that unfired earth stabilizes the relative humidity of a house at 60% around the year [9], and that the absorption capacity of earth blocks can reach 10 times that of ordinary brick [10].

The disadvantage of the earth material dwells in its sensitivity to climate change which makes it relatively fragile. Compressed stabilized earth brick (CSEB) presents itself as one of the types of stabilized earth materials which aim to improve the mechanical performance of earth [11]. Several studies which have shown its resistance to compression, which can reach that of ordinary brick [12], and its good contribution to the regulation of internal humidity in buildings by comparing it to brick and to other common building materials [13]. Several studies have examined the hygroscopic behavior of earth brick: whether it is compressed and or stabilized by examining the effect of stabilizers which may constitute it and the influence of their percentage [14-16] or the effect of compaction [16]; but the majority of this research was carried out on the scale of the material or on the level of the wall [17, 18]. Indeed the type of stabilizer and its concentration modifies the microstructure of the material and thus causes a big change in its hygrothermal behavior [15]. Stabilization decreases the hygroscopic capacity of the earth [16, 17]. Some have experimentally examined the temperature and relative humidity in earthen material buildings [19-21]; but few studies have evaluated the quality of indoor air by measuring condensation and relative humidity in buildings made of CSEB.

The hygroscopic behavior of a material differs according to the nature of the climate, and according to the domestic activities and the behavior of the occupants [22]. The studies examining the effect on indoor air quality were mostly performed for humid climates. Very few have studied hygroscopic behavior in a hot and dry climate, and from our observations, even in a dry climate, a building can have risks of condensation in the absence of adequate ventilation, especially in winter and mid-season. Zhang et al [5] examined the behavior of a building in earth brick in the desert climate of the Turpan Prefecture in Northwest of China, assessing its relative humidity and indoor temperature. Therefore, the objective of this work is to examine the contribution of CSEB in the regulation of indoor relative humidity, and the generation of condensation, following the domestic activities, and depending on the contributions of the water vapor generated during the use of the building, by comparing it to other materials commonly used in construction, and this for three Mediterranean sub climates: mild Mediterranean climate, temperate climate, dry and cold semi-arid climate, desert climate and very desert hot climate.

2. Earth construction and climate

The effectiveness of earth material strongly depends on the climate, and in particular on the rain which is the first responsible for the degradation of earth building, especially if it is not stabilized [23]. During its history, Algeria has used raw earth for buildings since ancient times. The country experiences precipitation rates that encourage earth construction; it rains in the south a few days a year and in the north between 70 and 100 days a year [24].

Algeria presents a variety of climates which goes from the Mediterranean climate (Köppen classification Csa) to Tell and more exactly in the north of the country, to the desert climate (Köppen classification BWh) in the south, crossing the highlands with a semi-arid climate (Köppen classification BSk), and other inland cities whose climate varies from warm temperate climate, steppe climate, to a semi-arid Mediterranean climate. The desert climate itself is classified according to its aridity: Desert climate in the pre-Saharan zone, typically Saharan hot desert climate and Hyper-arid climate.

Ghedamsi et al [25] produced a map of climatic zones in Algeria based on the heating and cooling energy costs. Following this map, we selected five cities to test our hygroscopic behavior of the CSEB matrix: Oran (mild Mediterranean climate), Constantine (a temperate climate), Elbayadh (dry and cold semi-arid climate of the highlands), Bechar (desert climate), Naama (steppe climate) and Adrar (very hot desert climate).

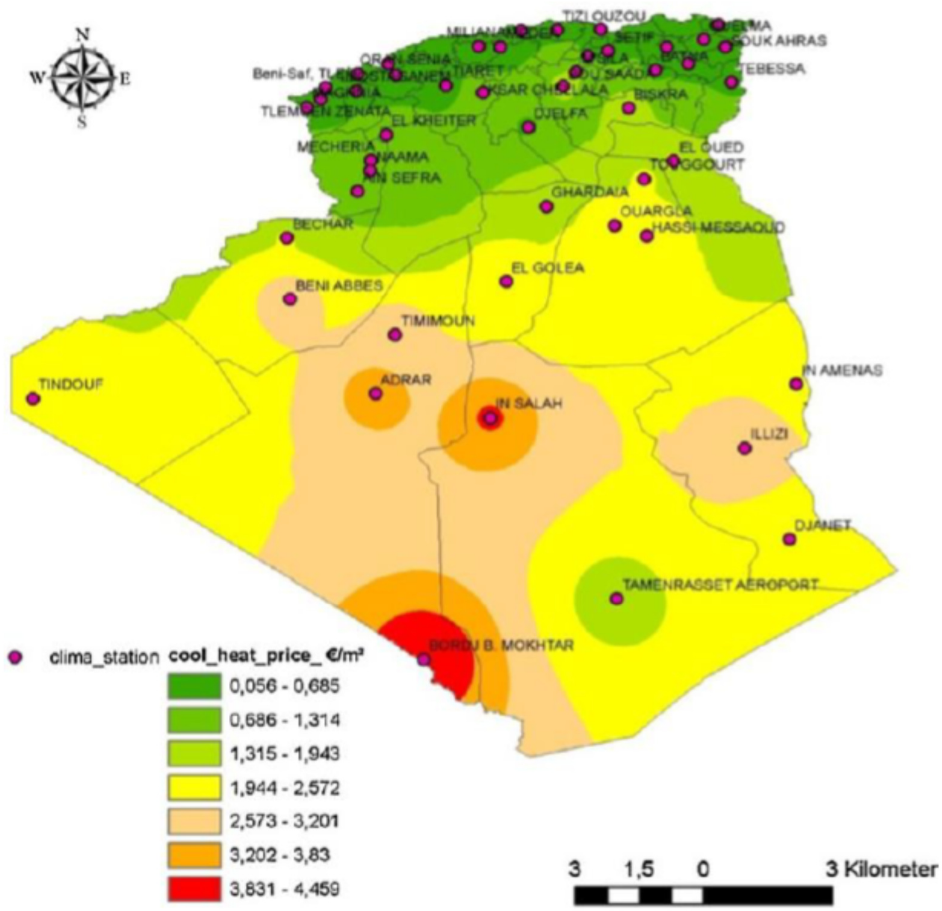

Fig. 1. Climatic zones in Algeria according to energy consumption costs [25]

3. Building Characteristics

The compressed stabilized earth bricks (CSEB) used in this work was thermally and hygroscopically characterized in the work of Miloudi et al [26] and mechanically in the work of Mahdad et al [27]. Table 1 describes the characteristics of this CSEB material. Our simulations are carried out on a two-storey building whose standard plan of one of these apartments is given in Figure 2. The different layers of the building envelope are defined from the outside to the inside of the area in the table 2.

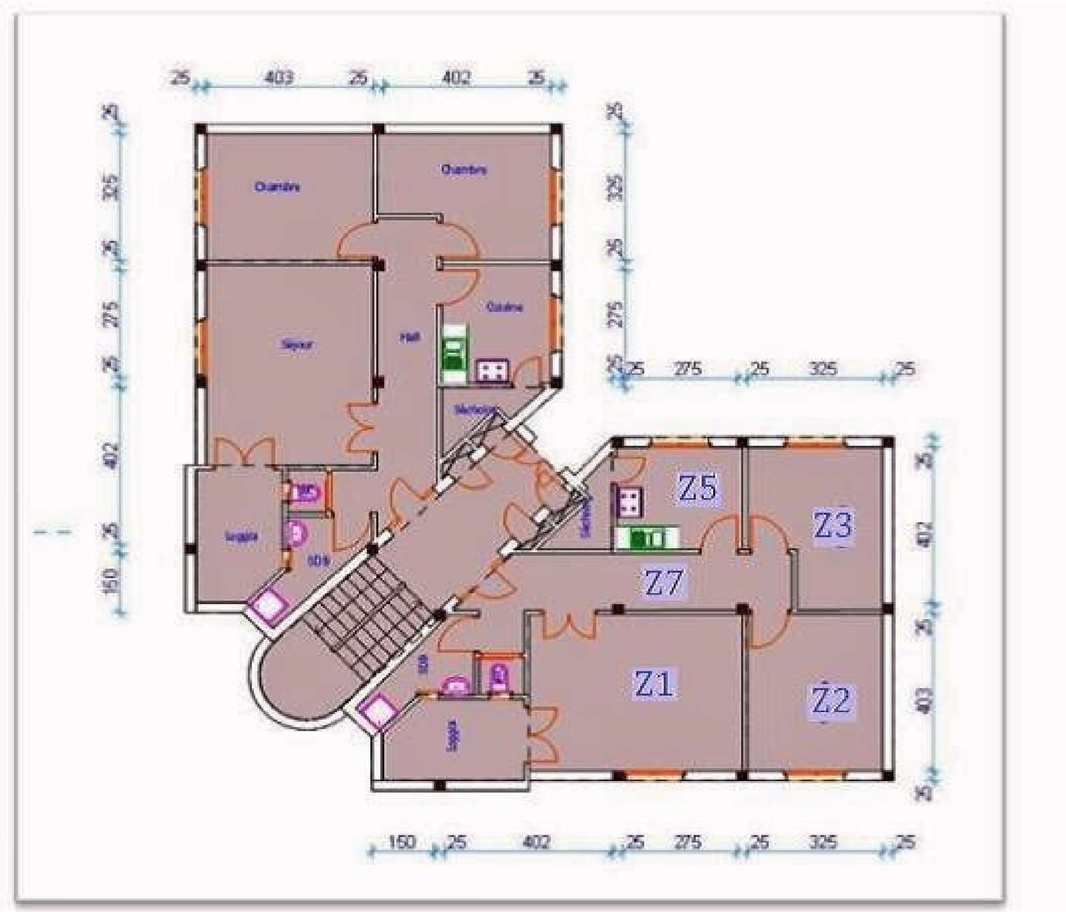

Fig.2. Standard floor plan of studied building

Table1

CSEB properties [26] [27]

Property	
Thermal conductivity [W/m°K]	0.75
Specific density [kg/m^3]	2125
Bulk density [kg/m^3]	2100
Specific heat [J/kg.K]	1054
Vapor permeability in air “δp” [kg/m².s.Pa]	1,175. 10^{-11}
Water vapor permeability “W” [kg/m².s.Pa]	5,9. 10^{-10}
Water vapour diffusion resistance factor “μ” [-]	17,03
Total porosity [%]	23%
Open porosity [%]	19%
Closed porosity [%]	4%
Resistance in compression (MPa)	7,1

Table 2

Composition of the building components

Designation	Material and thickness	U [W/ (m².K)]
External wall	CSEB 14 cm	2.804
Inner Walls	CSEB 12 cm	3.030
Low floor on ground	Tiling 2cm Cement mortar 2 cm Sand 1cm Reinforced concrete 4cm Stones 20cm	2.494
Middel floors	Tiling 2cm Cement mortar 2 cm Sand1 cm Reinforced concrete 4 cm Slab 16 cm Internal finishing 2 cm	1.846
Roof	Cement mortar 2 cm Slab 16 cm Reinforced concrete 4cm Watertight layer1 cm	2.102

The ground floor is in direct contact with the ground while the ceiling of the top floor is in contact with the outside atmosphere. The windows have a **PV**C frame with single glazing, their heat transfer coefficient U and solar factor are 5.75W / m²K and 75% respectively. The occupancy characteristics are assumed to be the same for each apartment, and they are managed by the building use scenarios as shown in the histograms 3-4, and in Table 3.

Table 3

Use schedule and Powers released by household appliances

<table>
<tr><th>Apparatus</th><th>Zone</th><th colspan="2">Use schedule</th><th>Power w</th></tr>
<tr><td>Refrigerator</td><td>Z5
(Cuisine)</td><td colspan="2">24/24</td><td>100</td></tr>
<tr><td>Television</td><td>Z1, Z4, Z3</td><td>In Winter:
Z1 :Occupied
Z3 :18h to23h
Z4 :21h to23h</td><td>In Summer:
Z1 : occupied
Z3 :9h to 12h&
18h to 24h
Z4 :14h to 17h &
21h to 23h</td><td>150</td></tr>
<tr><td>Computer</td><td>Z2, Z3</td><td>Z2 : 13h
to14h & 18h
to23h
Z3 :17h to 23h</td><td>Z2 : 10h to12h &
14h to 17h & 21h
to 24h</td><td>100</td></tr>
</table>

			Z3 : 9h to12h & 18h to 24	
Cooker	Z5 (Kitchen)	Occupied		550

We have assumed a mechanical exhaust ventilation for stale air at 15m³ /h for the bathroom and the toilets, these values are recommended by the document [28]. However, for the kitchen and the other rooms of the apartment, we assumed scenarios of door and window openings as indicated in the table 4. The aeraulic modeling of the building is carried out with TRNSYS / COMIS coupling through TYPE 157 which exchanges information between the two programs at each time step, in order to calculate the air flow exchanged between the zones and between zones and outside, from weather data transmitted to COMIS through TRNSYS.
The boundary conditions of the apartments on the ground floor and upstairs are identical.

Table 4

Scenarios openings of doors and windows

Period	Windows		Doors	
	Closed	Opened	Closed	Opened
Summer	10h – 18 h	18h – 7h	-	24h: de 7h to 18h at 100% and from 18h to 7h at 10%
Winter	10h to 09h	09h – 10h at 50%	18h – 10h	10h – 18h

The TRNSYS Buffer Storage Humidity Model [29] was used to calculate the moisture adsorption-desorption of building materials.

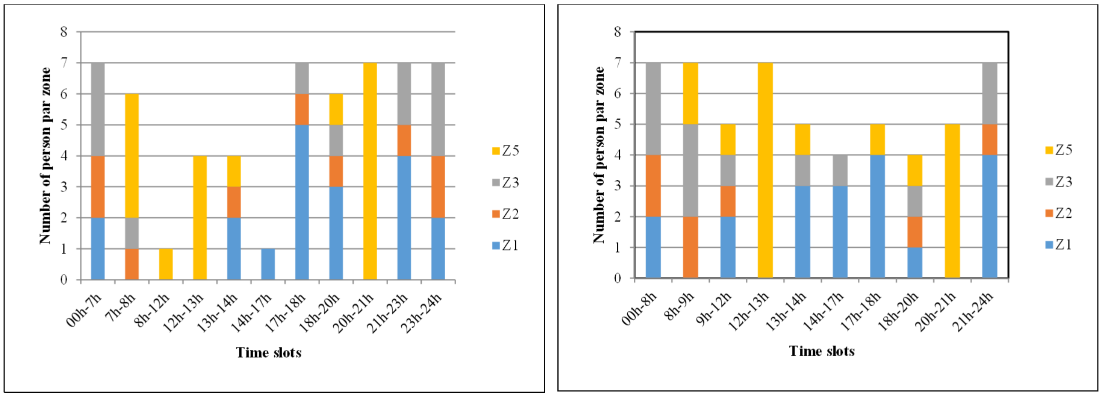

Fig. 3. Occupancy scenarios of the different zones in winter for the apartment (left during the week, right for the weekend)

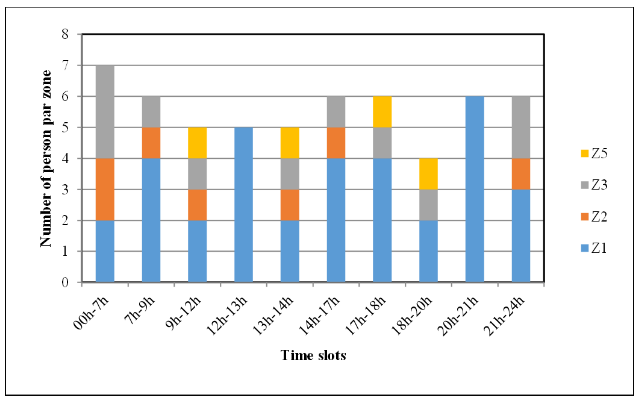

Fig. 4. Occupation scenarios of the different zones in summer for the apartment

Tables 4 and 5 give the values of the parameters of the Buffer Storage Humidity Model for CSEB materials and aerated concrete.

Table 5

Parameters of the buffer storage humidity model for a standard apartment in the building studied / CSEB case

zone	Surface Buffer Storage			Deep Buffer Storage		
	κ_{surf}	M_{surf}	β_{surf}	κ_{deep}	M_{deep}	β_{deep}
Z1	0.005	684	163	1	19	54.
Z2	0.005	500	119	1	14	40
Z3	0.005	625	149	1	15	50
Z5	0.005	420	100	1	9	33
Hall	0.005	400	95	1	143	31

Table 6

Parameters of the buffer storage humidity model for a standard apartment in the building studied / case Aerated concrete

zone	Surface Buffer Storage			Deep Buffer Storage		
	κ_{surf}	M_{surf}	β_{surf}	κ_{deep}	M_{deep}	β_{deep}
Z1	0.04	717.02	162.96	1	44.23	54.32
Z2	0.04	522.72	118.8	1	32.1	39.6
Z3	0.04	654.72	148.8	1	37.71	49.6
Z5	0.04	138.24	99.8	1	24.89	33.23
Hall	0.04	415.53	94.44	1	22.23	31.49

Table 7 describes the configurations used in this study. The composition of the floors is the same as that of the reference case (Table 3).

Table 7

Composition of the walls of each configuration

Configuration	External walls		Internal walls	
Plaster	Plaster 8 cm, aerated concrete 25 cm, Cement mortar 2cm	2.07 W/m²k	Plâtre 2 cm, aerated concrete 10 cm, Cement mortar 2cm	3.29 W/m²k
Aerated concrete	Aerated concrete 14 cm	3.70 W/m²k	Aerated concrete 12 cm	3.91 W/m²k
Brick	Cement mortar 2 cm, red brick 25 cm, Cement mortar 2cm	2.57 W/m²k	Cement mortar 2 cm, red brick 10 cm, Cement mortar 2cm	3.65 W/m²k
Concrete blocks	Cement mortar 2 cm, aerated concrete 25 cm, Cement mortar 2cm	2.57	Cement mortar 2 cm, aerated concrete 10 cm, Cement mortar 2cm	3.73 W/m²k

4. Results and discussion

Our analysis of the results is based on indoor air relative humidity as well as surface condensation as indicators of air quality. Condensation occurs when the water vapor pressure at a certain point reaches the corresponding saturation vapor pressure for the temperature at that point. It can be apparent (surface condensation) or hidden (internal condensation). Surface condensation can occur in the summer when a window is poorly sealed, allowing outside hot, humid air to enter the cool room, or in winter, when the thermal insulation of the building envelope, including its exterior walls, roof and windows, is insufficient, lowering the surface temperature inside the building [30].

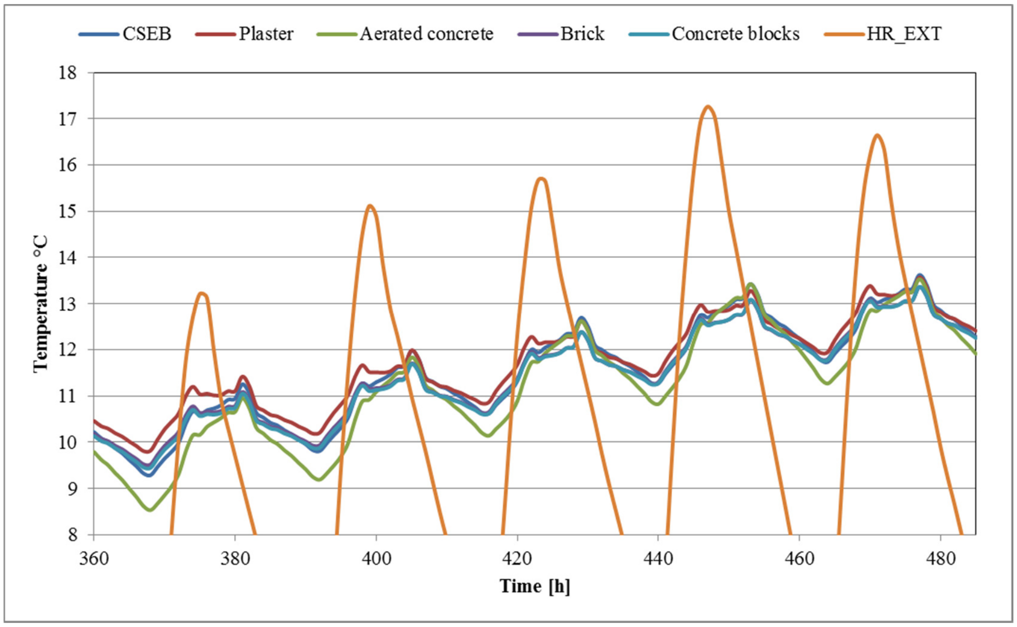

Fig.5. Temperature of zone Z1 of the apartment on the ground floor for the different materials tested during 5 days in January

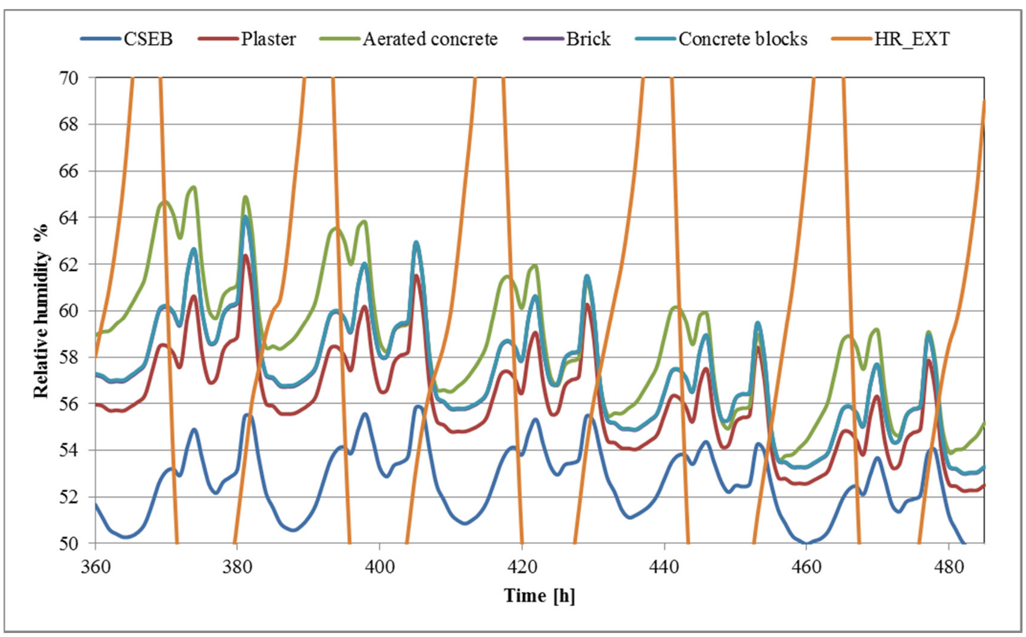

Fig. 6. Indoor relative humidity in zone Z1 of the ground floor apartment for the different materials tested during 5 days in January

Figures 5-8 compare the temperature and relative humidity in zone Z1 (living room) on the ground floor for the different materials tested, for five days in mid-July and five days in mid-January for the city of Bechar.

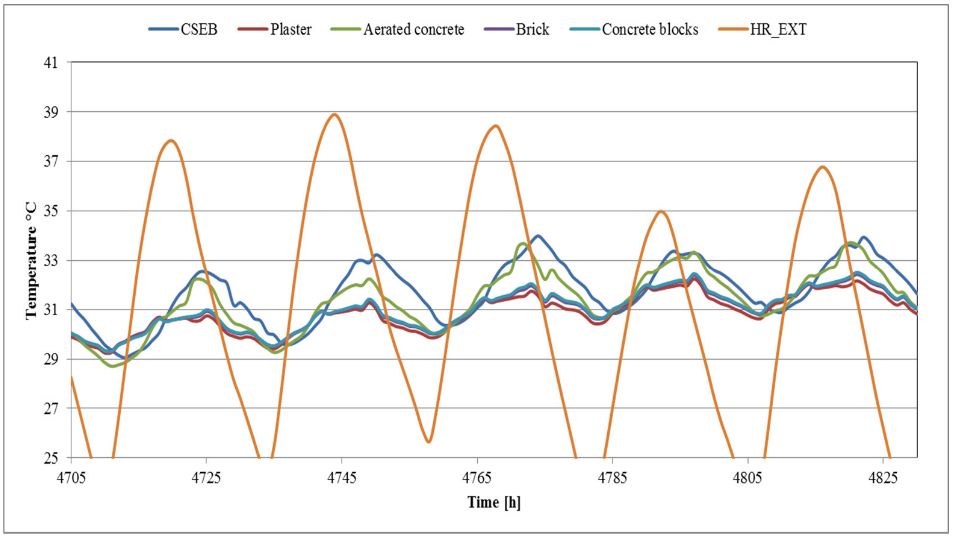

Fig.7. Interior temperature of zone Z1 of the ground floor apartment for the different materials tested during 5 days in July

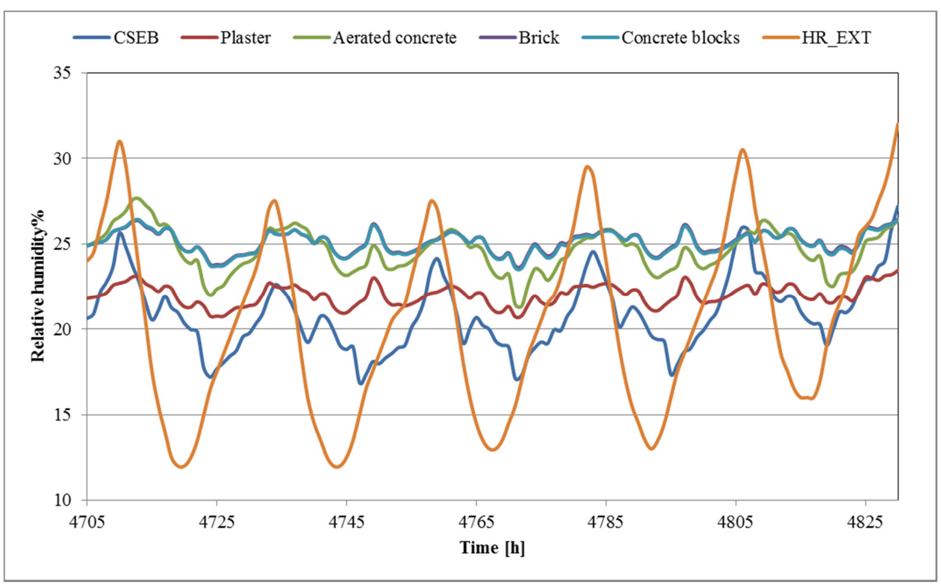

Fig.8. Indoor relative humidity in zone Z1 of the ground floor apartment for the different materials tested during 5 days in July

The effect of the humidity regulation by the CSEB material is well observed in the two figures. In fact, its curve is below all the others and varies with less amplitude in summer. This is due to its higher moisture sorption power [26].

The five configurations examined stabilize the temperature of the room and keep it lower than that of the outside during the hottest hours of the day. In the evenings, this temperature drops with a difference of 4°C compared to that during the day, without reaching the outside temperature which becomes lower in the evenings, which shows the insufficiency of the natural ventilation proposed. Differences of more than 6°C were observed between the night temperature of the room and that of the outside. The temperature with CSEB is higher than with the other materials tested. In addition, the relative humidity associated with CSEB in summer is the lowest, and varies with greater amplitude compared to other configurations. The behavior of the plaster wall is fairly close to that of brick and concrete block but with lower values. The humidity with aerated concrete evolves with a lower amplitude than that with CSEB, it sometimes reaches values higher than that of brick and concrete block but always remains higher than that with CSEB and plaster.

The annual total amount of condensing hours is shown in Figure 5.20 for the six climate zones and for both CSEB and aerated concrete.

Condensation occurs in winter, especially in December and between 5 a.m. and 7 a.m. It also occurs in the intermediate period for the cities of Oran, Constantine and Elbayadh. The risk is higher for the top floor because its roof is exposed to low temperature of outdoor air. The risk of condensation in Constantine is greatest, due to the relatively high humidity combined with very low temperatures in winter. Comes after that of the city of Oran which is less important even if the city presents a fairly humid climate in winter, but with milder temperatures. On the other hand, the probability of having this phenomenon in Adrar is almost zero, only 3 hours of condensation was observed for this city, in the kitchen on the first floor.

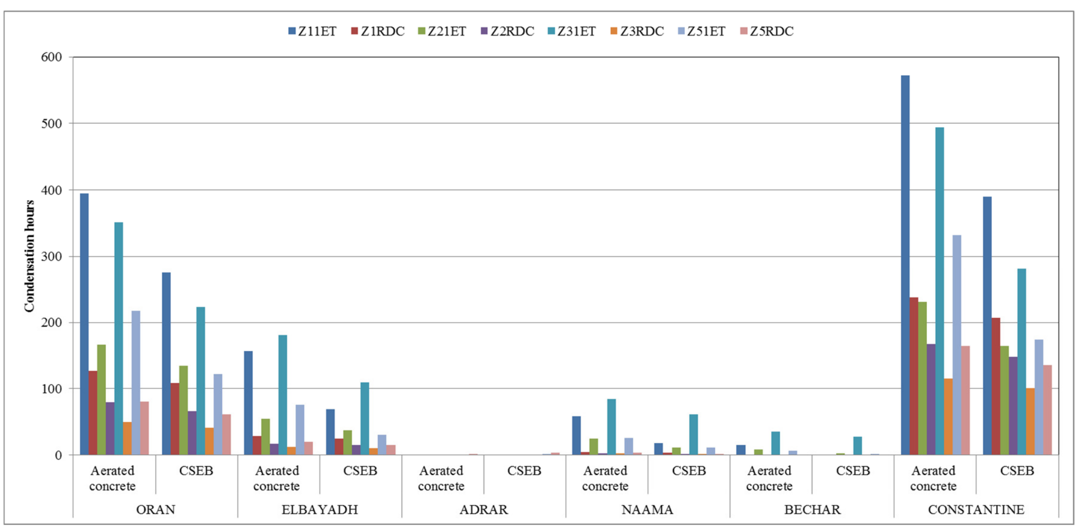

Fig.9. The total number of hours of condensation for CSEB and Aerated concrete in the different climatic zones

The top floor roof sees more hours of condensation compared to the other walls as shown in Figure 10, which gives an example of these percentages for the CSEB in Constantine. The western surface, even protected, sees more hours of condensation than the northern and southern surfaces (which is also protected). The main reason for this is that, as condensation usually occurs early in the morning [30], direct solar radiation first strikes surfaces facing north, below the horizon, after that towards the south and this reduces the number of hours of condensation with respect to surfaces facing west. The protected southern surface presents a greater risk of condensation than that of the unprotected eastern surface; and we can explain it by the solar radiation which can reach the east surface in the first place.

The CSEB presents satisfactory results in comparison with aerated concrete, especially for rooms on the top floor. For all the cities examined, it is the kitchen that is most sensitive to the integration of this material, except in Naama and Bechar where Z1 on the first floor was the most influenced. This can be explained by the less humid climate of these latter cities, where the humidity supply in the building is mainly based on the internal water supply (occupants and activity).

The impact of CSEB is significant in Constantine where differences of more than 200 hours have been determined between the two materials for zone Z3.

In Oran, the CSEB reduces the condensing hours by a percentage ranging from 15 to 24% for rooms on the ground floor and from 19 to 44% for rooms on the first floor. Nevertheless, for the city of Elbayadh, the reduction of these condensation hours varies between 32% to 60% in the 1st floor apartment, while its contribution for the areas of the ground floor is relatively poor with reduction percentages ranging from 6% to 22%. Unlike the cities of Constantine and Oran where the Z3 zone has seen a good reduction, in Elbayadh it is the Z1 which has the hours of condensation better reduced with a percentage of 56%.

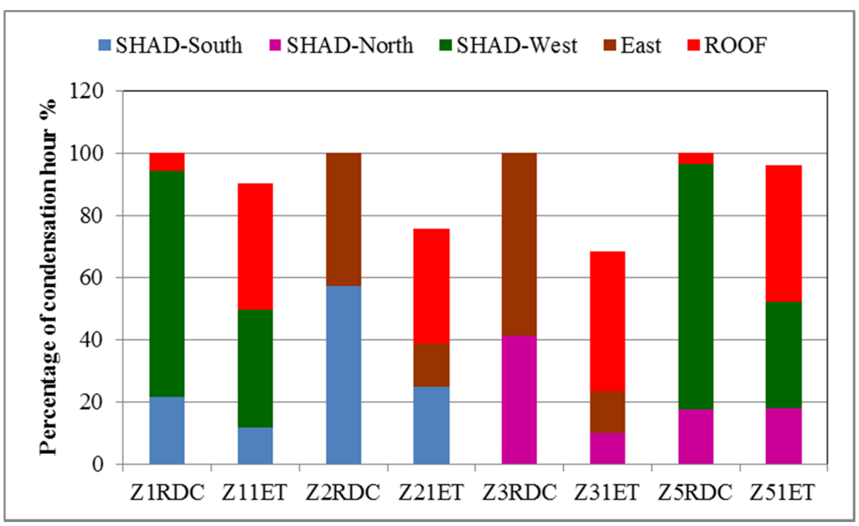

Fig.10. Percentage of occurrence of condensation on each orientation, for the BTCS, City of Constantine

Condensation on the interior surfaces of the enclosure occurs at 100% relative humidity which remains on these surfaces for periods of a few hours [31]. So for more information on the hydric behavior of the studied building, we show a distribution of the frequencies of occurrence of the indoor air relative humidity for the CSEB material and the aerated concrete (Concrete) for representative cities. The results obtained are shown in figure 11.

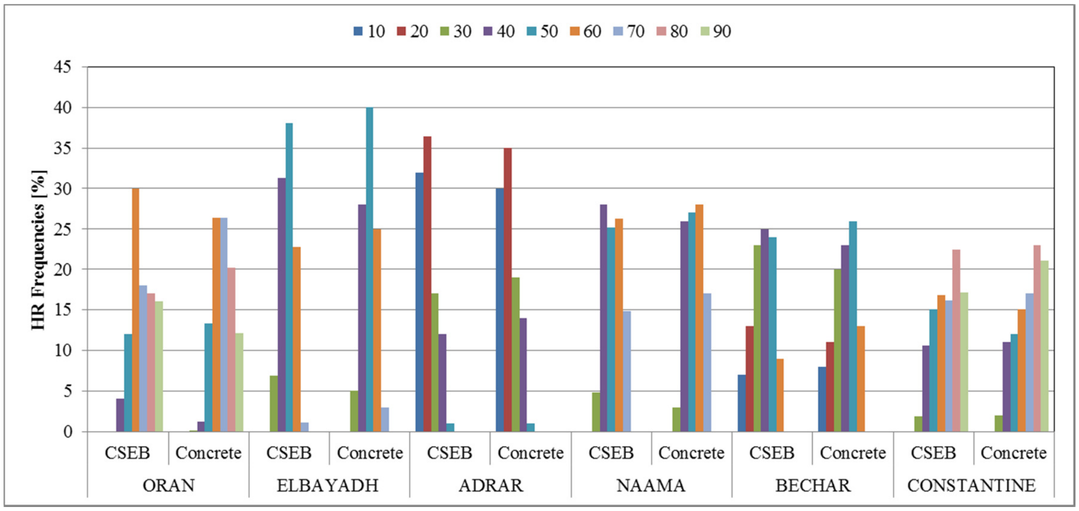

Fig.11. Occurrence frequencies of the relative humidity for CSEB and aerated concrete for six Algerian climatic zones

The difference between these frequencies is clearly visible. The CSEB generated lower relative humidity than those obtained for a aerated concrete. Cities with a dry climate are the least affected by the change in materials; however, for north cities the occurrence of high humidity is higher for aerated concrete than for CSEB. For Adrar the relative humidity does not exceed 40% in winter, however, and for more than 32% of the year it does not exceed 10%. These results illustrate the non-production of condensation in these homes because of the high aridity of its climate, in winter and in summer. For oran, the time of occurrence of RH 60% and 70% increases by 9% in comparison with the CSEB. For the city of Constantine, the time to produce 90% humidity increased with a difference of 4% for Concrete. Indeed, for the city of Béchar, a decrease in the times of humidity occurrence of 20, 30 and 40% was observed; on the other hand, a relatively slight increase in the times of occurrence of the humid 60% and 50% is illustrated.

The time during which the relative humidity exceeds 80% is estimated at 21% in Constantine and 13% in Oran, for aerated concrete against 17% and 16% for CSEB for the two cities respectively. Molds can develop if the local relative humidity is larger than 80% for a sufficient period of time (more than a week) [32].

These results show the aridity of the Saharan climate, in fact, the relative humidity is outside the optimal range, which is defined in [28] [33] and [34] to be between 40% to 60%, is more than 46% of time (estimated over one year) at Bechar and 86% at Adrar. Concerning Oran and Constantine cities, the indoor relative humidity is within this optimal interval 52% of the time in Oran and 42% in Constantine which shows that for the majority of the year, the buildings in these northern cities do not respect indoor air quality criteria. This is due to the amount of water vapor produced associated with the poor insulation of the walls, in addition to the low rate of air renewal by natural ventilation which must be regulated so as to better evacuate the stale air without lowering the internal temperature. At the contrary, the relative humidity is within the optimal range 93% over a year in Elbayadh and 78% in Namma.

6. Conclusions

The aim of this work is to examine the thermo-aero-hydric behavior of buildings in CSEB and therefore assess its contribution in the regulation of humidity and the reduction of the occurrence of condensation, by simulations using the TRNSYS software coupled with COMIS . Six Algerian cities representative of the six sub-climates were selected. The results highlight the contribution of the CSEB material in stabilising the indoor relative humidity of buildings, also in limiting the effects of condensation thanks to its adsorption effect.

The construction with the earth brick was very successful in hot and dry climate thanks to its creation of a thermally comfortable microclimate. However, the thickness of the brick CSEB chosen for these simulations (12 to 14 cm), reduces the comfort when compared to other building materials with larger thicknesses.

The phenomenon of condensation occurs in winter, caused in particular by internal water vapour production or insufficient ventilation for hot and dry climates like that of the city of Bchar. Its occurrence was for rooms on the top floors in contact with the exterior and which are close to humidity sources. However, the high aridity of the hyper-desert climate prevents the occurrence of condensation, even with poor ventilation.

The contribution of CSEB in reducing condensing hours also varies from one climate to another. For coastal cities with a humid and mild climate, the CSEB reduces these hours from 24% to 44%. However, for the cities of the high plateaus with a very cold and arid climate, the percentage was higher is around 32% to 60%. This can be justified by the very cold winters in these regions combined with internal water supplies and the absence of natural ventilation. The study also showed the importance attached to the combination of natural ventilation with hygroscopic material in improving the indoor air quality articularly as a result of domestic activities that generate more water vapour and humidity, which can harm not only the health of the occupants but also the durability of the building.

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