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The Effect of Changes in Environmental Conditions on the Mechanical Behaviour of Selected Paint Systems

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ABSTRACT
The impact of relative humidity (RH) and temperature variation on the mechanical behaviour of paintings on canvas was investigated, based on the various environmental recommendations that are applied by museums and institutions worldwide. Paint samples were constructed based on the works of twentieth-century artists such as Soulages and Riopelle. The various samples are based on criteria such as paint media, additives, pigment type, canvas type, thickness, type of application, and drying time. Once they are fully dry, paint films behave as elastic, viscoelastic, or viscoplastic materials depending on the chemical nature of their components. These properties, as well as tensile strength, were determined by a series of tensile tests. Other samples were included, originating from discarded oil paintings on canvas from the seventeenth and nineteenth centuries. To carry out mechanical tests under controlled conditions of temperature and RH, a climatic chamber was built around the column of a universal testing machine. Samples were submitted to stress relaxation tests to observe their response to changes in environmental conditions. RH was increased from 20 to 90% and temperature from 15 to 60°C. Reactivity diagrams were drawn based on the results. The endurance limit under mechanical fatigue was determined from the diagrams and helped define the risks associated with each painting type when exposed to the accepted environmental recommendations.

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Painting; stress-relaxation; mechanical degradation; relative humidity; temperature; mechanical behaviour; sensitivity diagrams; degradation risks

Introduction

This study examines the reactions of paint systems to the environmental conditions recommended for exhibition, transport, and storage. Different types of paint, notably modern and contemporary productions, have technological characteristics which differ from 'traditional paint', and therefore may have specific mechanical behaviours.

Towards the end of the 1970s understanding of the mechanical behaviour of artists' paints was developed (Stout 1974; Ronca 1978), and stress in paint films was defined and evaluated. At the beginning of the 1980s, some studies addressed these topics with a different approach (Hedley 1981; Berger and Russell 1982; Colville, Kilpatrick, and Mecklenburg 1982). In parallel, other studies on the mechanical behaviour of paint have made use of equipment constructed for examining biaxial behaviour (Roche 1995; Young and Hibberd 1999) or for tensile testing within environmental chambers to control relative humidity (RH) and temperature (Mecklenburg 2007; Roche 2016b).

Mechanical properties can be addressed through different methods depending on the specific aims of the study:

- Static tests with a universal testing machine (UTM), using traction, can provide data on Young's modulus, strain and elongation at break, elastic limit, viscoelastic areas, plastic and permanent deformation, creep, and relaxation.
- Static UTM testing associated with an environmental chamber provides a continuous curve during relaxation of stress or deformation in relation to RH or temperature. This is a destructive method.
- Nano-indentation at constant temperature and RH can measure the following characteristics: reduced Young's modulus, micro-hardness, and resistance to scratching on a small scale. Associated with a micro-imaging technique to visualise and analyse the surface, this can be carried out on a mounted cross-section of paint (Salvant 2011).
- Extensometry with or without contact permits the measurement of displacement and deformation of a material, and the deduction of its mechanical characteristics.

Since 1995, we have obtained data on sensitivity to RH and temperature for a number of techniques of paint application through an experimental biaxial set-up. During this current study, a new experimental set-up was designed including a monoaxial UTM in an environmental chamber. Through mechanical tests undertaken in this controlled environment, we were able to obtain data on sensitivity to RH and temperature for three modern paint types and two traditional

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ones. After evaluating the mechanical behaviour and response of the test materials to RH and temperature, a comparison was made with different recommended environmental conditions.

Recommended environmental conditions for paintings: state of the art

Previous research defining recommended RH and temperature values for the storage and exhibition of works of art is summarised in Table 1. Although they are not always specifically targeted at paint, these accepted standards or recommendations apply to organic and hydrophilic materials, which are traditionally present in paintings.

Sample description

Materials and paint layers in paintings can be extremely diverse and complex. To understand the mechanical behaviour of paintings generally, we have looked at different types of paint systems. This initial part of our study focuses on only a few variables, namely, the thickness of the paint layer and the nature of the paint medium. As this work progresses, several other factors will be introduced in order to study other types of paint, and to collect more historical materials.

The paint reconstructions were inspired by paint layers observed in the works of several artists, but are not intended to replicate fully any specific technique. As well as the duration of ageing and ageing conditions, pigment type, pigment volume concentration, and paint manufacture has also been shown to influence some mechanical characteristics. Table 2 presents the first set of paint systems collected, created, and tested.

Table 1. Selected published recommendations for environmental conditions.

Author/Institution	Year	Recommendation
Thomson (National Gallery, London)	1986	Museums: 50–2012;55% RH ±5% 19°C in winter, 24°C in summer Historic houses/churches: 40–70% RH, constant temperature
Canadian Conservation Institute, Ottawa (Note 10/4)	1993	Constant RH between 40 and 60% (50% target), daily fluctuations ≤5%, monthly fluctuations ≤5% 'Human comfort zone', in winter, slightly lower (18°C) to maintain acceptable RH
Mecklenburg (Smithsonian Institution, Washington D.C.)	2007	Values between 37 and 53% RH or 45% target ±8%, 21±2°C Specific ranges for materials in a canvas painting
Bizot Interim Guidelines for Hygroscopic Materials (Bickersteth 2016)	2014	40–60% RH, fluctuations no more than 10% RH per 24hr stable temperature between 16 and 25°C
AICCM recommended Interim Temperature and RH Guidelines	2014	45–55% RH, with ±5% per 24 h 15–25°C, with fluctuations of ±4°C
AIC Interim Guidelines	2014	45–55% RH, ±5% total annual range 40% min, 60% max 15–25°C temperature

The paint systems consist of prepared paint layers on a stretched canvas support, aged naturally. The test materials were cast by hand, on a canvas measuring 24 × 32.5 cm. Priming layers were applied by brush or roller. The paint layers were applied using a build-up of tape to a thickness of 4 mm on each side of the canvas. The paint was applied inside the two ridges of tape and smoothed out with a metal spatula to achieve a homogenous film. It is expected that the dry thickness of the film will be less than the casting thickness. Samples were then cut into 40 mm wide strips of approximately 180 mm of length (Figure 1). The cast samples are all relatively young and fresh, having naturally aged in standard conditions for between six months and three years. Artificially aged samples will be considered at a later stage to simulate more degraded paint films. Additional samples were included, originating from historic materials dating from the seventeenth and the nineteenth centuries.

Equipment

A Lloyd RX2500 UTM was used, with an airtight polymethyl methacrylate and polystyrene chamber fitted around the column for insulation. A Preservatech Mini One humidity generator was connected to the chamber. Temperature regulation was obtained by hot air pulsing within the chamber. Both RH and temperature were controlled by electronic sensors integrated in the cycle. Temperature and RH were recorded throughout with a datalogger placed inside the chamber. The UTM was externally operated by a computer. The set-up (Figure 2) was used to undertake

Table 2. Paint systems investigated.

Sample ID	Support	Medium	Paint specifications	Paint thickness
TP-1	Linen canvas (14 × 12 threads/cm)	Oil	Seventeenth-century oil painting, red–brown ground layer, animal glue.	~0.79 mm
TP-2	Linen canvas (18 × 18 threads/cm)	Oil	Nineteenth-century oil painting, oil-based lead ground, glue size.	~0.53 mm
OP-1	Linen canvas (12 × 14 threads/cm)	Oil paint	Glue-sized, oil-based lead ground, thick monolayer of cobalt blue oil paint (Leroux™), cast 2014	~2.2 mm
OP-2	Linen canvas (12 × 14 threads/cm)	Oil paint	Glue-sized, oil-based lead ground, thick even layers of cobalt blue paint and ivory black oil paint (Leroux™), cast 2014	~2.8 mm
AP-1	Polyester canvas (20 × 14 threads/cm)	Acrylic paint	Acrylic-based primer, thick layer of carbon black Golden™ paint mixed with 1/3 Golden™ high solid gel, cast 2017	~2.2 mm

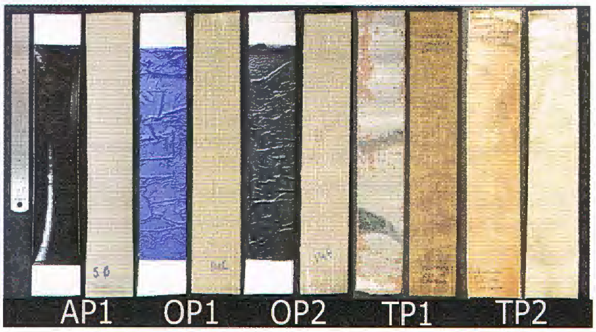


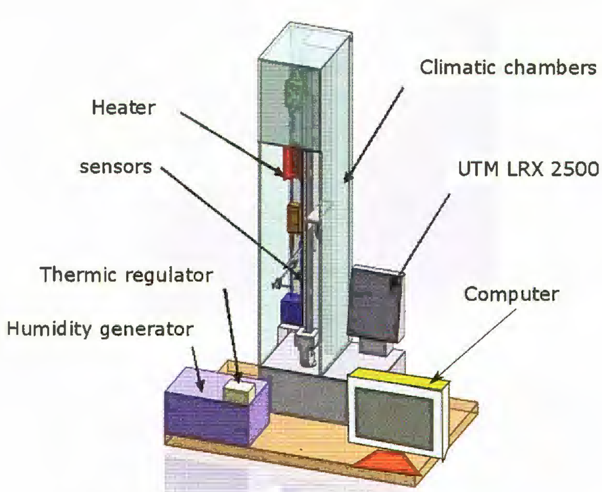
Figure 1. General view of samples, for identification, see Table 2.

stress relaxation tests on paint samples (with constant elongation) as a function of RH and temperature variation.

Tensile and stress relaxation tests

Tensile tests are undertaken to measure the mechanical strength of a material before its breaking point. Samples were held by the grips on both extremities along vertical axes, with a distance of 180 mm between the grips. The tests were executed in stable indoor conditions (21°C, 50% RH), with a crosshead speed of 10 mm/min. Tests were repeated on five samples of each type of paint system. The measurement of the load at breaking point for each type of sample was used to evaluate the endurance limit of the paints, which was defined as 'minimal tension variation' ($V_{mini}t$).

In static mechanics, stress relaxation is the evolution of tension in the material when constant deformation is maintained. The elongation constant can be manually set or can be obtained through an initial pre-defined load (*N*). The stress relaxation properties of a material reveal its capacity to react to externally applied stress. This test simulates the tension exerted on a painting when it is stretched on a conventional stretcher.



Initial load applied to samples

The recommended average tension for a painting on canvas in normal RH and temperature conditions (55% and 20°C) is approximately 200 N/m, depending on the type of paint (Capriotti and Iaccarino Idelson 2004). This results in a force of 8 N for a 40 mm wide sample. In a stress relaxation test at a constant RH, the tension induced by the initial load decreases until it reaches a stable value. This relaxation occurs for a minimum of 1 h. It is estimated that the value for the initial load at 30% RH corresponds to approximately three times the value of the load at 55% RH, therefore ~24–25 N.

Testing procedure

The testing procedure (Figure 3) was undertaken in three stages.

In stage 1, the sample is placed within the UTM grips, and the chamber is closed tightly and stabilised at 30% RH. The initial temperature is room temperature, approximately 20°C. Stage 2 commences after the interior is stabilised. The stress relaxation test is then initiated. An initial load of 25 N is applied to the sample, and the tension diminishes until it reaches a constant value. Finally, in stage 3, either the temperature or the RH is modified independently. The RH programme is set to increase from 30 to 90%, with the temperature kept constant at room temperature (~20°C). For the temperature programme, the temperature regulator was set to blow hot air until the internal temperature of the chamber reached 60°C, with the RH was maintained at approximately 30%. The load exerted on the samples were recorded every 10 s.

Results

The results can be presented as curves with the load variation as a function of RH or temperature change. These are not linear, and they can be divided into several parts, depending on the response of different components of the paint sample. They can be described mathematically by polynomial functions. The response diagrams obtained allow us to calculate the values for tension exerted in the painting at different levels of RH or temperature.

Response of paintings to RH change

Figure 4 can be interpreted in the following manner.

AP1 This curve displays an almost constant tension level between 30 and 55% RH. There is a linear tension decrease between 65 and 85% RH. The RH has a plasticising effect above 65% RH. Hydrophobic

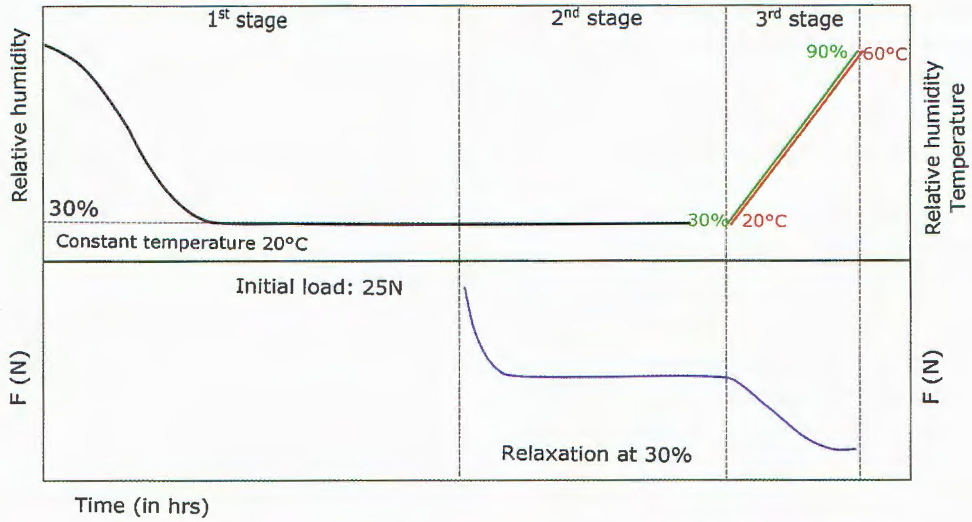


Figure 3. Testing procedure: first stage stabilisation of the environment; second stage relaxation; third stage increase in *T* or RH.

OP1 The decrease in tension of this paint sample is almost linear. The tension decreases from 310 N/m (at 30% RH) to 26 N/m (at 85% RH). The thick paint film imposes its mechanical behaviour on the other materials. This sample is sensitive to water and RH because of the presence of a canvas made from natural materials.

OP2 The decrease in tension of this paint is almost as linear as for sample OP1 but the tension decreases from 245 N/m (30% RH) to 84 N/m (85% RH). The response to the moisture of this sample is lower, probably because the mass of hydrophobic materials is more important.

TP1 The curve consists of three distinct zones: an initial progressive decrease in the slope, between 30 and 40% RH, until it becomes linear, between 50 and 70% RH, and a final zone above 70% RH where the slope increases again. These three zones correspond to the behaviour of the animal glue size initially, then the oil paint layer, and finally the canvas. This paint type is very sensitive to water.

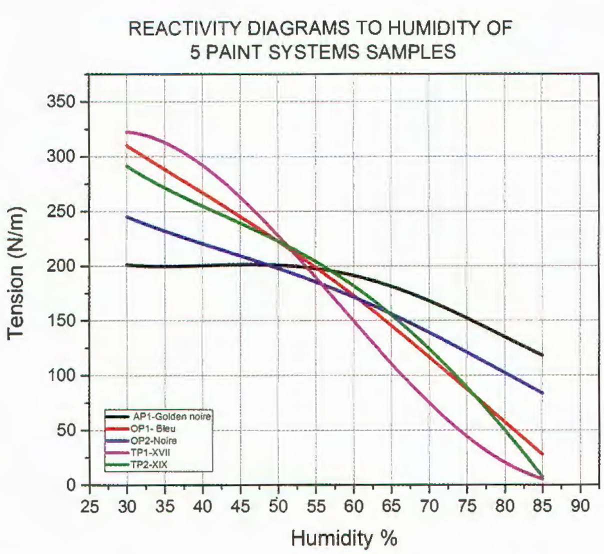
TP2 The curve is not linear but the variations in slope are small. We can however distinguish two parts: between 30 and 60% the decrease in tension is smaller than between 60 and 85% RH. This painting is slightly less responsive than TP1. The priming layer, made of oil and lead white, is not very hydrophilic, therefore the canvas itself is the only material that responds quite strongly to RH variations.

These paint samples are all sensitive to changes in RH to varying degrees. The acrylic paint AP1 is the least responsive and the 'traditional' paint TP1 is the most responsive.

Response of paintings to temperature change

Figure 5 can be interpreted in the following manner.

AP1 The tension of 200 N/m remains constant during the entire duration of the temperature programme. This paint sample is very stable during changes in temperature from 20 to 60°C.



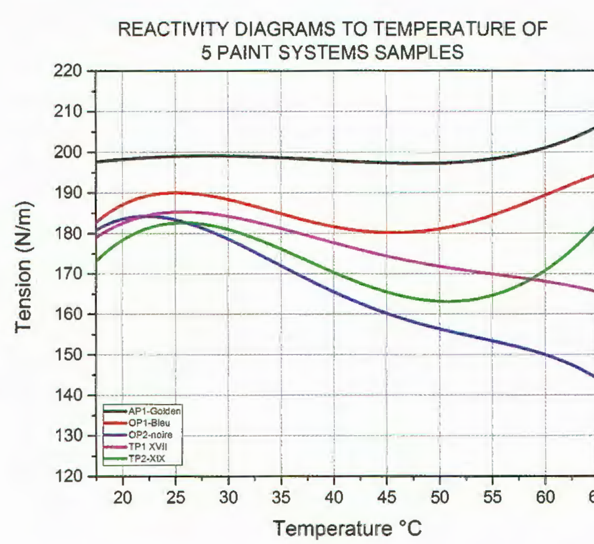


Figure 5. Response to temperature variation for the five paint

OP1 There is a small increase in tension from 20 to 25°C (3 N/m). The tension then decreases to reach a minimum of 180 N/m and then increases to a value of 190 N/m. The maximal recorded difference is 10 N/m. This paint sample is stable during increases in temperature.

OP2 Between 20 and 25°C, tension is maintained at approximately 182 N/m. The curve then decreases progressively to 60°C to reach a tension of 150 N/m. The maximum tension difference is approximately 32 N/m. This paint sample is the most responsive.

TP1 Despite a slight increase between 20 and 30°C, the tension remains quite stable. From 30°C, tension decreases by 16 N/m.

TP2 Tension in this sample reaches a maximum at 26°C (182.5 N/m), and a minimum at 50°C (163 N/m), finally reaching 170 N/m at 60°C.

The acrylic paint sample (AP1) has almost no response to increases in temperature between 20 and 60°C. The other paint samples tested are very slightly responsive to increases in temperature.

The increase in RH had a much greater impact on the paint samples tested than the increase of temperature, so the effect of RH on the degradation of the types of paint studied was investigated further.

Degradation risk within the recommended RH values

Variations of RH and temperature subject paintings to periodical variations in tension, which can lead to mechanical fatigue within the paint. Mechanical failure can appear, on a short or long term, in the form of cracks, networks of cracks, or lifting paint. To evaluate the risk of mechanical failure we have used a simplified form of the endurance limit of paints ΔDp (the change in Dp) and the minimal tension variation $V_{mini}t$ (Roche 2016a) obtained from the calculated ultimate tension at break and the paint thickness.

Minimal tension values were compared to the tensions of the test paintings according to the environmental conditions described in Table 1. The results are shown in Table 3.

Table 3. Minimal tension variation compared to the variations in tension calculated from environmental guidelines.

Paint samples	Roche 2016a	Thomson 1986	CCI 1993	Mecklenburg 2007	Bickersteth 2016
	$V_{mini}t$ N/m	$\Delta_{tension}$ 55 ± 5% N/m	Δt_{ension} 50 ± 5% N/m	$\Delta_{tension}$ 45 ± 8% N/m	$\Delta_{tension}$ 50 ± 10% N/m
TP1	17.8	77.1	79.6	122.3	143.7
TP2	13.2	37.3	41.5	64.2	74.1
OP1	123.7	49.1	50.1	85.5	95.2
OP2	137.2	26.3	26.5	44.2	49.6
AP1	7.0	4.2	9.7	3.0	9.4

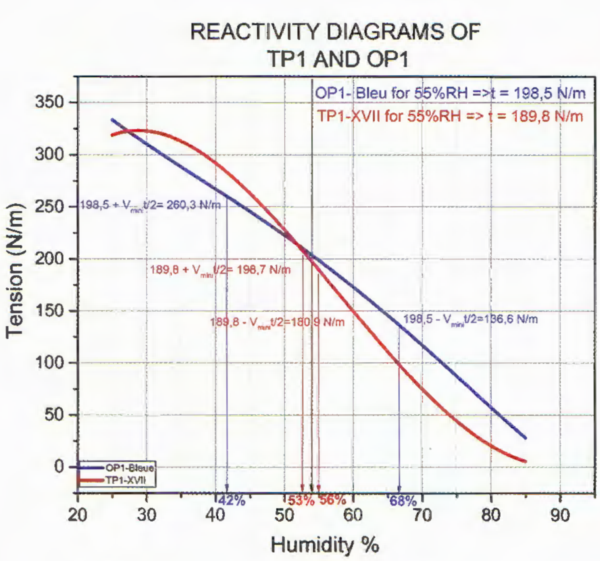
In the case where $V_{mini}t$ is less than the variation in tension ($\Delta_{tension}$, delta $_{tension}$), it can be concluded that the painting will not suffer from the change in environment to which it is subjected. This is the case for paint samples OP1 and OP2 which seem to adapt well to different conditions. Paint sample AP1 seems to react well in quite dry conditions, as proposed by Thomson and by Mecklenburg. More humid conditions are less appropriate for this type of painting. Traditional paintings such as TP1 and TP2 have tension variation values which are much higher than the $V_{mini}t$ in recommended environmental conditions. In these cases, the risk of mechanical failure increases the higher Δt is than $V_{mini}t$. When the recommended environmental conditions permit a larger range of conditions, the risk is even greater.

Defining optimal conditions for samples TP1 and OP1

It is possible to determine the optimal conditions for these specific paint types by using the response diagrams for RH change of the samples TP1 and OP1 (Figure 6).

At 55% RH, the tension is 189.8 N/m for TP1 and 198.5 N/m for OP1. Knowing that the $V_{mini}t$ are, respectively, 17.8 and 123.7 N/m by adding and splitting half of the minimal variations in tension of TP1 and OP1 at 55%, it is possible to obtain the maximum and minimum values for the tension. By projecting these values along the *x*-axis, we may obtain the RH variations for TP1 and OP1, which correspond to the optimal conditions for these paint types.

The graphical representation shows that for the protection of TP1, the RH must remain between 53 and 56%, while for OP1, the RH may vary between 42 and 68% without any risk to the painting.



Conclusion

A number of environmental guidelines have been proposed over the past 20 years, with the targets most commonly aimed at by museums and for indoor collections being an RH of 50 ± 5 and a temperature of 20 ± 1°C. This study has highlighted the differences in response to RH and temperature for different types of paint systems, and a way these can be assessed on model samples. Some of the paint types have minimal response to changes in environmental conditions within the recommended range, while others show greater sensitivity. The risk of mechanical failure is not identical for different paint types, which makes environmental control challenging in exhibition spaces. In order to eliminate any possible unknown factors, it would be ideal to evaluate specific risks for each paint type by plotting its known or experimentally derived mechanical data alongside environmental data collected in the exhibition space over at least a year.

Disclosure statement

No potential conflict of interest was reported by the authors.

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