Construction and Building Materials 370 (2023) 130631

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An integrated approach to the monitoring of rising damp in historic brick masonry

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ARTICLE INFO

Keywords:
Historical buildings
Materials deterioration
Environment
Soil
Moisture
Brick masonry
Soluble salts
Flooding

ABSTRACT

Monitoring rising damp in historic masonry buildings requires an integrated approach, including not only the quantification of moisture in materials over time, but also the investigation of the supply of water from the ground, the evaporative capacity of the surrounding air, and the presence of potentially hygroscopic salts. However, this approach is seldom applied, hence our knowledge of the phenomenon of rising damp in real historic masonry structures is often only partial. In this paper, the proposed approach was applied to the church of Santa Croce in Ravenna, Italy, an outstanding example of masonry building affected by rising damp and related materials' deterioration. Santa Croce is a Byzantine church surrounded by an archaeological site and the whole area is presently located under the water table level, requiring a continuously operating pumping system to prevent the flooding of the entire zone. The testing and monitoring of moisture and salts in the church's materials started in September 2020 and is presently running. The data collected so far are presented and discussed in this paper, providing a contribution to a better understanding of this phenomenon. Moreover, during the monitoring period, a pumping system failure caused the flooding of the area in the period August-November 2021, allowing to investigate the impact of this event on the moisture in the materials. The protocol of testing described in this paper may provide a promising and effective method to investigate rising damp and is a starting point in view of its mitigation.

1. Introduction and research aim

The uncontrolled presence of water is one of the main factors that threaten cultural assets throughout the history of architecture [1–2]. Through the natural phenomenon of capillarity, water is spontaneously absorbed from the ground due to the porous nature of most of the building materials [3], such as brick, mortar, and stone [4]. This process, called rising damp, is detrimental for porous materials, as it may involve the ingress of harmful soluble salts, the occurrence of frost damage, and the swelling of clay impurities contained in some materials (e.g., sandstone) [1]. It also makes materials more vulnerable to any deterioration mechanisms, such as chemical attack by pollution, wind erosion, biological growth, etc. [5]. Finally, the presence of moisture in materials' pores may lead to defects and failures when conservation and repair materials are applied [6–7], jeopardizing the success of restoration works.

Even today, there is a strong need for fully effective methods to fight this commonly encountered problem, which particularly affects historic and heritage masonry structures [1]. To this aim, reliable techniques for the quantitative assessment of moisture and its monitoring are necessary [8–9]. Accurate and effective monitoring is of paramount importance not only to assess the drying effectiveness of the applied repair solutions [10–11] but also to study the parameters controlling rising damp in real historic buildings, in a preventive conservation approach [12–13]. In fact, while the phenomenon of capillary absorption of water in porous building materials is widely investigated in literature since many years [14–15], and it is also studied through a modelling approach [16–17], there is still a strong lack of knowledge about the capillary ascending flow of water in real historic masonry walls [11,13,18–19]. For this reason, a thorough and holistic diagnostic approach is necessary [1,12,20], as any effective, compatible, and durable restoration project is the result of a successful diagnostic survey. Otherwise, wrong intervention could be carried out. In the case of rising damp assessment, the integrated approach should include [20]:

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https://doi.org/10.1016/j.conbuildmat.2023.130631
Received 20 November 2022; Received in revised form 1 February 2023; Accepted 2 February 2023
Available online 13 February 2023

- identification of the features of the masonry walls under investigation, in terms of structure, modifications, past restoration works, presence of finishings preventing water evaporation, etc.
- quantification and monitoring of moisture (i.e., liquid water content) in materials, via destructive and/or non-destructive testing
- analysis of the presence of soluble salts in the masonry, which could promote the retention of water due to their hygroscopicity, besides causing materials' deterioration by crystallization cycles
- investigation of the ground, in terms of water sources that may supply moisture to the walls
- investigation of the environment in terms of internal and external climatic conditions, i.e., air temperature and relative humidity (which may promote or prevent the evaporation of moisture from the masonry) and rain (which may add up to rising damp).

In this study, this integrated approach to rising damp assessment was applied in the Santa Croce church in Ravenna, Italy (Fig. 1a), a Byzantine monument of great historical significance, which was originally part of the Galla Placidia Mausoleum (part of the Early Christian Monuments of Ravenna, in the UNESCO World Heritage List) [21–24]. Due to the long-term subsidence, the floor of the church is presently under the water table level [24], hence a continuous pumping system prevents the flooding of the building by transferring water from the soil to the city sewer system, while the building remains not used. Rising damp is one of the main causes of deterioration in the church and this problem is exacerbated by the fact that there is no emergency system, thus flooding might occur in case of pumping system failure, as happened in August 2021 (Fig. 1b). The city of Ravenna is located in northern Italy, about 8 km from the Adriatic Sea. According to the Köppen Climate Classification, it is in the Humid subtropical climate area (Cfa). Over the period 1991–2021, the following average values were recorded [25]:

- monthly precipitation equal to 49 mm in January, 61 mm in February, 56 mm in March, 68 mm in April, 61 mm in May, 54 mm in June, 51 mm in July, 54 mm in August, 77 mm in September, 80 mm in October, in 87 mm in November, 69 mm in December
- monthly temperature equal to 5.0 °C in January, 5.9 °C in February, 9.6 °C in March, 13.5 °C in April, 18.3 °C in May, 23.1 °C in June, 25.6 °C in July, 25.1 °C in August, 20.4 °C in September, 15.9 °C in October, 10.9 °C in November, 6.2 °C in December
- monthly relative humidity equal to 81 % in January, 77 % in February, 73 % in March, 71 % in April, 66 % in May, 60 % in June, 57 % in July, 61 % in August, 67 % in September, 76 % in October, 80 % in November, 81 % in December.

The present study was carried out in the frame of a wider project aimed at developing new methodologies to create effective risk management in cultural heritage areas and increase the resilience of regions [24,26]. In particular, the aim of this study was to investigate rising damp as a cause of materials' deterioration, not only by monitoring the moisture amount in the walls along a 21 month-period but also by trying to correlate moisture with the characteristics of the ground and the surrounding atmosphere.

2. The building

The church was built by the last Byzantine empress Galla Placidia in the V century [21] and passed through various stages over time (Fig. 2) [22], presently having the form of a single nave with apse and bell tower (Fig. 3a-d) [23]. The structure is constituted by brick masonry, with only very small areas still covered by plaster in the interior, mostly in the apse (Fig. 3d). The church was originally connected to the Galla Placidia Mausoleum, while today no connection is visible anymore and a narrow street (Fig. 3a) separates them. Thanks to the excavations carried out in the 20th century, the remains of the early stages of the church and the Roman Domus located in the area before the church's construction were disclosed [24,27–28], hence the church presently forms a complex with the surrounding archaeological site (Fig. 1a and 3b). The internal floor of the church and the surrounding ground level are approximately 3 m below the street level (Fig. 3a and 3c), so the main entrance located in the west façade is not the original one, but it was built in the 17th century at the street level (Fig. 2). From the main entrance, one can reach the internal floor by descending a wooden ladder (Fig. 3c). The masonry walls of the church were built during several phases, as shown in Fig. 2. The thickness of the north, west, and south walls, which were investigated in this study, is about 60–62 cm.

Today, a pumping system discharges the groundwater into the city sewer network and prevents the building from being permanently submerged. In case of pumping system failure, the land is exposed to flooding, and the management of the situation is made even more

Fig. 1. a) the church of santa croce in September 2020 (south wall with bell tower), with the surrounding archaeologic area; b) the same zone during the flooding due to the pumping system failure in August 2021.

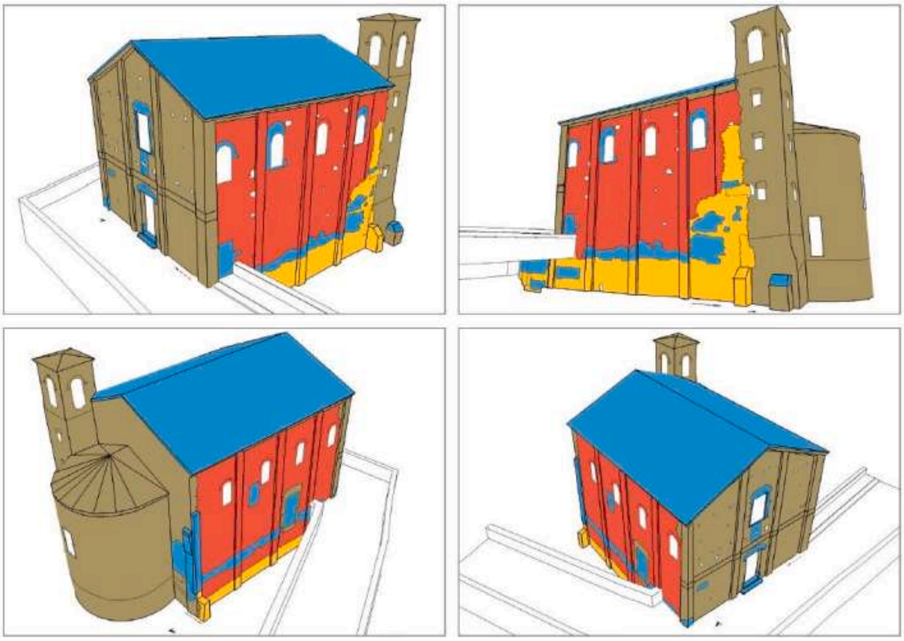

Fig. 2. Main phases of the church's construction: Phase 1 – AD 424–432 (yellow); Phase 5 – Mid of 12th century (red); Phase 7 – CE 1602–1612 (brown); Phase 8 – 20th century (blue) [28]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article)

Fig. 3. The church of Santa Croce in Ravenna: a) exterior - south façade; b) exterior – east façade and apse; c) interior – main façade (west wall) and entrance; d) interior – east wall and apse.

complicated by the fact that the church and the surrounding archaeological site are under two different authorities.

By visual observation, the church is strongly affected by rising damp, and various deterioration patterns are present in building materials. The external surface of the masonry is affected by colour change (Fig. 4a), bricks flaking and crumbling, possibly due to freeze–thaw and/or salt crystallization cycles (Fig. 4b), mortar joints' deterioration, efflorescence, and occasional plant growth (Fig. 4d). The interior is mostly affected by intense biological growth in the lowest part (Fig. 4c). The internal floor is constituted by soil and is also affected by deposits of pigeons' guano.

3. Materials and methods

3.1. Testing period

The onsite inspections started in September 2020 and are presently running. From August 2021 to November 2021, the church was submerged (Fig. 1), due to a pumping system failure, which allowed the investigation of the church also in the worst scenario.

3.2. Samples collection and characterisation

In September 2020, 46 samples of bricks and bedding mortars were collected from the walls of the church, both from the internal and external sides. The samples were collected by chisel and by drilling, in both case in the first ~ 2 cm from the surface. Five samples were also collected from the soil constituting the interior floor of the church. The following tests were carried out on the samples:

- determination of the moisture amount by gravimetry. The samples were immediately put inside airtight containers and transported to the laboratory, where moisture (M) was determined as:

$$M = \frac{(moist\ mass - dry\ mass)}{dry\ mass} \times 100$$

where the dry mass was obtained after drying in a ventilated oven at 100 ± 5 °C up to constant mass

- analysis of soluble salts. The analysis was carried out by grinding the samples, putting them in deionized boiling water for 10 min, filtering by blue ribbon paper filter, and performing the ion chromatography in a Dionex ICS 1000. According to the procedure adopted, the detection limit for the anions in a sample is about 0.01 wt%
- determination of the amount of calcium carbonate in the mortar samples, by grinding and reaction with hydrochloric acid in a Dietrich Frühling calcimeter
- X-ray diffraction analysis (XRD) of the powdered mortar samples, in a Malvern Panalytical Empyrean Series 3.

A selection of the most representative results is reported in this paper.

3.3. Moisture monitoring and salts analysis in the permanent sampling points

Considering the challenges related to monitoring moisture in ancient masonry, the "permanent sampling holes" method was used in this study [20,29]. According to this method, a hole (diameter ~ 14 mm) is created by a low-speed drill in a header brick of the masonry, for a length of about 2/3 of the brick, i.e. about 10–15 cm. The low-speed drilling is expected not to significantly alter the moisture amount, or at least to alter it to a minor extent, while using high-speed drill might cause a loss of moisture up to 4 % [30–31]. During drilling, the powder is collected and used for the first moisture measurement, which is carried out by gravimetry, as explained above. Then, fragments of the same brick in which the hole is drilled are placed inside the hole, which is sealed. In subsequent measurements, the brick fragments are collected and used for moisture measurement by gravimetry, because it was demonstrated that the fragments, in a period of about 3 weeks [29], reach the equilibrium with the surrounding brick in terms of moisture. In this way, a reliable monitoring campaign can be carried out even in heterogeneous masonry, as the measurement is performed always in the same bricks, moreover, the damage to heritage buildings is minimum. Of course, the fragments extracted from the hole are introduced again inside the holes after moisture determination, for further measurements. The method of the permanent sampling holes provides a measurement of moisture in

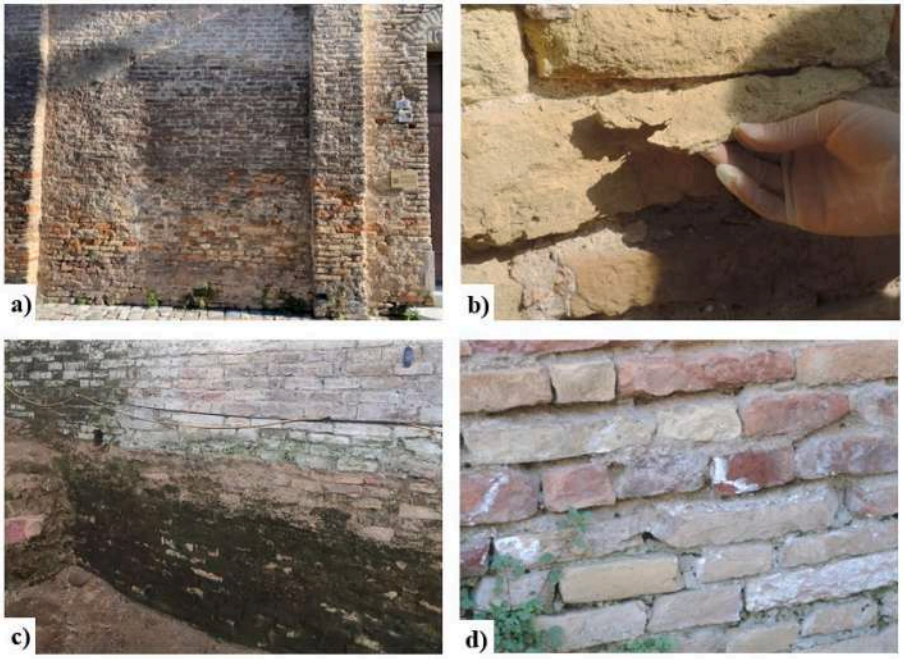

Fig. 4. Examples of materials' deterioration patterns in the church: a) darkening due to rising damp in the main façade (west); b) flaking and scaling of bricks (south façade, exterior); c) biological patina (north wall, interior); d) salt efflorescence and deterioration of mortar joints (north wall, exterior).

the first 10–15 cm from the surface, which might be different from the moisture at the centre of the wall (thickness 60–62 cm), especially in the upper part of the moist zone, where the evaporation front retreats inside the wall [32]. However, one of the main advantages of the use of this method is that the measured value of moisture is representative of the moisture in the entire brick where the hole is located, which allows to neglect the transient moisture variations that may occur at the masonry surface due to specific climatic conditions (high relative humidity, occurrence of surface condensation, rain). For this reason, the measurement is considered robust enough to allow reliable long-term onsite monitoring, as evidenced in previous studies [20–33].

In September 2020, the first three “permanent sampling holes” (L, M, N) were created on the external side of the south masonry, at different heights along a vertical line, as shown in Fig. 5, in a part of the masonry dating back the V Century (yellow in Fig. 2). In April 2021, two “permanent sampling holes” were created on the internal side of the south wall (point Q, approximately in correspondence to the external points L-M–N) and on the internal side of the west wall (point P, just above the level of the street), as in Fig. 5. Notably, the internal side of the west wall is covered by soil up to approximately the street level, as shown in Fig. 5-right. Point P belongs to the façade wall, built in early XVII Century (Fig. 2). The moisture measurements were carried out on different dates, according to the authorisation by the two different authorities in charge of the church interior and the external area, respectively.

The fragments in the holes were also used for the determination of the water absorption of the relevant bricks (i.e., the moisture at saturation) and for the calculation of the saturation degree. After oven drying up to constant mass (dry mass), the brick fragments were partially immersed in deionised water for 4 h, to favour the saturation of the samples and the expulsion of the air contained in their pores, then they were totally immersed in deionised water up to constant mass (saturated mass). Water absorption (WA) and saturation degree (SD) were determined, respectively, as:

$$WA = \frac{(saturated\ mass - dry\ mass)}{dry\ mass} \times 100$$

$$SD = \frac{M}{WA} \times 100$$

The brick powders that were collected during the drilling of the holes were also used, after the determination of moisture, for the analysis of soluble salts, according to the same procedure described in 3.2.

3.4. Investigation and monitoring of the environment

Monitoring the soil and the environment was considered of paramount importance to understand the rising damp phenomenon affecting the church, as the capillary absorption of water by masonry is influenced by three main factors: 1) the supply of water from the ground; 2) the water evaporation rate from the walls, which depends on the air relative humidity, wind speed, and direct solar radiation; 3) the characteristics of masonry materials [1]. Moreover, the presence of hygroscopic salts, such as sodium chloride or calcium nitrate, in the wall could play an important role in the moisture presence [34–35]. For all these reasons, the following aspects were investigated:

- level of the underground water table (depending on the pumping rate)
- salinity of the soil and the water
- air temperature and relative humidity inside and outside the church
- rainfall in the area.

Visual observation of the crypt below the apse (Fig. 3d) shows that the water table is 20–30 cm below the ground level, i.e., just below the

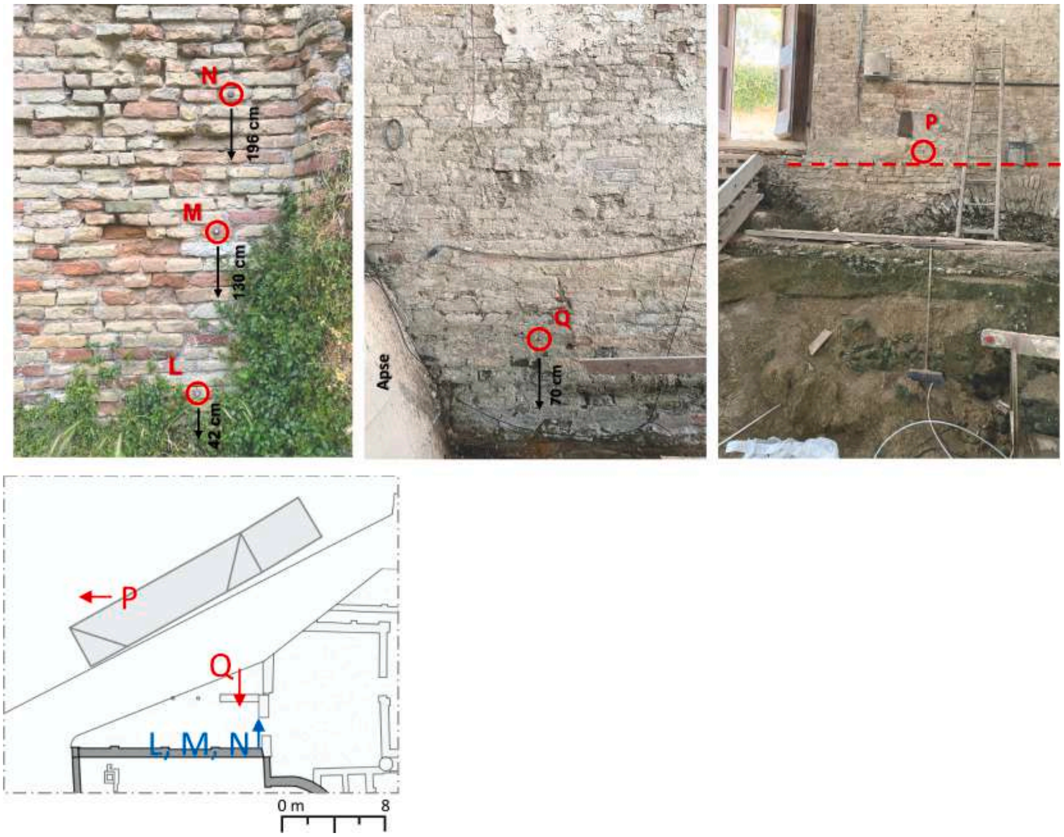

Fig. 5. Above, from left to right: permanent sampling points L-M–N (south wall, exterior), Q (south wall, interior), P (west wall, interior; the dotted line indicates the road level). Below: location of the sampling holes in the church plan.

floor of the church.

The salinity of the soil and water was investigated by collecting: five samples of the soil constituting the interior floor of the church (Sept. 2020); a sample of water during the flooding which affected the church (Sept. 2021, in the zone in Fig. 1).

The temperature and relative humidity of air were monitored by two portable sensors with dataloggers (RS 172 by RS Components; temperature: resolution 0.1 °C and accuracy ± 2.0 °C; relative humidity: resolution 0.1 %, accuracy ± 5.0 %) located inside and outside the church about 2 m above the ground (Fig. 6).

Moreover, the collection of climatic data on the area of Santa Croce was carried out, exploiting the monitoring network of ARPAE (Agenzia Regionale per la Protezione Ambientale - Regional Agency for Environmental Protection), Emilia-Romagna Region, Italy. In particular, the data concerning air temperature, air relative humidity, and rain were collected. The weather monitoring station used in this study is located in the city centre of Ravenna, where also the church is located, about 700 m far from it, in the SSE direction, at the same distance from the Adriatic Sea and at the same altitude.

4. Results and discussion

4.1. Samples characterisation

The calcium carbonate amount and the results of XRD analysis of some significant mortar samples collected from the south and north walls are reported in Table 1. The two walls exhibit joint mortars having different compositions, consistently with the different ages of construction of the investigated zones, namely the early V century for the south façade and the mid-XII century for the north façade (Fig. 2). In particular, the $CaCO_3$ amount in the samples of the south wall is much higher than in those of the north wall, while aggregates composed of quartz, feldspars and mica were found in both (the traces of vermiculite might be due to the weathering of mica [36–37]), likely due to local availability of this kind of sand [38]. Calcium carbonate is ascribed to the carbonated lime binder, but in the case of the two samples from the south wall, the percentage of $CaCO_3$ seems too high to be ascribed to the binder only [39–40], even in presence of a high binder to sand ratio, hence this compound could be presence also in part of the aggregate, such as ground shells, which are visible also at the naked eye in the south wall.

The values of moisture found in the samples collected on 21/9/2020 are reported in Table 2 and provide an interesting overview of the water distribution in the internal surfaces of the church's walls, after the hot and dry summer season. In the south wall, moisture decreases with height, as expected, although the values are slightly scattered, likely due to the heterogeneous nature of historic fired-clay bricks. Considering that moisture amount at saturation in bricks is commonly about 20–24 wt%, the south wall appears moist up to a height of about 1 m, with intermediate moisture percentages. The north wall exhibits a much higher moisture content (although not saturation) up to 80 cm, while the higher points are basically dry. Considering that the samples were collected inside the church and the evaporative conditions indoors are the same, the higher moisture found in the north wall compared to the south one can be explained based on the different orientations and/or different materials (in particular, mortar joints) in the two walls. In the west wall, some moisture is present at about 3 m, i.e., just above the road level.

The types and amounts of soluble salts in some significant samples are reported in Table 3. The salts found in the masonry are chlorides, likely due to the salinity of the ground in Ravenna, sulphates, which typically come from the soil, and nitrates, which could derive from the underground burials and/or the pigeons' guano accumulated on the internal floor [41]. It is interesting to notice that the amounts of salts in the walls are extremely scattered, and not dependent on the height. Even samples collected approximately at the same height differ to a great

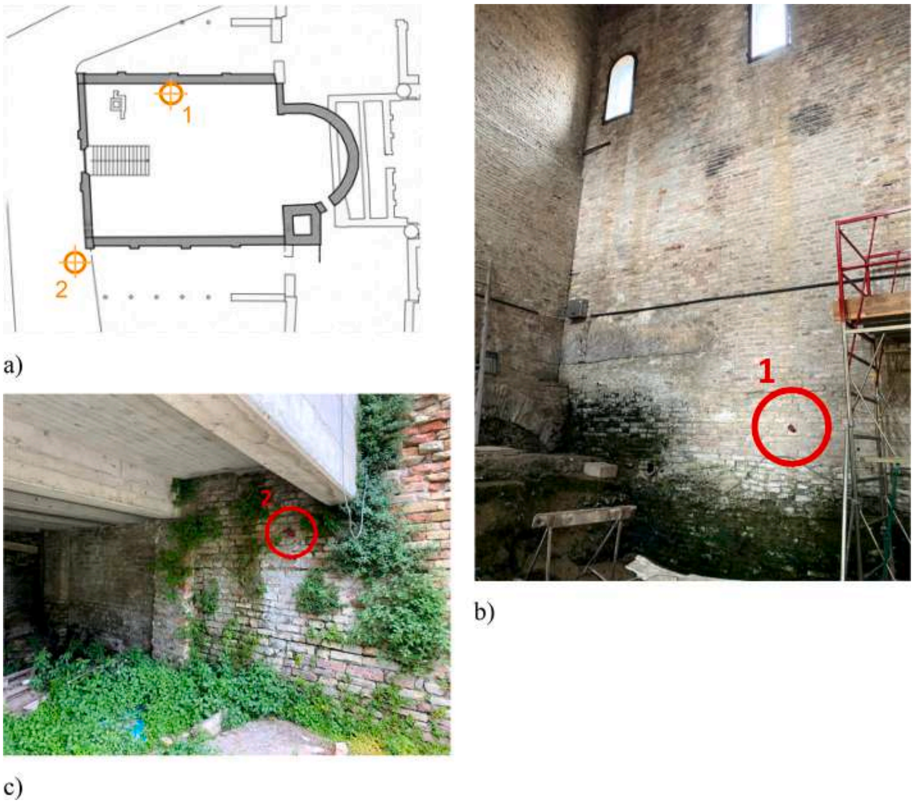

Fig. 6. a) plan of the church with the location of the sensors (dataloggers) for the monitoring of air temperature and relative humidity; b) and c) the internal (#1) and external (#2) sensors, respectively.

Table 1
Characterization of four mortar samples (collected on 21st Sept 2020): $CaCO_3$ amount determined by calcimetry and results of the XRD analysis (+++ = dominantly present, ++ = present, + = present in minor amount, tr = traces, ~ = possibly present, / = not present, C = calcite, Q = quartz, M = muscovite (mica), A = albite (feldspar, plagioclase group), S = sanidine (potassium feldspar), S = vermiculite (phyllosilicate), G = gypsum.

Sample	Location and height	$CaCO_3$ (%)	XRD results						
			C	Q	M	A	S	V	G
mortar (#13)	South wall (interior), 0.5 *m*	52.9	+++	++	tr	tr	tr	/	~
mortar (#30)	South wall (exterior), 1.1 *m*	68.0	+++	++	tr	tr	tr	~	/
mortar (#2)	North wall (interior), 0.5 *m*	31.8	++	+++	+	/	tr	tr	/
mortar (#4)	North wall (interior), 1.8 *m*	38.6	++	+++	tr	tr	tr	~	~

Table 2
Moisture in the samples collected on 21/9/2020 (first 1–2 cm from the surface).

Sample (and internal identification label)	Location	Height from church ground level (m)	Moisture (wt.%)
brick (#D)	South wall (interior)	0.3	8.0
brick (#12)		0.5	11.2
brick (#E)		1.0	6.7
brick (#F)		1.7	0.7
brick (#14)		1.8	5.0
brick (#A)	North wall (interior)	3.0	15.6
brick (#1)		5.0	15.9
brick (#8)		5.0	15.1
brick (#B)		0.8	12.1
brick (#C)		1.7	3.4
brick (#3)		1.8	5.4
brick (#10)		1.8	4.8
brick (#H)	West wall (interior)	3.0 (+0.3 from road level)	6.9
brick (#24)		3.1 (+0.4 from road level)	6.1

Table 3
Salts amounts in samples collected on 21/9/2020 (first 1–2 cm from the surface).

Sample (and internal identification label)	Location	Height from church ground level (m)	Cl^- (wt. %)	$SO_4^=$ (wt. %)	NO_3^- (wt. %)
brick (#26)	South wall (exterior)	0.8	2.74	0.55	1.00
brick (#27)		0.9	0.87	1.76	0.24
brick (#28)		0.9	0.96	2.79	0.64
mortar (#30)		1.1	0.36	0.22	0.14
brick (#D)	South wall (interior)	0.3	0.06	0.19	0.03
brick (#12)		0.5	0.12	2.38	0.11
mortar (#13)		0.5	0.04	0.53	0.07
brick (#18)		0.7	0.09	1.33	0.51
mortar (#19)		0.8	0.04	0.48	0.22
brick (#17)		0.9	0.47	0.79	0.34
brick (#E)		1.0	0.34	0.37	0.08
brick (#F)		1.7	0.03	0.65	0.01
brick (#14)		1.8	0.23	3.31	0.11
mortar (#15)		1.8	0.08	1.29	0.05
mortar (#21)		1.8	0.18	0.42	0.20
brick (#31)	North wall (exterior)	1.0	0.05	0.12	0.01
brick (#32)		1.0	2.23	0.69	0.12
brick (#A)	North wall (interior)	0.3	0.04	0.12	0.01
brick (#1)		0.5	0.02	2.99	0.04
mortar (#2)		0.5	0.02	0.05	0.03
brick (#8)		0.5	0.05	2.79	0.03
brick (#7)		0.6	0.05	1.50	0.32
mortar (#9)		0.6	0.01	0.05	0.01
brick (#B)		0.8	0.03	2.30	0.06
brick (#C)		1.7	0.55	0.28	0.15
brick (#3)		1.8	0.29	0.81	1.33
mortar (#4)		1.8	0.21	0.67	0.93
brick (#G)	West wall (interior)	0.2 (from road level)	0.15	2.91	0.05
brick (#H)		0.3 (from road level)	0.07	4.29	0.09
brick (#24)		0.4 (from road level)	0.09	9.05	0.19

extent in terms of salts (e.g., comparison of bricks 26–27-28; or bricks 31–32). In terms of chloride:

- 16 out of 30 samples exhibit Cl^- <0.1 wt%, which can be considered negligible, in the authors' experience, as this chloride amount is usually already present in original bricks and is commonly found in masonry in non-marine environments [33]
- 9 samples exhibit Cl^- amounts between 0.1 and 0.5 wt%, which can be considered low, although not negligible
- 3 samples exhibit Cl^- amounts between 0.5 and 1 wt%, which can be considered high
- 2 samples exhibit Cl^- amounts > 2 wt%, which can be considered extremely high.

These data are very difficult to interpret, as a certain scattering is normal in ancient bricks, that exhibit an intrinsically high heterogeneity, but the fact that more than half of the samples have basically no chloride does not match with the extraordinarily high chloride amounts found in some samples, unless some bricks were recovered from previous buildings exposed to a harsher marine environment. As a matter of fact, the practice of reusing bricks from demolished buildings was very common in ancient times [42–43], hence the results suggest that this could have happened also in this church. Considering the values in Table 3, it can be concluded that chloride may locally cause some deterioration in the bricks, especially in the external surface of the walls, owing to relative humidity variations, but overall they seem not in a sufficient amount to exert a significant hygroscopic action in the masonry walls.

The sulphate amounts are very high, although with a high scattering. Sulphate could derive from the soil and/or the construction materials, such as bricks and mortars joints (especially if manufactured with gypsum), while the scattering of data can be ascribed to the features of ancient brick, characterised by extremely heterogenous porosity. Considering that the soil and flooding water were found to contain no particularly high amount of sulphate ions (see Section 4.3), that no evidence of mortars containing sulphate is present, and that the scattering is very high, it is possible that some salt-laden bricks were used in the construction, as suggested in the analysis of chloride. In any case, sulphates could be responsible for the flaking observed in several bricks on the external surfaces of the church, a typical kind of damage found especially in the case of sodium sulphate, which exhibits an outstanding volume increase when passing from the anhydrous form (thenardite) to the decahydrate one (mirabilite) [44].

Nitrates are present in the walls of the church, owing to the causes mentioned above. However, their amount is generally limited, except for some samples (5 samples in the range 0.3–1 wt% and 2 samples in the range 1–1.33 wt%). As in the case of chloride, nitrates might be responsible for local damages due to crystallization cycles, but they seem not enough to involve a significant hygroscopic behaviour.

4.2. Moisture monitoring and salt analysis in the permanent sampling points

The moisture data collected during the monitoring period are

Table 4
Moisture in the permanent sampling points used for monitoring and moisture at saturation, wt.% [°: data measured in the same zone, i.e., in adjacent bricks with respect to the ones with the permanent sampling holes; *: 24/2/22; **: 3/3/22]. The flooding period was between August and November 2021.

Point	Location	Height from the church floor level (m)	Moisture at saturation	21/9/20	27/4/21	2/7/21	24/2–3/3/22	4/7/22
L	South wall (exterior)	0.4	21.5 ± 0.7	6.9	19.6	–	19.9 (*)	16.9
M		1.3	23.0 ± 2.7	1.2	6.7	–	18.4 (*)	3.6
N		2.0	27.9 ± 0.2	0.3	0.0	–	12.8 (*)	1.2
Q	South wall (interior)	0.7	15.2 ± 0.3	8.8 (°)	6.3	6.6	14.0 (**)	5.4
P	West wall (interior)	2.9 (+0.2 from road level)	21.5 ± 2.2	9.2 (°)	13.9	–	12.2 (**)	11.2

reported in Table 4, together with the water absorption values (=moisture amount at saturation) of the brick fragments. The data allow to make some interesting remarks:

- the water absorption values are those averagely found in historic fired-clay bricks in the area (about 20–24 %). Brick N is more porous and brick Q is less porous than the average, but still in the range of values found in historic masonry buildings
- in September 2020, after the hot and dry summer season, moisture was present in the south wall in intermediate amounts (saturation degree 32 % in L and 58 % in Q), mostly in the first ∼ 1 m above the floor. The fact that moisture amount decreases with height is typical of masonry affected by rising damp. Moisture was slightly higher on the internal side compared to the external one, likely due to the fact that no ventilation is present inside the church hence the water evaporation is hindered there (par. 4.3), while the lower relative humidity and the natural airflow on the external surfaces favour the moisture loss. Also in the west wall, moisture was intermediate (saturation degree 43 % in P), which means that the water capillary rise reaches and passes the road level
- in April 2021, after the cold and humid season, moisture in the south wall was considerably more abundant and reached a higher level, being close to saturation in L, intermediate in M, and absent 2 m above the floor, which seems to suggest an equilibrium line around 160–180 cm. On the internal side, the moisture amount was slightly lower, which suggests that rain may have contributed to the wetting of the wall on the external surface. Also in the west wall, moisture was higher compared to the previous date
- at the end of February – beginning of March 2022, i.e., about 3 months after the removal of the flooding water in the area, the situation was completely different. Moisture was present in much higher amounts (e.g., SD equal to 93 % in L, 92 % in Q, and 80 % in M) and up to an impressive height ($\gg$2 m). In fact, the saturation degree found in N (height 2 m) was equal to 46 %. The fact that 3 months after the removal of water the wall was still very wet must not surprise, as bricks and mortars are much faster in absorbing water than in drying [45], the latter being strongly influenced also by the climatic condition (see 4.3). The west wall exhibited a moisture amount comparable to the previous year, hence it was probably less affected by the flooding. In fact, the wall below point P is underground on one side (below the street) and covered with soil on the other side (Fig. 5-right), hence the evaporation in this part of the wall is always inhibited, and moreover the bricks were not directly in contact with water during flooding
- in July 2022, the moisture distribution was basically the same present before the flooding.

The soluble salts present in the bricks with the permanent sampling points were measured and the results are reported in Table 5. Given the low amounts of ions found, a possible hygroscopic behaviour was considered negligible in this case and the moisture found in the walls should be ascribed only to capillary water rise, as discussed also in par. 4.1.

Table 5
Salts found in the permanent sampling points at the date of drilling (21/9/20 for L-M–N and 27/4/21 for Q-P).

Point	Location	Height from the church floor level (m)	Cl^- (wt.%)	$SO_4^{=}$ (wt.%)	NO_3^- (wt.%)
L	South wall (exterior)	0.4	0.04	0.05	–
M		1.3	0.01	0.06	–
N		2.0	0.05	0.07	0.08
Q	South wall (interior)	0.7	0.05	0.16	0.14
P	West wall (interior)	2.9 (+0.2 from road level)	0.05	0.26	0.05

4.3. Monitoring of the surrounding environment

For a deeper understating of the rising damp phenomenon, the role of the surrounding environment, namely soil, underground water, and climate, was investigated.

The salts found in the water collected from the church area during flooding, in terms of anions, were chloride (Cl^- = 259 ppm) and sulphate ($SO_4^{=}$ = 100 ppm). Brackish water, a broad term used to describe water that is more saline than freshwater but less saline than true marine environments [46], is defined as water having a total dissolved salt content higher than 500 ppm [47], hence the flooding water can be considered as slightly brackish. However, since water is considered brackish when chloride content is higher than 400 ppm [48], the Cl- amount found in the water sample, although quite high, is below this threshold. Sulphate ions are present in water, but in a limited amount, i.e., only double with respect to Ravenna tap water, where sulphates are 51 ppm [49]. The salts found in some samples of soil collected inside the church are reported in Table 6. The data show that sulphate and chloride ions are present in very limited amounts.

Crosslinking the data on salts found in the wall, the water, and the soil, it seems that the supply of chloride from the ground is limited, despite the coastal location of Ravenna. Consequently, the brick masonries of the church exhibit a low amount of this salt, apart from some occasional bricks, probably recovered from previous buildings. The amount of sulphate ions found in the soil was quite low, but not negligible, hence the prolonged ascending capillary flow could have led to some accumulation of these salts in the most porous bricks and the subsequent deterioration. Differently from the water, some nitrates are present in the soil, confirming their origin from the deterioration of organic matter and their transport into the masonry by rising damp.

In Figs. 7-8, the air temperature and relative humidity measured by the sensors inside and outside the church are reported, together with the

Table 6
Amounts of salts found in three samples of soil collected from the ground inside the church (collection date: 21/9/2020 for S5-6–23 and 2/7/21 for S36-37).

Soil sample	Cl^- (wt.%)	$SO_4^{=}$ (wt.%)	NO_3^- (wt.%)
S5	0.02	0.13	0.08
S6	0.05	0.21	0.07
S23	0.02	0.05	0.02
S36	0.01	0.03	0.04
S37	0.02	0.10	0.18

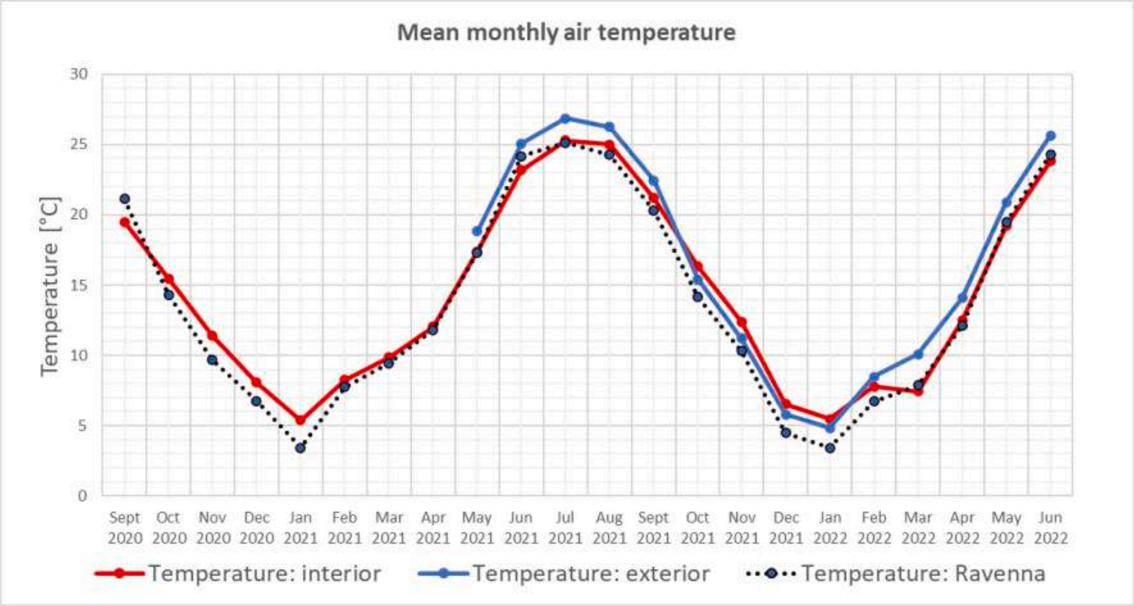

Fig. 7. Mean monthly values of air temperature inside and outside the church.

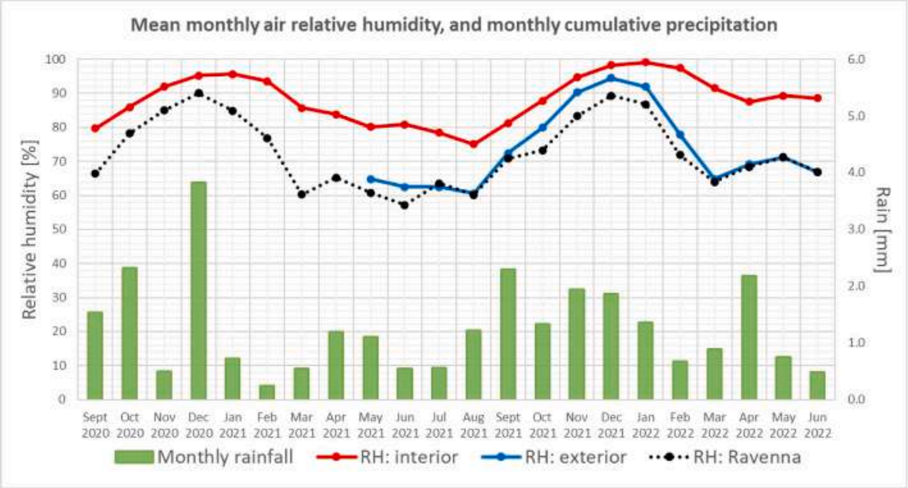

Fig. 8. Mean monthly values of air relative humidity inside and outside the church, and rainfall.

same parameter and the amount of rain precipitation monitored by ARPAE in the city centre of Ravenna. In terms of temperature inside and outside the church, the values during the cold season are only slightly higher inside, being the mean indoor temperature in Nov. 2021, Dec. 2021, Jan. 2022, and Feb. 2022 just + 1.1 °C, +0.7 °C, +0.7 °C, and −0.7 °C compared to the outdoor one. This is due to the absence of heating inside the building. During the hot season, the temperature inside the church is colder than outside (about −1.5 °C in the period June-August 2021), due to the absence of direct solar radiation inside the building. The situation is very different in terms of air relative humidity, which is systematically higher inside the church than outside. In November-February, the air relative humidity inside the church is close to saturation (>95 %), and it is very high also outside (>90 %), so in that period the evaporation of water from the masonry is almost totally inhibited, especially inside, where the RH never decreased below 86.0 % in Nov., 94.6 % in Dec., 94.1 % in Jan., 85.8 % in Feb. (in the same months, the minimum RH values outside were 58.9 %, 79.0 %, 51.3 %, and 33.9 %). Notably, in the other months, the mean relative humidity decreases outside, but it remains very high inside, the difference being + 15–20 % during summer (May-August) and + 5–10 % during spring and autumn. Even if some differences were found in the temperature inside and outside, they seem too limited to account for such a huge difference in relative humidity. On the whole, the mean monthly relative humidity inside the church is basically higher than 80 % all along the year, which can be ascribed to the absence of ventilation in the building (windows permanently closed), aimed at preventing the ingress of birds and the subsequent damage, and certainly reduced the evaporation rate of the walls through the internal surface, as confirmed also by thermal imaging [50]. Considering that the total absorption rate of water from the ground and the total evaporation rate of water through the masonry's surfaces come into balance and a steady state is established [4], it is clear that the evaporative conditions on both sides of the walls play a key role in determining the height of rising damp. On the other hand, the constantly humid air inside the church prevented the occurrence of cycles of crystallization-dissolution of salts [51], and in fact the physical–mechanical damage owing to this deterioration mechanism is present mostly in the external masonry surfaces.

Considering the rainfall values in Fig. 8 and the data in Table 4, there seems to be no particular correlation between monthly cumulative rain and moisture amount in the walls, probably because the level of the underground water table is kept constant by the pumping system and is independent from the rainfall. Of course, some water absorption of wind-driven rain by the walls cannot be excluded, but it is likely a transient effect. This suggests that other factors play a major role in the phenomenon of rising damp, namely the rate of moisture evaporation and the level of the water table. To take into account all the factors influencing the capillary water rise in the walls of the church, a modelling will be carried out in future steps, exploiting both the data collected in this study (moisture in the walls at different dates, *T*-RH monitoring, masonry materials' characteristics) and others that are presently under collection (monitoring of the water table, wind, further measurement of moisture in the walls).

5. Conclusions

An integrated monitoring campaign was carried out in the church of Santa Croce, including materials' characterization, soil, and underground water characterization, monitoring of moisture (liquid water) in the walls, monitoring of climatic data, and air monitoring inside the building. This campaign provided reliable and quantitative results on the "health state" of the building under investigation.

The moisture measurements carried out with the permanent sampling point method showed that the water content in the walls decreases with height, as expected in masonry affected by rising damp, with a strong influence from seasonality (especially in the south wall, where the level of capillary rise varies approximately between 1 and 1.80 m). However, for an appropriate understanding of the problem, different aspects were taken into account. First, the indoor microclimate of the church was shown to play a key role. As a matter of fact, the evaporation rate of water from masonry depends on the air relative humidity, which remains between 80 % and 95 % inside the church all along the year, slowing down or even totally hindering the evaporation of water through the internal surface of the masonry, hence the water vapour removal from the interior of the church will have to be addressed in a future repair intervention. Although this parameter was only qualitatively considered in this study, it was shown to cause higher moisture amounts in the inner side of the walls and hence to influence the overall level of rising damp. Conversely, the influence of salts and their hygroscopic behaviour on moisture content was considered negligible. Nevertheless, the locally high amounts of chloride, sulphate and nitrates are likely responsible for some physical–mechanical damage induced by salt crystallization cycles. Specific investigations seem necessary to monitor the level of the water table in the ground below the church, which are in progress. The present monitoring confirmed how strong the impact of the unexpected flooding that occurred in August 2021 was. In fact, it caused: (i) a dramatic increase of moisture in the walls, both in terms of saturation degree and height of capillary absorption; (ii) a persistent moisture presence in the walls, for many months after the end of the flooding.

The building under investigation can be considered an outstanding example of rising damp, because of the superficial nature of the groundwater, owing to the long-term soil subsidence and the consequent lowering of the structure.

CRediT authorship contribution statement

Elisa Franzoni: Conceptualization, Methodology, Funding acquisition, Project administration, Supervision, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Bensu Berk:** Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Mattia Bassi:** Investigation, Data curation, Formal analysis, Visualization. **Clelia Marrone:** Investigation, Data curation, Formal analysis, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Acknowledgements

This research has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement n° 821282 (Project SHELTER, Sustainable historic environments holistic reconstruction through technological enhancement and community-based resilience). The contents reflect only the authors' view, and the European Union is not liable for any use that may be made of the information contained therein.

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