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Wireless environmental monitoring coupled to NDT for decay risk analysis (at St. Joseph Chapel in Reims, France)

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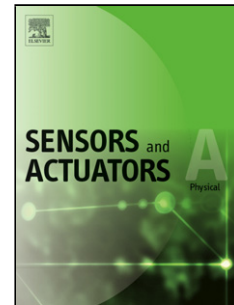
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COUPLED TO NDT FOR DECAY RISK ANALYSIS (AT
ST. JOSEPH CHAPEL IN REIMS, FRANCE)

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Résumé

Dans cette partie, le site étudié est la chapelle Saint Joseph intégrée au complexe éducatif du même nom. La façade principale, donnant sur la rue de Venise, a été restaurée en 2012 tandis que les murs donnant sur la cour et isolés de la rue ont été laissés en l'état. Le premier critère de choix des capteurs est défini en fonction de la récupération des données. En effet, le fait de pouvoir collecter les données en temps réel permet de détecter d'éventuels problèmes techniques et d'éviter une perte de données trop importantes en intervenant rapidement. D'autre part, les contraintes liées au suivi en extérieur, comme l'absence de source d'électricité pour alimenter les capteurs ou de connexion à internet pour le transfert des données, obligent à trouver des moyens les plus autonomes et indépendants possibles. Dans le but de répondre à ces différentes problématiques, deux plateformes de capteurs sans fil différentes, Smartmote et Wasmote (Libelium), ont été testées pour l'enregistrement et l'envoi des données en temps réel.

Le système Smartmote est pourvu de capteurs uniquement de température et d'humidité relative. Cette plateforme est constituée de capteurs branchés à des nœuds eux-mêmes communicant en sans-fil avec une station de base qui, elle, nécessite une connexion internet et une source d'électricité. La plateforme Smartmote fonctionne avec une très faible consommation d'énergie, suffisante pour une surveillance à long terme (au moins un an), et un excellent taux de transfert de données.

La plateforme Wasmote a été programmée pour mesurer, enregistrer et transmettre les paramètres de température, humidité relative, et concentrations en O₃, NO, NO₂ et SO₂. La plateforme est branchée sur un panneau solaire comme source d'énergie et dispose d'un module 3G pour le transfert des données. Wasmote est apparu comme la meilleure solution pour réaliser des mesures multiparamétriques peu coûteuses, et cela malgré sa récente mise sur le marché expliquant l'instabilité de la partie logicielle et quelques problèmes techniques.

La fréquence de mesure est un paramètre déterminant dans la qualité des mesures et de leur interprétation ainsi que pour la longévité du dispositif. Sachant que plus la fréquence de mesures est élevée, plus la consommation d'énergie le sera également, il convient d'évaluer le meilleur équilibre entre quantité de mesures nécessaires à une bonne interprétation des variations journalières et économie d'énergie. Pour cela, trois fréquences de mesure différentes ont été testées, 1, 12 et 60 mesures par heure, à l'aide des données de température

enregistrées avec Smartmote. La fréquence de 12 mesures par heure apparaît comme le choix le plus judicieux en termes de rapport qualité/consommation d'énergie.

Les données obtenues grâce à cette surveillance environnementale ont permis de diviser l'année en deux périodes d'intérêt présentant des tendances différentes : d'avril à septembre, la température est élevée et l'humidité relative est faible, et d'octobre à mars, la température est faible et l'humidité relative est élevée. En hiver, de novembre à février, 15 cycles de gel/dégel ont été déterminés, avec une température minimale de -8°C et une amplitude quotidienne maximale de 11°C . Cette fréquence des cycles n'était pas suffisante pour produire des dommages visibles en un an, cependant à plus long terme, ces cycles conduisent à des altérations dues au mouvement de l'eau liquide associé à la formation de glace à l'intérieur de la pierre. Les variations quotidiennes ont mis en évidence une inversion de température entre la façade côté cour et la façade côté rue et un délai de 2 à 4 heures entre les pics maximaux des deux façades. La concentration moyenne de NO_2 était quatre fois plus élevée dans la rue que sur le terrain de jeu, en relation directe avec la pollution automobile. De plus, la variabilité diurne du NO_2 était corrélée avec les variations de température de chaque façade. En outre, une concentration élevée de SO_2 (220 ppb), comparativement à la moyenne nationale (2 ppb), a été observée du côté de la rue en octobre.

Les principales altérations observées sur la façade non restaurée étaient de la salissure, de la biocolonisation et des pertes de matériel dues aux conditions environnementales et des impacts datant de la Première Guerre Mondiale. En parallèle, la colorimétrie a été utilisée pour suivre l'évolution de la surface des pierres sur 200 positions de chacune des façades. En comparant les deux campagnes de surveillance, à intervalle d'un an, les variations de luminance se sont révélées plus élevées sur la façade non restaurée que sur la façade restaurée. Alors que le monitoring de l'environnement a mis en évidence le risque pour la façade restaurée face à la rue d'être plus affectée par la pollution, la colorimétrie a montré que cette façade évoluait plus lentement que la façade protégée de la rue et non restaurée.

**WIRELESS ENVIRONMENTAL MONITORING COUPLED TO
NDT FOR DECAY RISK ANALYSIS (AT ST. JOSEPH CHAPEL
IN REIMS, FRANCE)**

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Highlights

- Two sensors platform were tested due to their remote data transfer (3G and WiFi).
- The wireless platforms used must be defined in relation to the need of the study.
- The measurement frequency should be carefully chosen to get the most relevant data.
- The effects on stones due to T and RH changes require more time to be quantifiable.
- SO₂ level was especially high on the street side that leads to a faster yellowing.

ABSTRACT

The development of the best strategies for building stone conservation requires the most suitable micro-environmental monitoring method coupled to the observation of the stones surface evolution. For that purpose, two different wireless sensor platforms were tested for monitoring two façades of the Saint Joseph Chapel (Reims, France). The Smartmote system recorded the temperature (T) and the relative humidity (RH) with very low energy consumption and excellent data transfer rate. The necessity to plug the base station to an internet connection and an electricity source was a complication. The Wasmote platform was constituted by a 3G module and plugged to a solar panel. This system appeared as the best cost solution and multi-parametric possibilities (T, RH, O₃, NO, NO₂ and SO₂) even if the incompatibility between some software functions disabled the use of the low energy consumption mode. Data obtained thanks to this environmental monitoring during one year were divided in two periods of interest with different daily amplitude patterns between both façades: high T and low RH from April to September, and the reverse from

October to March. The NO₂ variations depended mainly on the temperature variations while the SO₂ variations were conditional upon the anthropic activities. In parallel, colorimetry was used on 200 positions on each façade at one-year intervals. Comparing the two monitoring campaigns, luminance varied much more on the non-restored façade than on the restored façade. Environmental monitoring has to be coupled with NDT monitoring campaigns to assess the real weathering evolution of a monument.

Keywords: wireless sensor networks, monitoring, cultural heritage, preventive conservation, weathering, colorimetry.

1 Introduction

To put in place the best strategies for cultural heritage conservation, indoors and outdoors, it is essential to monitor the environmental parameters [1]. Indeed, stone weathering has multiple origins due to the combination of intrinsic properties of stone (e.g. porosity and mineralogy) and extrinsic parameters (e.g. temperature and relative humidity and/or pollutant concentrations) [2].

Temperature and relative humidity variations are directly responsible for wetting/drying cycle which may lead to salt crystallization into the pores or freezing in case of negative temperatures. The salt or ice formation entails a high pressure exerted inside the stone [3,4,5,6,7] and at long-term it leads to material loss decay: blistering, scaling, delamination, granular disintegration and other alteration patterns [8]. Brimblecombe and Grossi [9] predicted the behavior of stones in conditions of the climatic change and showed that temperature conditions could have the strongest

impact in stone decay. Otherwise, the models predicted an increase of limestones surface recession in the near future, especially in urban areas [10].

The sulfur dioxide (SO_2) is largely emitted by the energy transformation and the manufacturing industry sectors [11]. The main source of nitrogen oxides NO_x (NO and NO_2) is the road transport, essentially emitted during combustion phenomena. More than 70% of NO_x emissions by vehicles are NO [12], which reacts with ozone and other oxidants to form NO_2 . Thus, NO_2 is mainly encountered in urban areas and is often a good tracer of road traffic emissions [12,13]. The ozone (O_3) is a secondary pollutant produced under UV-light during complex atmospheric production/consumption reactions with some primary pollutants, mainly NO_x and Volatile Organic Compounds (VOCs) [14]. Thus, O_3 reacts with NO to produce NO_2 [15] and its concentration is higher in periurban and rural areas. Even so for now the atmospheric pollutants, particularly SO_2 and NO_x , are major weathering agents for stones. In presence of water they form strong acids which enhance dissolution, especially in Ca-rich stones. The consequences on building surfaces can be features induced by material loss and soiling [16], salt efflorescences, crack growth, which favorize biological colonization [17].

Environmental monitoring has become increasingly common in recent decades for cultural heritage studies [18,19]. Because of the high spatial variations of atmospheric parameters at the scale of a city [20,21], the data collected by main weather stations from national associations of air quality monitoring are not sufficiently precise to assess clearly the effects of atmospheric pollutants on a monument. Thanks to the progress of monitoring technologies [20], it has been possible to guarantee low cost systems [22,23] and continuous monitoring for comprehensive long-term heritage studies in a great variety of assets [1,18].

One of the cheapest and relatively reliable systems to measure temperature and relative humidity is the HOBO or iButton® sensors data logger, which are widely used in a lot of different fieldwork (biology, agriculture, medicine, cultural heritage) [1,18,22,24]. In spite of that, it is not possible to measure the pollutants concentration with this system for now, and the need to retrieve data manually makes it somewhat constraining. The remote data transfer appeared as the solution to monitor. In the era of new technologies, the wireless networks were widely developed and 802.15.4, ZigBee, Wi-Fi (802.11b/g), BLE (Bluetooth Low Energy) and 3G/GPRS [25,26] offer several options in the field of sensor monitoring.

Some studies [1,22] have already and successfully used wireless sensor networks (WSN) with WLAN connectivity and Wi-Fi access for remote real-time monitoring of temperature and relative humidity for cultural heritage conservation especially in indoor environments due to the limit of Wi-Fi network proximity. Very recently, the possibility to use the mobile connectivity (3G) as well as the remote data transfer [27] appeared, avoiding problematics linked to the Wi-Fi system installations.

This research had two main goals.

The first aim of this study was to determine the most suitable and optimal monitoring method applied to cultural heritage conservation.

The second aim was to relate the evolution of building stones to the microclimate recorded by the sensors.

To undertake these goals, two different methods of monitoring and data transfer were used in order to determine the microclimate and air pollution levels at two different façades of the Saint Joseph Chapel (Reims, France). The two systems were Smartmote (Wi-Fi) and Waspmote (3G). Finally,

to establish a link between environmental conditions and stone surface evolution, visual observation and colorimetry measurements, both Non-Destructive Techniques (NDT), were performed on the stone surface at one-year interval.

2 Case study

2.1 St. Joseph's Chapel (Reims, France): History and description

The monitoring campaign was carried out at Saint Joseph Chapel located in the city center of Reims (France) (Fig.1). The Chapel is 28 meters high from the ground to the tip of the nave and it is constituted from local limestones (Euville, Courville and Savonnières). Moreover, the Savonnières limestone is particularly used in current restorations of Reims architecture [28].

This neo-Gothic monument was designed by the nationally renowned architect Edouard Lamy and completed in 1876. During the First World War (WWI), the stained glasses were destroyed and the façades riddled by shoot impacts but the chapel and her spire were remained standing while surrounding buildings were completely devastated. That was due to German military strategy to use the tip to calculate the shutting distance and thus the necessity to keep it intact. During the decades following the war, the rebuilding and the reorganization of this zone finally led to the creation of a four-lane and a high traffic road, called rue de Venise.

Saint Joseph's main façade, in front of the rue de Venise (Fig.1.c), was restored from March to September 2012 (Fig.1.d and e). During this process, the blocks of limestone were cleaned by dry

ice blasting or replaced, and holes were filled with a lime-based screeding. Finally, the entire façade surface was covered by a whitewash layer.

2.2 The climate in Reims

The climate of Reims region is “temperate, with warm summer and without dry season” (Cfb) [29]. Thus the environment is soft and wet with dry winters, and eventually stormy summers. During the last ten years, the precipitations represented around 600 mm per year which is low if compared to the rest of the country, with a mean about 800 mm [30]. The total pluviometry, from May 2015 to September 2016, represented 830 mm, including 500 mm from May 2015 to May 2016, and distributed equally over the period (Fig.2).

Mean temperature and relative humidity were 11°C and 82% respectively [30].

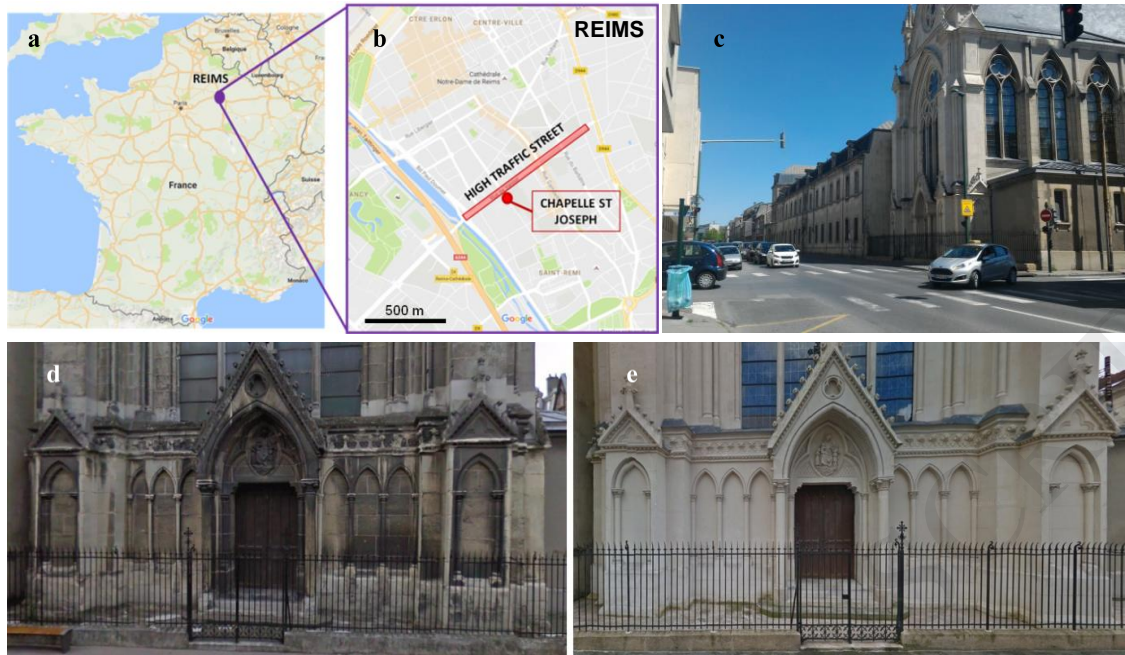


Fig.1 (a) Location of the city of Reims in France [31], (b) location of the Chapel St. Joseph in Reims [32], and (c) view of the high traffic street “Rue de Venise” with the Chapel St. Joseph at left. (d) The “street façade” on rue de Venise in April 2011 and (e) in June 2016, respectively 1 year before and 4 years after the restoration

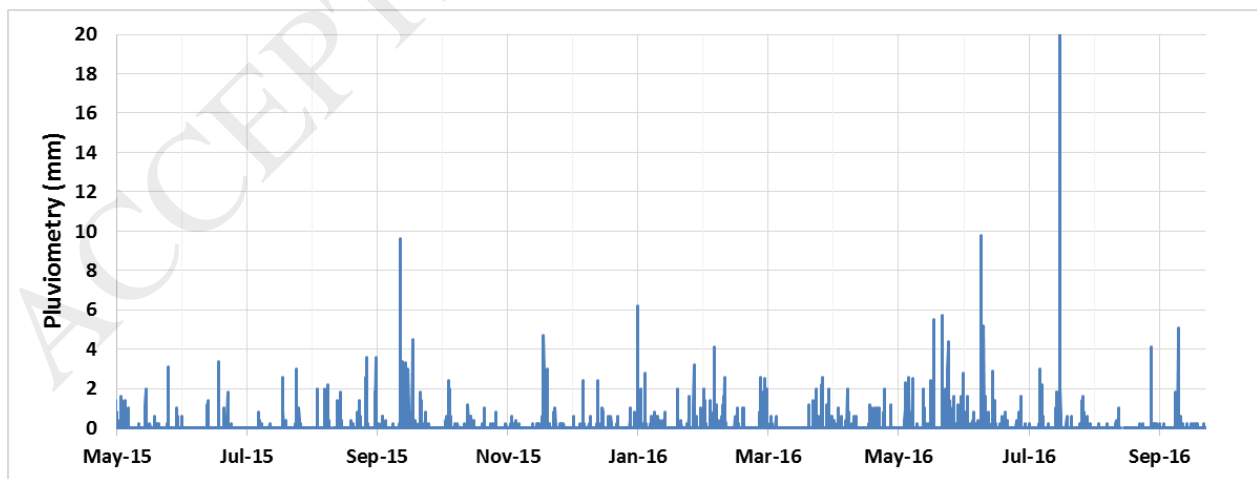


Fig.2 Pluviometry in Reims from May 2015 to May 2016. Data from [30]

3 Methodology

The two façades studied were respectively called « Street façade » and « Playground façade » (Fig.3). The « Street façade » facing northwest and overlooking a very high traffic street (rue de Venise). The « Playground façade », oriented northeast, dates from the construction of the Chapel and is located in a yard protected from the street by derelict buildings.

3.1 Platforms and sensors

Two different wireless sensor platforms, Smartmote [33] and Waspote [25], were used. Both platforms monitored temperature and relative humidity, and Waspote also recorded O₃, NO, NO₂ and SO₂ levels.

Both façades were monitored with each platform placed at 5 meters height from the ground (Fig.3).

3.1.1 *Smartmote*

The network was deployed following the guidelines resulting from the tests conducted on the platform in several cultural and natural heritage scenarios [34,35] to ensure communications quality [22].

A MySQL database software for information storage and remote access was used, transmitting wireless communications over the 2.4 GHz ISM (industrial, scientific and medical) band using tree topology and a CC2520 radio transceiver [36]. Fig.3.a showed the locations of the motes and the base station (Fig.3.b) spaced 25 meters apart.

The Sensirion SHT25 T/RH sensors [37] used were protected inside Hygrosens and Sensirion sintered polyethylene filters (Fig.3.c). The operating range for these sensors was 0 % to 100 % for RH with a precision of ± 1.8 % and -40 °C to $+125$ °C for T with a precision of ± 0.2 °C. The sensors were subject to the maximum and standard tolerances [37].

3.1.2 *Wasmote from Libelium*

The Wasmote PRO v1.2 motes (Fig.3.d) were used with a hardware interface of the SIMCom SIM5818E module for the remote data transfer by 3G. This technology was available only since April 2015. Both modes GSM and WCDMA were utilized, with 2GHz active frequency band and 500 dBmof TX power and -78 dBmofRX level value for base station selection.

The used sensors board was Gases PRO Board v1.0 plugged to temperature, humidity, pressure, O₃, NO, NO₂ and SO₂ sensors. The power supply consisted in a 6600mAh Li-Ion rechargeable plugged to a rigid solar panel (7V, 500mA, Fig.3.e). The operating ranges for these sensors are shown in Table 1.

The implementation of this platform required to encode the system to save the data following these steps: (i) CSV file creation, (ii) parameters measurement, (iii) obtained data written in the csv file, (iv) file sent to a FTP server, (v) delay before redo the steps (ii) to (v).

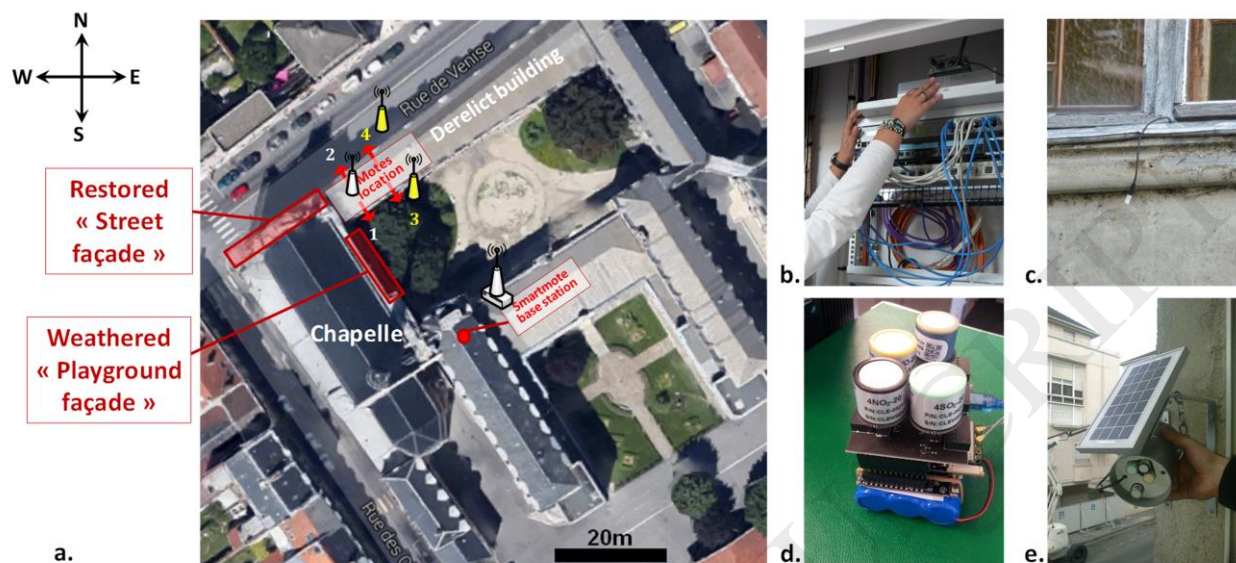


Fig.3 (a) Monitoring schema of the wireless sensor networks installation. Black mote/base station represented the Smartmote platform, yellow notes represented the Wasmote platform. Points 1 and 2 were the T/RH sensors. Points 3 and 4 were T, RH, P, O₃, NO, NO₂ and SO₂sensors. Point 2 and 4 located on Street side. Points 1 and 3 located on Playground side. (b) Smartmote base station installation and location and (c) Sensirion T/RH sensor. (d) Wasmote PRO v1 with Gases PRO Board v1.0 and (e) sensors and platform located on street side

Table 1 Operating range of Wasmote sensor

	T (°C)	RH (%)	SO ₂ (ppm)	NO (ppm)	NO ₂ (ppm)	O ₃ (ppm)
Range	-40 to 85	0 to 100	0 to 20	0 to 250	0 to 20	0 to 5

Precision at 20°C/1 atm.	± 1	± 3	± 0.1	± 0.5	± 0.1	± 0.005
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3.2 Colorimetry

The colorimetry is a Non-Destructive and non-invasive Technique (NDT), portable, rapid to use and reliable. This technique was used to monitor the decay evolution on each façade because it allows to identify the type and degree of chromatic alteration over time [38,39]. The measurement campaign was performed in May 2015 and May 2016. This month was chosen due to the climatology. May is the first month in which rain is scarcer and thus, the humidity of the walls is not influenced by rain phenomena.

The data were recorded with a MINOLTA CR-400 colorimeter using the D65 illuminant, a beam of diffuse light of 8-mm diameter, and a 0° viewing angle geometry, with an included specular component and the spectral response closely matching the CIE standard observer curves [40]. The measurements were expressed following the CIE L* a* b* system. The L* parameter is Lightness and registers values from 0 (black) to 100 (white). The a* and b* parameters are Cartesian chromatic parameters. They vary from -60 to 60, a* from green to red, and b* from blue to yellow.

The measurements were done on 200 different positions on each façade, spaced between 50 and 160 cm in height and 20-30 cm in length. In this study, five readings were done on each position, then the average, minimum and maximum were determined for each façade, on playground and on street, in May 2015 and May 2016. The colorimetric variations on both façades were mapped with the software Surfer® 11 using kriging as gridding method.

4 Results

4.1 Environmental Monitoring Setup

4.1.1 *Smartmote*

The platform implementation needed to fit specific conditions: (i) the location for the mote had to be linked to the sensors and preferentially be protected from rain and (ii) the base station needed to be plugged to an energy source and to an internet connection. Electrical power supply and Ethernet connection were chosen in this case.

In this study, the base station was located at 25m from the mote and took into account deployments factors [22] in order to strengthen a correct wireless communication quality. In spite of having some unavoidable obstacles due to construction factors and activities in the place (e.g. tree, walls, public presence), the registered wireless parameters (RSSI, CORR) [22] guaranteed excellent communications between them to make possible the wireless communications with the minimum of interferences.

The Smartmote platform was able to record the data during the complete studied period, from its installation in May 2015 to September 2016, and it is still operating. Data were collected each 1 minute.

4.1.2 *Wasmote*

Contrarily to Smartmote, Wasmote installation and measurement protocol had not been tested before this study for cultural heritage monitoring. Due to that, an initial period for checking the battery life, the data transfer and the optimization of the communications was needed. Thus, data were collected each 5 minutes from 9th to 23rd October 2015.

The Wasmote platform should be completely autonomous in energy (solar panel) and data transfer (3G mobile connectivity). The only requirements were to find the best place according to the needed data and enough solar energy to recharge the batteries. One advantage was the very “low energy consumption mode” included in the functions.

During the testing period (October 2015), there was a loss of data on the playground platform due to the corruption of the SD card. Indeed, the remote data transfer by 3G was not activated during this period because the programming issues were not still solved. The 3G module had been recently launched and the software was not completely stabilized, leading to code and technical issues. Indeed the use of the power sleep mode function (very low energy consumption mode) interfered with the 3G module that created systematic errors during the data transfer such as the failure of the file upload on the FTP server. The power sleep mode was thus replaced by a simple delay function, knowing that the minimum power demand was 3mA [27]. In addition, double rechargeable batteries were added to the system.

After solving this energy problem, data sampling restarted with a frequency of 1 hour, from 1st April to 20 May 2016 on the playground side and to 29st August 2016 on the street side.

Thus Wasmote recorded the parameters during some parts of the studied period, as shown in Fig.4.

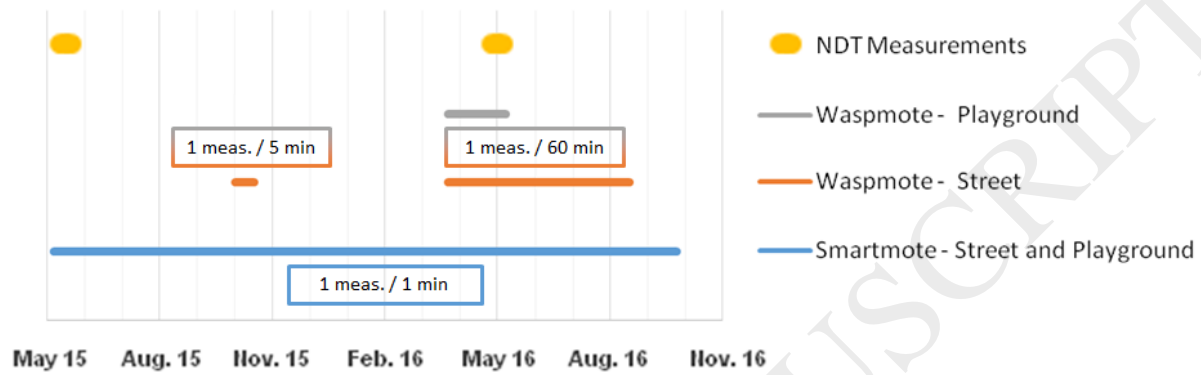


Fig.4 Data acquisition periods for Wasmote and Smartmote, and stone parameter measurements by NDT

4.2 Environmental Data

4.2.1 Temperature and Relative Humidity

4.2.1.1 Wasmote vs Smartmote

The temperature and the relative humidity recorded by Wasmote and Smartmote followed the same variations in spite of an offset between the values given by the both systems (Fig.5). The temperature values recorded by Wasmote were consistently higher of 1°C , while the relative humidity values recorded by Smartmote were 14% higher (Fig.5). Wasmote sensors were calibrated by the manufacturers while Smartmote sensors were autocalibrated [27,37]. These differences were constant during the studied period.

For this study, the analysis took into account the temperature and relative humidity data from Smartmote due to the fact that the data loss was less important for Smartmote.

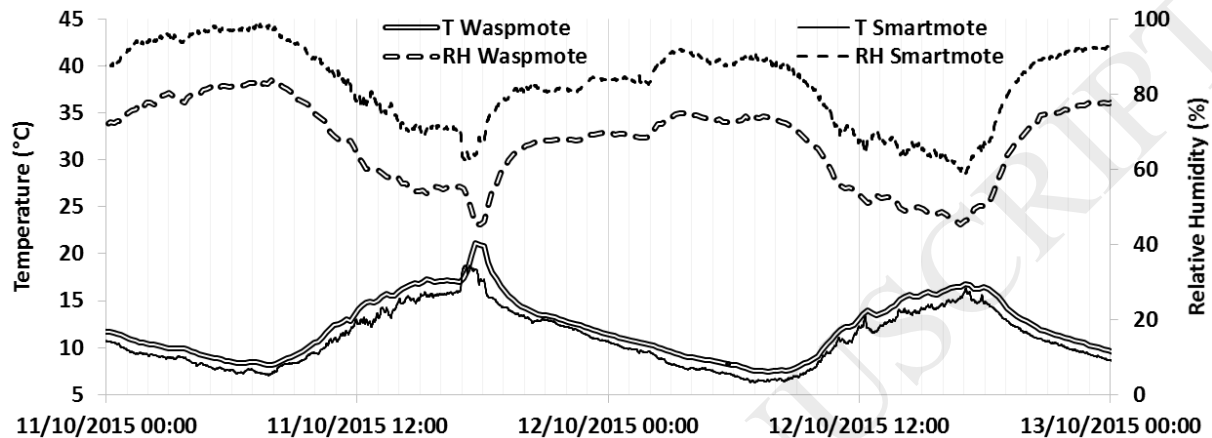


Fig.5 Temperature and relative humidity measured on street side by Smartmote and Waspote

4.2.1.2 Seasonal and daily variations

During the studied period the temperature was comprised between -8 and 45°C, with a mean of 13°C. The relative humidity varied from 18 to 100%, with a mean of 80%. During all the year, temperature reached its maximum values during the morning in the playground and in the evening in the street, due to the orientation to the church in relation to solar insolation (Fig.6).

The annual temperature and relative humidity variations could be divided in two periods of interest (Fig.7): (I) April-September (6 months) characterized by high temperature values and low relative

humidity, and (II) October-March (6 months) with relative humidity increased and temperature decreased.

From October to March, the recorded temperature varied from -8 to 20°C and relative humidity from 40 to 100%. In this period, 40.7% of the temperature values were found above the annual mean while humidity conditions exceeded the annual mean during 32.4% of the time.

During 15 days, whose 8 days in a row from 16th to 24th February, the temperature was comprised between -8 and 3°C and relative humidity at saturation indicating possible freezing phenomena.

The Fig.6 focused on the daily variations that highlighted two patterns of the temperature and the relative humidity distribution between playground and street side. During this period, the inversion of temperature between street and playground led to a delay between maximum peaks of both facades. This delay varied from 2 to 4 hours. The temperature on playground reached maximum values up to 5°C higher than on street. During this period, the mean of the daily amplitude of temperature was 12.5°C on the playground side, and 12.4°C on the street side (Fig.6).

From April to September, temperature varied from 5 to 40°C and relative humidity from 20 to 100%. In this period, 70% of the temperatures were above the annual mean while the relative humidity was below the annual mean value during 45.3% of the time.

The maximal temperature on the playground was followed directly by the maximal temperature on the street, without any remarkable time delay. Contrarily, in September, a temperature inversion delay of 5 hours was observed. The temperature on the street reached maximum values up to 4°C

higher than on the playground. Moreover, the mean of the daily amplitude of the temperature reached 16.4°C on playground, and 17.8°C on street side (Fig.6).

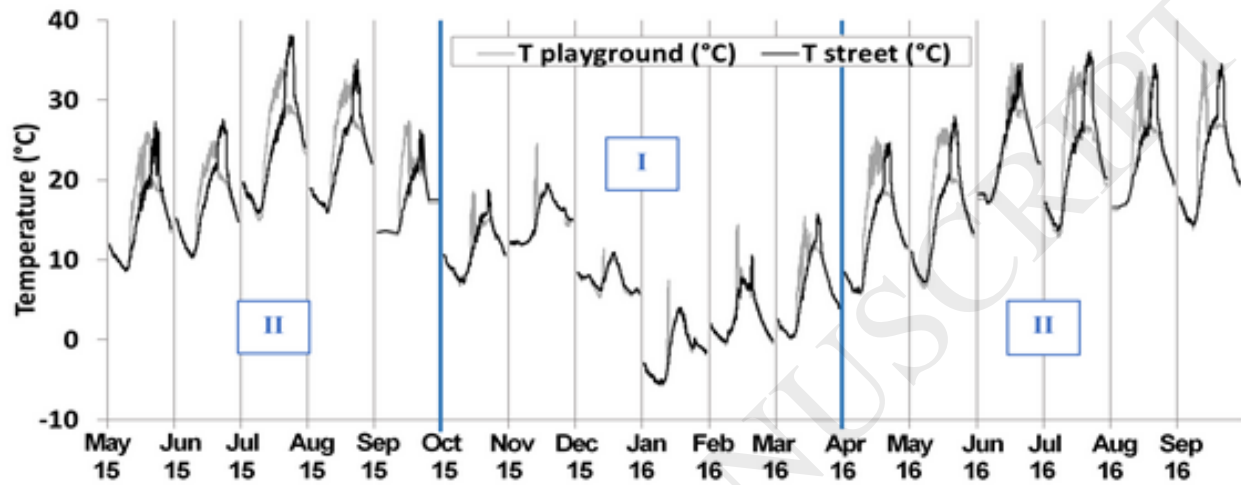


Fig.6 Typical daily variations of temperature of both façade per month

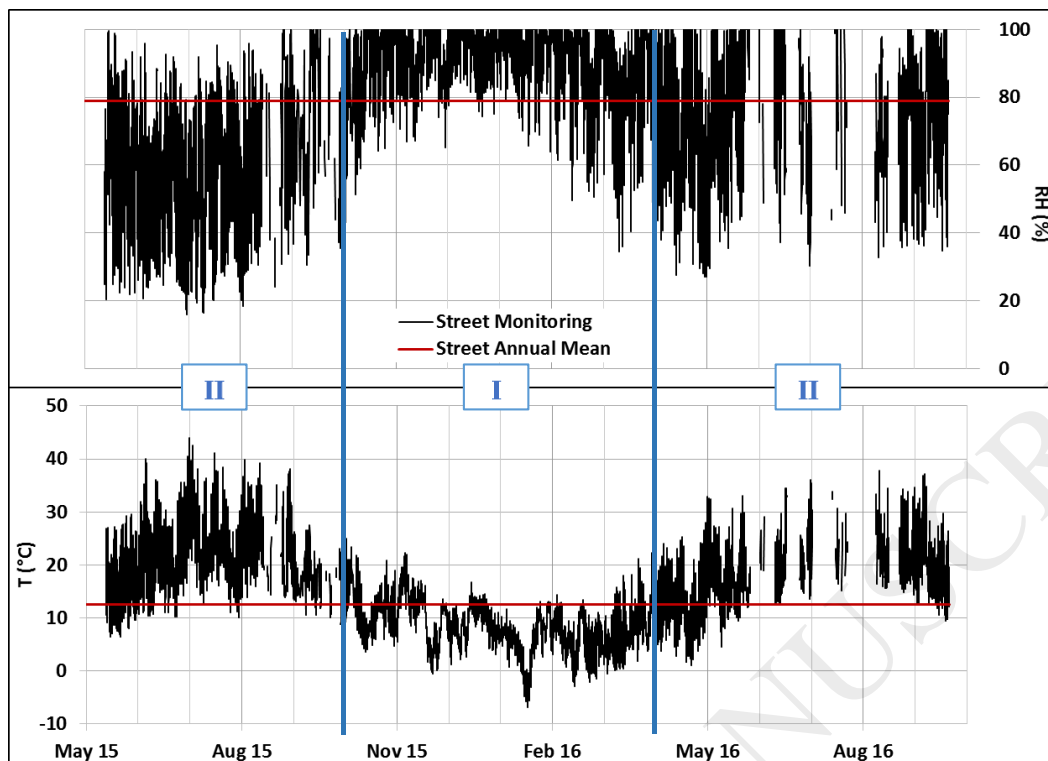


Fig.7 Temperature and relative humidity measured each minute by Smartmote and calculated mean from 10th May 2015 to 20th September 2016, divided in two periods, from October to March (I) and from April to September (II)

4.2.2 Atmospheric Pollutants

On the street side in October 2015, O₃ concentration was stable over time with a mean value about 59 ppb with a standard deviation σ of 39 ppb and a maximum of 237 ppb. In April and May, the mean values on both sides were very close, 34 ppb ($\sigma = 47$ ppb) on the playground and 33 ppb ($\sigma = 33$ ppb) on the street. However, the highest values were recorded on the playground side with a

maximum value of 369 ppb versus 204 ppb on the street side. The O₃ level had no evident trend in function of time, location or climatic parameters.

The mean value of SO₂ concentration was 220 ppb ($\sigma = 20$ ppb) and the maximum of 266 ppb. SO₂ variations were inversely correlated to temperature (Fig.8). The levels of SO₂ were under the limit of detection from April to May.

NO was under the limit of detection on playground and street side during all the recorded periods.

On street side in October 2015, the mean value of NO₂ was 82 ppb ($\sigma = 18$ ppb) and the maximum was 269 ppb.

The highest concentration of NO₂ was recorded in May at 295 ppb on the street side against 147 ppb on the playground. (Fig.8).

In April and May, from 8:00 to 20:00, the NO₂ values on the street were at least four times higher than on the playground. (Fig.9), with mean values equal to 15 ppb ($\sigma = 40$ ppb) on the street and equal to 3 ppb ($\sigma = 12$ ppb) on the playground. During the night, the values on both sides were similar and comprised between 0 and 5 ppb. Moreover, the lowest values were observed from 1st to 18th April, during the spring holiday period and especially on the playground side.

In both periods, the concentration followed the temperature variations over time (Fig.8 and Fig.9)

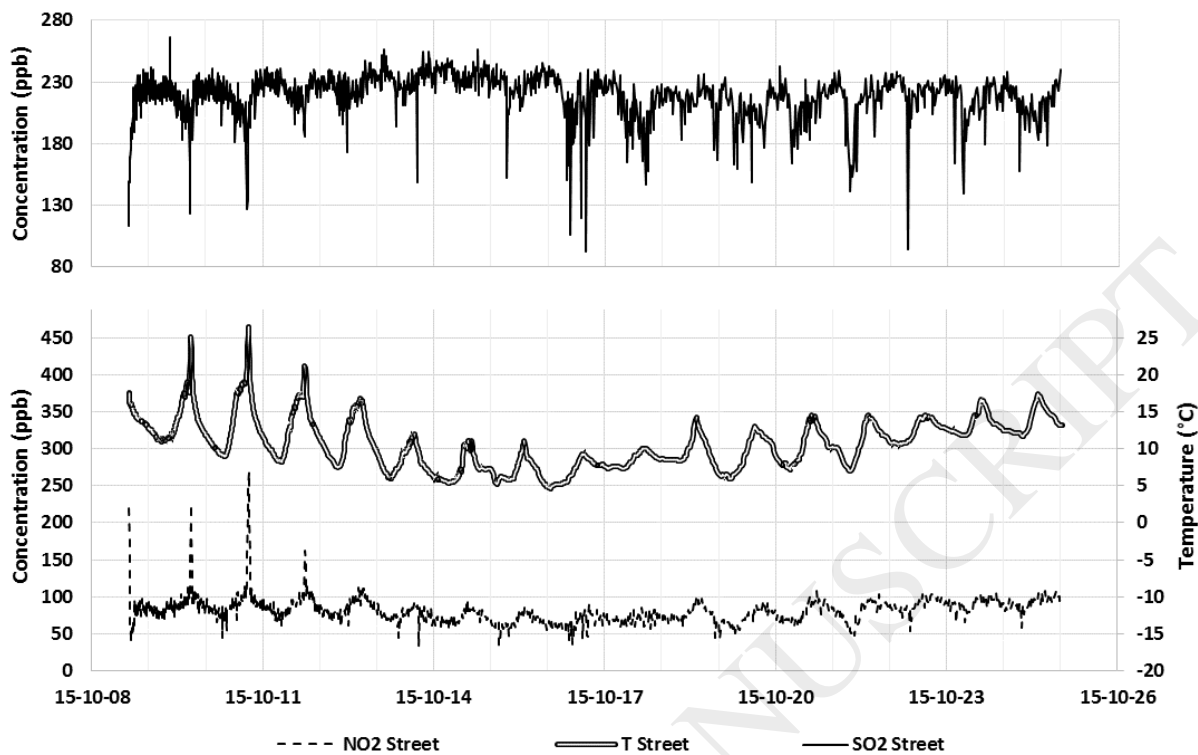


Fig.8 NO₂, Temperature and SO₂ measured on street side in October 2015

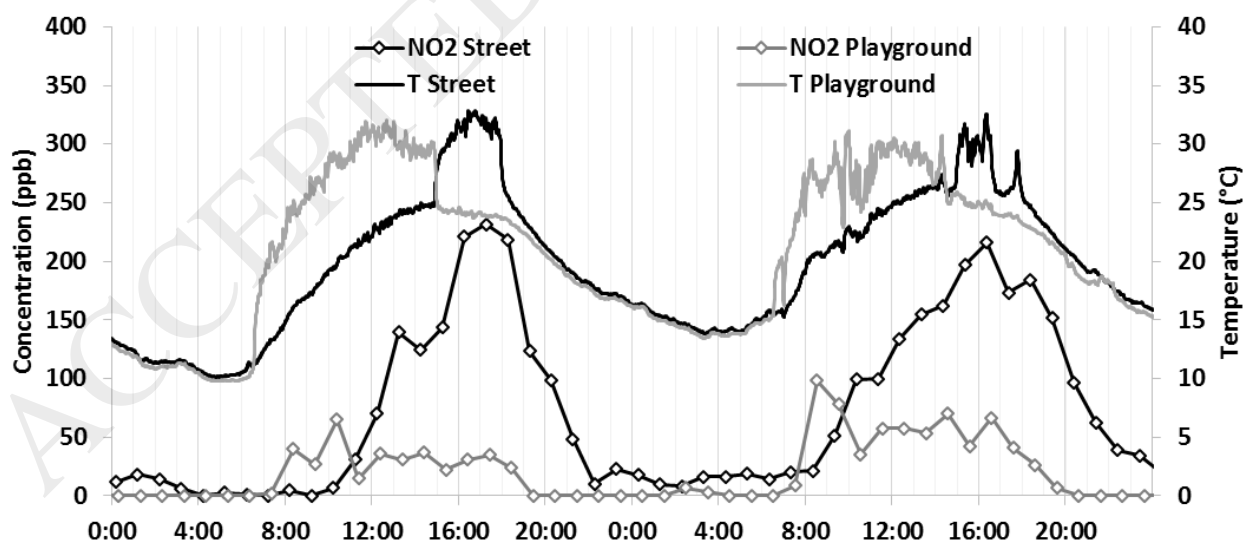


Fig.9 Temperature and NO₂ concentration on playground and street during the 6th and 7th May 2016

4.3 Façade Surface Monitoring

4.3.1 *Observations*

A previous study of decay forms was carried out to identify the incipient weathering on the restored façade (street) and the obvious alteration on the non-restored one (playground).

Four years after the restoration, on the street façade, chromatic alterations due to soiling (Fig.10.a) and biological colonization as green areas from the ground to few centimeters high (Fig.10.b) were clearly visible. On the playground façade, the main deterioration was material loss due to WWI projectile impact (Fig.10.d), blistering (Fig.10.e, f) bleaching and soiling (Fig.10.d, f).



Fig.10 Lower part of an arch (a), floor and stairs (b) of the street façade in June 2016, 4 years after the restoration. Projectile impacts (d), blistering (e,f) and soiling (f) on playground façade in June 2016

4.3.2 Colorimetry

The playground façade showed higher dispersion in all the parameters than the street façade. As shown on Table 2, the street values of L^* were very high (70-88) that meant light to very light colors. On the playground, a wide variation of values was measured, from maxima close to the street ones to minima low as $L^*=40$ (Fig.11). The a^* parameter showed less variations, reaching values of 3 on the playground façade. The parameter b^* showed yellower tones on the playground façade with values up to 25.

The Fig.11 confirmed that the differences from a position to another were more important on the playground, up to 9.5, than on street side, up to 4.2.

Concerning the two campaigns, no differences were observed from mean values and standard deviations except for the b^* parameter on street façade, those the difference between 2015 and 2016 appeared statistically significant using the Mann-Whitney tests. Nevertheless, some information could be extracted from maxima and minima evolution.

On the playground, the minimum values of L^* decreased of 5 units between the two measurements. (Table 2). This difference showed in Fig.11 (b, c) where the lowest values in 2015, located on the edges, decreased while the highest values, on the center of the column, remained stable.

On the street façade, the decrease of minimum and maximum L^* values were less important, lower of 1 from 2015 to 2016 (Table 2) and in a homogeneous way on all the surfaces (Fig.11.g, h).

On the street, the maximum values of a^* increased in 0.6 units (Table 2).

Fig.11 (d, e) highlighted a homogenous increase of b^* with time. On the street, the increase up to 2 from 2015 to 2016 was also visible on the cartographies (Fig.11.i, j).

Table 2 Mean, standard deviation σ , minimum and maximum of L^* , a^* and b^* parameters on playground and street in 2015, 2016 and the differences Δ between 2016 and 2015

		L^*				a^*				b^*			
		Mean	σ	Min	Max	Mean	σ	Min	Max	Mean	σ	Min	Max
Playground	2015	70.2	<i>1.0</i>	45.5	82.7	1.1	<i>0.2</i>	0.0	3.0	16.4	<i>0.7</i>	8.1	24.5
	2016	69.6	<i>1.0</i>	40.7	82.4	1.0	<i>0.2</i>	0.0	3.0	16.4	<i>0.7</i>	9.0	25.3
	Δ	-0.6	-	-4.8	-0.3	-0.1	-	0.0	0.0	0.0	-	0.9	0.9
Street	2015	79.9	<i>0.6</i>	70.7	86.9	1.3	<i>0.1</i>	0.5	2.0	11.8	<i>0.3</i>	9.0	16.5
	2016	79.4	<i>0.8</i>	70.0	85.1	1.3	<i>0.1</i>	0.3	2.6	12.6	<i>0.4</i>	9.5	18.7
	Δ	-0.5	-	-0.7	-1.8	0.0	-	-0.2	0.6	0.8	-	0.5	2.2

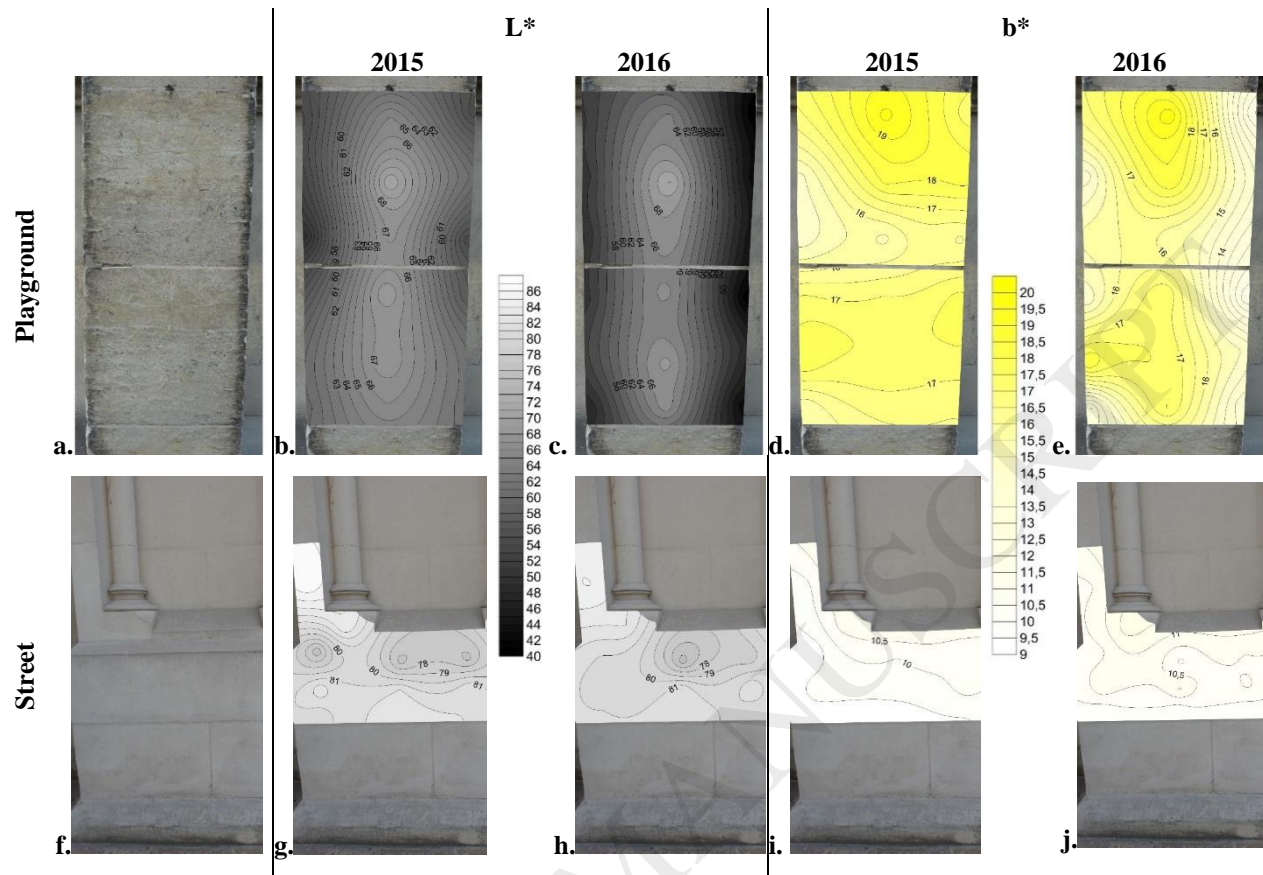


Fig.11 Column on playground facade (a, b, c, d, e) and street facade (f, g, h, i, j), representing the cartographies of L^* values in May 2015 (b, g) and May 2016 (c, h), and the cartographies b^* values in May 2015 (d, i) and May 2016 (e, j)

5 Discussion

5.1 Comparison of the two wireless sensor networks (WSN)

5.1.1 Setup

Environmental WSN allows a low cost and multi-parameters monitoring to assess the environmental effects on building stones at multiscale. In this study, two systems, Smartmote and Waspote, were used to monitor cultural heritage microenvironment. Both techniques count with advantages and disadvantages that will condition their utilization in future campaigns.

The main advantages of Smartmote sensors network are the reliability, excellent data transfer rate and link quality, showed in other studies under different outdoor and indoor conditions [22] and confirmed in this study. Smartmote is also a very low consumption system and consequently it allows a long-term running conditioned by the use of several batteries for the motes. In addition, the short-term measurements are very accurate (e.g. 1 data/min) that is very useful in daily cycle assessment.

The first disadvantage is that the distances between motes and base station need a previous study because of the signal strength and the presence of obstacles may induce a loss of data. The second one is that the base station must be plugged to electrical and internet sources to get real-time data. This condition is especially difficult to achieve in natural environments or old buildings not used for public purposes. The values of relative humidity obtained with Smartmote (mean about 80%) were well adjusted to the average value given by the local meteorological station (mean about 82%).

Waspote platform can be used as autonomous in energy and data transfer thanks to solar panel and 3G connectivity. Also its size favored its location and on-site setup. In cultural heritage

monitoring, this is a great advantage since most of the sites does not count with electrical or Ethernet connections.

Theoretically, the data recovery is 100% because the data are saved in a unique csv file that is sent immediately after each measurement. The data transfer rate depends on the 3G coverage during the upload. Consequently, the failure of the transfer does not affect the backup of the measurements in the csv file as long as the storage on the SD card is safe. Nevertheless, in real measurement conditions, Waspote showed recovery issues due to the unstable software. The main issue was the incompatibility between the function of file upload to the FTP server and the low energy consumption mode. This problem led to run out of energy. The recharge of the batteries by the solar panels was not enough for a long term monitoring, particularly in a low insulation area as Reims. Only if the measurement frequency is low enough, the night discharge of the solar panel would be compensated by the day charge.

5.1.2 Measurements Frequencies

Three different measurement frequencies were tested (Fig.4). One measurement per minute was acquired during the entire studied period with Smartmote. One measurement per 5 minutes was acquired on street side in October 2015 with Waspote, then one per hour from April to May 2016. The choice of the measurement frequency for Waspote depended on the energy consumption. The batteries were completely discharged after 15 days with one measurement per 5 minutes, and after 6 months with a frequency of measurement reduced to 1 per hour.

The green curve of the Fig.12 represents the temperature measured by Smartmote every minute during two days. The two other curves with lower measurement frequencies, every 5 minutes and every hour, were extracted from the green curve. The results obtained with a measurement every minute or every 5 minutes were very similar (Fig 15). Nevertheless, the curve made with one measurement per hour was too smooth to observe detailed daily variations.

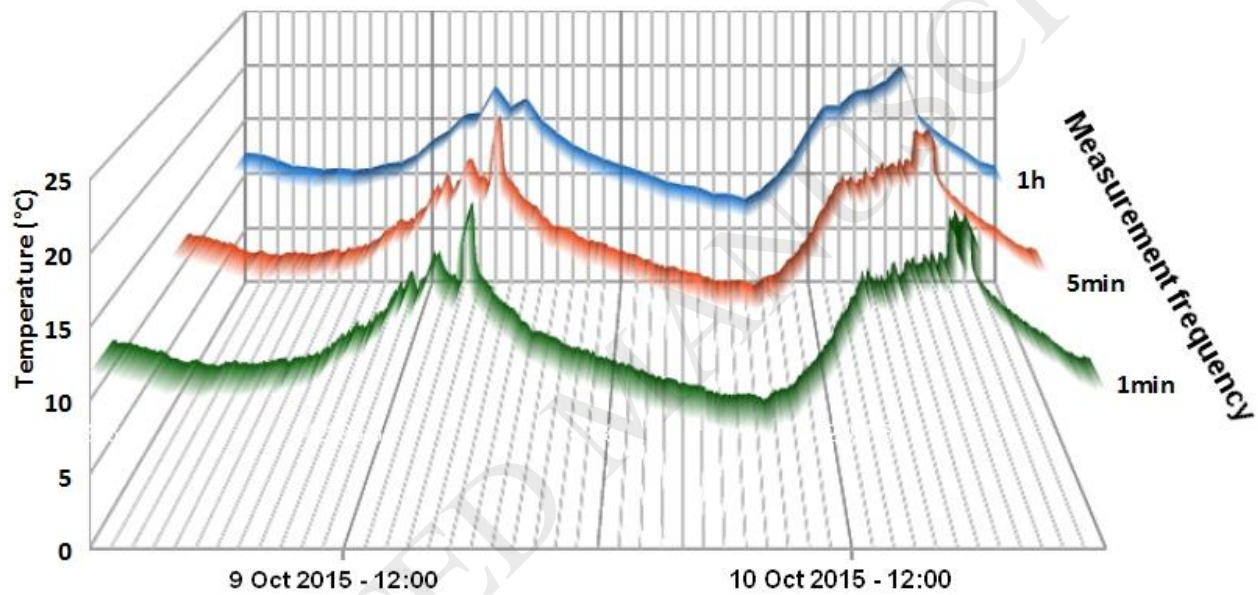


Fig.12 Comparison of temperature measurement with different acquisition frequency selected from the initial measurement coming from Smartmote every 1 minute

5.2 Effects of the environmental variations and pollution level on the evolution of building limestone surface

Stones are affected by thermal changes due to the differential expansion between components [41]. As recorded by both Waspnote and Smartnote, the thermal stress supported by the stones was significantly higher from May to August, with periods of great amplitude of temperature, up to 25°C. Taking into account the light colour of the stones, corresponding to an albedo over 43% [42], the temperature reached on the surface of the material is considered equivalent to the environmental temperature recorded by the sensors [43]. Thus, the stones were submitted to an average daily temperature variation of about 17°C during four months over a year that represented 120 cycles of expansion/contraction. Due to the porosity of the stone and the low differences in temperature, the expected damage will be mainly granular disaggregation at long term. This decay produced by the measured temperature changes does not induce the necessity of a prevention protocol.

The variations of humidity are responsible for biological colonization. The relative humidity was particularly high from October to January, above 60%. The colorimetric analysis showed a trend to greenish equally on the surface of both façades, namely the parameter a^* , which decreased slightly from 2015 to 2016, with a difference around 0.1.

In winter, from November to February, 15 daily freeze/thaw cycles occurred with temperature above -8°C and a maximum daily amplitude of 11°C. At long term, these shrinkage/expansion cycles lead to material loss decays due to the liquid water movement associated with ice formation inside the stone (blistering, scaling, delamination, granular disintegration) [3,5,6,8] as highlighted on the playground façade. On the restored façade, no signs of freeze thaw were observed. This frequency of cycles could be enough to produce early stage of structural damages depending on the amount of water within the stone although not to produce visible changes in one year. A

continuous monitoring is thus needed in order to know the time needed for freeze-thaw in producing a real damage on the stones.

On unsheltered areas, acid rain leaches the surface that dissolves limestones and Ca-rich materials. This effect leads to the whitening of the surface, that means an increase of L^* values, and even causes erosion at long-term [39,44,45]. The pluviometry values obtained in one year in Reims (500 mm) were too low to make measurable an erosion phenomenon.

On the analyzed surfaces, the L^* values only decreased, up to 5 on the playground and below 1 on the street. The playground surfaces were subject to an important blackening located particularly on areas already affected by soiling, while the street surfaces were equally and slightly blackened. The soiling is generated by the deposition of particles [16,39].

The atmospheric pollutants affect building stones differently and more or less directly.

The presence of sulfuric acid H_2SO_4 in the atmosphere leads to increase the acidity of rain that enhances the stone dissolution [3,46]. This acid is produced by the oxidation of SO_2 , and O_3 and NO_x catalyzed this reaction.

Moreover, on rain-sheltered surfaces, the gases are adsorbed on the stone surface, SO_2 is oxidized in sulfuric acid H_2SO_4 and NO_2 in HNO_3 . Those acids react with the calcite $CaCO_3$, corrode the surface and form sulfates $CaSO_4$ and nitrates $Ca(NO_3)_2$ [47,48]. The production of sulfates is characterized by a yellowing, namely an increase of colorimetric b^* values.

In this study, the level of NO was under the limit of detection during all the operating periods because of its high reactivity with O_3 to be transformed in NO_2 [15]. The diurnal variability of NO_2

was corroborated [12,13] with a strong relation with temperature (Fig.8) and also five times higher on April-May than on October. The level of O_3 was two times higher in October than in April-May. Moreover, the concentration mean of NO_2 was four times higher on the street than on the playground.

Moreover, high SO_2 concentration (220 ppb), compared to the national mean (2 ppb), was observed on the street side in October and was under limit of detection in April-May. No data were recorded on playground side in October due to the software programming issue. In addition, the b^* values increased more on the street side, with a difference of 2 in average in one year. Even if the b^* values on playground were initially two times higher than on street, the yellowing was less important over time, up to 0.5.

These values draw attention to two different facts. The first fact is the rise of pollutants in October compared to spring values. This is explained by the beginning of the heating of the buildings and surrounding dwellings (heating oil). During this month, the production of sulfuric acid could be widely enhanced, and thus the dissolution of stone increased, more particularly on the street façade. The second fact is the recording of high pollutants values on the street façade in relation to the playground. That was easily explained by the high traffic influence with the consequent emission of gazes and particles as products of the combustion.

6 Conclusion

In this research, two sensors platform were tested, Wasmote (Libelium) with a new remote data transfer by 3G for the cultural heritage monitoring and Smartmote, a reliable platform that works with a remote data transfer by Wi-Fi and has already been tested with good results [1,22].

The use of one or another wireless platforms must be defined in relation to the specific need of the study following the advantages and disadvantages of each.

Smartmote recorded two parameters in this study, T and RH, because this system is too expensive in an initial approach to record more parameters. Energy demand is the lowest with this setting, exhibiting great autonomy. The biggest inconvenient is that the base station depended on an electricity source and an Ethernet connection.

Wasmote is the best solution for the multi-parametric monitoring (O_3 , NO, NO_2 , SO_2 , T, RH) in a low cost way. Wasmote does not need a base station, using the 3G as remote transfer data, but the use of an external energy source as solar panel is strongly recommended for now and until the programming issues are solved.

The use of a low measurement frequency leads to the loss of information although using a high measurement frequency increases the risk to fasten the discharge of the battery depending on the implemented WSN. Indeed the Wasmote development is still in progress but it will have to improve its energy demand and get the same accuracy as Smartmote.

Despite the short duration of the study, from May 2015 to May 2016, the environmental monitoring coupled to colorimetric analysis and visual observation highlighted the following facts:

The temperature and relative humidity variations recorded in one year gave rise to an equivalent of 120 cycles of expansion/contraction of the stone and to 15 daily freeze/thaw cycles. The consequences on the stone generated by the temperature and relative humidity changes require

more than one year to be quantifiable. However, the data give trends to set the decay risk and the intensity of the decay agents.

The pollution level in O₃, SO₂ and NO₂ was particularly high (33 to 250 ppb) compared to the national means (2 to 40 ppb), due to the location of the monument in front of a high traffic street. On the street façade, the recorded concentration of NO₂ was four times higher than on the playground façade, and the concentration in SO₂ was also very high on the street side (220 ppb) that leads to a faster yellowing.

Finally, the complexity of the surrounding environment of a monument and the surface state of building stones involved the necessity of a detailed monitoring. Indeed the stones surface evolved differently in a same environment, as brought out by the colorimetry, and in addition each part of the monument is not subject to the same climatic conditions. These conditions must be taken into account to anticipate stones behavior with respect to the weathering.

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Conflict of interest

The authors confirm that there is no conflict of interest in this research.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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