Monitoring and Improvement of Indoor Environments in Cultural Heritage

J. Frick[1], M. Reichert[1], G. Baumbach[1], S. Song[1], A. Neuwirth[1], M. Krüger[2], K. Schmitt[3], J. Huber[3], M. Ebermann[4], L. Pockelé[5], A. Khanlou[6], A. Ekonomakou[6], J. Balau[7], G.M. Revel[8], M. Arnesano[8], F. Pietroni[8]

ABSTRACT

The Energy Performance of Buildings Directive (EPBD) [1] leads to energy-efficient buildings. However, refurbishment of existing buildings to an energy-efficient standard results in airtight buildings and affects the indoor climate. There is clearly a need for developing new methods for continuous detection of indoor pollution considering all key factors and for studying and identifying the best systems that allow an efficient control of the indoor environment.

Coordinated by the Materials Testing Institute (MPA) of the University of Stuttgart the EU-FP7 project "Cost-Effective Tools for Better Indoor Environment in Retrofitted Energy Efficient Buildings – CETIEB" was initiated on 1st October 2011 [2] with 15 industrial and research oriented partners from 6 European countries and Taiwan. CETIEB develops cost-effective, innovative solutions for better monitoring indoor environment quality and investigates active and passive systems to improve. The focus lies on developing cost-effective solutions to ensure a wide application of the resulting systems. These tools and systems could be used as well in cultural heritage buildings, museums, archives and showcases. This paper aims to show the possibilities with a focus on monitoring of indoor environments and the use of advanced mineral materials.

Keywords

Indoor Environment, monitoring system, air pollution, VOC sensor, thermal comfort, thermal insulating mortar

1. Introduction

New and refurbished buildings in Europe have to meet the requirements concerning thermal insulation and air tightness, as well as primary energy demand for heating, illumination, ventilation and air conditioning. In future net zero energy buildings will be the state of the art.

Refurbishment to an energy efficient standard leads to tight buildings (whole envelope: windows, walls, etc.) and affects the indoor climate. In case of refurbishment the inhabitants or users would not be accustomed to the new situation, therefore, the air exchange rates could be lower than required if no mechanical ventilation is installed or the system performance is not optimised. In addition, in trying to increase the energy performance of buildings, the indoor environment quality is often degraded due to the lack of exchange with the outdoor environment.

People in Europe spend more than 90% of their time indoors (living, working, and in transport). In more than 40% of the enclosed spaces, people suffer from health- and comfort-related complaints and illnesses. As early as 1984 the WHO reported an "increased frequency in buildings with indoor climate problems". The complexity of the problem and the building of related symptom clusters were later described as "Sick Building Syndrome" [3 – 6]. Major symptoms of Sick Building Syndrome observed are allergy, lethargy, headaches, dry eyes, irritated throat and skin. Indoor office air may also be associated with productivity and sick leave cases of the office's occupants [7, 8].

Improving the health and comfort of the European population in those spaces, consequently creates a huge potential of economic and societal benefits, manifested in increased productivity, reduced sick leave cases and medical costs, as well as the prevention of potential liabilities. There is clearly a need for developing new methods for continuous detection of indoor pollution integrating all the different parameters that interact, and to study and identify the best systems that will allow an efficient control of the indoor environment.

1 University of Stuttgart, Germany, Materials Testing Institute: juergen.frick@mpa.uni-stuttgart.de, manuela.reichert@mpa.uni-stuttgart.de, Institute of Combustion and Power Plant Technology: Guenter.Baumbach@ifk.uni-stuttgart.de, songshuyang1985@hotmail.com, Adolf.Neuwirth@ifk.uni-stuttgart.de

2 TTI GmbH – TGU Smartmote, Germany, krueger@smartmote.de

3 Fraunhofer Institute for Physical Measurement Techniques, Germany, katrin.schmitt@ipm.fraunhofer.de, jochen.huber@ipm.fraunhofer.de

4 InfraTec GmbH, Germany, m.ebermann@infratec.de

5 R.E.D. srl, Italy, luc.pockele@red-srl.com

6 S&B Industrial Minerals S.A., Greece, A.Khanlou@sandb.com, A.Ekonomakou@sandb.com

7 SCHWENK Putztechnik GmbH & Co. KG, Germany, balau.johann@schwenk.de

8 Università Politecnica delle Marche, Italy, gm.revel@univpm.it, m.arnesano@univpm.it, f.pietroni@univpm.it

1.1 General objectives of the project

The main objective of the project "Cost-Effective Tools for Better Indoor Environment in Retrofitted Energy Efficient Buildings – CETIEB" (www.cetieb.eu) is to develop innovative solutions for better monitoring the indoor environment quality and to investigate active and passive systems for improving it. The focus lies on cost-effective solutions to ensure a wide application of the developed systems:

- Development of monitoring systems (wireless and/or partly wired) to detect indoor environmental comfort and health parameters. A modular version will be developed to allow end users a quick check of the indoor air quality.
- Development of control systems to optimize the indoor environment quality and energy efficiency. Measures are innovative passive plaster materials using photo catalytic and phase change materials, plant based biofilters, and active air flow controlling components. Provision of alarm values for action, if automatic control is not sufficient.
- Modelling of indoor environments for the assessment and validation of monitored data to optimise the control parameters and systems.

The project structure is given in Figure 1 and the partners in Table 1.

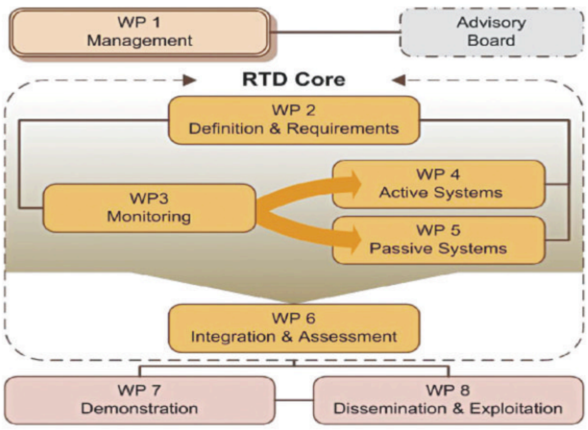

Figure 1 Structure of the project

1.2 Possible use for cultural heritage related buildings and objects

Indoor air quality, illumination and thermal comfort are parameters that affect cultural heritage buildings and objects. Improper climatisation and illumination in museums or VOC emissions (volatile organic compounds) in showcases and archives could be harmful to precious objects. Therefore some tools of the CETIEB project could be used to assess and improve indoor environments with special regard to the requirements for cultural heritage buildings and objects. The following technologies are of special interest:

- VOC detection: In showcases with normally a low air exchange and storage facilities in archives sometimes show high amounts of VOC (e.g. acetic acid, formaldehyde, formic acid, etc.) with concentrations up to several ppm or mg/m3 [9], [10] potentially harmful to objects. Up to now only sampling over a period of time with additional analysis is available. CETIEB aims to develop systems for VOC online monitoring in real time.
- Illumination: The intensity of light and the fraction of ultraviolet light are of special interest for galleries and show cases. Within the CETIEB project cost-effective RGB sensors and broadband UV and visible light sensors will be evaluated and included in the monitoring system.
- Thermal comfort: State of the art for HVAC systems in thermostat-controlled environments is the measurement of temperature at one point in a room. By monitoring the Mean Radiant Temperature in a room, as developed in CETIEB, more precise information is provided to assess the thermal comfort. Effects of discontinuous flow of visitors and the impact on works of art can be included in the analyses. Moreover, such a system could find a wide applicability in living environments in some countries (e.g. Italy) where several buildings are part of the cultural heritage.
- Thermal insulation: Energy efficiency for cultural heritage buildings is a difficult task. Sometimes it is only possible to insulate inner walls because of highly decorated façades. Within CETIEB a thermal insulation and storage render system based on mineral binders will be developed. The system is diffusion open and can be adapted to the specific needs of cultural heritage buildings.
- Photocatalytic plaster: The render system can include a photo-catalytic finish with TiO_2 as the active component to reduce VOC and other harmful organic substances. At the moment the long wave part of the ultraviolet spectrum (UVA) is used to activate the photo catalyst. New active components on the market work with longer wavelengths in the visible region of the spectrum as well. Several combinations of active lighting and photocatalytic plaster could be useful for the applications in cultural heritage (e.g. showcases).

2. Useful technologies

2.3 Monitoring and measurement tools

One objective of the project is to develop technologies needed for monitoring relevant parameters that affect indoor environment. The idea is to go beyond the traditional and existing environmental temperature and humidity monitoring systems, extending the possibilities to monitor human health and well-being factors inside buildings. The CETIEB project is aimed to deliver a cost efficient wireless or partly wired system especially designed for monitoring indoor environment parameters (Figure 2).

Table 1 CETIEB project partners.

Consortium
Universität Stuttgart (MPA (coord.), IGE, IFK)
Delap & Waller EcoCo Ltd., Dublin
S&B Industrial Minerals S.A., Athens
Solintel M&P S.L., Madrid
Universita Politecnica d. Marche, Ancona
R.E.D. SRL, Padova
TTI GmbH - TGU Smartmote, Stuttgart
Fraunhofer-Gesellschaft, IPM Freiburg
InfraTec GmbH, Dresden
CEA INES, Grenoble
STAM SRL, Genova
Schwenk Putztechnik GmbH, Ulm
Consorzio TRE, Napoli
FCC Construccion SA, Barcelona
NTUST, Taipei

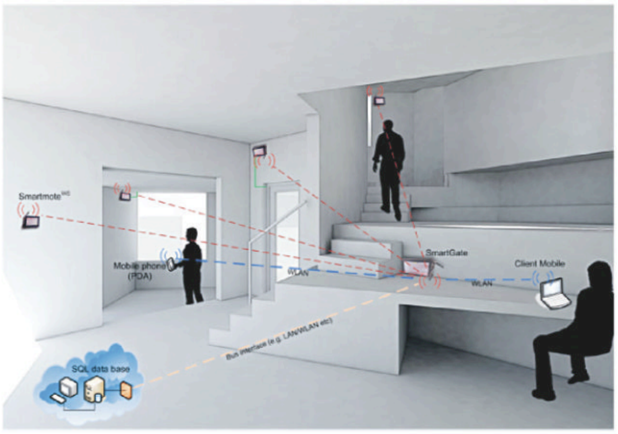

Figure 2 Cost-effective portable wireless monitoring system.

The monitoring and measurement technologies developed within the project will be a step forwards in terms of:

- Provision of cost-effective and simple to use monitoring systems that allow for monitoring of a large variety of indoor environmental factors.
- Provision of advanced sensor technologies to better measure and assess indoor environment factors with respect to human health and well-being.
- Provision of data collection and analysis software that could be used to better monitor, assess, evaluate and control the indoor environment.

Short and long-term monitoring systems require the application of specific sensors. Although a lot of commercial sensors for determining air quality and comfort are available, there is demand to develop adequate sensors that are optimised for the monitoring task. This could be with respect to cost-effectiveness or higher accuracy, precision or reliability. Such sensor technologies could be either integrated into the portable wireless monitoring system or could be integrated into active control systems for permanently improving the indoor environment. Several types of sensors will be developed within the project, e.g. VOC (with medium and high sensitivity), CO_2, thermal image sensors (infrared sensors for multi-point temperature analysis), and indoor light spectrum.

2.3.1 Detection of VOC

One key challenge within the project is the detection and monitoring of VOC for the assessment of health related parameters. Actually, there is increasing demand to obtain more spectral information in many gas sensing applications, particularly with regard to the analysis of multi-component mixtures, reducing cross-sensitivities between adjacent and overlapping absorption bands, and lower detection limits. Infrared absorption spectroscopy as a broadband and selective measuring principle potentially fills this gap. Based on substance-specific absorption spectra (see Figure 3) the discrimination between the components of a mixture and a quantitative measurement of their concentrations is possible. In particular the wavelength ranges of 3 – 5 µm and 8 – 11 µm (mid and long wave infrared) are of interest. The hybrid integration of a bulk micro machined high finesse Fabry-Pérot filter and a pyroelectric detector results in a very compact spectrometer module. Existing instrument designs can be easily adapted to such a tuneable detector. InfraTec has developed such devices for the spectral range of 3 – 5 µm [11, 12] and 8 – 11 µm [13, 14] Fraunhofer IPM integrated the module in a compact measurement device (Figure 4). The measurement time for one spectrum with most stable conditions is around 8 min.

As a VOC representative acetaldehyde (CH_3CHO, peak absorption at 3.65 µm) was measured in nitrogen in the concentration range from 0 to 25 ppm (see Figure 5). The achieved resolution is better than 5 ppm. From literature the maximum values of single VOCs like acetic acid (CH_3COOH) could be up to 2.3 ppm (5698 µg/m^3) in new showcases [9] or up to 1.9 ppm in storage cabinets (average 4700 µg/m^3) [10]. Therefore the real-time detection of single VOCs is visible if the detection range could be further improved.

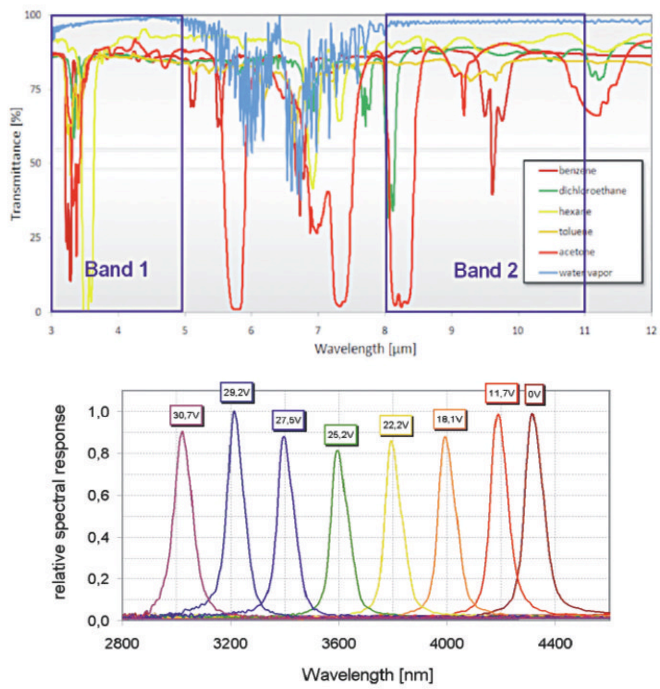

Figure 3 Left: Infrared absorption spectra of typical VOCs and water vapor (high concentrations). The most interesting bands are marked. Right: Spectral response of the micro spectrometer module from InfraTec.

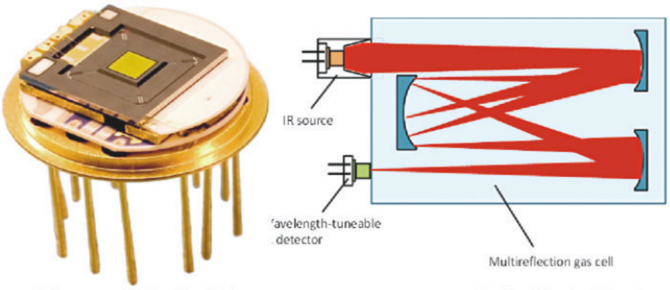

Figure 4 Left: Micro spectrometer module (InfraTec). Right: Integration in a White cell (Fraunhofer IPM).

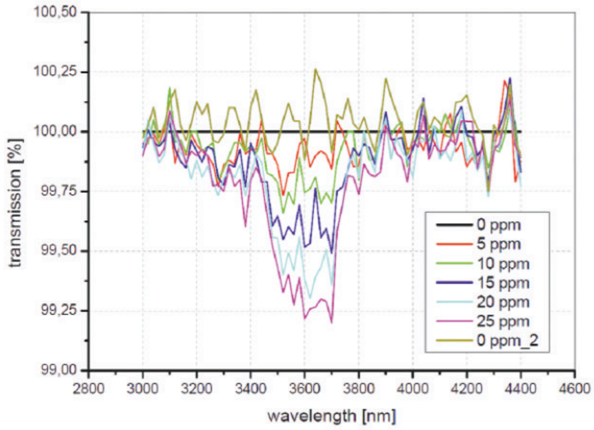

Figure 5 Measurement of acetaldehyde in N2 from 0 to 25 ppm in 5 ppm steps.

2.3.2 *Illumination*

Illumination is a major task in museums, archives and for cultural heritage objects. To avoid degradation intensity, spectrum and colour should be controlled [15]. TTI-Smartmote and RED have developed, integrated and assessed cost-effective light sensors in the monitoring system. Three types of sensors are available: Two global UV (SU-100 sensor, Apogee Instruments) and visible light sensors (SP-110 pyranometer, Apogee Instruments), mostly useful for intensity assessment, and one so-called RGB sensor, based on TAOS TCS 3414 CS with diffuser and filter developed by RED, to assess the colour of light (Figure 6).

The visible region of light is between approximately 380 and 780 nm. The obvious way to measure this would be by a spectrophotometer, which detects the light intensity in function of the wavelength at intervals of few nm.

An alternative way is the use of a so called RGB sensor. These sensors are silicon based photo-sensors measuring radiation from 300 nm to 1100 nm overlapping the photopic spectral sensitivity of the human eye. The unwanted radiation (IR and UV) needs to be filtered. In addition, Red, Green and Blue filters based on the colour matching functions defined by the CIE [16] are reproducing the RGB values as if they were observed by the human eye. Now, instead of hundreds of values coming from the measurement of the spectrum by a spectrophotometer, only four values are given by the sensor: clear (only filtered for IR and UV), Red, Green and Blue. These values can be transformed into XYZ values in the CIE colour space. Obviously, the filters of the sensors do not match completely the colour matching functions of the CIE and need to be calibrated.

Figure 6 Light sensors in test situation. Left: RGB. Middle: global visible. Right: global UV.

Within the CETIEB project such a low-cost sensor solution for light intensity and light spectra was realised. The sensor has been developed to determine the Colour or Correlated Colour Temperature of 'white light' with the objective to simulate the natural colour temperature of daylight in function of the time of the day and the latitude of the location.

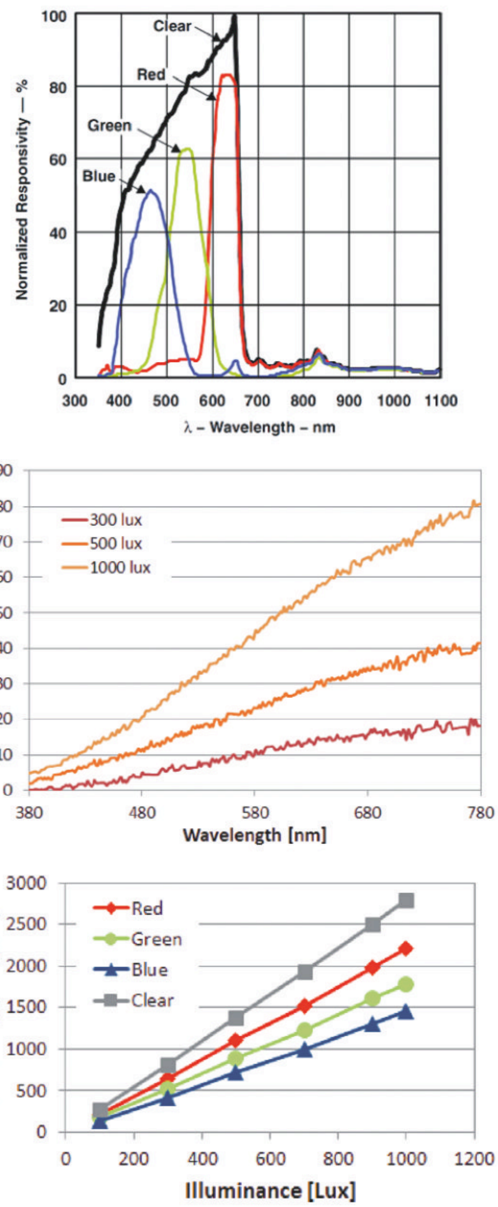

Figure 7 Top: Spectral responsivity of RGB sensor [17]. Middle: Spectrum of halogen bulb light source, measured with spectrophotometer. Bottom: Calibration measurement.

For cultural heritage purposes the sensors can be evaluated and calibrated against measurements with spectrophotometers (see Figure 7). The first step would be a single assessment of light sources (e.g. LEDs, sun behind window glass, halogen lamps, etc.) with sensors and spectrophotometer. The spectrometer is necessary to control if unwanted parts of the spectrum are present, because the sensors cannot detect emission lines due to the low resolution. Then the sensors can be used for online monitoring of indoor illumination.

2.3.3 Thermal image sensors

Another aspect of the CETIEB project is the development of a low-cost infrared system for real-time measurement of human thermal comfort performed by Università Politecnica delle Marche. The monitoring device, including a set of sensors in a bulk unit, can be installed on the ceiling of the occupied room. The system measures on indoor surfaces and environment to derive comfort parameters (as Predicted Mean Vote – PMV) for several positions in the space. Further features are the detection of people present or triggering fire alarms automatically.

Since the measurement is not a single-point one and is not only based on temperature, the HVAC control strategy can be improved which offers potentials of energy savings.

PMV is the average comfort vote, using a seven-point thermal sensation scale, predicted by a theoretical index for a large group of subjects when exposed to particular environmental conditions.

As indicated in (1) the PMV is affected both by environmental parameters (air temperature t_a, relative humidity RH, mean radiant temperature t_r, air velocity v_a) and subjective parameters such as the metabolic rate M and the clothing insulation I_{cl}.

$$PMV = f(t_a, RH, t_r, v_a, M, I_{cl}) \qquad (1)$$

Mean Radiant Temperature (MRT, t_r) appears to be one of the most influential parameters in order to provide a good estimation of PMV. Therefore a measurement system for a good estimation of this parameter is needed. The IR system is adopted to provide real-time measurement of thermal images of the indoor environment and derive comfort parameters. Basics of the system are shown in [18]. Advanced signal processing algorithms allow the calculation of thermal comfort parameters by taking into account all sources and thermal loads in the room (see Figure 8).

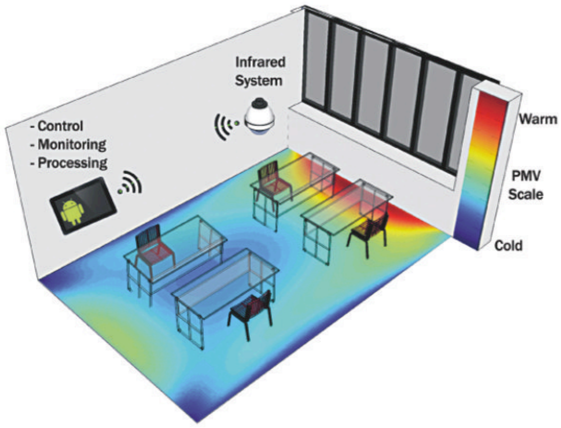

Figure 8 Principle sketch of IR system scenario.

The thermal image sensors find several fields of applications, from industrial to sanitary, public and residential, where providing an adequate comfort condition to occupants is essential. The system could be of special interest also for museums and cultural heritage buildings with respect to energy efficiency, thermal comfort of visitors and objects, and security (e.g. fire detection).

2.4 Advanced materials

2.4.1 Thermal insulation

Another goal of the project are mineral-based thermal insulating, highly porous, lightweight renders by the use of expanded perlite developed by Schwenk and S&B (see Figure 9). Actually, expanded perlite will inhibit the transfer of heat from inside to outside and vice versa and therefore the variation between maximum and minimum indoor temperature is decreased in comparison to the regular plasters used. With an additional layer of render containing phase change materials (PCM), the heat capacity of mortars will be increased and walls will adsorb or release thermal energy from the indoor environment creating much easier a comfortable environment for humans.

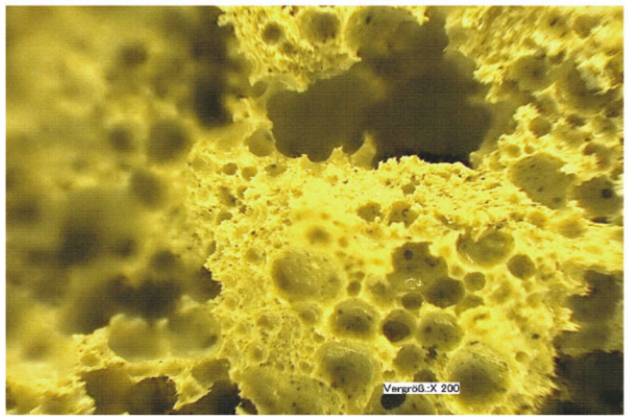

Figure 9 Visible porosity from around 0.1 to 2 mm of the developed insulation render (scale 200 times).

Figure 10 Application of the insulation render in one step up to 5 cm.

Table 2 Technical parameters of the developed renders.

Parameter	Insulation render	Storage render
Dry density [g/dm³]	360	435
Compressive strength [N/mm²] after7 days after 28 days	0.71 1.04	1.90 1.83
Thermal conductivity [W/(m² K)]	0.077	0.082
Shrinkage after 28 days [mm/m]	1.2	1.4
Water vapour diffusion equivalent air layer thickness [cm]	15,8	25,6

The render system is machine workable and could be installed in layers up to 5 cm in one step (Figure 10). The technical parameters are listed in Table 2.

Important for cultural heritage buildings is the mineral base. At moment the binder is a special sulphate resistant cement for the use in modern buildings. The system is diffusion open and can be adapted for the use in cultural heritage buildings by varying the binder system (e.g. lime or roman cement).

The combination of insulation and thermal storage is attractive for the insulation of inner walls at cultural buildings where an outer insulation is impossible due to decorative façades.

2.4.2 Photocatalytic plaster

The photocatalytic plaster will be used as thin finish layer on the render system. It uses the ability of nano-Titania (TiO_2) to degrade harmful substances. To reduce the high costs of the catalyst it is combined by a special procedure with perlite microspheres which enhance the effect by scattering the light (Figure 11).

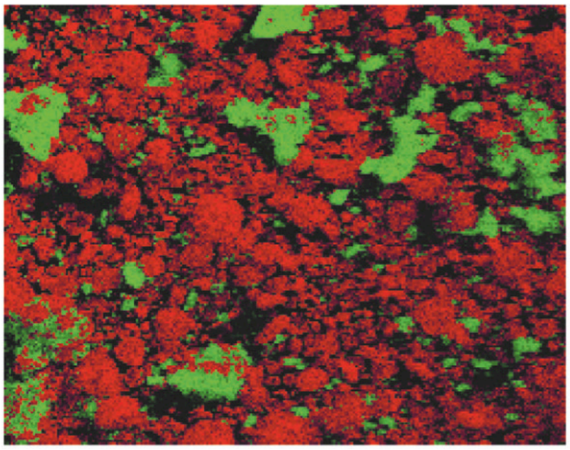

Figure 11 Disposed TiO2 on perlite micro spheres.

Various tests have been performed to find the most promising compositions. Some of them using the catalyst/perlite powder are shown in Figure 12. Measurements on the plaster layer were performed with NO_x as test analyte, whilst measurements with VOC are still on-going. At the moment the long wave part of the ultraviolet spectrum (UVA) is used. A plaster containing a new modified TiO_2 catalyst which can be activated already by light in the visible region is under investigation.

If the new materials work sufficiently with light in the visible region, the plaster could be used directly to reduce harmful VOCs in cultural heritage applications (e.g. showcases). Otherwise combinations of active lighting and photocatalytic plaster can be developed, e.g. an active box which filters the air.

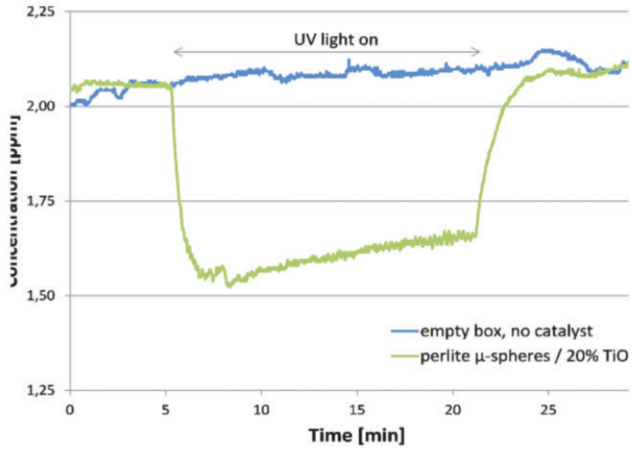

Figure 12 VOC degradation by TiO2 on perlite (powder sample).

3. Conclusions

CETIEB is an on-going European project which develops solutions for the assessment and improvement of indoor environments in respect of health related aspects and thermal comfort. It has been shown that some major developments are very useful for the monitoring and enhancement of indoor environments in cultural heritage buildings and objects like showcases or storage cabinets.

At the EWCHP conference CETIEB wants to disseminate the results and discuss possible applications in the field of cultural heritage.

4. Acknowledgements

This work was funded by the European Commission, Grant agreement no. 285623: CETIEB project, under the 7th Framework Programme.

5. References

[1] DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings, Official Journal of the European Communities, EN, L 1/65 – L71, 4.1.2003.

[2] European project: Cost-effective tools for better indoor environment in retrofitted energy efficient buildings – CETIEB. FP7 Grant agreement no. 285623, www.cetieb.eu

[3] World Health Organization (1986). Indoor air quality research. EURO Reports and studies. 103: 1-64

[4] Environmental Protection Agency. Indoor Air Facts No. 4 (revised) Sick Building Syndrome. http://www.epa.gov/iaq/pubs/sbs.html (retrieved December 2009).

[5] Bakke et al. 2008. Symptoms, complaints, ocular and nasal physiological signs in university staff in relation to indoor environment–temperature and gender interactions. Indoor Air 2008; 18:131–143

[6] Björnsson E, et al. 1998. Symptoms related to the Sick Building Syndrome in a general-population sample: associations with atopy, bronchial hyper responsiveness and anxiety. Int J Tuberc Lung Dis 1998; 2:1023-1028.

[7] Mendell M.J. 2007. Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: a review Indoor Air 2007; 17; 259-277

[8] Mendell M.J., Heath G. A. 2005. Do indoor pollutants and thermal conditions in schools influence student's performance? A critical review of the literature Indoor Air 2005; 15; 27-52

[9] Schieweck, A.; Salthammer, T. 2011. Indoor air quality in passive-type museum showcases. Journal of Cultural Heritage 12 (2011) 205–213

[10] Volland, G.; Hansen, D.; Knjasev, V.; Meyer, F. 2013. Air Quality in Storage Cabinets of the „Schinkel's Legacy at the Kupferstichkabinett Berlin – Causes and Effects. Accepted to be published in Restaurator. International Journal for the Preservation of Library and Archival Material.

[11] Neumann, N., Ebermann, M., Kurth, S., Hiller, K. 2008. Tunable infrared detector with integrated micromachined Fabry-Pérot filter, J.Micro/Nanolith. MEMS MOEMS 7(2), 021004-01 - 021004-9 2008.

[12] Ebermann, M., Neumann, N., Kurth, S., Hiller, K. 2009. Design, Operation and Performance of a Fabry-Pérot-Based MWIR Microspectrometer, IRS² Conference, Nürnberg, 2009.

[13] Ebermann, M., Neumann, N., Hiller, K., Gittler, E., Kurth, S. 2010. Recent Advances in Expanding the Spectral Range of MEMS Fabry-Pérot Filters. Proc. SPIE, Vol. 7594, 2010.

[14] Neumann, N., Ebermann, M., Gittler, E., Meinig, M., Kurth, S., Hiller, K. 2010. Uncooled IR Sensors with Tunable MEMS Fabry-Pérot Filters for the Long-Wave Infrared Range, IEEE SENSORS 2010 Conference, 2010.

[15] Delgado, M.F.; Dirk, C.W.; Druzik, J.; WestFall, N. 2011. Lighting the World's Treasures: Approaches to Safer Museum Lighting. COLOR research & application. Wiley, 36(4), 238-245.

[16] CIE, 1986. Colorimetry, second edition. Technical Report CIE 15-2-1986. Vienna, Austria: CIE Central Bureau.

[17] TCS 3414 CS datasheet at www.taosinc.com

[18] Revel, G.M.; Sabbatini, E.; Arnesano, M. 2012. Development and experimental evaluation of a thermography measurement system for real-time monitoring of comfort and heat rate exchange in the built environment. Meas. Sci. Technol. 23(3), 035005 (12pp).