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Analysis of evapotranspiration processes in the Sassi of Matera (southern Italy)

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Abstract

The Sassi of Matera (Basilicata region, southern Italy), inhabited since the Paleolithic period, has become an important tourist attraction in recent years. This interest has led to remarkable restoration of homes excavated in the tufaceous rock and suffering from severe moisture problems. To improve indoor hygiene conditions, the best way is to install HVAC systems. However, designing these systems must take into account the water coming from the walls. The awareness of the amount of water released into the environment due to evapotranspiration could be of great help in dimensioning the HVAC system. This paper illustrates the first results of a numerical analysis of the interaction between the mass of wet tuff and the internal environment of rock-clad dwellings.

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Keywords: The Sassi of Matera, historic buildings, recovery

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1. Introduction

The territory of Matera (Basilicata region, southern Italy) has been inhabited since the Paleolithic period and the earliest settlements, otherwise known as Sasso Caveoso and Sasso Barisano, were edified between two *grabiglioni*. The dwellings consisted of simple caves enclosed by a wall of excavated tuff blocks. Indoor environments were vaulted rooms built in the open space promoting further adaptations and extensions. Groups of dwellings around a common courtyard evolved into the social structure of the *vicinato* (neighborhood) sharing their facilities (e.g. tanks).

The water supply was highly organized, being collected on the plateau above and brought down by gravity for distribution to the community. As the town grew, more houses were excavated and built up on the hillside; the roofs of the houses below often acted as streets for the houses above.

This structure was left untouched until the 18th century. The continuous expansion and related interventions of the 19th and 20th centuries favoured the refusal of the ancient principle of land management based on the water supply and drainage on the plateau above. Matera and its urban fabric became the symbol of the misery of peasant life in southern Italy. Because of the concern of the Italian Government about this situation, legislation passed in 1952 led to the rehousing of the dwellers of the old quarters in new buildings and the desertion of the old town centre in the 1950s.

The Sassi is under the protection of the Italian State under the provisions of Law n. 771 of 11 November 1986, which allocated 50 M€ only for the conservative restoration and renovation of the dwellings.

The Sassi and the Park of the Rupestrian Churches of Matera have been included in the Word Heritage List since 1993, because "*The Sassi quarter of Matera is the best surviving and most complete example of continuity in the Mediterranean region of this type of settlement, which developed in close harmony with the ecosystem*".

The restoration and recovery works now in progress should follow the criteria set out by the Venice Charter for the Conservation and the Restoration of Monuments and Sites [1]. These are very important and valuable tools to achieve the goal of conservation (compatibility, minimal intervention, reversibility, distinguishability, expressive authenticity, durability and respect of the original tissue). During the past decades, The Sassi have become a very popular tourist attraction. This interest has fostered the cultural and economic revival of Matera resulting in important restoration and recovery works that caused it to be declared the European Capital of Culture 2019. Moreover, this event has accelerated the process of renovation of the old dwellings which are becoming private homes and hotel facilities. The recovery, now in progress – especially in the Sasso Barisano – is quite easy from a structural perspective, while it is challenging in terms of layout design. In particular, the retaining walls are affected by serious problems relating to dampness, which affect the indoor environmental quality in terms of thermo-hygrometric and indoor air quality. This means that to make The Sassi habitable, HVAC systems need to be installed whose design requires considerable care regarding dehumidification and ventilation issues.

The idea forming the base of the research that we are carrying out is that if we are able to find the causes responsible for the presence of water within the tuff bank and solve the problem upstream by reducing the evaporation in the various rooms with less complex systems. This paper outlines and discusses the preliminary results of a numerical analysis on the tuff bank-walls-indoor environment interaction based on the data collected via in-situ and laboratory tests.

2. The Sassi

The recovery of historic buildings starts with gaining in-depth knowledge. No work can be performed on a building artefact, which is evidence of the past, without first having investigated the construction techniques with which it was made, the work that it has been subjected to and any structural and plant modification [2, 3, 4]. This same course can be extended to a different scale from that of the building to that of the neighborhood. This is the case of The Sassi: first the long history and the particular architecture of The Sassi should be taken into consideration before even thinking of rehabilitation. If you have never been to this city, just imagine two slopes that depart from the valley of the Gravina Torrent up to the Civitas walls. These two slopes are separated by a ridge, along which one of the two great torrents of Matera flowed, with the houses of the two oldest districts, Sasso Barisano and Sasso Caveoso, which make up a complex urban fabric on the sides of the slopes. These dwellings, built over the centuries using different techniques, are superb examples of the ancient and long-lost human ability to adapt to its habitat without upsetting it.

First there were cave-dwellings, which were dug out in the tuff with a downward inclination so as to favour solar radiation during the winter season and reduce it in the summer. To reduce heat exchange with the outside, the opening of the cave was very small, which contributed to making it an unhealthy environment. In some cases, the vault of the cave was extended towards the outside, forming a *lamione*.

The first groups of the rupestrian city consisted of the *vicinati*, dwellings gathered around a common courtyard.

In 1204 the name "Sassi" appeared for the first time in an official document, probably to identify the nature of the places [5].

The rupestrian city had a water supply system consisting of a series of wells and tanks called *palombari*, fed from the ground water coming from the hills, and by a network of rainwater collecting wells [6].

At the end of the fourteenth century, the first non-hypogeal houses in The Sassi appeared. In the two centuries that followed, the rupestrian city was affected by a middle-class settlement phenomenon, becoming the subject of building investments [6]. This led to a mixed architecture that saw mansions rising alongside the poor caves and a heavy increase in the population. Buildings were rising everywhere, eliminating some elements that had characterized the urban fabric of the Sassi. The first *palazziate* houses, that is, on several levels appeared. Figure 1 shows an example of the transformation of a well and an inhabited cave.

At the end of the eighteenth century the people of Matera lived mainly in The Sassi. The construction of buildings continued throughout the nineteenth and twentieth centuries to the extent of covering one of *grabiglioni*; and from the castle the two torrents reached the Gravina Torrent collecting the grey and black water of the housings along the way, and piping that led to the public and private tanks inside the homes.

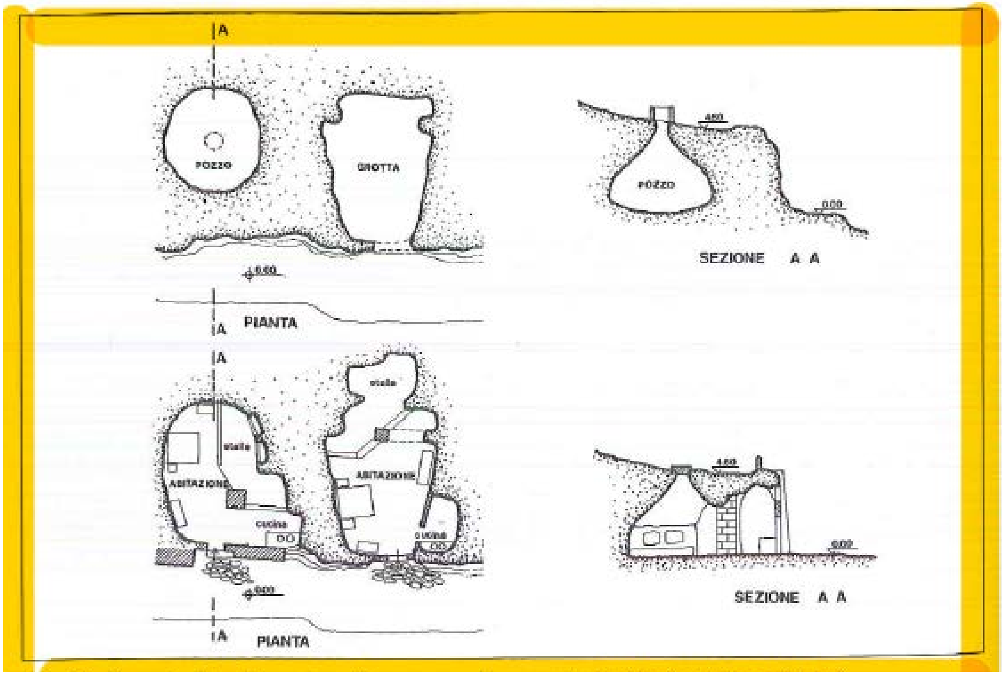

Fig. 1 - Example of the transformation of a well and an inhabited cave. (Rota, 1990).

The increase in the population of the Sassi, shown in Table I, led to the transformation of several reservoirs into the living environment, causing an unbalance in the water supply, unhealthy dwelling environments and a drastic decrease in hygiene conditions. This is when public fountains became increasingly more popular, such as the Ferdinandea, which in 1832 replaced the one built in the same place in 1577, and public tanks like the Palombaro Lungo, which is a few dozen metres from the Fontana; the largest tank in Matera with a capacity of almost 5 million litres.

The Ferdinandea and the Palombaro Lungo fountains are actually two components of a complex water system, fed by a spring in the Castle area at the summit of the city, and by rainwater and characterized by the presence of the *grabiglioni* and a piping system conveying the water to the public tanks and the private ones inside the houses.

It therefore seems plausible that closing the tanks, covering the *grabiglioni* to build roads, and above all building the aqueduct (around 1926) and the road network, may have upset the balance that had been created over the centuries and may have completely changed the function of the water system. In addition to this, after depopulation pursuant to the Special Law for the rehabilitation of The Sassi in 1952 (Table 1), the authorities failed to maintain the small collecting channels whose purpose was to convey water to the tanks and in doing so, avoid its dispersion. Moreover, it should be noted that, to cover The Sassi, the tuff on which The Sassi are built is affected by karst topography with fractures arising due to the dissolution action of rainwater, which foster the stagnation of water.

The Sassi are under the protection of the Italian State pursuant to the provisions of Law n° 771/1986, which allows the population to return to The Sassi and which designates The Sassi as being of exceptional national interest. The Sassi are bound by the national law for the protection and conservation of the cultural heritage [7]. Increasing tourism to the site may also have negative impacts on the presentation and ambience of the property and should be governed by visitor management.

In 1993 the Bureau of UNESCO recommended the inscription of this site List and reminded the competent authorities that the on-going restoration and rehabilitation works at Matera should be in conformity with international standards of conservation (Venice Charter) and requested the authorities to propose a shorter and more explicit name for this property, that was nominated under the name of "Matera": the historical town of I Sassi and the Archeological and Natural Park of the Gravina Civilization.

Table 1 - Percentage of inhabitants of the city living in The Sassi of Matera. Values from [5] modified (* assumed datum).

Year	Residents in The Sassi		Residents in the centre	Percentage of residents in The Sassi
	Total	Per hectare		
1732	10630	354	540	95
1819	9885	329	815	92
1901	12745	424	4336	74
1911	13684	454	4042	77
1921	13300	443	5057	72
1931	13334	444	16829	79
1936	14424	480	7645	65
1951	15266	509	14912	51
1961	6552	218	32010	17
1971	2298	76	42272	5
1981	1700°	57	49012	3
1991	1950	65	48969	3
2001	1953	62	55935	3
2011	2127	71	58638	3

The Italian authorities, by letter dated 1 October 1993, assured the World Heritage Centre that all restoration works in Matera will be undertaken in conformity with the international standards as expressed in the Venice Charter. Furthermore, the Italian authorities proposed to change the name of the site into "I Sassi di Matera" [8].

In 2007 the name of the property became The Sassi and the Park of the Rupestrian Churches of Matera [9].

3. Rehabilitation of The Sassi

In recent years, The Sassi have been the subject of major restoration works to the structure, but above all to plant engineering that has completely changed the image of the Rioni (districts) bringing them back to life. No longer are they just a series of uninhabited caves, but they are a pleasant succession of houses, shops and hotels that occupy the caves and lamioni. Evidently, the constraint imposed by UNESCO in compliance with the Venice Charter has strongly influenced and continues to influence the rehabilitation work, whose aim is, among other things, to ensure thermal comfort and air quality inside the rooms through HVAC&R systems.

One of the major problems of The Sassi is related to the high relative humidity of the air. This in turn, is due to the evaporation-transpiration from the walls that are against the tuff rock. Nevertheless, from surveys carried out by the authors, it seems that in some places these walls do not lean directly on the rock, but a cavity of variable thickness has been created between the false tuff walls and the tuff rock that is then filled with waste material. This waste material, coupled with the high relative humidity values and the low surface temperatures, creates condensation on the internal surfaces.

Evidently, the combination of these phenomena causes unhealthy hygienic conditions, which are worsened by poor ventilation in the rooms of the rock-clad dwellings. And air quality should not be ignored since tuff, as is known, emits Radon, which is carcinogenic.

4. Role of the Designer

From the above discussion, it is clear that in such a situation, the HVAC&R system designer faces a number of problems.

For example, from a technical-organizational point of view, it is not easy to position the machines, which cannot stay outside. This means that the rooms need to be identified and this often leads to expensive solutions being adopted with little appeal to a client who wants to keep to a low budget. The frugal customer who wants to spend little also looks at saving on operating costs; therefore, the systems designed to guarantee certain performances do not meet with these requirements with repercussions on thermal comfort and IAQ.

An example is that of rock-clad dwellings. These residences have a constant surface temperature of 12 °C, so achieving thermal comfort [10, 11] necessarily requires the use of a heating system that must be switched on even in summer, but whoever is operating the system does not turn on the heating, a little to save and a little out of ignorance.

In the summer season the situation inside the caves is virtually unsustainable, with air temperatures reaching a maximum of 15 °C and relative humidity values around 85% compared to external temperatures that generally exceed 30 °C with a relative humidity of around 40%.

To ensure the air changes for the IAQ in the caves, ventilation is required. This means that areas for the fans need to be identified and an air system needs to be designed so that it can be inspected, maintained and sanitized [12, 13]. Even in this case, often the cost of the system is high and the customer complains.

These problems increase greatly when it comes to hotels, because a very demanding clientele has to be satisfied, often coming from countries where there is little energy saving awareness. For example, many hotels have large bathtubs and, therefore, taking the coincidence factor into account, boilers that provide a high amount of energy and large accumulations have to be considered in a situation in which there is no room to do so. Similarly, summer cooling needs to be envisaged, even when it is not necessary, so as not to receive complaints from tourists who are used to living with air conditioning systems running continuously in their country.

Unfortunately, in this complex situation, the institutions have not been much help. In 1994, the City of Matera published the document [14] *1st and 2nd biennial program of work for the conservation and recovery of the Rioni Sassi (Law n° 771/86) - Technical standards for the implementation of works* [14], in which as regards the sanitation of underground rooms, Art. 7 speaks exclusively of *the implementation of forced suction stacks embedded in the bearing walls and the implementation of horizontal insulating cavities to guarantee suitable insulation of the tuff rock in the walls and floors*, which leaves some perplexity, since already by the end of the last century technology allowed the implementation of HVAC systems that could undoubtedly improve the environmental conditions in the caves. Even more doubts arise from reference to the horizontal insulating cavities, at least for two reasons: the first is that we do not understand what it is, perhaps a kind of floating floor; the second is that much of the moisture comes from the vertical walls, which on the other hand are not considered.

In 2013 the Office of the Sassi in the town of Matera published the General Provisions of Recovery 2013 [15], whose Annex D quotes the *Technical Regulations for the implementation of interventions*, which require investigations into the physical and technical characteristics of the envelope and submission of a report on the diagnosis of the microclimate in the environment to be recovered. In addition, of course, and in a redundant manner, compliance with what has already been provided for by legislation. Unfortunately, this document is very far from reality when it requires *an assessment of the physical characteristics of the materials of the shell of the rooms*, i.e.:

- *water permeability by capillarity and wetting by heavy rain;*
- *air permeability;*
- *water vapour permeability;*
- *thermal conductivity in the two situations of dry and wet material in the condition in which it is located during the investigation phase.*

In fact, these measures are complex, they are performed by few laboratories and we do not understand the usefulness in this case.

5. The research objective

From what has been said it is clear that The Sassi rehabilitation is a double challenge from a plant engineering point of view. Thermal comfort and air quality need to be guaranteed and the two things are closely linked because the internal thermo-hygrometric conditions determine the formation of lichen resulting in a worsening of air quality.

It is therefore clear that a correct and as far as possible definitive consolidation of The Sassi must necessarily require in-depth knowledge of the phenomena that determine the presence of water inside the tuff bank, and hence the walls of the caves and, in part, the housing above for the part leaning against the rock.

The idea behind the research, the preliminary results of which are submitted herein, and are not meant to define a solution, is that, as mentioned, the water which was once collected in domestic tanks are today dispersed in the tuff rock, resulting in a high evaporation-transpiration phenomenon within the environment and therefore of poor living conditions which, combined with the unique architecture of the site, result in an objective difficulty of plant design. If this were so, the problem could be solved by restoring the previous hydrogeological balance or by creating a new one. But how? It's easy to think that we should make a thorough investigation of the current state of the system of rainwater regimentation, but how can this be done? And how can we ensure that all possible infiltration in the tuff is eliminated?

Models to simulate the evaporation-transpiration trend as a function of the microclimatic sizes are considered appropriate to help identify the project microclimatic conditions in the environment, especially as regards the relative humidity values, and which ensure the thermal comfort not only from an objective but also from a subjective point of view.

6. The research method

In 2015, two properties that were being restructured; a house located below street level in the Sasso Barisano near the cathedral, that is, in the upper part of the district (Figure 2), and another house in the lower part of the Sasso Barisano (Figure 3) were chosen as in-situ laboratories. In both of the dwellings samples were taken from the walls so that the water content and the physiological humidity could be measured [16, 17] and were carried out measurements of microclimatic parameters.

Few samples have been taken, because for the time being the method and model need to be developed correctly. Once these have been fully defined, a widespread measurement campaign can be carried out if the initial assumptions are correct. After one year, the samples and measurements were repeated only in the dwelling near the cathedral, which was still under construction, so that a comparison between the water content values and the physiological humidity measured in 2015 and 2016 could be made. In fact, in the meantime, works on the other house were completed and the building was occupied, therefore the internal temperature and humidity conditions have completely changed.

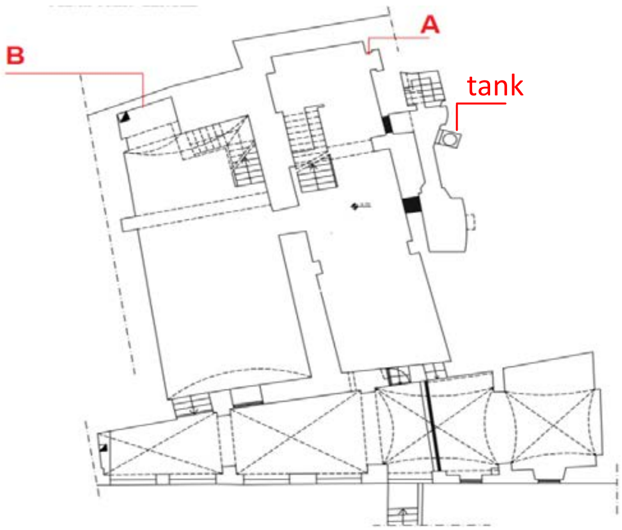

Fig. 2 - Layout of the dwelling in the upper part of the Sasso Barisano with indication of the vertical samples.

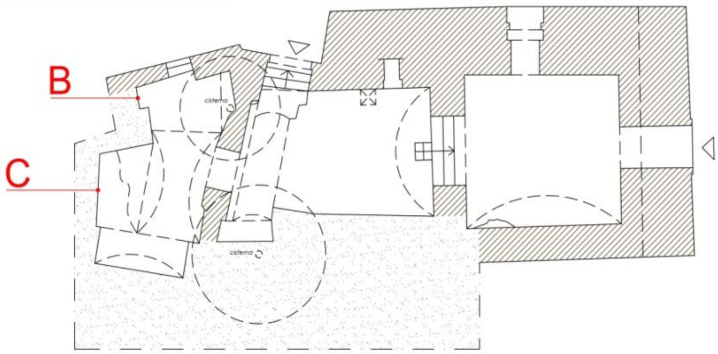

Fig. 3 - Layout of the dwelling in the lower part of the Sasso Barisano with indication of the vertical samples.

6.1. Water content and physiological humidity measurements

Following the measurement protocol defined by the Inequalities research group, formed by lecturers of the DIIN (Department of Industrial Engineering) of the University of Salerno and the DII (Department of Industrial Engineering) of the University of Naples [17], samples were taken at different heights that refer to the road surface and at two different depths from the vertical plane of the wall (Table 2). In 2016 the samples at one height were only taken along vertical plane A, average between the previous two, because, as mentioned, the purpose of the measurement was to check by how much the water content had changed in a year with a view to defining the evapotranspiration model. Again, in 2016 samples were taken from the bottom floor along vertical B to check the trend of the water content moving below street level (it was not possible to take samples along vertical A due to the conformation of the property).

Table 2 - Height relating to the road surface and measurement depth taken from the vertical plane of the sample wall of the dwelling in Figure 2.

Abbr	Height [m]		Depth [m]	
	2015	2016	2015	2016
A1	-3.50	-2.90	0.10	0.10
A2	-3.50	-2.90	0.45	0.45
A3	-1.60	-	0.10	0.10
A4	-1.60	-	0.45	0.45
B1	-	-4.10	-	0.10
B2	-	-4.10	-	0.45
B3	-	-1.16	-	0.10
B4	-	-1.16	-	0.45

Table 3 shows the values of wet mass, m_u, dry mass, m_a, and water content referred to the mass of the dry sample, U_a, and wet sample, U_u [18] of the 6 samples. It is evident that the water content on the internal surface of the wall is lower than that at a depth of 0.40 m, which suggests a high evapotranspiration, hence justifying the high relative humidity values of the air that are illustrated herein. The fact that the water content is practically constant along vertical height B seems to confirm the hypothesis that the problem of water in the walls, at least in the case of this property, is due to a more general presence of water in the tuff on which The Sassi are located.

Table 3 - Water content values measured on the 6 samples.

Abbr.	S[1] [cm]	m_u[2] [g]	m_a[3] [g]	U_a[4] [%]	U_u[5] [%]
A1	10	21.872	19.131	14.3	12.5
A2	45	24.501	20.411	20.0	16.7
B1	10	29.155	25.978	12.2	10.9
B2	45	28.560	24.069	18.7	15.7
B3	10	26.844	23.711	13.2	11.7
B4	45	27.885	21.435	30.1	23.1

NOTES: [1]Sample depth, cm; [2]Initial mass of the sample (wet mass), g; [3]Dry sample mass at the end of drying in oven, g; [4]Water content referred to the dry sample: $U_a=(m_u - m_a)/m_a \cdot 100$, %; [5]Water content referred to the wet sample: $U_u=(m_u - m_a)/m_u \cdot 100$, %.

To determine the equilibrium water content (physiological humidity), the samples were conditioned with the salt solution method [19]. Table 4 shows the physiological mass values, m_f, and the equilibrium humidity referring to the dry sample, $U_{a,f}$, and the difference between the water content and the equilibrium humidity referring to the dry sample mass, ΔU_a, of the 6 samples. Analysing the values of ΔU_a it is evident that the total water content in the tuff is very high compared to the physiological humidity, which confirms the need for action to prevent evapotranspiration, determining an increase in the specific humidity in the air, and a reduction in the surface temperature of the wall, leading to the formation of lichens.

Figures 4a and 4b, respectively show a comparison between the water content and the physiological values measured in 2015 and in 2016 at points A1 and A2 of Table 3. In the first measurement, very high water content was detected on the surface compared to the water content in depth, whereas the second measurement showed an inversion. A possible explanation could lie in the fact that the first measurements were performed when the site was first opened, after a long period of neglect of the property characterised by poor ventilation, while the following measured were performed later, after about a year, when the property was ventilated due to the absence of doors and windows. The slight increase in depth may also be due to accidental changes in the water content of the adjacent tuff rock due to infiltrations from the road above. As to the variations observed in the physiological content, these are probably due to the distribution of salts in the tuff.

Table 4 - Values of the equilibrium water content measured in 2016 on the 6 samples.

Abbr.	$m_f{}^1$[g]	$U_{a.f}$[%]	ΔU_a[%]
A1	19.240	0.6	13.8
A2	20.800	1.9	18.1
B1	26.051	0.3	11.9
B2	24.238	0.7	18.0
B3	23.764	0.2	13.0
B4	21.853	2.0	28.1

NOTES: [1]Mass of the sample at the end of conditioning at t = 20 °C and UR =75 % (physiological mass), g; [2]Equilibrium humidity referring to the dry sample, $U_{a,f} = (m_f - m_a)/m_a \times 100$, %; [3]Difference between water content and equilibrium humidity referring to the dry mass of the sample, $(U_a - U_{a,f})$. %.

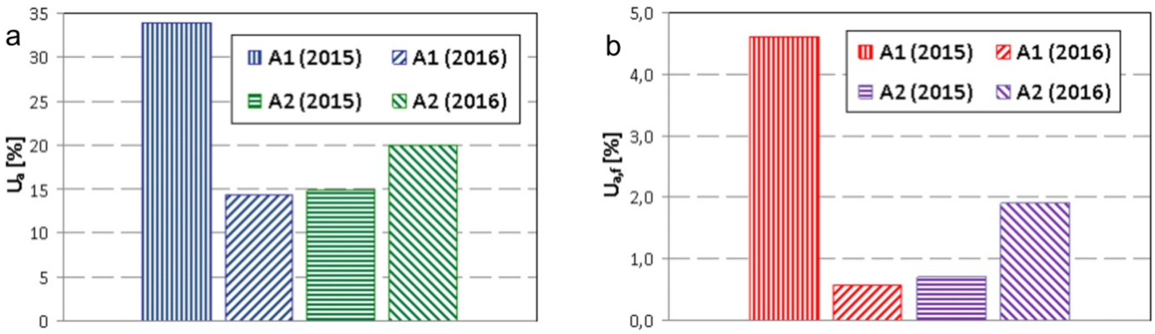

Fig. 4 – Water content (a) and equilibrium water content (b) values measured in 2015 and 2016 at sampling points A1 and A2.

6.2. Thermohygrometric measurements

The temperature and humidity measurements, which were taken in 2015 to check the thermal comfort conditions inside, also supported the generation of the wall evapotranspiration model in 2016. For this reason, in Figures 5a and 5b, only the temperature and relative humidity values of the air acquired from 19 July to 7 September 2016 are summarised.

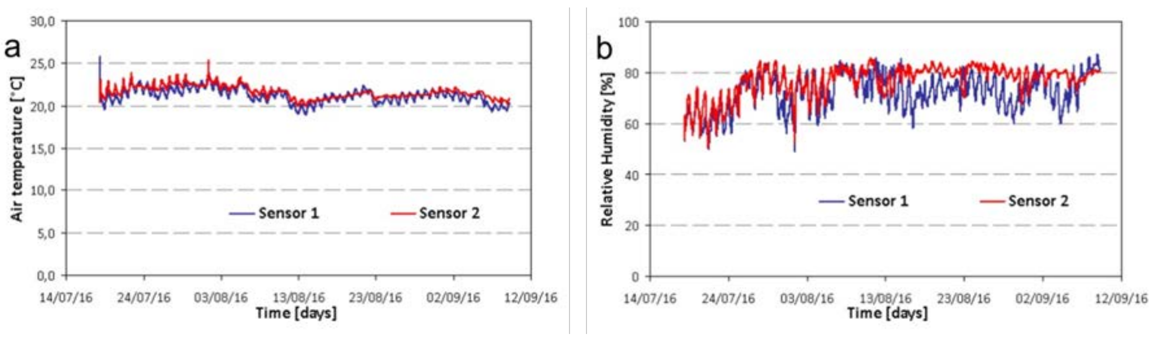

Fig. 5 – Air temperature (a) and Relative humidity (b) trends.

6.3. Numerical analysis

The numerical analysis was aimed at simulating the evapotranspiration processes that affect the tuff inside The Sassi. Given the complexity of these processes, the VADOSE/W software [20] was used for modelling. This commercial code implements the finite element method and requires the knowledge of the thermal and hydraulic parameters that are representative of the tuff [21], along with the boundary conditions in terms of temperature (T) and relative humidity (RH).

Two main simulations were carried out in bi-dimensional conditions considering a tuff wall with a height of 2.00 m and thickness of 0.30 m. In the simulation I, the boundary conditions were fixed according the information gathered from the sensors (Sect. 6.2); moreover, the time span of the simulation was posed equal to the data acquisition period of sensors (i.e., 40 days). In the simulation II, typical values of the heating season were set: T = 20 °C and RH = 50%. For both simulations, three cases were considered:

1) presence of groundwater at a height of –1.00 m from the foot of the wall;
2) timely flow of entry water (for example due to leakage in hydraulic networks) at the top of the wall (i.e., 2.00 m from the foot of the wall);
3) simultaneous presence of groundwater at –1.00 m and flow at 2.00 m from the foot of the wall.

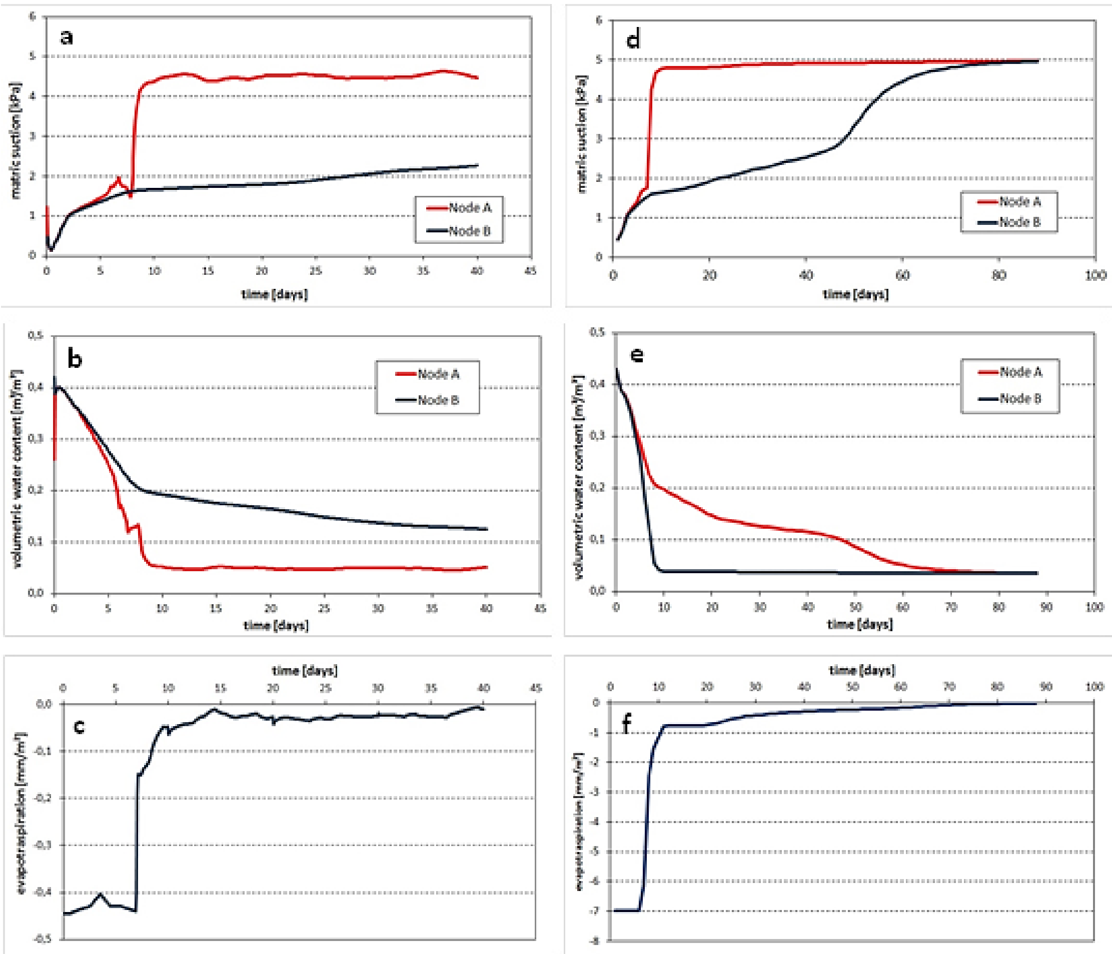

Fig. 6 - Trend over time of the matric suction, volumetric water content, and evapotranspiration of the wall for case 2 of simulation I (a, b, c) and II (d, e, ,f).

7. Results

The output data of the numerical analyses allow obtaining the trend over time of the parameters pertaining to the tuff wall, (i.e., matric suction, in kPa, and volumetric water content) as well as to the ones referring to the interaction between the wall and the external environment (namely, the evapotranspiration of the wall) expressed in terms of the evaporated water layer (in mm) per wall surface unit (in m^2)..

Figure 6 shows some of the results obtained for the case 2 of simulations I and II with reference to two nodes (A and B), of the mesh respectively positioned on the outer and on the inner surfaces of the wall, at 0.30 m from the foot of the wall.

In general, the results of simulation I highlight that, during the evapotranspiration process, the values of parameters at hand do not converge to an unique value and that, at the end of the considered time period, variations of volumetric water content in the wall does not match the maximum volumetric water content that should be transferred into the environment. This implies that the evapotranspiration process does not end in 40 days. On the other hand, in simulation II, the evapotranspiration process is exhausted after 88 days from the beginning of the process; moreover. the maximum water content transferred into the environment is shown in Figure 6e and equals 0.39 m^3/m^3.

8. Conclusions

The preliminary results of a research aimed at simulating the complex interactions between the tuff walls of The Sassi of Matera and the indoor enviroment have been presented and discussed. To this aim, a parametric numerical analysis was carried out so that once the thermal and hydraulic properties of a modelled tuff have been set, the evapotranspiration process can be compared to the internal thermo-hygrometric conditions. Obviously, this research must be continued by increasing the number of on-site laboratories and diversifying the situations in order to validate the numerical model and, therefore, achieve the goal of providing the professionals, who are working in the rehabilitation of the Sassi, with a tool that is easy to use and that can predict with good approximation how to design the HVAC&R system to make the interiors livable.

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