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Published in:
Construction and Building Materials

DOI (link to publication from Publisher):
10.1016/j.conbuildmat.2019.04.244

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Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
Makhlouf, N. N., Maskell, D., Marsh, A., Natarajan, S., Dabaieh, M., & Afify, M. M. (2019). Hygrothermal performance of vernacular stone in a desert climate. *Construction and Building Materials*, *216*, 687-696. https://doi.org/10.1016/j.conbuildmat.2019.04.244

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Hygrothermal Performance of Vernacular Stone in a Desert Climate

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ABSTRACT

Remote desert communities are often the most vulnerable to temperature extremes, as lack of access to reliable electricity prevents the use of active cooling or heating. Hence, there is a need to investigate how the building envelope itself can be used to passively regulate indoor environments. Readily available vernacular building materials in such areas are thought to aid in not only attenuating temperature swings but also moisture regulation, which improves comfort in a dry climate. Thus, the aim of this research is to investigate the hygrothermal properties of three different stone types commonly used as building materials in the Western Desert of Egypt: sandstone, limestone and, uniquely, Karshif, a rock rich in sodium chloride. The materials' thermal conductivity, moisture sorption and buffering, water vapour resistance, porosity distribution and phase composition are experimentally investigated. Our results show that the local perception of limestone buildings having poor indoor comfort, despite the material's superior thermal conductivity and specific heat capacity is only explainable through the relative superiority of sandstone and Karshif in moisture buffering. Vernacular materials need to be tested in environmental conditions representative of their local climate, rather than standardised conditions, as the latter may paint an incorrect picture of performance which, in the case of Karshif, led to partial dissolution under relative humidity of greater than 80%. However, testing under typical desert conditions demonstrates that both Karshif and sandstone are viable building materials that exhibit excellent moisture regulation behaviour. Since building materials in desert conditions may have to withstand atypical weather extremes, including rain, local materials need to be utilised within carefully designed wall assemblies or treated wall sections and, in the case of Karshif, not used in areas where relative humidity regularly reaches 80%. These findings are an important contribution in validating the performance of vernacular stone, and more widely, in demonstrating the importance of selecting appropriate testing conditions.

KEYWORDS

Hygroscopic, hygrothermal, Salt, Dynamic Vapour Sorption, sorption-desorption isotherm, Karshif, vernacular stone; Desert Architecture; Western Desert of Egypt

1 INTRODUCTION

Globally, the twin challenges of reducing energy use in buildings and improving the indoor environment have become core parts of both mandatory and voluntary design standards. It is well-known that heat and moisture transfer through the building's external envelope can have a passive effect in regulating the indoor environment and improving building energy efficiency [1]. Low carbon, natural materials – traditionally used for vernacular construction – often exhibit a greater ability to regulate the indoor environment, than modern conventional building materials [2]. In communities remote from the main urban conurbations, readily available vernacular building materials are therefore likely to be not only more suitable, but also a practical solution to ensuring good indoor thermal environments.

At the same time, there is growing concern around the long-term sustainability of modern building materials, which are often faster to build with and are perceived to be more durable, in remote communities. An unintended consequence of their use, arising from their poor thermal performance, is a rise in the installation and use of air-conditioners (see Figure 1). Their presence in a remote desert location, such as Siwa Oasis, is likely to exacerbate conditions if artificial conditioning becomes the primary means of obtaining thermal comfort. In fact, recent evidence of indoor surface temperatures crossing the contact pain threshold suggests that, in some instances, use of lightweight modern materials could result in extreme discomfort [3]. The rise in the use of modern materials also seems to have prompted changes in the use of vernacular materials. For example, in the Siwa region of Egypt, studied here, limestone walls are now built to 0.15m thickness[4] compared to the traditional thickness of 0.40m, which would provide greater thermal mass [5].

In remote desert areas, vernacular materials are thought to aid in not only attenuating temperature swings but also moisture regulation, which is crucial given the dry climate. This occurs due to the materials' inherent hygroscopic properties, i.e., the sorption and desorption of moisture from the environment in periods of high and low relative humidity respectively. This is commonly referred to as moisture buffering, and can be understood as a process of the material "adapting" to the surrounding environment [6]. Materials with high moisture buffering capacity contribute towards regulating comfortable indoor environments in extreme weather conditions, with high cooling demand [7]. Hence, there is a need to investigate how construction materials, and thereby the building envelope itself, can be used to passively regulate indoor environments.

Earth based construction is well-known for its moisture buffering ability [8, 9, 10]. One of the benefits of moisture transfer between earth walls in hot climates is that when indoor humidity decreases, the release of moisture content from the wall can work to passively cool the air due to the latent heat of evaporation [6]. Although this property of earth has been attributed to the presence of clay minerals, anecdotal evidence has suggested that some stones could demonstrate similar behaviour due to their porosity structure. However, the interaction between the temperature and moisture performance of these materials has not been studied, especially for hot dry climates.

Figure 1: AC units appear on building facades in Siwa Oasis (courtesy Mona El-Kabbany)

2 STUDY BACKGROUND AND AIM

Local stones – often sandstone or limestone – are commonly used as construction materials in many remote desert areas. In addition, Karshif, a building material unique to areas in the Western Desert of Egypt including Siwa Oasis [11], Gara Oasis [12], and Baharia Oasis, is also studied. Karshif is derived from the Miocene, Quaternary, and more recent salt lake deposits [11]. It is composed of salt (sodium chloride) with a salty mud impurities. Walls are usually built to a thickness of 0.3-0.6 m [4, 11] with a maximum thickness of about 0.8 m, providing high thermal mass.

All three studied materials, limestone, sandstone and Karshif are sourced from the Gara Oasis. The Gara Oasis is located to the north east of Siwa Oasis, at a distance of 120 km of direct off-road access. Siwa Oasis is centred at 29° 120 N and 25° 530 E, in the north western part of the Western Desert of Egypt. The region of Siwa Oasis, covering an area of 7800 km^2, was deemed as a “natural protectorate” in 2002, i.e. an area that requires special management and protection [13]. A unique feature of this area are the four distinctive natural saline lakes along with natural springs [11, 13, 14, 15]. The climate of the Siwa Oasis is classified as hot-arid, with short winters and long summers. Climatological data shows a monthly average maximum temperature of 31°C (Standard Deviation (SD) = 6.2) over the year, a monthly average minimum temperature of 17.3°C (SD = 7) [16], and average monthly relative humidity (RH) of 43.8% (SD = 7.1) [15]. Monthly maximum temperature could reach 38.8°C in July and August [15, 17], while being dry at average minimum RH around 33% in May. RH raise during winter period to reach 63% in January and December [17], while annual average RH is 45 % [15]. From January until June precipitation could reach 2mm. Evaporation ranges from 283 mm/month in July to 67 mm/month in December.

The aim of this study is to evaluate the mechanisms, and overall potential, of passive cooling of three types of stone used for construction in the Western Desert. This is achieved by characterising their material, thermal and hygroscopic properties and comparing with evidence of in-situ performance. Our objectives are to physically and chemically characterise the materials and establish the hygrothermal properties. These are demonstrated through investigations of thermal conductivity, moisture sorption isotherms, moisture buffering and water vapour resistance, under conditions representative of their intended desert environment.

3 MATERIALS

The three different stone types that are investigated are shown in Figure 2. Karshif can be defined as an evaporite stone [11]. It is an evaporite deposit typically composed of Sodium Chloride ($NaCl$) and secondary salt Potassium Chloride (KCl) with impurities of quartz, feldspar, calcite and clay minerals [14]. Therefore, it is known to be very sensitive towards excess water content, which could cause disintegration and deterioration.

Prior to testing, all specimen were cut into parallelepiped rectangular and uniform shapes in order to have flat surfaces. Specimen were left to dry in 80 ºC oven for at least one week, then left in a climate controlled room at 20±2 ºC and 50±2 %RH.

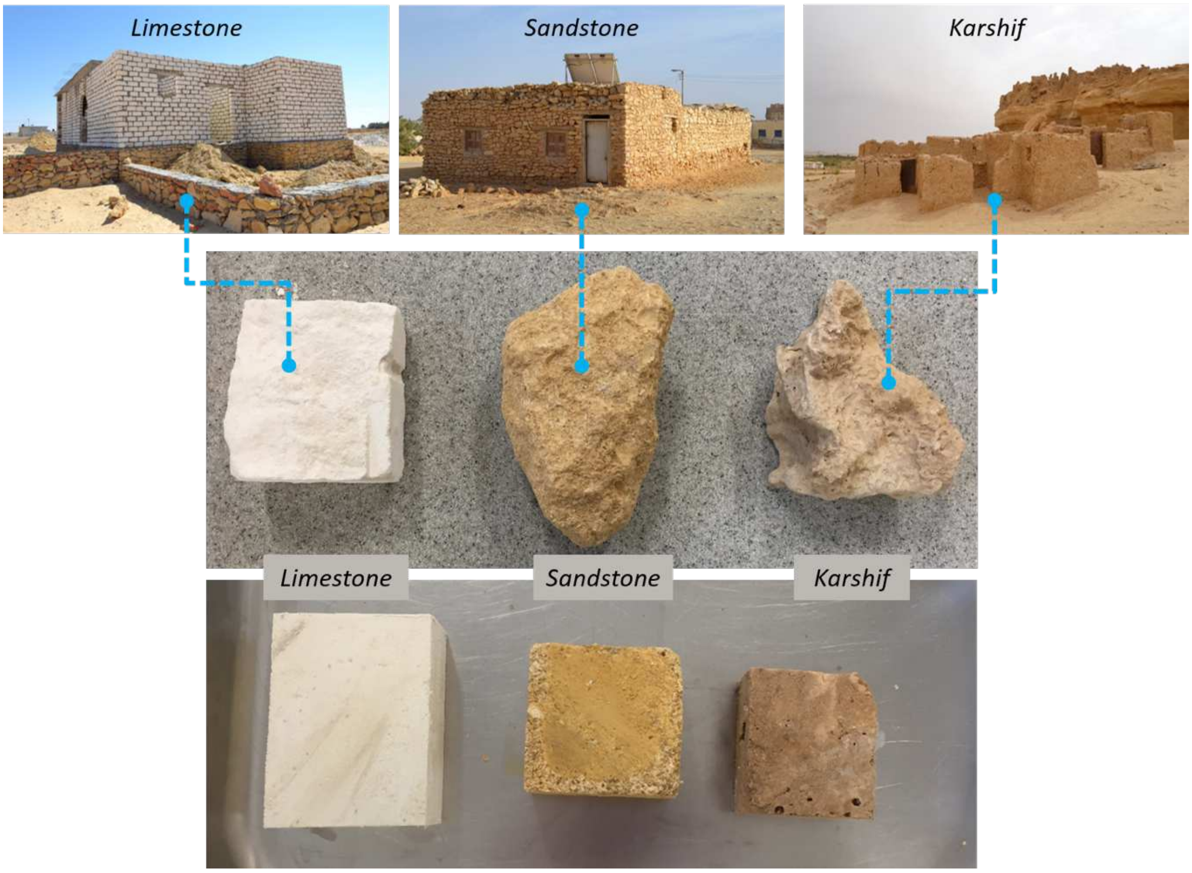

Figure 2: Illustration of the chosen building materials based on construction typologies in Gara Oasis (upper), Material samples before (middle) using water saw to cut into parallelepiped shape (lower)

4 METHODS

Each of the stone types were experimentally tested three times, to determine their phase assemblages, physical and hygrothermal properties, using the following methods.

4.1 Phase Characterisation

Powder X-ray diffraction (PXRD) analysis was used to identify phases with a Bruker D8 Advance instrument using monochromatic CuKα1 L3 (λ = 1.540598 Å) X-radiation and a Vantec superspeed detector. A step size of 0.023 °2θ and step duration of 0.2 seconds were used over a range of 5 – 80 °2θ. Phase identification was done using Bruker EVA software. Powder was produced by manually crushing samples using mortar and pestle, and was prepared for XRD by pressed glass slide method.

4.2 Physical Characterisation

Specific surface area was measured using the BET [18] method for nitrogen gas adsorption, with a Micromeritics 3flex Surface Characterization Analyzer. Three samples of each material were tested, with a sample mass of approximately 0.75±0.05 g. All samples were dried in a 105 °C oven for 24h, and then dried for a further 24h under a nitrogen atmosphere at 105°C in a degassing unit (Micrometrics FlowPrep 060).

An Autopore Mercury Porosimitry (PASCAL 440, Thermo Scientific) was used to determine the porosity size distribution and average pore diameter of the materials. Three samples of each material were tested. Before testing, samples were dried in 105°C oven for at least 24h until constant mass was achieved. Samples were tested in solid state, with a sample mass of approximately 0.6 g, at temperature of 21±2 ºC.

4.3 Hygrothermal Properties

4.3.1 Thermal properties

The thermal properties were measured using ISOMET 2114, a transient plane source device, and using a surface probe IPS 1105. A flat surface of at least 60mm diameter is satisfactory for the probe, with a minimum thickness of the material to be 20mm. Non-homogeneity and anisotropy were overcome through testing three specimens for each material and ten repeats of the thermal conductivity measurement (i.e. 90 readings in total). This method's validity for small samples has been previously verified [19]. Measures of thermal conductivity, λ (W/mK), thermal diffusivity (m^2/s), and volume heat capacity (J/m^3K) were obtained.

4.3.2 Dynamic Water Vapour Sorption (DVS) test

The study followed BS EN ISO 12571:2013, using the climatic chamber method. A Dynamic Vapour Sorption (DVS) machine was used to produce a continuous isotherm for the climatic chamber method on sample masses ranging 45-80 mg. In order to ensure materials had 0% moisture content at the beginning of a test, specimens were dried in an oven at 105 ºC until constant mass was recorded and then held for 360 min at 0% humidity at the set temperature. RH was set to increase from 0-95% and then back to 0% with 5% step change at a constant temperature. The step change is triggered when the gradient of mass change with respect to time (dm/dt) <0.002 wt.%/min. For each step, the moisture balance was considered to be reached if the change in mass did not raise more than 0.002% per minute.

To investigate the appropriateness of the ISO 12571 standard for observed environmental conditions of the region, the steady state temperature was varied. The objective was to determine the materials' performance with mean summer peak (38.8°C) through the hottest months in summer (July/August) and maximum summer peak that could reach 44°C, and to examine their response within). To allow for a comparison to the ISO standard, the full RH cycle (0-95%) was applied at 23°C and 38°Cfor the three materials. Additionally, to reflect realistic RH of the region each material was tested for RH 25-65% at 23°C, 38°C and 48°C over five cycles.

4.3.3 Water Vapour Resistance

BS EN ISO 12572:2016 was followed to determine water vapour resistance of the three materials. Both dry cup and wet cup methods were applied. Three samples of each material were tested. For the dry cup, silica gel was used to provide 0% RH. For the wet cup, a saturated salt solution using potassium nitrate (KNO_3) was used to provide 94% RH. All samples were left in a climate chamber at 23°C and 50% RH until constant mass change was achieved. Daily weight measurements were taken using OHAUS scale with readability up to 0.01g.

4.3.4 Moisture Buffering Value (MBV)

Following preparation, specimens were sealed on 5 faces using aluminium tape leaving one exposed surface. Due to the irregularity of the source rock, they were cut to provide the maximum possible surface area.

The standard NORD test [20] was used which exposed the materials for 8 hours at 75% RH and 16 hours 33% RH both at 23°C in an environmental chamber. A screen was placed around the mass balance to minimize the influence of air movement over the surface of the specimens during testing. An anemometer was used to measure wind speed at the specimen surface and was found to be an average of 0.1 m/s. All materials were weighed constantly on scales during testing. This method allows for the calculation of the Moisture buffering value (MBV) using the following equation (1):

$$MBV = \frac{\Delta m}{A.\Delta RH} \qquad (1)$$

While Δm is the difference as an average of the last four cycles between initial mass m_0 and maximum mass change m_8 at 8 hours in high RH, A is exposed area of the material and ΔRH is the difference in RH between high and low.

5 RESULTS

5.1 Phase characterisation

A distribution of the mineralogical composition was found throughout the material samples, as summarised in Table 1. At least two samples of each material were analysed, and so the consistency of each phase's presence has been stated for each material.
Among the phases present were those expected to have a weak or negligible influence on hygrothermal interactions, including silicas and carbonates. Quartz was also present in all samples, with a trace amount of cristobalite found in some of the Karshif samples. Calcium carbonates of some variety were present in all the materials, mostly calcite and dolomite.
Also found were phases expected to exert a strong influence on hygrothermal interactions: halite (NaCl salt), clay and sulfates. Halite was present to some extent in all samples, as expected of materials found from around the salt lake area. Calcium sulfates were present to some extent in all the material types except limestone. A range of hydration states were found, from dehydrated (anhydrite) to partially hydrated (calcium sulfate hydrate) to fully hydrated (gypsum). These observations are in broad agreement with Rovero et al. [14] who concluded Karshif to be an evaporite deposit composed of NaCl and secondary salt KCl with impurities of quartz, feldspar calcite and clay minerals.
A clay mineral was present in some of the Karshif and sandstone samples - given that a soil in this environment would be classified as an Aridisol, this clay mineral is likely to be kaolinite [22].

Table 1: Phase composition

Phase	**Formula**	**Karshif**	**Sandstone**	**Limestone**
Quartz	SiO_2	●	●	●
Cristobalite	SiO_2	◍	○	○
Dolomite	$CaMg(CO_3)_2$	●	●	○
Calcite	$CaCO_3$	●	○	●
Aragonite	$CaCO_3$	○	○	◍
Halite	NaCl	●	●	●
Anhydrite	$CaSO_4$	●	○	○
Calcium Sulphate Hydrate	$CaSO_4.0.67H_2O$	◍	◍	○
Gypsum	$CaSO_4.2H_2O$	◍	◍	○
Kaolinite	$Al_2Si_2O_5(OH)_4$	◍	◍	○

● = always found, ◍ = sometimes found, ○ = not found.

5.2 Physical Characterisation

Table 2 presents specific surface area and porosity results for BET and Mercury Intrusion Porosimetry (MIP) tests respectively. The three materials had a relatively small average specific surface area (1-3 m^2/g). However, Karshif had a larger average specific surface area than sandstone and limestone. This indicates that Karshif has the potential to adsorb a greater quantity of adsorptive (such as moisture) from the surrounding environment, compared to sandstone and limestone.

Regarding porosity, limestone had the highest (by skeletal density) amongst the three materials, followed by sandstone and then Karshif. Regarding pore size distribution, Karshif had a comparable pore surface area to limestone and sandstone, but a significantly lower average pore diameter. This would suggest that the size distribution of porosity in the Karshif tended towards smaller pores compared to those in the sandstone, and much smaller than those in limestone.

Table 2. Physical Properties

Analysis	Karshif	Sandstone	Limestone
Porosity (by skeletal density) (%)	21.29	27.10	31.70
Bulk density (g/cm^3)	1.97	1.82	1.71
Pore surface area (m^2/g)	4.66	4.71	3.47
Average pore diameter (nm)	74	172	335
Average specific surface area (m^2/g)	3.0	1.8	1.7

5.3 Hygrothermal Properties

The mean of all hygrothermal results are presented in Table 3. The coefficient of variation for the thermal conductivity and specific heat capacity were all less than 5% and the coefficient of variation for the water vapour resistance factor and moisture buffering value are presented in brackets.

Table 3 Mean Hygrothermal properties

Sample	Thermal Conductivity* (W/mK)	Specific heat capacity* (kJ/kgK)	Water vapour resistance factor - "Wet" cup (μ value)	Water vapour resistance factor - "Dry" cup (μ value)	Moisture Buffering Value (g/m^2 RH%)
Karshif	1.62	0.71	3.11 (13.8%)	15.77 (9.1%)	3.48 (12.3%)
Sandstone	1.11	0.75	13.81 (11.4%)	22.81 (13.7%)	3.00 (10.5%)
Limestone	0.70	0.82	6.20 (15.4%)	13.99 (5.1%)	2.30 (11.4%)

Coefficient of variation: <5% for columns with *; other columns as indicated in brackets.

5.3.1 Thermal Properties

Table 3 demonstrates that limestone had the lowest thermal conductivity and the highest specific heat capacity among the three materials tested. These correspond to high thermal resistance (hence heat or coolth loss) and high thermal mass respectively, both highly desirable thermal properties in building materials. Dabaieh et al. [12] also reported thermal conductivity of Karshif to range between 1.65 to 2.35 W/mK, which indicates the variability of performance of natural building materials, and the difficulties of considering thermal performance in isolation.

5.3.2 Dynamic Vapour Sorption (DVS)

The sorption and desorption of the different materials are presented in Figures 3 and 4. Karshif shows distinctly different behaviour compared to sandstone and limestone, with respect to both adsorption and desorption. It continues to increase in mass weight even after RH drops down, with mutually consistent results at both 23°C and 38°C.

The maximum change in mass for both sandstone and limestone is 2.6 % but Karshif, adsorbs 80% and 150% at 23°C and 38°C respectively. In addition, Karshif sorption isotherm (Figure 3) indicates a large hysteresis area between 55-95% RH, while limestone and sandstone (Figure 4) show very limited hysteresis within this same range. Pictures obtained from the built-in camera on the DVS demonstrate that a drop of water developed on top of the Karshif sample until reaching a dissolution point at around 75-78% RH, after which dissolution occurred (Figure 5). This leads to an atypical desorption curve as the liquid water remains present on the scales.

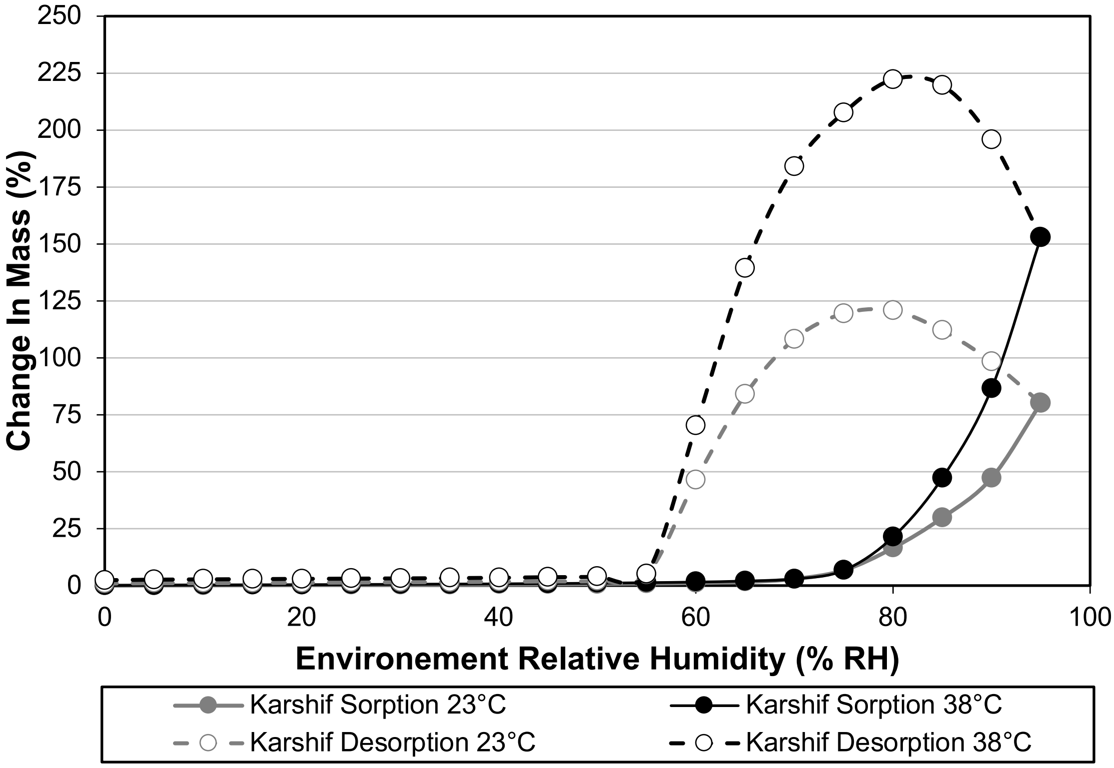

Figure 3: Combined moisture sorption isotherm for Karshif, 0 -95% RH at 23°C & 38°C

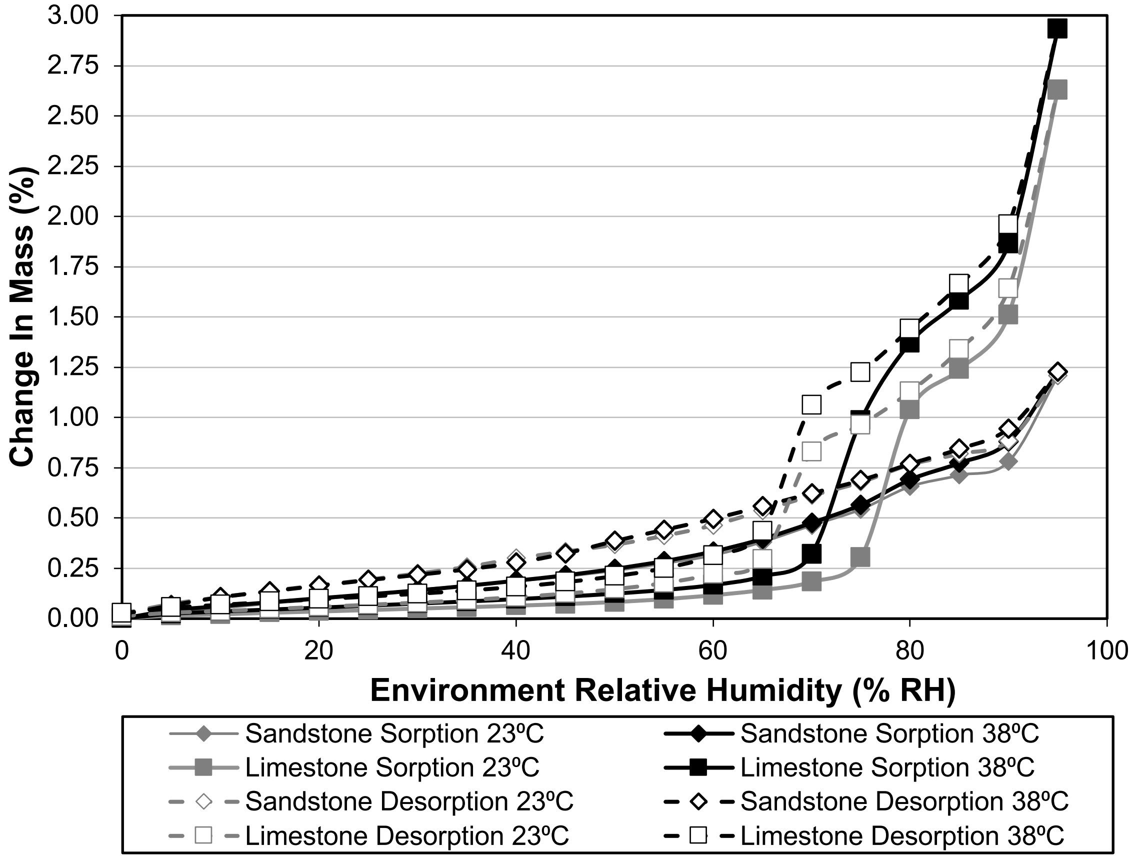

Figure 4: Combined moisture sorption isotherm for Sandstone and Limestone, 0 -95% RH at 23°C & 38°C

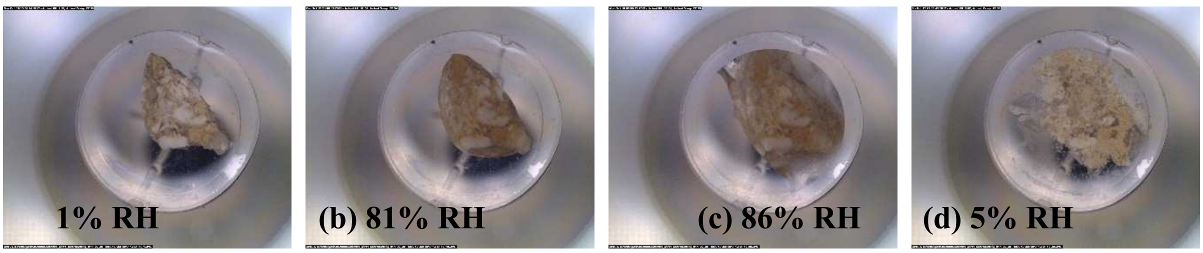

Figure 5: Period recorded pictures for Karshif sample using DVS built-in camera for full cycle test 0-95% RH at 23ºC. (a) Start of sorption test at 1% RH Sample is dry. (b) A drop of water on top of a sample at 81% RH. (c) Material dissolved in water at 86% RH. (d) Dry sand/clay left after desorption at 5%

5.3.3 Water Vapour Resistance

The "wet" and "dry" cup water vapour transmission are presented in Table 4. During "wet" cup testing for the Karshif sample, a crystalline growth was observed (Figure 7). This is comparable to the observations from the DVS, where at high RH (as with the wet cup) the material dissolves, allowing crystal regrowth at the material surface when the environmental RH returns to 50%.

Sandstone shows high vapour resistance factor at both dry and wet cup tests. Karshif shows the least water vapour resistance factor in wet cup test. Accordingly, moisture can easily penetrate into the material in a high humidity environment. Due to its phase composition, water is held in its cavities causing partial dissolution of the material if high humidity persists, and then acts to humidify the surrounding dry atmosphere when RH drops.

Figure 6: Images of Karshif when: salt forms around the seal during wet cup test (left) and the inner exposed surface is at the point of dissolution causing a muddy appearance (right).

6 Analysis and Discussion

The results have indicated the varying characteristics and hygrothermal properties for different vernacular building materials. Al-Taweel [5] and Petruccioli & Montalbano [23], both comment on the improved thermal comfort of Karshif buildings in the Siwa region. In contrast, our results (Table 5) indicate that buildings built with Karshif should perform the worse thermally than sandstone and limestone constructions, indicating that other material factors may play a significant role. The hygrothermal performance is dependent on the mineralogical composition, as well as the physical properties. The unique characteristics of the Karshif vapour sorption led to further analyses into real world performance below.

6.1 Effect of physio-chemical composition on hygrothermal performance

The phases of most interest in these materials are those which are likely to have strong interactions with moisture. This is either due to their ability to undergo a dissolution/precipitation process (halite), a hydration/dehydration process (calcium sulphates) or having a large charged specific surface area (clay).

Previous investigation of the geological formation immediately around the Gara Oasis have found limestone to contain both kaolinite and gypsum [24] The co-existence of halite with calcium sulphate phases in various states of hydration is of particular interest, given that dehydration transformations in calcium sulphates are facilitated by the presence of salt water [25]. From the different mineralogical constituents (Table 1), it is observed that Karshif and Sandstone contain halite (NaCl salt), calcium sulphates and clay, whereas limestone does not. At the same time, these stones have a significantly higher moisture buffering value. As identified in Figure 3, Karshif quickly increases in mass at 70-75% RH and a thin layer of liquid (assumed to be saturated salt solution) condenses around the sample and causes dissolution of the halite within the stone. The continuous increase in mass for Karshif even after RH decreases is due to the condensation of water onto the samples, effectively making a salt solution. Saturation humidity for sodium chloride is 76% [26] which is comparable to the humidity when Karshif sample starts to dissolve. The impact of the dissolution of halite has been observed within the moisture sorption curves (Figure 3) as well as the "wet" cup test

(Table 6). Whereas the "dry" cup test and moisture buffering test never expose the material to relative humidities significant for dissolution.

Both the thermal and moisture sorption relate to the physical and chemical characteristics of the material. There is a correlation between the bulk density and pore size with the thermal conductivity and specific heat capacity. However, none of these materials provide significant resistance to thermal transmission and have almost similar specific heat capacity. Given the dry environment of a desert, moisture buffering properties are an important factor to provide indoor thermal comfort as this allows the regulation of humidity levels in the indoor environment when humidity is low.

Limestone seems to have the best thermal properties among the three materials, attributed to its higher porosity and larger pore diameter. These porous characteristics of the limestone help not only to provide better insulative properties but also higher moisture sorption characteristics and lower vapour resistance compared to sandstone and Karshif when only considering the "dry" cup test. Although limestone has the better thermal properties of the three materials, the performance is not that significant when considering the multiple criteria of a material's role in regulating the indoor environment [27], specifically the role moisture sorption and buffering can have on the thermal performance and comfort.

6.2 Development of appropriate sorption isotherm for context

Various adsorption isotherm typologies were identified by Sing et al. [28], which have since been used to analyse the adsorption of water vapour for a variety of materials [29, 30, 31]. Given the range of partial pressures used in these tests, it was not possible to state the isotherm type with confidence. However, comparison of certain features in these isotherms (Figure 3 and 4) with those of the established typologies can be used to interpret the materials' behaviours. Limestone's sorption isotherm showed very little hysteresis on desorption, which is typical for non-porous or macroporous materials. This suggests that limestone exhibited neither a large extent of mesoporosity, nor a strong adsorbent-adsorbate interaction. Consequently, limestone was able to release all the adsorbed moisture content back to the surrounding environment. Sandstone demonstrated a small extent of hysteresis, which indicates a greater extent of mesoporosity, and/or an adsorbent-adsorbate interaction, compared to limestone. This interpretation is supported by the smaller average pore diameter (Table 2) and wider prevalence of moisture-interacting phases (Table 1) in sandstone compared to limestone. Karshif demonstrated a very strong hysteresis effect. This was largely attributed to the moisture's interaction with halite, as material dissolution was visibly observed (Figure 5). A higher extent of mesoporosity (Table 2) and presence of other moisture-interacting phases (Table 1) could also have contributed to this.

The phenomenon of dissolution of these materials is not commonly observed in the buildings in the Gara Oasis, unless for Karshif at atypical devastating heavy rain occasions, like what have been observed in 1928, 1930, 1970, 1982 [32], and in 1985 [5] in Siwa Oasis and during 1980's in Gara Oasis [33]. This could indicate that this testing approach is not appropriate for the true typical moisture sorption-desorption isotherm behaviour, as the desorption curve is impacted by the presence of a salt solution that would not typically be observed. The typical tested conditions, following ISO 12571:2013, of the vapour sorption (0-95%) and desorption isotherm (23 °C) do not represent the conditions observed in the Gara Oasis where these materials are used. Cycling between 0 and 95% RH has also shown to produce abnormal desorption patterns that would not be typically induced. Therefore, a development of the standard vapour sorption testing is required to represent local conditions. The three materials have been exposed to five repeated cycles of 25-65% RH at 23 °C, 38 °C, 48 °C as represented in Figure 7, 8 and 9 respectively. This allows for a greater understanding of the material's performance under real conditions, which is not achieved when testing solely at 23 °C.

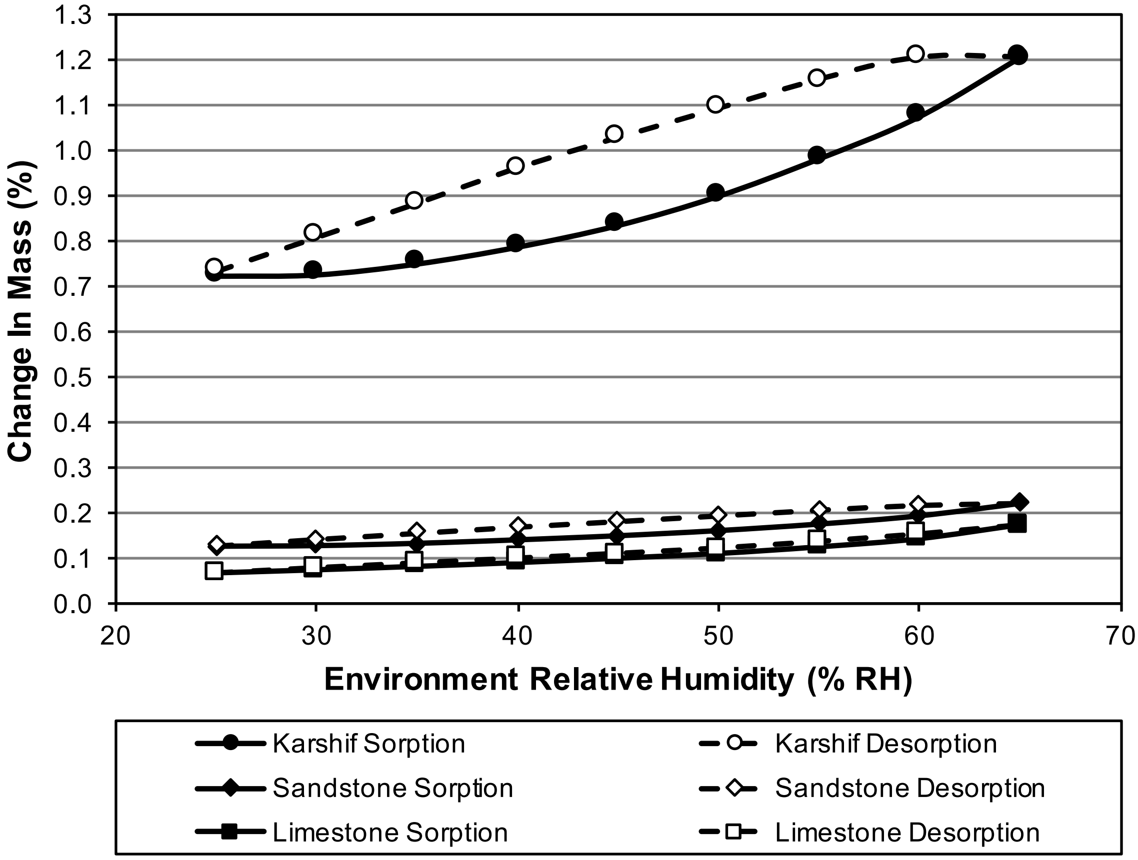

Figure 7: Final cycle of moisture sorption isotherm between 25-65% RH at 23°C

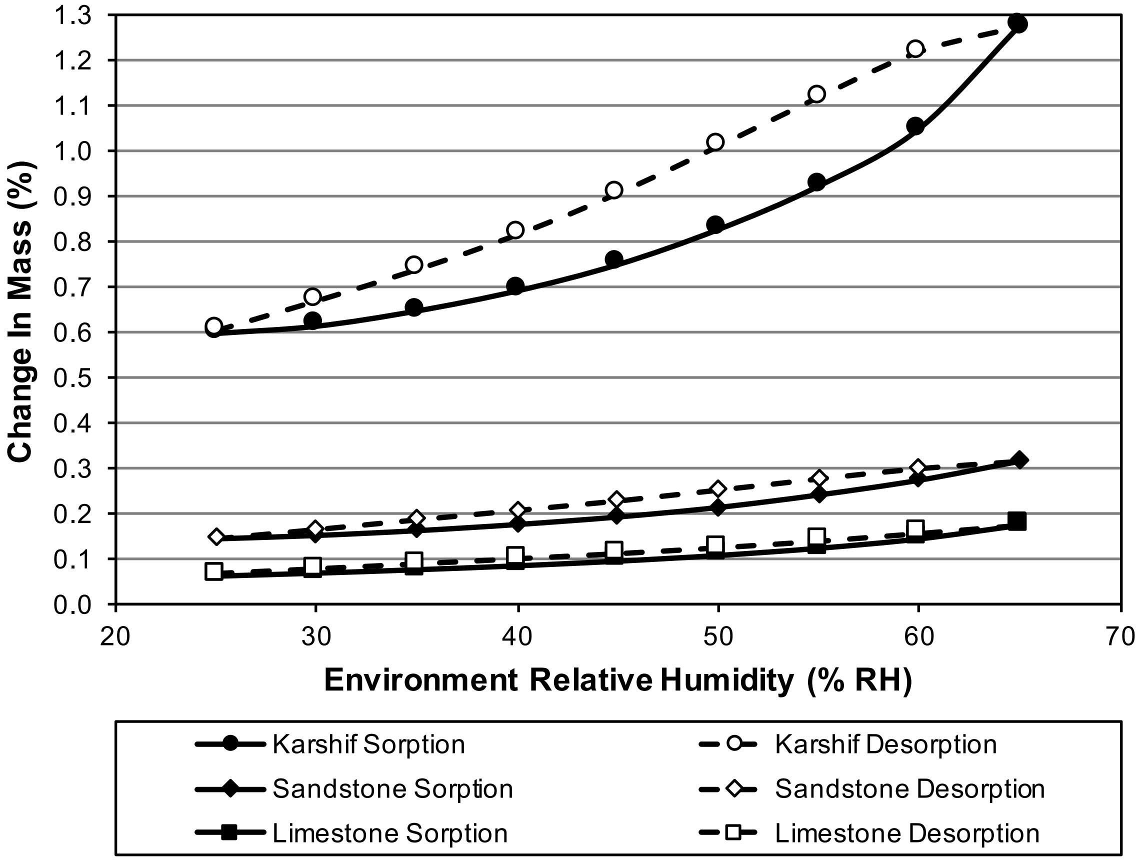

Figure 8: Final cycle of moisture sorption isotherm between 25-65% RH at 38ºC

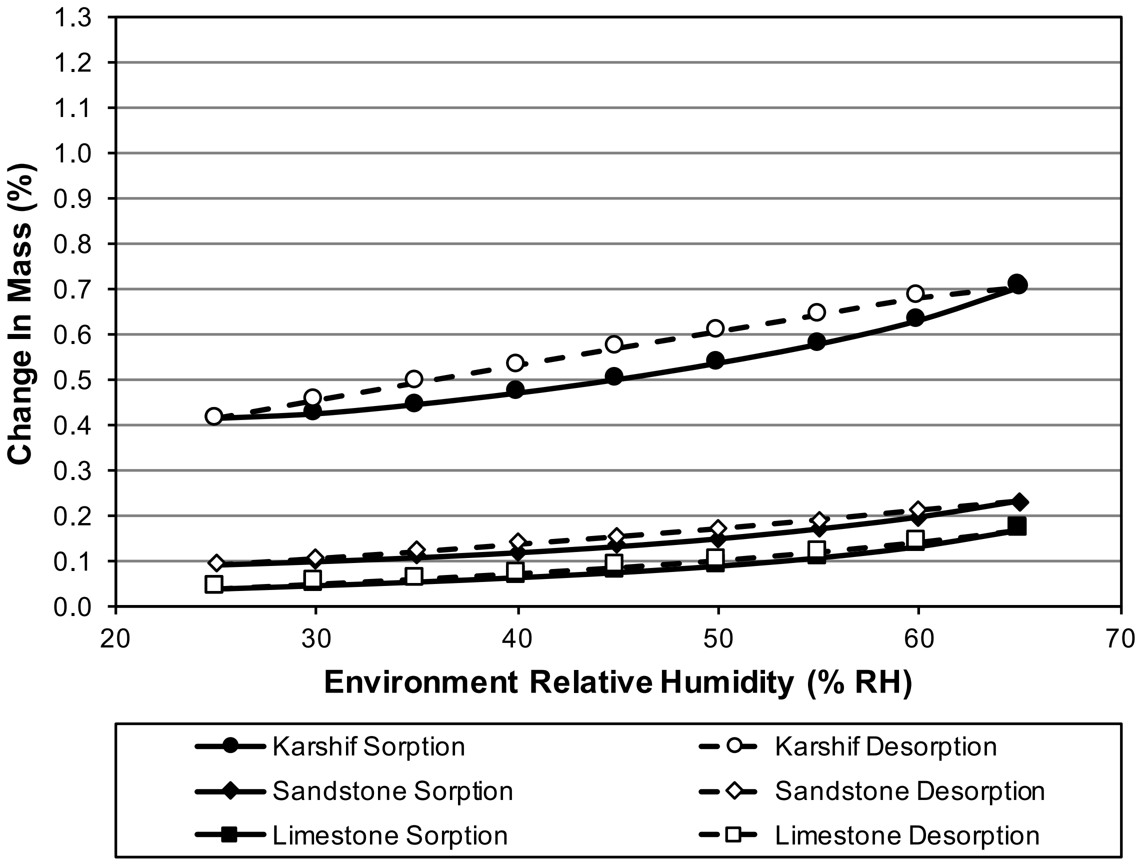

Figure 9: Final cycle of moisture sorption isotherm between 25-65% RH at 48ºC

The change in the environmental temperature fundamentally allows for varying absolute mass of moisture to be stored in the air. Therefore, a consistent RH for varying temperatures does not result in isobaric conditions. In addition to a differing partial pressure, varying temperature may affect each material differently, in some cases resulting in structural changes and reactions (such as salt dissolution) to occur at different temperatures. This will have the impact of changing the amount of moisture a material can hold. Variation in adsorption capacity is observed in Figure 3 and 4 for the full cycle and Figure 7, 8 and 9 for the reduced cycle. The change in sorption capacity at 25% and 65% RH can be observed from Figure 10.

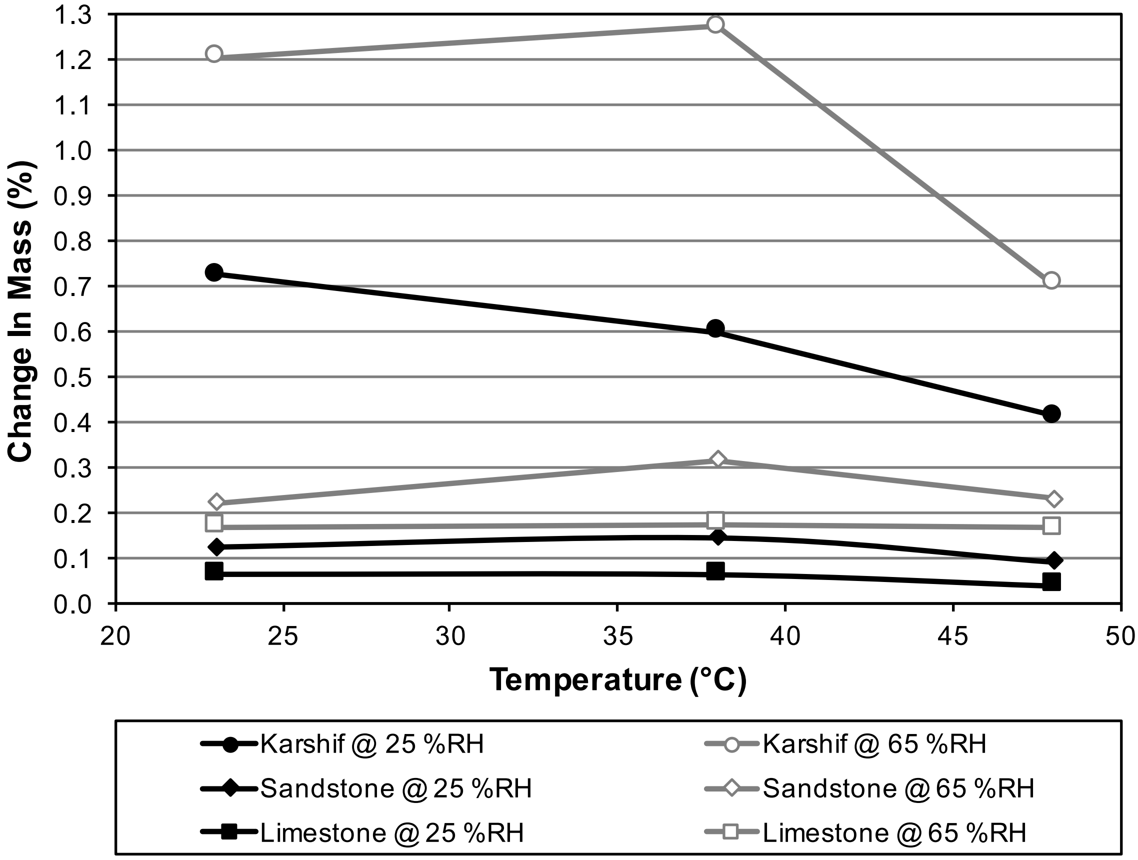

Figure 10: Impact of temperature on moisture sorption at 25% and 65% RH

For each of the materials the change in temperature results in a change in mass. However, for Limestone, there is a seemingly negligible difference with increasing temperature, but the difference between the change in mass from 23°C to 48°C represents a 36% drop in sorption capacity. This decrease in capacity over this range is observed for all of the materials with the exception of sandstone, but is most pronounced with the Karshif material where there is a 43% reduction. Over this range, it can be observed that there is no consistent trend in sorption capacity, with some materials absorbing the most moisture at 38 °C. This suggests the need to consider different environmental conditions during testing to allow for accurate design, and to account for the complex nature of differing materials' hygrothermal regulation performance.

7 CONCLUSIONS

This study has investigated the physical and chemical properties of three common vernacular building stones. These include sandstone and limestone, common to desert regions in many parts of the world, and Karshif, which is unique to the Siwa Oasis at the Western Desert of Egypt.

In contrast to the local understanding of limestone, which suggests that it is unsuited to buildings because of its poor thermal properties, it is shown that limestone has better thermal properties than both sandstone and Karshif, but limited hygric properties. This finding may explain the local experience of limestone as providing less thermal comfort than the other two stones, due to its lower capacity for moisture regulation.

Karshif's sensitivity towards moisture has been attributed to its high salt content. Indeed, under extreme conditions of high humidity, this material undergoes partial dissolution. However, testing under the hot and dry conditions normally found in the region of Siwa Oasis, it is demonstrated that it is a viable building material that exhibits good moisture regulation behavior. Similar behavior is also observed for the third tested material, sandstone. Hence, our results support the use of sandstone and Karshif for moisture buffering in buildings.

Rain in dry desert areas is a source for ground water and crop irrigation, but is also an agent of building deterioration. Hence, building materials within this region have to withstand these atypical extreme weather events. Therefore, local materials need to be utilised within carefully designed wall assemblies or treated wall sections and, in the case of Karshif, not used in areas where RH regularly reaches 80%. Without this, there is a risk of a shift towards concrete or other modern materials which, though durable, carry heavy negative environmental impacts.

Methodologically, it is shown that the use of standardised testing conditions for vernacular materials may paint an incorrect picture of their true performance. For example, it was observed the partial dissolution of Karshif at regionally atypical relative humidities, and even a variation in performance under non-isothermal and non-isobaric conditions. However, a much clearer picture of true performance was obtained under test conditions typical of the regions from which the material was sourced. Hence, it is suggested that the environmental performance of vernacular materials is tested within the environmental context they are likely to experience under true conditions, rather than adopting standard conditions which may be atypical in use.

Overall, the importance of considering the moisture properties of building materials in addition to their thermal properties is clearly demonstrated. In fact, the only explanation for the local perception of limestone as a building material that produces lower internal comfort – despite its superior thermal properties to both sandstone and Karshif – is through our demonstration of the latter materials' superior hygric properties. Hence, differences in moisture sorption behaviour have the potential to impact the indoor environment and the energy use of buildings. It is therefore critical for designers to understand the impact that the choice of materials has on the comfort of occupants and building energy performance.

8 ACKNOWLEDGEMENTS

This research is supported by Newton-Mosharafa Fund under PhD joint supervision scheme and EPSRC Centre for Decarbonisation of the Built Environment (dCarb) [grant number EP/L016869/1]. Authors are thankful for the cooperation of lab technicians at Bath University. Thanks to Ms Shaghayegh Mohammad for her support in recording final data.

Also thanks should go to local community of Gara Oasis, particularly Mr Soliman Mohamed, who facilitated the transportation of materials from this remote area.

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