Journal of Thermal Analysis and Calorimetry, Vol. 56 (1999) 1219-1232

ENVIRONMENTAL RESEARCH FOR ART CONSERVATION AND ASSESSMENT OF INDOOR CONDITIONS SURROUNDING CULTURAL OBJECTS*

M. Odlyha, N. S. Cohen, R. Campana and G. M. Foster

Chemistry Department, Birkbeck College, University of London, 20, Gordon St.
London WC1H OAJ, UK

Abstract

This paper describes the results and conclusions of research directed towards the development and evaluation of a chemical sensor which would provide information on the quality of indoor environments surrounding cultural objects. In our case these objects were paintings housed in major European galleries and the main objective is their preservation through an improved understanding of their microenvironment. The concept was to prepare and expose test tempera paintings which would behave as dosimeters and integrate the environmental response at these locations. Artificial ageing of similar samples was performed to provide a means of calibrating the test paintings. Samples from the test paintings were compared with artificially aged samples and this enabled the sites to be ranked in terms of their suitability for exposure of cultural objects.

Additionally, novel methodology involving piezoelectric sensors was designed for monitoring the relative humidity and temperature of the microenvironment of paintings. Dielectric techniques were also used for measuring the effect of relative humidity fluctuations on artists' materials and novel non-invasive dielectric techniques in the microwave region were used for the determination of their moisture content.

Keywords: environmental monitoring, indoor environments, museums and galleries, risk assessment, tempera paint dosimeters

Introduction

The concept of using test tempera paintings as dosimeters in galleries and the resulting data from their exposure at selected sites has been recently reported [1–3]. The work was conducted in collaboration with the FOM Institute (Amsterdam, NL) and IROE (Florence, It) and supported by the EU Environmental Programme. The results presented in this paper focus on the Birkbeck contribution and contain thermoanalyti-

---

* Plenary lecture.

1418-2874/99/ $ 5.00

Akadémiai Kiadó, Budapest
Kluwer Academic Publishers, Dordrecht

cal and spectroscopic data i.e. the results of evaluation of some of the pigmented strips in the test tempera paintings by differential scanning calorimetry (DSC), dynamic mechanical thermal analysis (DMTA) and infrared spectroscopy (FTIR).

Sample preparation

A set of differently pigmented temperas was prepared. This has been fully described elsewhere [1], but a brief outline of the procedure is given here. The tempera medium was prepared according to a recipe used by restorers at the Opificio Pietre Dure (Florence, Italy). The yolk was separated from the white of an egg. The foam from the egg white was then discarded and the liquid part was mixed with the yolk. A few drops of vinegar and a solution of mastic in white spirit were also added. The paint was then deposited (wet layer thickness 200 μm) on a sheet of Melinex using a film applicator. It was allowed to cure for a period of three months before it was subjected to artificial ageing.

Artificial ageing

The paint films were cut into strips and exposed in a light ageing cabinet at the Conservation Department of the Tate Gallery (London) for 4, 8, 16, 32 and 64 days. The lighting facility uses 6 Philips TLD94 58 Watt daylight rendering fluorescent light filtered with a perspex VE ultraviolet filter with a cut-off wavelength of 400 nm. Light intensity was 18000 lux. Cooling fans maintained the temperature at 4–5°C above ambient and 5–10% below ambient RH. This gave average values of 28–29°C and 27–28% RH during the period of ageing.

The effect of pollutants was also studied. Samples were exposed for 4 days to flows of SO_2 and NO_x (10 and 16.7 ppm respectively) in a chamber maintained at a temperature of 23°C and RH at 55% in the TNO Laboratories, The Netherlands [1].

Thermal ageing of samples was carried out in an oven at the Conservation Department of the Tate Gallery at a temperature of 60°C and 55% RH. No light was admitted to the oven. Samples were exposed for 7, 14 and 21 days.

Natural ageing

Other samples, after their period of curing, were exposed in selected major art galleries and historic monuments. A range of pigmented and unpigmented samples (strip size 35×10 mm) was selected and mounted on a dark card supported in a frame (14×19 cm) to create a test tempera painting which was then exposed at the chosen site.

In this paper data from only three of the inorganic pigmented temperas will be discussed in more detail, namely lead white (basic lead carbonate), smalt (quartz sintered with cobalt oxide) and Naples yellow (lead antimoniate). Results are presented from the artificial ageing experiments and compared with the natural ageing of samples from the same batch exposed at the sites for a nine month period. Sites were chosen to provide a range of environmental conditions for the test tempera paintings (Table 1). Each site is labelled with a three letter code: Tate Gallery (TAT),

Table 1 Summary of field site data

Site	RH/%	T/°C	Light intensity/ lux	UV intensity/ μW/m^2	Number of visitors
ALC	20–80	6.5–28	80–1000	7500 (UV-A)	417 461
RDO	28–64	16–29	2–12	0	negligible
RNW	42–71	17–24.5	<100	0	848 791
SAC	54–68	8.8–21	30–600^a	30 (UV)	8 200
TAT	40–60	19–22	<200	0	190 000^b
UFF	30–60	13–30	120–150	500–700 (UV-A)	1 044 350

a) Occasional direct sunlight gives illuminance of up to 30 000 lux

b) Number of visitors to the Clore Gallery specifically, rather than to the entire Tate Gallery

Rijksmuseum, Amsterdam (RNW and RDO), Uffizi Gallery, Florence (UFF), Sandham Memorial Chapel, Burgclere, UK (SAC) and Alcázar, Segovia, Spain (ALC). Two sensors were placed in the Rijksmuseum. One was exposed in the Nightwatch room (RNW), diagonally opposite the famous painting by Rembrandt with a further sensor in the depot 'Oost' storage area, which is located in the attic (RDO). The sensor was placed in the middle of one of the storage racks where, like the paintings, it cannot be reached by direct sunlight. Overall light intensities are also very low.

In the Tate Gallery the ERA dosimeter was exposed in the Clore Gallery close to the painting 'The Opening of the Walhalla' by Turner (1775–1851), N00533, oil on mahogany. The light, temperature and relative humidity levels in the Clore Gallery are controlled.

At the Uffizi Gallery, the ERA sensor was located in Leonardo's room on an S-SW wall next to 'The Baptism of Christ' by Andrea Verrocchio and Leonardo da Vinci (painted between 1472–1475) and opposite the predella by Luca Signorelli on which colorimetric measurements have been performed [4]. Previous monitoring in the Botticelli room of the Uffizi Gallery has detected in addition to NO_x, observed levels of nitrous and nitric acid indoors (formed from the reaction of NO_2 and H_2O in heterogeneous phase) of up to 12 μg m^{-3} [5].

In Sandham Memorial Chapel, Burghclere, UK, the sensor was placed to the upper left of the painting 'Sorting and Moving Kit-Bags' on the north wall. At this location the sensor, just like the painting, on some occasions could be illuminated by sunlight entering through one of the windows, although blinds are normally used to avoid high levels of illumination by direct sunlight. At this site piezoelectric sensors, which are discussed later in this paper, were also used to monitor variations in values of RH and temperature close to the surface and back of the painting to determine whether a gradient developed across the painting.

The ERA sensor at the Alcázar was placed in the Cord Room. This name derives from the cord that surrounds it. According to Segovian legend, Alphonse X (the wise) ordered this Franciscan cord to be placed there as a sign of penance for his excessive pride. The walls are decorated with a tapestry showing the Battle of Arcila, a 15th cent. panel of the annunciation, another of St. Barbara and St. Lucia and a triptych altar made of carved and gilded wood showing different saints and martyrs. The lighting in the room was unfiltered daylight. The high value registered by the paint dosimeter needs to be taken into consideration for the future preservation particularly of the tapestry in the room.

After artificial and natural ageing, samples were evaluated by DSC, DMTA and FTIR. DSC provides information on the thermal stability of the material. Thermooxidative degradation studies were made to determine the chemical state of the paint at the start and after its exposure to the various ageing conditions. The changes on ageing or exposure to certain environments were evaluated in terms of a change in the peak shape which could be directly linked, with the aid of mass spectrometric data, to the chemical changes in the samples [1].

DSC evaluation

Samples for DSC were prepared as follows: they were lightly scraped from the Melinex substrate and the powdered samples were weighed (1 to 2 mg) in open micro Al crucibles (5 mm O.D.) on a Sartorius electronic micro balance. They were then heated in O_2 (60 cm^3 min^{-1}) in a Shimadzu DSC–50 analyser at 10°C min^{-1}. DSC measurements were made in triplicate.

DSC curves are presented with individually scaled vertical axes to emphasise their similar features. All the pigmented tempera control samples are shown to illustrate the characteristic shape of the DSC curves (Fig. 1). The intensity of the peak maximum is high in the case of sienna due to the higher medium content. In the case of the pigmented basic lead carbonate and azurite there are additional contributions which appear from the pigment alone.

The main response in each case is from the oxidative decomposition of the binder. DSC curves of unpigmented tempera and also of egg components such as

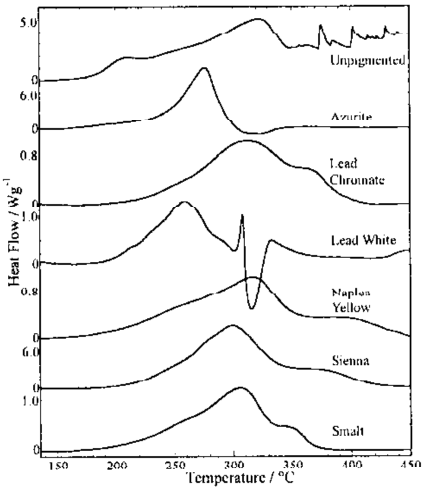

Fig. 1 DSC curves for the thermooxidative degradation of the differently pigmented tempera control samples

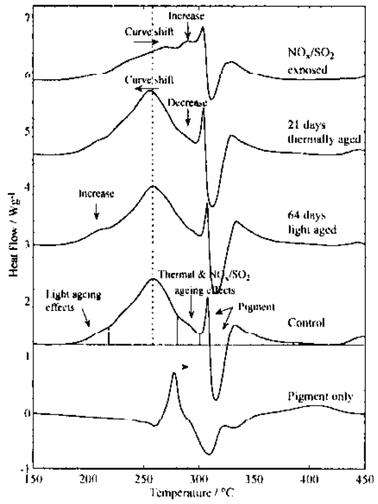

Fig. 2 DSC curves for the thermooxidative degradation of the artificially light aged basic lead carbonate (lead white) tempera samples

cholesterol provide evidence for this. The overall shape and temperature of this peak is modified through the presence of different metallic ions from the pigment.

After artificial ageing, with light, temperature or pollutants (NO_x, SO_2), similar changes can be seen in several of the pigmented temperas. Curves for lead white tempera are shown in Fig. 2. Light ageing causes changes at the low temperature end of the curve. Information on the chemical nature of the structures which evolve in this region was obtained from mass spectrometry [6]. Increased levels of saturated fatty acids (palmitic, stearic) were identified as cholesterol levels were depleted and its oxidation products were formed. The formation of these products with changes in the chemical composition are then responsible for the changes in the shape of the DSC curves.

Quantification of the changes described above was achieved by calculation of the partial area of the low temperature region of the curve (180–220°C in the case of lead white). A similar calculation was performed for the smalt tempera samples. In this case the partial area of the curve was calculated between 140–235°C and this is plotted against days of light ageing in Fig. 3. The graph can then be used to evaluate the degree of light ageing experienced by the samples exposed in the museum galleries. The values for the different sites are shown on the vertical axis on the right hand side of the graph.

Values for samples from sites such as Sandham Memorial Chapel (SAC) and the Alcázar (ALC) are high (Fig. 3) and exceed those for the 64 days artificially light aged sample. This is due to the environmental conditions at the sites (Table 1) and the variable and high light levels, which include UV radiation.

The accepted procedure for determining the amount of damage suffered by an object on exposure to museum conditions is to determine the total light exposure received (calculated from the product of time and light level) [7]. An interesting point from Fig. 3 is that all gallery sites show light exposure levels significantly higher

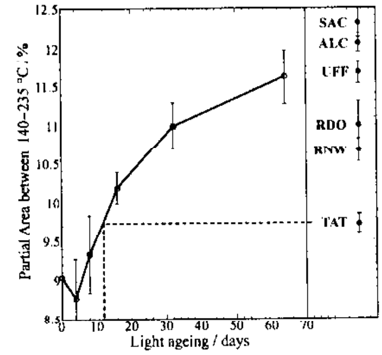

Fig. 3 Calibration graph for the artificially light aged smalt tempera samples

than would be expected, given that average museum light levels of 200 lux over the period of nine months' exposure is calculated to be 504 Kluxh. Tate Gallery, the lowest, shows ageing equivalent to 12 days at 18000 lux which can be calculated to give a value of 5.2 Mluxh. This clearly exceeds the expected level. RNW and RDO give values equivalent to about 28 and 30 days of light ageing and 11.2 and 13.8 Mlux respectively and the Uffizi Gallery those of 29.4 days and 60 Mlux. Alcázar and Sandham Chapel sites are off the scale of the graph.

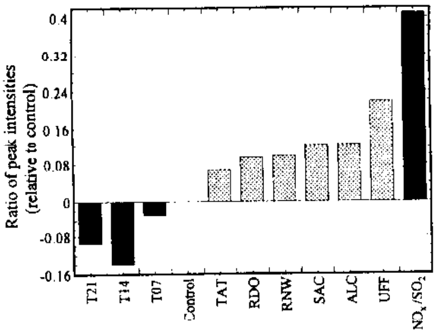

Fig. 4 Artificially aged (thermal and NO_x/SO_2) and naturally aged smalt tempera samples

Additionally, it is known that RDO (Rijksmuseum store) is a dark site and thus should be below TAT (Tate Gallery). The resulting order for the sensors, however, indicates that the Tate sample is the least light aged, which is somewhat surprising. It may be the case that the low temperature features on which the calibration is based are affected by other factors, such as pollutants (NO_x, SO_2), as well as light. These additional factors will not affect the artificially light aged samples, and thus the calibration curve is accurate. However, they will be present in the sensors.

Results from thermal and NO_x/SO_2 studies show that changes affect the high temperature part of the DSC curve. NO_x/SO_2 effects are particularly noticeable and result in an increase in the area of the peak at 300°C. A calculation was made based on the change in peak ratio of the peak at the high temperature end of the DSC curve (where NO_xSO_2 effects are dominant) to the major peak. Thus a plot is shown of the relative height of the peak between 335–400°C for the sensor samples alongside the data from the artificially aged thermal and NO_xSO_2 aged samples (where the relative height is expressed as a fraction of the total height of the main peak). The plot in Fig. 4 shows the difference in relative height between each sample and the control.

The ranking of exposed sensors shows that the Clore Gallery (in the Tate Gallery) exhibits the least chemical change followed by the Rijksmuseum store and Nightwatch, which are about the same, and then Sandham Chapel and Alcázar, which are higher and are about the same and finally the Uffizi Gallery which appears to be the most affected. Hence the order according to predominantly light ageing effects is:

TAT<RNW<RDO<UFF<ALC<SAC

In terms of predominantly NO_xSO_2 effects the order is as follows:

TAT<RDO=RNW<SAC=ALC<UFF

The position of the Uffizi sensor indicates that levels of pollutants are higher than at the other sites.

DMTA evaluation

DMTA was used to determine the physical state of the pigmented samples with the parameter of interest being the glass transition temperature (T_g). Samples were measured on a Melinex substrate. Although this substrate had many advantages and gave the paint coating enough mechanical stiffness to be measured the two transitions for the Melinex or PET (polyethylene terephthalate) polymer had to be considered. These occur at (1) beta transition –70°C (1 Hz) and the alpha transition at 120°C (1 Hz). The sample response fortunately could be measured between these transitions. Samples were measured in triplicate in the single cantilever bending mode and an applied frequency of 1 Hz and over the temperature range of –130 to 200°C at 3°C min^{-1}. Sample size was 5 mm×5 mm. Sample thickness was measured using a digital micrometer and was of the order of 150 μm.

Data for the differently pigmented temperas are presented as plots of tanδ *vs.* temperature (°C). tanδ is a ratio of the loss modulus (E'') to the storage modulus (E') as mentioned above. It can also be taken as the glass transition temperature (T_g). Since it is a ratio measurement differences in sample thickness are minimised. The tanδ traces are shown for the unaged (control) pigmented tempera samples together with the unpigmented sample and the Melinex substrate (Fig. 5). All the traces have been baseline shifted to give a zero tanδ value at –70°C.

Figure 5 shows that smalt tempera has the strongest tanδ response and this is followed by measurable peaks present in azurite and Naples yellow temperas. The unpigmented tempera sample has a weak tanδ response. An explanation for this can be given in chemical and physical terms; (1) induced polymerisation of the binding medium by the metallic lead, cobalt and copper ions: the cobalt ion has been shown to form network structures with lecithins composed of cross-linked aggregates [8] and

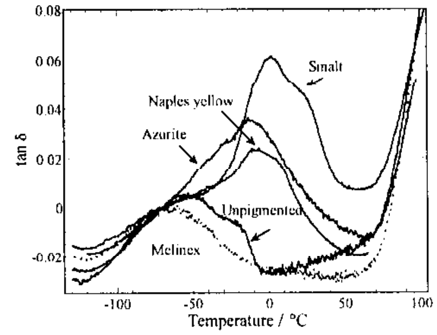

Fig. 5 DMTA curves (tanδ *vs*. temperature) for differently pigmented tempera samples

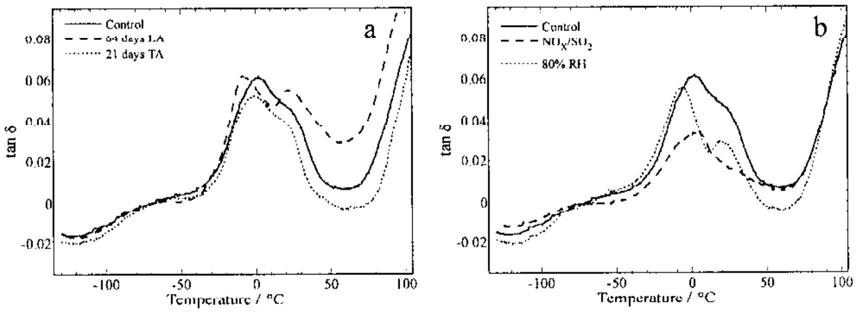

Fig. 6 DMTA curves (tanδ *vs*. temperature) for artificially aged smalt tempera samples. The curves have been vertically offset for clarity

(2) high pigment volume concentration in the smalt tempera sample. The pigmented tempera samples used in this study contained, on average, approximately 90 wt% pigment as determined by thermogravimetry [1]. Additional smalt tempera samples that were prepared with higher medium content (ca 40 wt%) did not show the equivalent high tanδ values.

The DMTA tanδ curves for artificially aged smalt tempera samples are shown in Fig. 6. To demonstrate the full range of effects, curves have been plotted which exhibit the most extreme changes in response to light, relative humidity, thermal and pollutant exposure with respect to the control which is also shown. The characteristic changes for the light aged samples can be described in terms of evolution of structures at higher temperatures with a shift of +17°C from 3°C to 20°C.

The precise shape and position of the complex DMTA curve was dependent on the pigment used. For example, Naples yellow tempera, unlike smalt tempera, appeared more as a single peak, but as can be seen from the fitted curve of the control sample shown in Fig. 7, this peak was complex and contained two main components, the major one, with a peak area 81% of the total, centred at –5°C and a minor feature at –43°C. In comparison, the main feature in smalt tempera control was located at

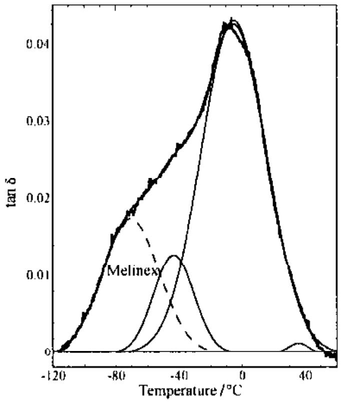

Fig. 7 DMTA curve (tanδ *vs.* temperature) for the Naples yellow tempera control sample, showing individual fitted components plus the Melinex (PET) peak

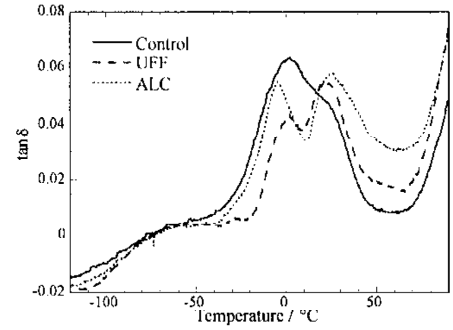

Fig. 8 DMTA curves (tanδ *vs.* temperature) for smalt tempera samples, naturally aged at selected gallery sites

2°C with the minor feature at 22°C. The behaviour of Naples yellow tempera on ageing was, however, similar to that in smalt tempera, with a small positive shift in peak temperature of the main feature with light ageing (to +2°C).

The DMTA curves of the smalt tempera sensors that had been naturally exposed in the museum and gallery sites are shown in Fig. 8. All show the enhanced evolution of high temperature structure characteristic of ageing, but it is interesting to note that the smalt sensor from the Clore Gallery in the Tate Gallery, where the light levels and atmosphere are controlled, is the least changed and is similar to the control, whereas that from the Alcázar, for example, where light levels are high, is significantly different. Figure 8 further shows that the curves for ALC and UFF move to higher temperatures in relation to the control smalt sensor. This demonstrates that the difference in conditions does influence the response of the smalt sensors and that the effect can be measured as a shift to higher temperatures. According to the data and the degree of change the sites have been ranked as follows:

Control<TAT<RDO<RNW<SAC<UFF<ALC.

The ranking confirms the order obtained through other techniques and also from the separate glass sensor measurements [1].

FTIR evaluation

In the infrared spectra of egg tempera the carbonyl peak was selected for monitoring changes in the tempera paint. The marker for the lipid component at 1746 cm^{-1} represents the carbonyl region from C=O bonds in the fatty acid esters. This broadens as the lipid portion is oxidised with the formation of long chain free fatty acids [9]. which have their absorption peaks at the lower wavelength of 1710 cm^{-1}. This is seen in the DSC curves as an increase in the low temperature shoulder of the broad exothermic peak and has been confirmed by mass spectrometry [1]. Changes in the width of the carbonyl peak were measured.

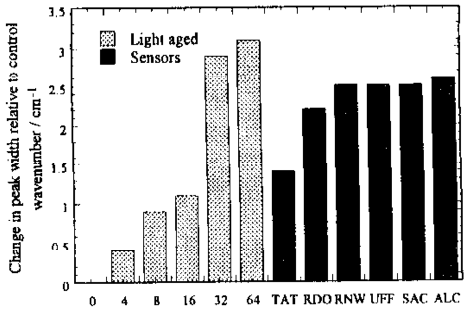

Fig. 9 Change in carbonyl peak width for basic lead carbonate tempera sensors: artificially aged (light) and sensors exposed at field sites relative to the control

The basic lead carbonate tempera samples, for example, show a steady increase in carbonyl peak width. In the unpigmented samples, the sensors all lie within 8 and 16 days of the light aged controls. The presence of the lead white pigment, however, locates the field site sensors between 32 and 64 days of light ageing (Fig. 9). The pigment has enhanced the oxidation effect due to the additional catalytic effect of the Pb^{++} ion.

Additional microclimate monitoring of RH and temperature

In the context of this project, localised relative humidity and temperature sensors were constructed. These are based on coated piezoelectric sensors where the polymeric coating absorbs and desorbs moisture over a range of relative humidities.

The piezoelectric humidity sensor is based on a modified quartz crystal resonator, where the frequency of oscillation of the crystal is modified by the properties of its coating. A coating was specifically chosen which reversibly absorbs and desorbs moisture over a range of relative humidities [10]. The sorption of water vapour results in a change of mass and this in turn results in a shift in oscillation frequency of

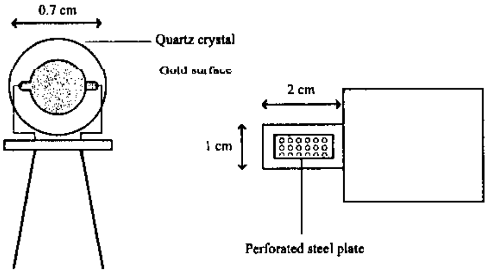

Fig. 10 Piezoelectric humidity sensor together with complete sensor in housing

the crystal that can be directly related, after calibration, to the RH value. Figure 10 shows the crystal resonator (5 mm gold coated surface onto which the polymer coating is applied) and also the sensor in its housing. The sensor surface is protected from dust by PTFE tape just behind the perforated steel cover. The size of the cover is about 2 cm×1 cm. Spacers above and below the steel plates were made to ensure a small distance between the steel plate and the surface of the painting.

The precise frequency of oscillation depends upon a number of factors, some of which are fixed, such as the thickness of the quartz, and some which may be modified, such as the mass at the surface of the device. The deposition of a coating layer will change the surface mass and therefore the oscillation frequency. The difference between the original fundamental frequency and the fundamental frequency after coating (the coating frequency) gives an accurate measure of the mass of deposited material. This may be quantified by the Sauerbrey equation:

$$\Delta F = -2.3 \cdot 10^6 F_0^2 \Delta m/A$$

where ΔF is the change in frequency in Hertz, F_0 is the fundamental frequency of the device in MegaHertz, Δm is the change in mass in grams and A is the active area in cm^2. It can be seen, using the Sauerbrey equation, that changes in mass of nanogram proportions will be detectable. Typical coating frequencies of 10 kHz are used which, depending upon the density of the material, equate to coating thickness of approximately 1 μm.

Sorbent materials commonly selected are polymers which are used as stationary phases gas chromatography since the sorbent properties are well characterised and the stabilities are known. However, in principle any volatile material may be used to coat the crystal. Once the crystal is coated with the sorbent material further changes in mass (and thus frequency) will occur as gas phase materials are absorbed or desorbed by the coating material. This is a partitioning phenomenon (as occurs on a gas chromatography column) between the gas phase and the condensed phase (coating material). The use of hydrophilic materials as coating materials allows, after calibration, the relative humidity of the ambient environment to be calculated. Calibration of the sensors was performed under laboratory conditions to relate frequency shift to given relative humidity values.

Platinum resistance thermometers were included in the completed modules to provide the corresponding temperature values. The hardware set-up consists of a standard PC connected via a GateWay unit to a number of sensor modules. The connection between the GateWay and the sensor modules utilises the SensNet protocol, a multi–drop asynchronous serial communication protocol.

Calibration of temperature and RH was performed by placing both sensors (in their housings) into atmospheres of known RH and temperature. The values read from the sensors which were expressed in machine units were then related to the known RH values. The latter were then entered into the calibration software of the computer. The sensors were also tested on a painting set up in the laboratory under an imposed RH gradient [c.24% (above) and c.70% (below)] [3].

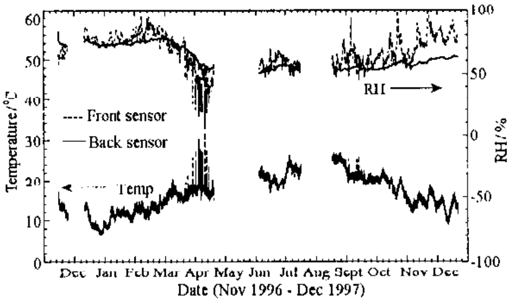

Fig. 11 Overall results from temperature and humidity monitoring at Sandham Memorial Chapel

The system was installed at Sandham Chapel alongside the ERA tempera sensors, the aim being to determine whether gradients of relative humidity and temperature exist across individual paintings. Measurements were made over an extended period by sensors located both in front and behind a selected painting. From the data (Fig. 11) it is possible to see the higher temperature and lower humidity in the summer months than the winter months, as expected given that there is no control of the environmental conditions within the chapel. It is also clear that the environment behind the painting is shielded somewhat from the extremes in front, although it is still possible to see changes that mirror the effect in front. Closer examination of the data [1] shows that there is an increase in temperature during the day with a drop at night. More specifically, however, the large spikes in both the temperature and RH data for April occur around noon and are caused by direct sunlight from either the windows or through an open door falling directly on the painting.

Dielectric measurements

Monitoring RH and temperature is also essential in studying the effect of humidification processes used in the treatment of paintings. At this stage the piezoelectric sensors have not as yet been applied to this area. Instead some basic research into the effects of humidification has been made using dielectric analysis both in the Gigahertz and lower frequency regions (10^{-4} to 10^5 Hz). In the Gigahertz region novel methodology has been developed for the direct determination of moisture content using a micro coaxial probe in conjunction with a microprocessor controlled network analyser [11, 12]. The network analyser generates the microwaves which are then reflected by contact with the sample. The reflection coefficient via a complex mathematical function makes it possible to measure directly the permittivity or dielectric constant of the sample over a frequency range (e.g. 1 GHz to 20 GHz) or at a single selected frequency as a function of time. The measured permittivity at the selected frequency and at a given temperature can be compared to that of water alone, to obtain the moisture content of the sample.

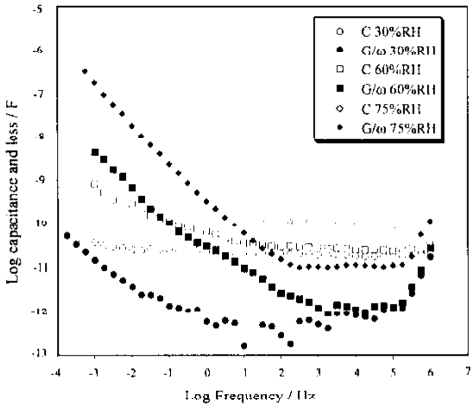

Fig. 12 Log capacitance (C) and loss (G/ω) *vs.* log frequency for mixed Prussian blue and basic lead carbonate paint film at 30%, 60% and 75% RH

In the low frequency range (10^{-4} Hz–10^{5} Hz) dielectric analysis was also used to study the humidification processes on painting canvases and paint films [11]. Typical curves for paint samples are shown. Two curves are presented for each sample at a particular value of RH. The upper curve in each case (G/ω) is the trace for the imaginary component of the complex capacitance, the lower curve (C) is the real component of the complex capacitance. Values for these parameters change with the exposure of the paint films to different RH environments (Fig. 12) and are accompanied by changes in the moisture content of the sample and in the glass transition temperature. The low frequency dielectric measurements have been used to provide some information on the mechanism of moisture transport through the samples [13].

Conclusions

Test paintings can be used as dosimeters for testing the quality of indoor environments. The results show that the sample exhibited in the Clore Gallery (within the Tate Gallery) is the least affected both from the DSC data for the small sensor and from the FTIR data for the unpigmented and basic lead white sensors. The interesting outcome from the DSC data is the fact that the effect of light can to some extent be distinguished from that of pollutants and temperature. This indicates that conditions at the Uffizi Gallery may need to be improved in terms of providing better filters for NO_x and SO_2 pollutants. With respect to the Alcázar and Sandham some improvement in the overall control of the environment is recommended as the data show that in all cases they appear in a high risk category. At the Alcázar some attention could be given to providing UV filters on the windows of the Cord room; in the case of Sandham Chapel blinds have already been installed.

The other outcome of this work is that it directly addresses one of the major problems facing chemists when they become involved in conservation science and are interested in understanding the mechanisms involved in ageing of materials. This is the preparation of fresh samples and how they are to be aged and the measurement of ageing effects. The next stage will be to determine whether there is similarity with naturally aged and historical materials. The preparation of such samples and understanding of effects of ageing is fundamental to research in conservation science where there is a need to understand the mechanism of change in historic materials. The other aspect is understanding changes which are made during the conservation treatment of paintings involving humidification and for this purpose dielectric analysis has been employed.

* * *

This research was supported by the Directorate General for Science, Research and Development, Commission of the European Communities, Grant no. EV5V–CT94–0548 and the authors are particularly grateful to Dr. Julia Acevedo. The authors would also like to thank: Mr. R. Belluci (Opificio delle Pietre Dure, Florence), Dott. I. D. van der Werf (FOM–AMOLF), Dott. M. Picollo (CNR–IROE) for the preparation of the tempera paints, Mr. S. Hackney and Dr. J. Townsend (Tate Gallery) for the light ageing, Dr. Havermans for NO_x and SO_2 and Christina Sitwell and Linda Bullock of the National Trust (UK), for their assistance at Sandham Chapel. Also thanks to Dr J. M. Slater (Birkbeck College) and Mark Appleton (Quartz Technology Limited, Northwood, London) for the construction of the piezoelectric sensors and the operating software. Finally, thanks to our ERA partners, Professor Dr. J. J. Boon and Drs. O. van den Brink (FOM, NL) and Dr. M. Bacci and Dott. M. Picollo (IROE, It) for evaluation of the ERA sensors.

References

1 M. Odlyha, N. S. Cohen, R. Campana and G. Foster, (UK), O. van den Brink and J. J. Boon, (NL), M. Bacci and M. Picollo, (It), Internal EU report 1998 Contract no. EV5V-CT94-0548, project title ERA (Environmental Research for Art Conservation).
2 M. Odlyha, J. J. Boon, O. F. van den Brink and M. Bacci, European Cultural Heritage Newsletter on Research, 10 (1997) 67.
3 M. Odlyha, J. J. Boon, O. F. van den Brink and M. Bacci, J. Thermal Anal., 49 (1997) 1571.
4 M. Bacci, F. Baldini, S. Baronti, A. Casini, R. Linari, F. Lotti, F. Meiners, M. Picollo and B. Radicati, 'Spectroscopic and Optical Investigations on a Luca Signorelli Predella' in 'The Uffizi Project', V. Cappellini, Ed., Giunti Industrie Grafiche, Prato, Italy 1993, p. 65–71.
5 F. De Santis, V. Di Palo and I. Allegrini, 'Indoor Pollution at the Uffizi Gallery' in 'The Uffizi Project' V. Cappellini, Ed., Giunti Industrie Grafiche, Prato, Italy 1993, p. 45–62.
6 O. van den Brink, P. B. O'Connor, M. C. Duursma, S. Peulvé and J. J. Boon, Poster presented at the 4th European Workshop on FTMS, Pont à Mousson (Fr), April 27–30, 1997.
7 D. Saunders and J. Kirby, in ICOM Committee for Conservation Preprints 1, 11th triennial meeting, Edinburgh, Scotland (1996) 87.
8 S. Osanai, T. Konishi and S. Yoshikawa, JAOCS, 73 (1996) 97.
9 R. J. Meilunas, G. Bentsen and A. Steinberg, Studies in Conservation, 35 (1990) 33.
10 J. M. Slater and E. J. Watt, Analyst, 116 (1991) 1125.
11 M. Odlyha, PhD. Thesis (1998) University of London 164.
12 M. Odlyha, G. Foster and M. Scharff, Thermochim. Acta, 321 (1998) 197.
13 M. Odlyha, D.Q.M. Craig and R. M. Hill, J. Thermal Anal., 39 (1993) 1181.