Methods and materials and the durability of canvas paintings: a preface to the topical collection Failure Mechanisms in Picasso's Paintings

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Abstract

Paintings experience chemical, mechanical and biological damage over time. Whereas chemical and biological alterations have been widely studied in the recent decades, the study of the mechanical behaviour of painted structures deserves more attention. Damage to paintings (such as cracks, flaking paints or delaminations) has been traditionally associated to humidity and temperature fluctuations. While such assumptions are not completely wrong, the environment is not always the reason behind the failure observed in paintings. A deeper insight into the interactions between pigment and medium, as well as between the different paint layers is crucial to interpret damage found in the painted surface, but also to take more informed conservation decisions to ensure paintings stability over time. The Failure Mechanisms in Picasso's Paintings Topical Collection in the journal SN Applied Sciences brings together a series of papers aimed to understand this relationship between the composition of painting materials and mechanical damage. Results suggest that slight modifications introduced by the artist in his works can induce different vulnerabilities, whose effects can be seen over time.

Keywords Detrioration · Failure Mechanisms · Temperature · Pigment effects · Paint durability · Mechanical properties of cultural materials

1 Introduction

There are both mechanical and chemical factors that affect the durability of canvas paintings. The environment can adversely affect these factors. Both very high and low relative humidity (RH) can damage paintings based on the materials used. The absence of hide glue reduces low RH effects. Low temperatures will damage paintings no matter the construction if low enough. On the other hand, cool temperatures reduce chemical degradation and moisture diffusion. Other factors include prolonged exposure to high light levels, the choice of materials used, how the materials are used and in what layered combinations, as well as conservation treatments (and this includes

cosmetic treatments such as cleaning as well as structural treatments such as linings).

Oil paint durability is largely affected by the pigments used in making the paints. Where lead, and copper compound pigments tend to result in durable paint, organic and earth color pigments often result in less durable paints. Mixing durable paints with less durable paints can enhance the durability of the mixture. Other factors that adversely affect durability of paintings can be the pigment volume concentration of the paints and mixing hide glues with the paints.

In this paper, an overview of the mechanical and dimensional properties of painting materials is presented. This approach to materials behavior started more than three

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decades ago and introduced a different way of looking at painting materials providing a thorough understanding of the chemical and mechanical aspects of failure mechanisms experienced by paintings, and laying the foundation for later research projects on the durability of paintings.

2 Mechanics

Over the years there has been considerable research into the chemical and mechanical deterioration of materials used in the making of cultural artifacts including paintings on canvas. In general, we are more familiar with some of the chemical aspects of deterioration, nevertheless the mechanical aspects are equally important.

The mechanical deterioration can be viewed as an assessment of the forces and deformations that paintings experience due to factors such as changes in temperature, relative humidity, impact and vibration. If it is possible to determine the magnitude and direction of those forces then it is possible to determine their effects.

Knowing how these factors affect the durability of canvas paintings makes it possible to compare these effects to the Picasso's paintings under discussion in this special issue.

2.1 Relative humidity effects

For typical paintings constructed using linen canvas, hide glue size, oil ground, and oil design layers, the forces from relative humidity have been well established [1–8]. For

Fig. 1 Relative forced developed in the separate layers of a typical canvas painting when restrained and exposed to different levels of RH. As the graphics show, due to the glue layer exposure to the extreme levels of RH are to be avoided. The thickness of the specimen layers shown are representative of those of an average painting

Fig. 2 Results of cycling an experimental “mock” painting to cycles of large changes in relative humidity. Additional cycling beyond the initial 9 cycles did no further damage as the cracks that occurred relieved the stresses due to the initial RH cycles. This model painting was constructed with a stretched canvas, a hide glue size and a stiff gesso acting as a design layer. The lower right corner shows the cracking results of a Finite Element computer analysis subjected to low RH

example, at low humidity very high forces are developed in the glue size or any other layer of the painting that is responsive to relative humidity. This can be a layer of paint that incorporates hide glue in the mixture. This is shown in Fig. 1. The typical damage caused by the environment is shown in Figs. 2 and 3.

For those typical paintings exposed to very high relative humidity the effect is to induce very high forces in the linen or cotton canvas. If the canvas is restrained, there is often no lasting damage. However, if the canvas is loose, the damage can be considerable because the canvas shrinks and the paint above is compressed. What frequently happens is that water condenses behind a hanging painting on a cold wall and gathers at its lower edge. This means that the painting has two entirely different environments, dry at the top and wet at the bottom. Figure 4 shows the movement of the canvas when there are two different environments. Figure 5 shows the damage to an actual painting when there is condensation behind it.

2.2 Vibration effects

In general vibrations due to transit causes no damage to paintings with the exception of the condition where the canvas is extremely loose and there is cracking along the inside stretcher bars due to impact [9, 10]. Impact due to dropping or toppling can cause severe damage. In general handling in museums is the source of most damage.

Fig. 3 Combination of crack patterns from stretcher expansion and cycling of large changes in relative humidity. The cracking in the corners due to low RH results from extremely high stresses in the glue size layer. This is illustrated in the inset graphic in the lower right corner

Fig. 4 Results of two different environments on a canvas painting. At the right the canvas is wet and shrinks causing buckling of the paint film. At the left the canvas is dry and pulled by the wet canvas on the left. Illustration courtesy of L. Fuster-López

2.3 Temperature effects

In general, low temperature can have beneficial effects. It reduces chemical activity, mold growth, and slows moisture diffusion [11]. However, if low enough, it can pass below the glass transition temperature (T_g) of paints and can cause serious cracking. For acrylic paints T_g is 10°C and for oil and alkyd paints it is around 0 °C [12]. On the other hand, high temperature is hazardous to paintings as it seriously increases chemical degradation (including hydrolysis), moisture diffusion, loss of unreacted fatty

acids the oil, and -in combination with high humidity- it also promotes mold growth.

Oil paints become brittle and glass-like at low temperatures. Modeling a painting as if subjected to a drop in temperature from 22 °C to – 20 °C produced a high stress field over the entire painting as shown in Fig. 6. This analysis shows the entire painting develop tension in the design layer [12]. Figures 7 and 8 show the cracks predicted in canvas paintings by computer simulation and an actual painting exposed to low temperature (Fig. 8).

Fig. 5 Damage to the lower edge of a painting due to moisture condensation from a cold exterior wall in the wintertime. The inset graphic in the lower right shows the increased force on the canvas when wet. Photograph courtesy of M. Rossi-Doria

2.4 Other factors affecting the stability of paintings

Equally important are the paints used in the making of the painting. It is important to start with the drying oil alone.

If one were to pour linseed oil onto a surface such as a polyester film and wait over time, it would never dry to a hard film. Figure 9 shows an eleven-year-old film of unpigmented cold pressed linseed oil. Even after eleven years

Fig. 6 Results of modelling a typical canvas painting when the temperature drops from 22 °C to – 20 °C

Fig. 7 Maximum principal stress and directions over the entire paint layer when the model temperature is lowered from 22 °C to – 20 °C. Any cracks that occur will be perpendicular to the maximum principal stress as shown in this figure

the film is still very soft and tacky. There are therefore other factors that cause a paint film to dry to a hard durable film. These include the pigment volume concentration (PVC) of the paints used in constructing the painting. Low PVC can

Fig. 8 Actual painting damaged by low temperature, not a severe change in relative humidity. In fact, research is now showing that low temperature is the most likely cause of much of the damage seen in collections in the eastern United States

make the paint film brittle and weak. Picture Courtesy of the Author.

However, if that same oil is mixed with basic lead carbonate (white lead pigment), after 14 years of drying, the lead white paint gets stiffer (increasing modulus) and stronger as drying time increases. Research suggests

Fig. 9 Eleven year old film of cold presses linseed oil which remains a soft tacky film

that this increase in stiffness can continue for a century or more. Figure 10 shows the stress–strain plots of basic lead white ground in cold pressed linseed oil at different drying times. These paint samples were uniformly cast on polyester film and easily removed for testing at different stages of drying. The strength of the paint is the stress level reached at the end of the test. All mechanical tests described in this paper were conditioned and

tested in an environment of 50% RH and 22°C. Oil paints made with white lead are remarkably resistant to the adverse effects of moisture [13].

The question to ask here is: do oil paints made with different pigments result in firm durable paints? The answer to this question is no. For example, paints made with different lead compounds result in different strengths, most notably is the 17.5 year old Naples Yellow which develops no strength at all as shown in Fig. 11. Paints made with pigments that don't develop into strong durable films are adversely affected by moisture and cleaning solvents [13].

Many other minerals sometimes used as pigments will make paints that will never develop any strength and will always be adversely affected by moisture [13]. These include silica, barium sulphate, and calcium carbonate. These might be considered as “inert pigments” and the mechanical tests performed on paints using these pigment are shown in Fig. 12.

Due to toxicity levels of white lead paints alternative white pigments such as titanium dioxide and zinc white are often used as substitutes for the lead white. They can be found in paint used separately or as mixtures of the two pigments. Figure 13 shows separate paints made with titanium dioxide and zinc oxide in cold pressed linseed oil. They have completely different mechanical behavior. The titanium dioxide paint seems to initially

Fig. 10 Stress–strain plots of basic lead white ground in cold pressed linseed oil at different drying times. As drying time goes on the paint gets stronger

Fig. 11 Oil paints made from different lead compound pigments. The paint made with basic lead carbonate and lead tin yellow develop the most strength where the paint made with Naples Yellow develops no strength at all

Fig. 12 Mechanical properties of paints made with "inert pigments" and cold pressed linseed oil. None of the paints develop any strength

dry properly but over time it starts to completely lose strength. The paint made with zinc white simply gets extremely stiff with time and ultimately gets quite brittle. Both these paints can have seriously adverse effects on the long term durability of paintings [14, 15]. This is shown in Fig. 14.

It might be useful to examine some combined effects of the environment and use of paint at this point. Figure 15

shows an image of a painting that was exposed to an extremely low wintertime temperature in Buffalo, New York. The cracking was almost immediate and covered the entire painting. The design layer was a mixture of oil and solvent based acrylics and the ground was a zinc white oil paint. The delamination started occurring soon after the painting cracked and was caused by the presence of the zinc white ground.

Fig. 13 Paints made with titanium dioxide and zinc oxide in cold pressed linseed oil. Paint made titanium dioxide ultimately loses strength whereas the paint made with the zinc oxide gets extremely brittle

There are other pigments that form durable oil paints and these are in general the copper compound pigments such as azurite, malachite, and verdigris. Figure 16 shows the mechanical properties of paints made with copper compound pigments and cold pressed linseed oil at different times in their drying history. Like the lead white paint these paints get stiffer and stronger as time passes. The lead white and copper compound pigments have something in common. These pigments are partially dissolved in the drying oils and supply the paint with metallic ions that help polymerize and crosslink the paint [15–17]. There is further evidence that copper and lead ions accelerate the drying of linseed oil. Figure 17 shows the weight gain due to oxygen uptake over time of linseed oil when placed on different substrates. The substrates were clean copper foil, lead sheet, brass foil, aluminum sheet, tin sheet and polyester film. As can be seen in these plots, the oils on the polyester, aluminum and tin substrates are the slowest to start absorbing oxygen. The oils on the lead, copper, and brass start gaining weight very rapidly [18]. (Fig. 18).

2.5 The hydrolysis of oil paint films

Hydrolysis, even in benign environments, causes the degradation of the mechanical properties and increases

the vulnerability of paints to atmospheric moisture and cleaning solvents [16, 18, 19]. All paints hydrolyze to one degree or another but paints made with the earth colors and organic pigments tend to experience the most severe effects of hydrolysis. Fundamentally hydrolysis weakens the paint film and makes it more susceptible to damage from environmental moisture and cleaning solvents. Figure 19 shows the results of stress–strain testing of both raw and burnt Sienna ground in cold pressed linseed oil at different drying times. Initially, after only 1.25 years the paints seem to be developing nicely. But after 8 years of drying the both paints dramatically lose strength and after 14.25 years the raw Sienna has lost all strength. It is important to note that these paints were continuously maintained in a benign environment of 45–50% RH and 22 °C. Nevertheless they lost considerable strength.

An excellent example of a painting containing both a durable paint, white lead, and a weaker paint made from the earth colors is shown in Fig. 19. Relatively high levels of atmospheric moisture affects the paint made with the earth colors without affecting the white lead paint (Fig. 20).

Other paints ground in cold pressed linseed oil that lose strength over time include raw and burnt umber, yellow ochre, red iron oxide, lamp black, alizarin crimson, and Cadmium yellow [15].

Fig. 14 Cracking and delamination of paint layers caused by titanium white, zinc white, and the mixture of the two pigments in this detail. twentieth century English Abstract, oil on canvas. Photograph courtesy of Richard Saltoun and taken by Steve Gayler

Fig. 15 twentieth century painting exposed to very cold temperatures which caused the initial cracking. The paint film was a mixture of oil and acrylic. The subsequent delaminating was caused by a zinc oxide oil ground. Painting courtesy of the owner and photograph by James Hamm

2.6 Contaminants

The addition of driers and contaminants can cause problems in paint film formation. This even includes naturally occurring minerals such as Manganese dioxide often found in

mined burnt umber. Figure 21 shows the increase in strength and brittleness as a function of time and percent manganese in burnt umber. Where on some paintings burnt umber paint may show signs of degradation due to moisture, in others it might show up as a brittle cracked and cupped paint [19]. The addition of even small amounts of zinc (for example in zinc oxide) causes similar problems.

2.7 Mixing different paints together

Research has shown that due to ion migration, all paints whether durable or not will develop considerably enhanced durability if they are applied over a white lead ground [13, 20].

In June 2007, three paints (yellow ochre, terre verte and alizarin madder lake, all in cold pressed linseed oil) were mixed with Grumbacher “Flake White” in alkali refined linseed oil. The pigments in the “Flake White” were lead carbonate and zinc oxide. The mixtures of the paints were 1 part white to 4 parts of the colored paints by volume. The paints were tested after 2.5 years of drying. Typical results are shown in Fig. 21. Figure 21 shows the stress–strain tests of several yellow ochre paints tested over time. The older paints were not mixed with any other paint and supplied by different manufactures. The youngest paint (2.5 years old) was

Fig. 16 Mechanical properties of paints made with copper compound pigments and cold pressed linseed oil. They get stronger as time passes

Fig. 17 Weight gain due to oxygen uptake over time of linseed oil when placed on different substrates. The substrates were clean copper foil, lead sheet, aluminum sheet, tin sheet and polyester film. As can be seen in these plots, the oils on the polyester, aluminum and tin substrates are the slowest to start absorbing oxygen. The oils on the lead, copper, and brass start gaining weight very rapidly

Fig. 18 Stress-strain testing of both raw and burnt Sienna ground in cold pressed linseed oil at different drying times. Over time and due to hydrolysis they lost most of their strength

Fig. 19 Effects of the hydrolysis of oil paint films. Atmospheric moisture can affect paint made with one pigment without affecting a more durable paint. Photograph courtesy of Matteo Doria Rossi

Fig. 20 Increase in strength and brittleness as a function of time and percent manganese in burnt umber oil paints. The paints were obtained from different manufactures and analyzed for manganese

the mixture and by far has developed the greatest strength even after drying for only a short time when compared to the much older paints. The terre verte and alizarin paints showed very similar results.

3 Conclusions

Departures to the extreme high and low RH levels can certainly cause damage to canvas paintings. But in reality most paintings can successfully sustain changes in RH in the range from 30 to 60% RH.

The primary support of canvas paintings with hide glue sizing is the hide glue and not the canvas. The hide glue's active response to low RH level can cause damage. There is little support to the paint film from the canvas and paintings with no or very little glue sizing are

Fig. 21 Stress–strain tests of several yellow ochre paints tested over time. The 2.5 year old paint was mixed with the flake white paint and the others were not. The mixed paint developed considerable strength in a relative short time

resistant to damage at low RH but vulnerable to especially high RH levels.

Low temperatures can be beneficial to the paintings unless the temperatures goes below the T_g of the paints. High temperatures are always hazardous to painting.

Paints made from certain pigments such as the earth colors, organic colors and certain inorganic pigments will rarely dry to form durable films and are susceptible to hydrolysis. Other pigments such as zinc and umbers containing manganese dry to extremely brittle films. Mixing white lead in even small amounts will enhance paints made with poorly performing pigments.

It is the combination of the materials (especially the paints) and environmental conditions that induce damage either from mechanical or chemical processes or both.

Compliance with ethical standards

Conflict of interest The author declares that they have no conflict of interest.

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