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The structure of canvas supported paintings

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Abstract

It is possible to get significant insight to the response of paintings to environmental change when examining the response of the individual paintings' materials. This paper is a survey of work completed and continuing on the physical and mechanical properties of artists' materials. Tests results of the individual materials show that fabrics can develop high tensile stresses at high humidity where paint and hide glues loose strength. It is also shown that where low humidity can increase the stiffness and strength of hide glues and oil paints, it is really low temperature that causes true embrittlement of paint films. Oil paints can become brittle as a result of being exposed to elevated temperatures and cleaning solvents, and if left in a moderately benign environment they remain fairly flexible. The mechanical properties of oil paints continue to change over long periods, well after they are considered to be dry. The pigments used in making paint have a significant effect on both the drying time and the ultimate mechanical properties of the paint.

Introduction

If the visual design of a painting is not considered, then paintings by different artists have a considerable amount in common. Many used linen, hide glue sizing, oil grounds, and oil paints in their construction, and this is true for a large number of artists painting in the 18th, 19th and 20th centuries in both Europe and America. The typical construction of a painting might be described as shown in Figure 1. The principal differences among artists, that is their uniqueness, are primarily the designs, colors, thickness, and application techniques of the ground and design layers. Certainly it can be said that artists chose different weights and weaves of canvases but the fundamental material is the same. It can also be said that the there is little difference between the varieties of animal glues and to some degree even oil the paints themselves. The basic construction of a canvas painting might be that a hide glue size is applied either hot or as a cold gel onto the surface of a stretched linen canvas. Over the glue size an oil ground is applied (and in earlier times a gesso ground) making the painting surface of the canvas somewhat smoother and reducing the texture of the canvas.

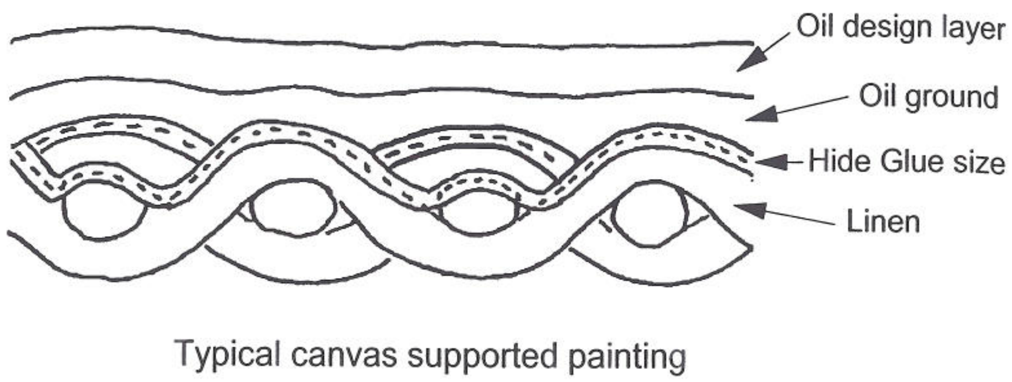
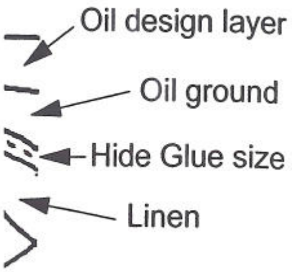


Fig. 1. *The construction of a typical canvas supported painting.*

The design layers are then applied over the ground. There are an infinite variety of these combinations of materials but nevertheless it can be shown that the way a material is applied doesn't significantly affect the fundamental properties of the painting as a structure and how that painting responds to environmental changes. If one is concerned about the preservation and conservation of canvas supported paintings then it is useful to focus on the similarities, not the differences among paintings. One important way to do this is to understand how the artist's materials respond to aging, temperature, relative humidity, shock, vibration, and conservation treatments. Once the material properties are defined the painting as a composite structure can be examined in considerable detail. This paper can only touch on some of the important highlights of the different aspects of the properties of cultural materials and the structure of paintings.

The structural properties of materials that need to be determined are the physical (dimensional) response to temperature and relative humidity, their mechanical properties and how these are affected by temperature, relative humidity, cleaning solvents, and chemical deterioration over time. The reason these properties are important is that paintings, primarily the grounds and design layers can crack, cup and flake off the support canvas. Cracking, cupping and flaking are all caused to a large degree by forces distributed through the painting materials in the form of stresses. When it comes to the effects of temperature and relative humidity, both the dimensional and mechanical properties combine to define the magnitude and direction of stresses developed in the materials. If those stresses exceed the strength of the materials, they will crack. Since all of the artists' materials tend to respond to environmental changes differently they have the ability to affect the stresses in other layers that make up the composite structure of a painting.



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Sample preparation and experimental proceedures

All of the animal glues, gesso films, and oil paints tested and described in this paper were especially manufactured and cast on polyester sheets in order to easily remove them at later dates. When dry and needed for testing, the samples were cut into uniform strips averaging 2.5mm to 3.5mm wide. The oil paint films had fairly uniform thicknesses with the thinner films of 0.075 mm and the thicker films of 0.2mm. The hide glues tended to have average thicknesses around 0.10mm. In this way all of the materials could be tested as free unsupported films. Over 200 oil paints were manufactured for the Smithsonian Center for Materials Research and Education (SCMRE) without adulterants, additives and any filler materials normally found in today's commercially prepared artists' oils. In this way it was possible to determine through a large test matrix those physical, mechanical and chemical factors that affect the drying and long term durability of oils and oil paints. These custom paint test results were then compared to similar tests of commercially prepared artists' oil paints.

The actual physical and mechanical testing of the materials were conducted using miniature tensile testing machines enclosed in environmental chambers. All of the tests of the materials were conducted while the materials were at full environmental equilibrium.

The dimensional response of materials to relative humidity

If a material swells and shrinks with increases and decreases in relative humidity (RH) it is because the material is gaining and loosing moisture from the atmosphere and the material is said to be hygroscopic. Figure 2 shows the change in moisture content of two samples of unpigmented cold pressed linseed oil. They had been allowed to dry for ten years in a controlled environment (40%-50% RH, 20°-23°C). One of the samples is untreated and the other has about 1.6 % (lead as metal) dissolved in the oil.

There is little affect on the weight change in either the ascending or descending relative humidity and this in not true for all materials. Figure 3 shows the moisture isotherm of a 1500 year old sample of Chinese arbor-vitae from a Japanese temple. The moisture absorption paths are different depending on whether the RH is increasing or decreasing and that the RH charges are large. This is called hysterisis. Further there is an entirely different moisture absorption path in the moisture isotherm if the RH cycle is not over a large range. It is important to keep in mind that all of the data points shown in all of the isotherm and swelling figures in this paper are at full equilibrium with the atmosphere and not a result of the rate of changing the RH. All woods, ivory, and to some extent hide glues exhibit hysterisis behavior. This hysterisis in the moisture absorption response is reflected in the dimensional response of the artists' materials and has significant consequences on how paintings respond to the different degrees of environment change.

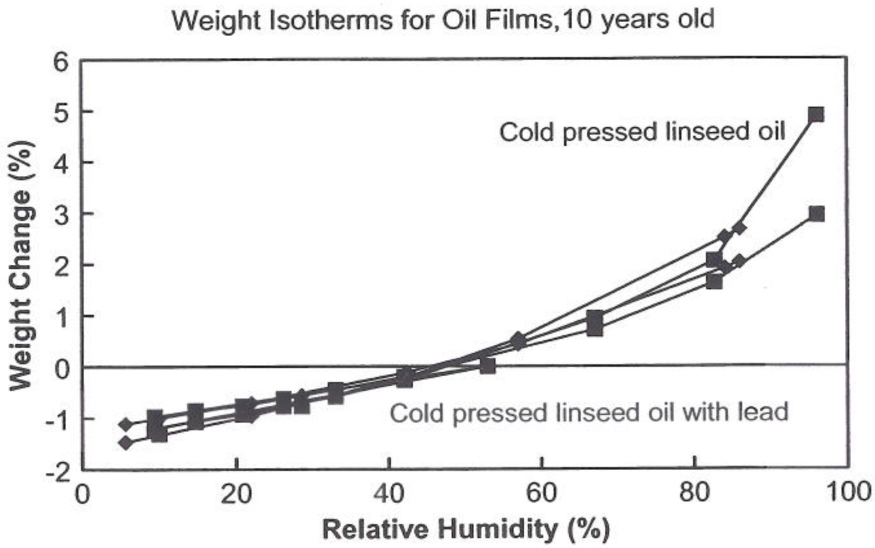


Fig. 2. The weight change of un-pigmented linseed oil with changes in relative humidity. The oil with the lead is slightly less responsive to moisture changes and this can possibly be the result of the drying effect of the litharge.

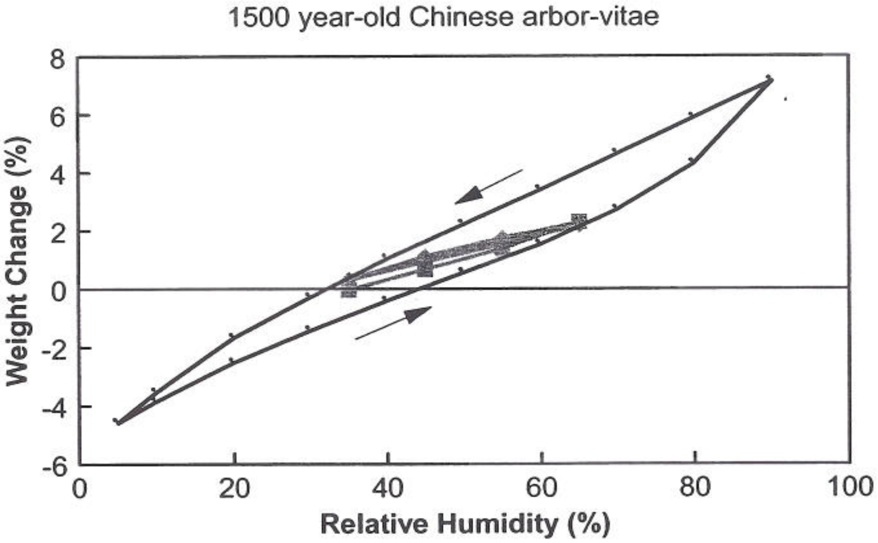
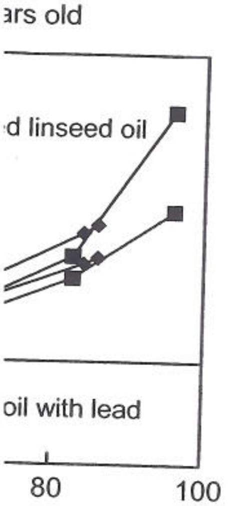


Fig. 3. The moisture isotherm of a sample of 1500 year old Chinese arbor-vitae taken from a Japanese temple. The isotherm shows the response to both large and small relative humidity cycles. (Test data courtesy of Dr. Sheila Fairbrass Siegler, Conservation Scientist, Coopersburg, Pa.)



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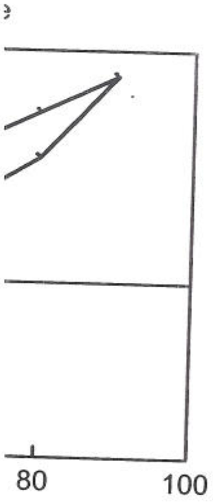

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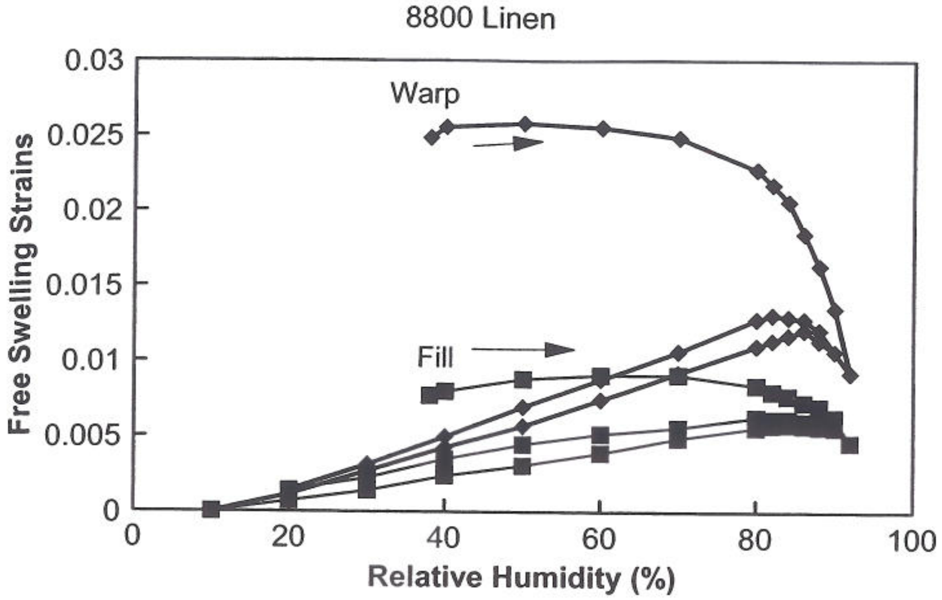


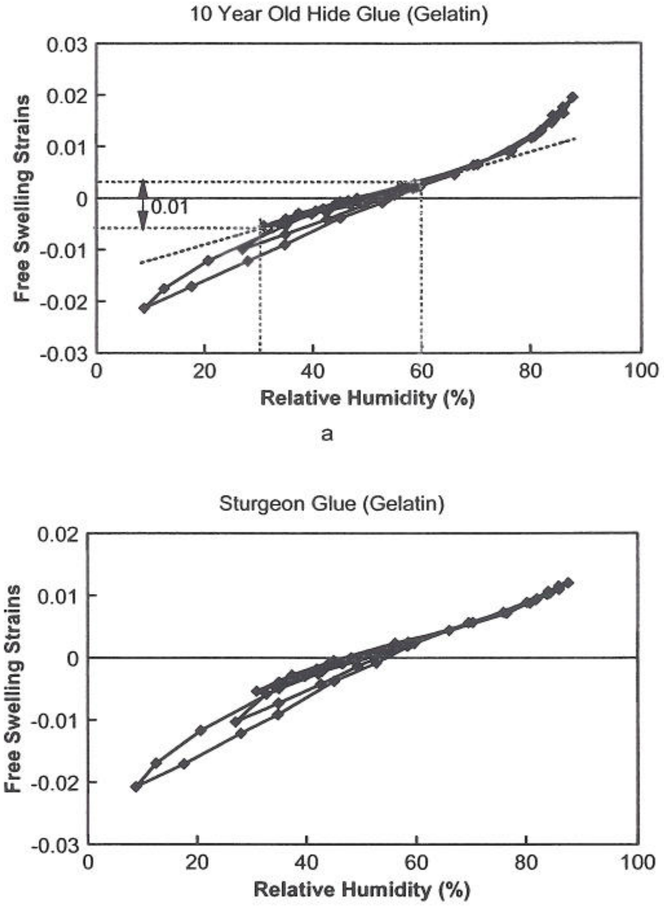
Fig. 4. The dimensional change of free hanging linen with changes in relative humidity. After the first cycle into high RH, the material settles into a repeatable behavior. This linen was type #8800 made by Ulster with a yarn count of 1.25 yarns/mm in both the warp and fill directions.

LINEN

Linen is the primary support of canvas paintings and has often been associated with the fact that paintings respond adversely to changes in relative humidity. If free to expand and contract it does change dimensions with changes in relative humidity [1, 2]. What is important regarding the dimensional response of linen to RH is that while it is expected to contract with desiccation, above 80% RH it also contracts. This is a result of the transverse swelling of the fibers and the weave geometry of the fabric. The high RH response of the linen shows up in the mechanical testing discussed later in the paper. The value of strain used in the plots in this paper is change in length of the specimen divided by the original specimen length. Strain is percent elongation divided by 100.

HIDE GLUE

Hide glue has been used for centuries and is made from animal parts such as skins and bones that have been freed of fat and boiled [3]. In this state it is gelatin and the quality of the glue depends on the source and the refinement during processing. It is an extremely strong material as long as the RH is below 75%. Above that level strength deteriorates significantly. With large changes in relative humidity, from 10% to 90% RH the dimensional change of both the hide and sturgeon glues shown in Figures 5a and b can change as much as about 4 ½ %. From 30% to 60% RG the change is about 1% elongation. The rate of dimensional change is the greatest at the extreme ends of the RH range and this one of the reasons that keeping the museum environment somewhere in the midrange RH is important. When used as size, hide glue can be applied to the canvas as a warm liquid or as a cold gel.



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Figs. 5a y b. *Figure 5a shows the swelling response of 10 year old hide glue with changes in relative humidity. There is a slight hysterisis in this material. Between 30% and 60% RH, there is about a 1% change in the length of the material. Figure 5b shows the swelling response of sturgeon glue with changes in relative humidity. As with the hide glue, there is a slight hysterisis in this material. Even the intermediate behavior is similar to the hide glue.*

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GESSO

Gesso was primarily used as a ground for wood panel painting and had been tried as a ground for canvas painting. It was found to be brittle and was ultimately replaced with oil grounds which retain a higher degree of flexibility for long periods of time [3, p18-19]. For that reason it is included in this discussion of artists' materials. Gesso can be a mixture of animal glue and either calcium carbonate, calcium sulfate or even other inert fillers. Both the dimensional and mechanical properties of gesso are dramatically affected by the ratio of the glue to the inert filler [4, 5]. This ratio is usually presented as the pigment volume ratio or PVC. The PVC is the percent volume of the inert filler to the total volume of the gesso. Figure 6 shows the free swelling strains of two different gesso mixtures and the hide glue with changes in relative humidity. These gesso mixtures were made from a hide glue and calcium carbonate and their response to the RH change is considerably less than the glue alone. The gesso with the pigment volume concentration (PVC) of 81.6% is extremely hard and brittle and due to the low volume of glue it shows little response to humidity changes. The gesso with the PVC of 58.3% is still somewhat flexible and shows a dimensional response about four times the 81.6% gesso sample.

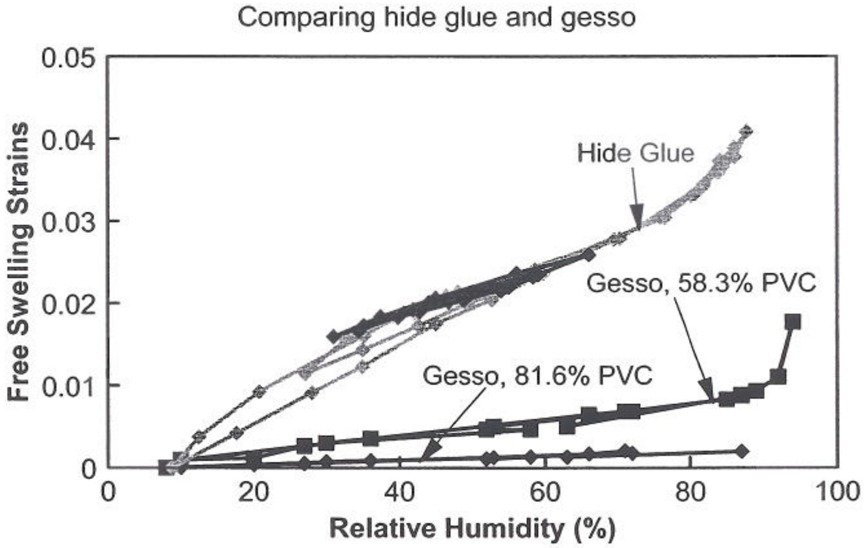

Fig. 6. The swelling response of gesso and hide glue with changes in relative humidity. The gesso mixtures have a significantly lower dimensional response the RH changes than the glue.

WOOD

Over centuries, wood has been the material of choice for the stretchers or strainers used to support the stretched canvases. It is still used today and is a material that is extremely hygroscopic. From both the dimensional and mechanical response to relative humidity wood is said to be orthotropic, i.e. wood responds differently in the three primary and mutually perpendicular directions. Those three directions are the longitudinal direction which is the direction parallel to the grain of the wood, the radial direction which is perpendicular to the concentric rings of wood, and the tangential direction which is parallel to the concentric rings in wood as shown in Figure 7.

Figure 7 also shows the RH related free swelling response in the three primary directions of modern Scotch pine. Wood cut in the tangential direction is the most responsive and is to be avoided when used is making panel paintings. The least responsive direction is the longitudinal direction. This is important to note since a large proportion of cracks seen in panel paintings are perpendicular to the grain of the wood indicating that layers other than the wood are responding to the environment. Michalski presents an interesting explanation of this occurrence [5]. Figure 7 shows the swelling response to large and small changes in relative humidity of 17th century Scotch pine grown in the same forest in Norway as the modern wood discussed in Figure 7.

The tangential direction shown is the most responsive direction and shows entirely different behavior depending on the magnitude of the change in relative humidity. The slopes of the swelling plots show are the estimated coefficients of moisture expansion as a function of relative humidity. The value of the slope (0.00071 / %RH) is the same as that given in the Forest Products Wood hand book [6]. The slope (0.000417 / %RH) of the dimensional change for the smaller change in relative humidity is considerably less that of the one from the larger RH range. This helps explain why many materials survive uncontrolled but moderate environments.

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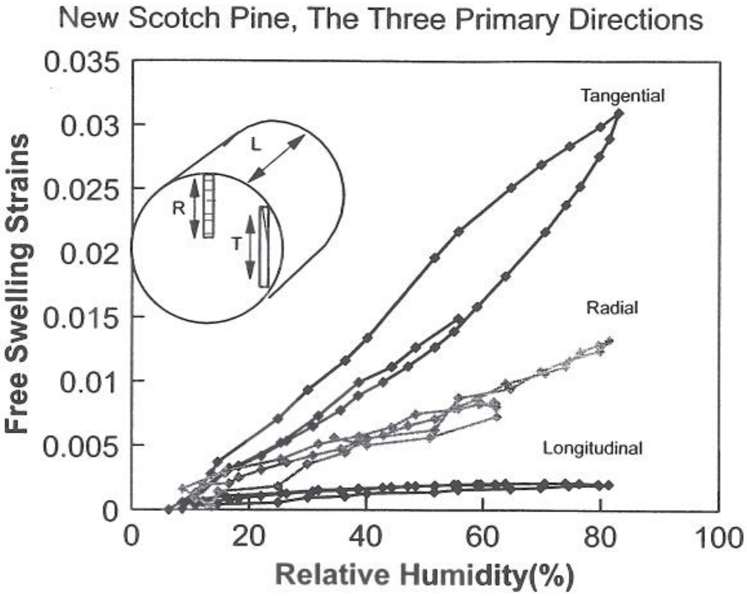

Fig. 7. The swelling response to large changes in relative humidity of wood samples in the three primary directions of modern Scotch pine. The most responsive direction is the tangential direction followed by the radial direction. The longitudinal direction is only minimally responsive to changes in moisture content. The best wood panels used for painting are typically cut in the radial direction since they exhibit the least dimensional response to changes in relative humidity.

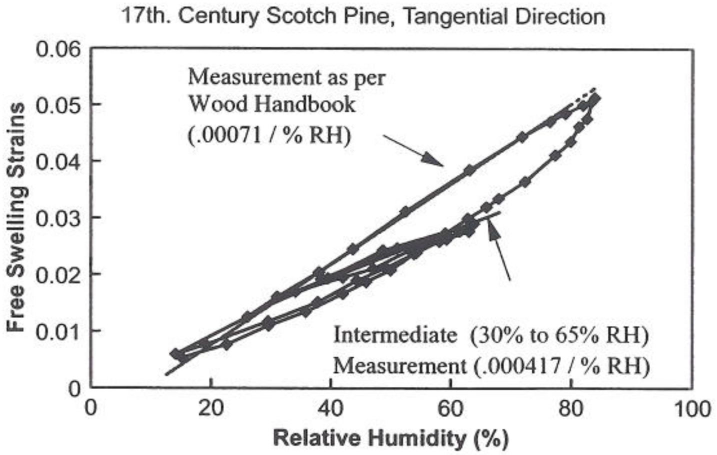

Fig. 8. The swelling response to large and small changes in relative humidity of 17th century Scotch pine grown in the same forest in Norway as the modern wood discussed in Figure 7. The tangential direction shown is the most responsive direction and shows entirely different behavior depending on the magnitude of the change in relative humidity.

OIL PAINTS

For most canvas paintings using drying oils such as linseed, safflower, walnut and poppy seed, the ground and the upper design layers combine to make all that is unique to the painting. At the same time these materials define what paintings have in common. There are some misconceptions as to what significantly affects the longevity and durability of paints. In this paper there will be an emphasis placed on the properties of oil paints due to their importance. Before discussing the dimensional and mechanical properties of oil paints it is important to comment on the drying time of these materials. Depending on the pigment and the drying oil used, paints can take from 2 days to 3 months to become "dry to the touch". In general paints containing lead, iron, copper, titanium, and manganese compounds tend to become dry to the touch in fairly reasonable times. Zinc is a slow drier and some paints such as those containing natural organic dyes such as alizarin really never fully become dry to the touch except as very thin glazes [7, 8]. It is also important to show that oil paints have changing mechanical properties for very long periods of time, perhaps throughout their entire history. This will be discussed in more detail in later sections.

One of the paints that is found in many traditional canvas supported oil paints is lead white (basic lead carbonate) ground in linseed oil. Figures 9a and b shows the dimensional response of lead white paints ground in cold pressed linseed and alkali refined linseed oils. Both of these paints are often found as grounds in canvas paintings. These paints do not exhibit significant response to changes in relative humidity. Other paints such as those made with titanium white have little response to relative humidity changes. Figure 10 shows the dimensional response to large changes in relative humidity of a 20 year old titanium white paint ground in alkali refined safflower oil. As with the other white paints shown, there is very little dimensional response to changes in RH. Some paints, however, do exhibit greater dimensional response to changes in RH. Paint made with the natural earth colors such umber and ocher will swell significantly at relative humidity levels above 60% RH. The primary reason is that these pigments contain clays that are highly hygroscopic and can swell significantly. Figures 11a and 11b show the dimensional response of yellow ochre and burnt umber ground in alkali refined linseed oil. The increased swelling above 60% RH is largely due to the clay found in the pigments.

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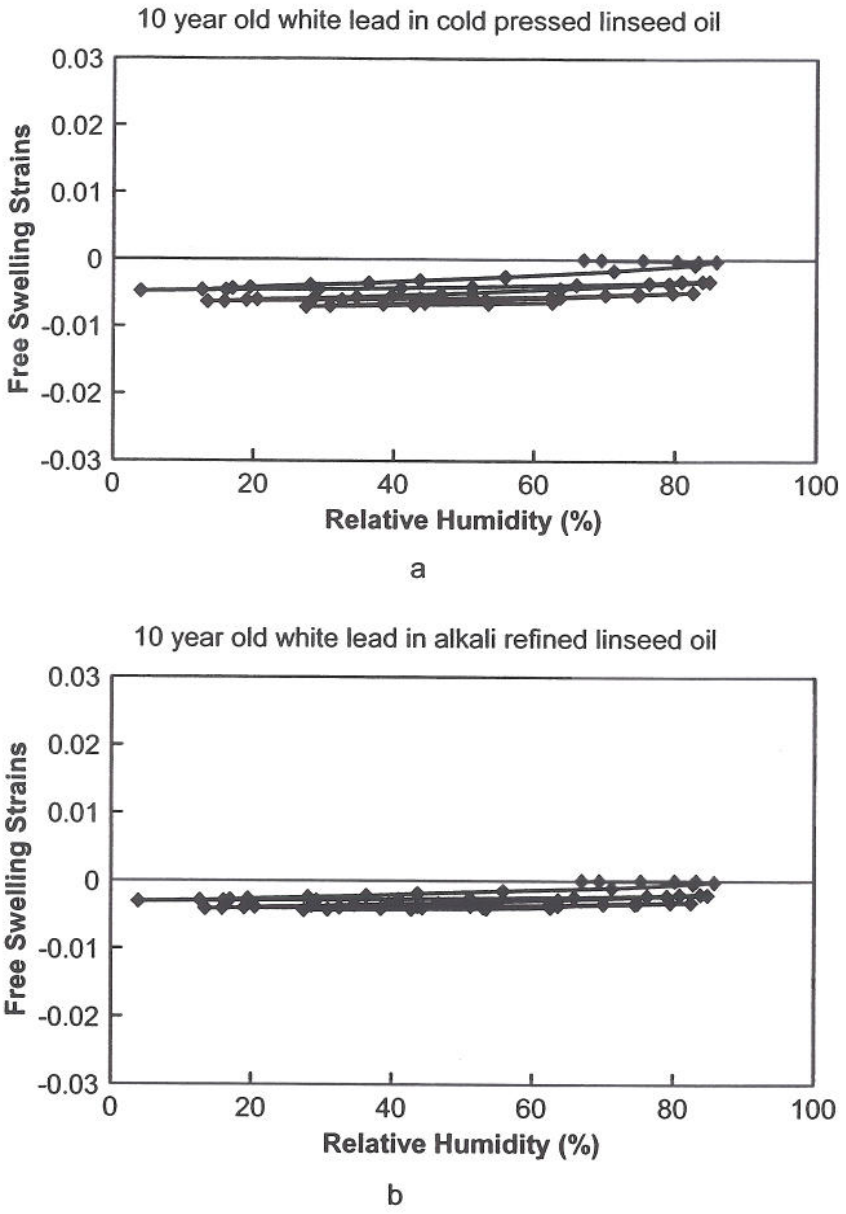


***Figs. 9a y b**. Figure 9a shows the swelling response to large changes in relative humidity of 10 year old white lead paint ground in cold pressed linseed oil. Even after a repeated exposure to large changes on RH, the paint shows little dimensional response. Figure 9b shows the swelling response to large changes in relative humidity of 10 year old lead white paint ground in alkali refined linseed oil. As with the white lead paint made with the cold pressed linseed oil, there is very little dimensional response to changes in RH. Alkali refined linseed oil is found frequently in today's commercially prepared artists' oil paints.*

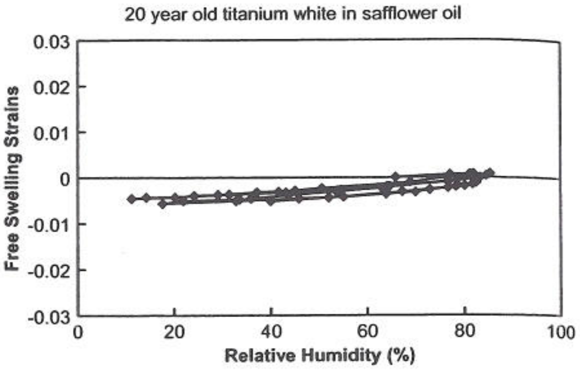
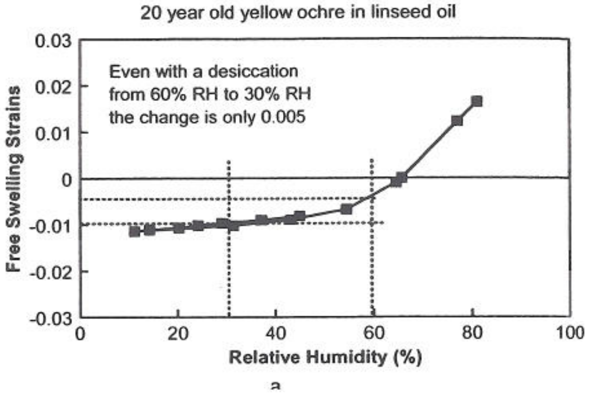
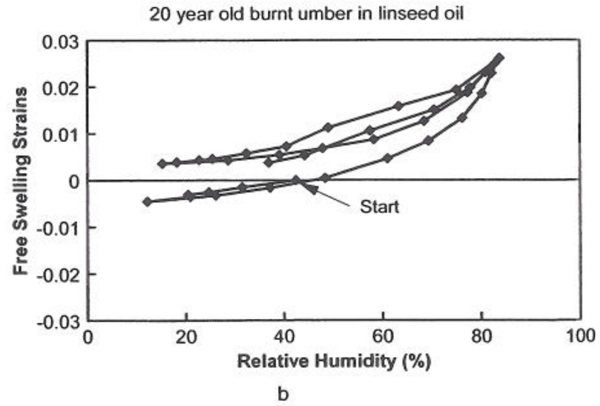


Fig. 10. *The swelling response to large changes in relative humidity of 20 year old titanium white paint ground in alkali refined safflower oil. As with the other white paints shown, there is very little dimensional response to changes in RH.*

If limited to the middle ranges from 30% to 60% RH the dimensional response of the paints is restricted to more modest changes. Excessively high relative humidity, above 70%, can present potential problems.





Figs. 11a y b*. Figure 11a shows the swelling response to large changes in relative humidity of 20 year old yellow ochre ground in alkali refined linseed oil. Limiting the exposure of the paint to a range between 30% and 60% RH keeps the dimensional response to less than one percent. Figure 11b shows the swelling response to large changes in relative humidity of 20 year old burnt umber ground in alkali refined linseed oil. This paint showed an initial permanent swelling in the first RH cycles before settling into repetitive cycles.*

SUMMARY OF SWELLING BEHAVIOR OF CULTURAL MATERIALS

If one looks at the dimensional response of the materials discussed above, there are some observations worth noting. The highest rate of change in dimension with respect to RH occurs at the extreme ends of the RH range. The midrange, from about 35% to 60% RH, is the least responsive. This suggests that considering the swelling data alone, the least damage to paintings in likely occur in that range. Unlike any other material, the fabric has the potential for serious shrinkage at high levels of relative humidity. Experience has shown that hide glues soften at those RH levels and the bond between the ground and the fabric is compromised. It is at high RH that paint often cleaves from the fabric support and this suggests an explanation of the mechanism. One other point that is worth noting is that the oil paints show low dimensional response to even very low levels of relative humidity. So low RH does not necessarily cause paint films to crack from a dimensional perspective. It is now important to show if low relative humidity or other factors cause the materials to become brittle.

The mechanical properties of artists' materials

While the dimensional properties of cultural materials to changes in relative humidity provide an initial sense of how they might behave as part of a painting, the mechanical properties provide the opportunity to actually quantify what happens to them as part of a composite structure. The mechanical properties also determine how strong materials are (strength) and how much deformation they can withstand before breaking elongation. The mechanical test or stress strain test in tension is illustrated in Figure 12. This particular test was conducted using a sample of American mahogany (tangential direction) at a rate of 30 seconds between test points and can be considered a moderately fast test. There are several important aspects to this test. The test shows the relationship between the strain and the stress (analogous to force and elongation). Stress is the amount of force applied to the specimen divided by the cross-sectional area of the specimen. The unit of measurement is the Pascal (Pa) which is Newton per square mm (in English units its pounds force per square inch (psi)). Strain is defined as the change in length of the specimen divided by the original length of the specimen. The unit of strain is mm per mm (inch per inch) which is usually considered unit less. There are elastic and plastic regions shown in this test. The initial elastic region is between strains of 0.00 and 0.005 and indicates reversible mechanical behavior. The initial plastic region is the strain above 0.005 and represents the region where the material is permanently deformed. The dotted line labeled the initial modulus (E) is the slope of the elastic region of the stress strain test and is a measure of the material's stiffness. The inverse of the stiffness is flexibility. If a material becomes excessively stiff and has no plastic region it is said to be brittle. The brittleness of a paint film or ground is of significant importance and the conservation of canvas paintings is intended to support brittle grounds and paint films. One final point should be made regarding figure 12. If the stress strain test is interrupted in the plastic region, the specimen unloaded, and then reloaded it will follow a path as indicated as the new elastic strain. The material will have a modulus that is slightly higher than the initial modulus and the elastic region is somewhat greater that the original 0.005. This is called strain hardening and occurs in all of the materials found in paintings.

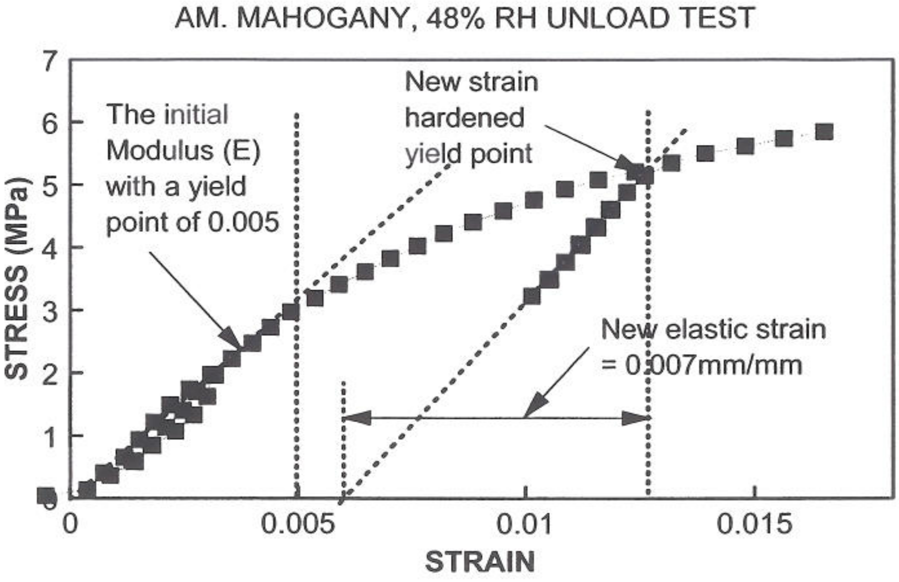
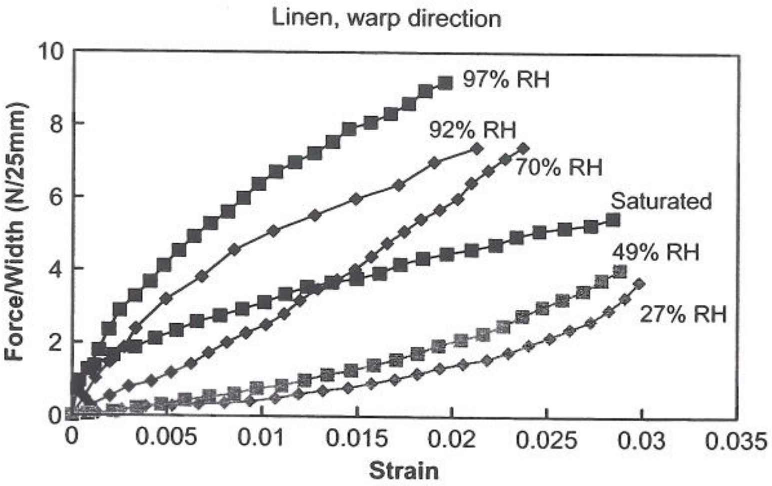


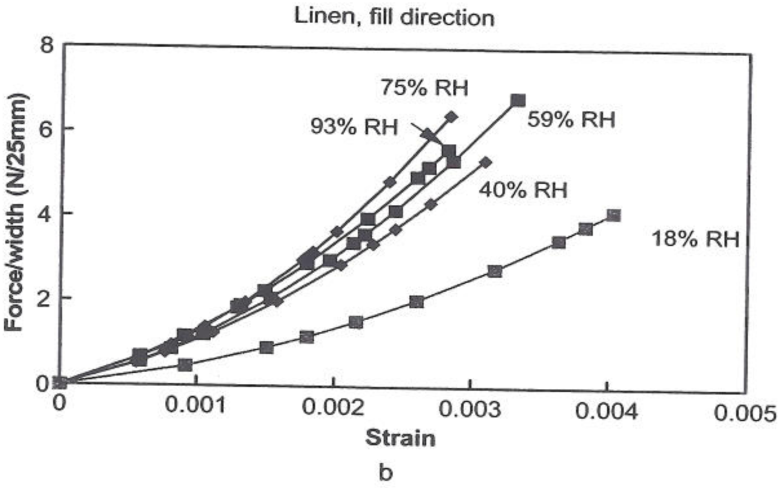
Fig. 12. The stress strain test of a sample of American mahogany cut in the tangential direction. This particular test illustrates several aspects of the tensile test. This includes the yield points, elastic and plastic regions, strength of the material (the stress at the end of the test) and the strain at failure.

LINEN

The mechanical tests of linen hold considerable interest since their behavior with respect to relative humidity is the opposite of the behavior of all other materials found in canvas paintings. Figures 13a and 13b show the force per width (note this is not stress) versus strain for the warp and fill directions of samples of Utrech #8800 linen. This is a medium weight linen with a yarn count of 1.25 yarns per mm in both the warp and fill directions. These tests only show the early portion of the tests and not the points of failure which are considerably higher than the other materials found in canvas supported paintings. In general linen is quite strong. It is so much stronger than any other material so that if a painting is stretched and the linen is in reasonably good condition, all the other layers of the painting will crack long before the linen will tear. The reason the force per width is used instead of stress is because it is not practical to determine the actual cross-sectional areas of a linen samples. The textile industry has developed a whole system of tests that effectively give very useful information for the purpose of comparing different textile properties [8].

The mechanical tests of the linen show that in low strain regions, the material is the most flexible at low relative humidity. It is the stiffest at high relative humidity levels. However when the material is saturated as shown in Figure 13a, the stiffness drops considerably. This is due to the slippage of fibers in the yarns. The behavior of linen with respect to relative humidity is a result of the weave or crimp structure of the textile. As the linen dries out the crimp is less pronounced and the test reflects straightening of the yarns. As the linen gains moisture, the yarns swell and the crimp becomes tighter, making it more difficult to straighten the yarns. The stiffness of linen is very important. If the linen is to act as the support for the rest of the painting, it should be stiff and strong. Ideally the hide glues and paint films supported by the linen should be more flexible than the support. As it will be shown the complete opposite is true, particularly at low relative humidity. At low relative humidity the canvas is flexible and the other materials are quite stiff. So in reality the canvas is being supported by the glue and paint layers. It is only at high relative humidity that the canvas is stiff and the other materials are quite flexible. The mechanical behavior shown in the linen illustrated should be considered fairly typical for linens. The biggest variation in the data when comparing different weight textiles is will most likely be reflected in the magnitude of the force/width values.



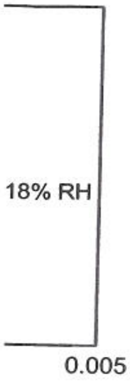


Figs. 13a y b. Figure 13a shows the force per width versus strain of Utrecht #8800 linen in the warp direction. The tests were conducted while the samples were at equilibrium at different relative humidity levels. These plots show only the early portion of the tests. Figure 13b shows the force per width versus strain of Utrecht #8800 linen in the fill direction. The tests were conducted while the samples were at equilibrium at different relative humidity levels. These plots show only the early portion of the tests and not to break.

One note here is that canvases can only develop tensile stresses, never compression stresses. Thus there is a limit to their active contribution in the mechanical deterioration of paintings.

HIDE GLUE

In general hide glue is a very strong material when it is in moderate levels of relative humidity. It looses both strength and stiffness in high relative humidity, above 75% RH. Figures 14a and 14b show the stress versus strain plots for hide glue and sturgeon glue respectively. In both cases the glues get stiffer and stronger with decreasing relative humidity. Also in both glues it can be seen that there are mid-ranges of relative humidity where the properties of the glues don't show significant changes. For the hide glue that range is from about 70% to 35% RH. The range for the sturgeon glue is lower, from about 40% down to 15% RH. Those test results that appear to stop short are a result of cutting defects in the edges of the test specimens causing premature failure. For a given relative humidity the sturgeon glue is stronger than the hide glue. If the humidity gets high enough the glues lose strength altogether, especially the hide glue. This means that if the back of a canvas painting gets wet or even exposed very high humidity, the bond between the



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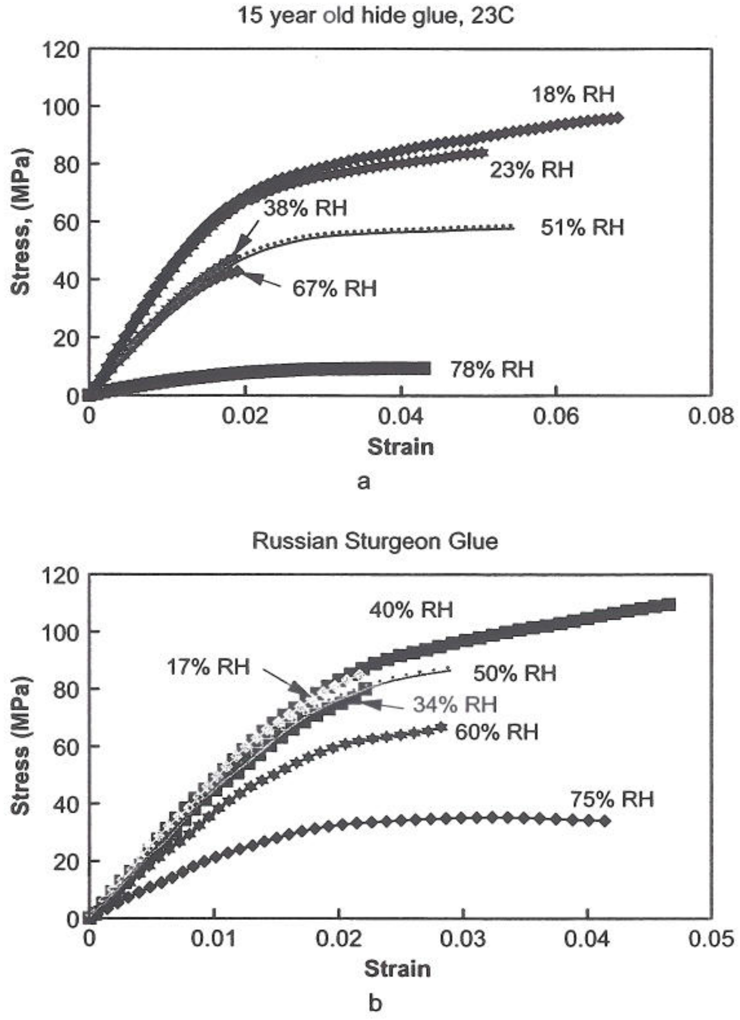
canvas and the ground of the painting has a very high potential of failing. Since the canvas is also wet it becomes stiff (develops a high modulus) and shrinks as shown in Figure 4 and cleaves the paint from the painting as shown in Illustration 1.



Figs. 14a y b*. Figure 14a shows the stress strain tests of 15 year old hide glue at different levels of relative humidity. The short plots shown in the 67% and 38% RH tests are a result of edge defects of the specimen meaning defects in this material can cause premature failure. Even so these specimens reached elongations of 2%. At high RH the hide glue is flexible and has little strength. At the lower levels of relative humidity the glue gets stiff and strong with out loosing flexibility. Figure 14b shows the stress strain tests of sturgeon glue at different levels of relative humidity. The short plots shown in the 17% and 34% RH tests are a result of edge defects of the specimen meaning defects in this material can cause premature failure. Even so these specimens reached elongations of 2%. At high RH the hide glue is flexible and has little strength. At the lower levels of relative humidity the glue gets stiff and strong with out loosing flexibility.*

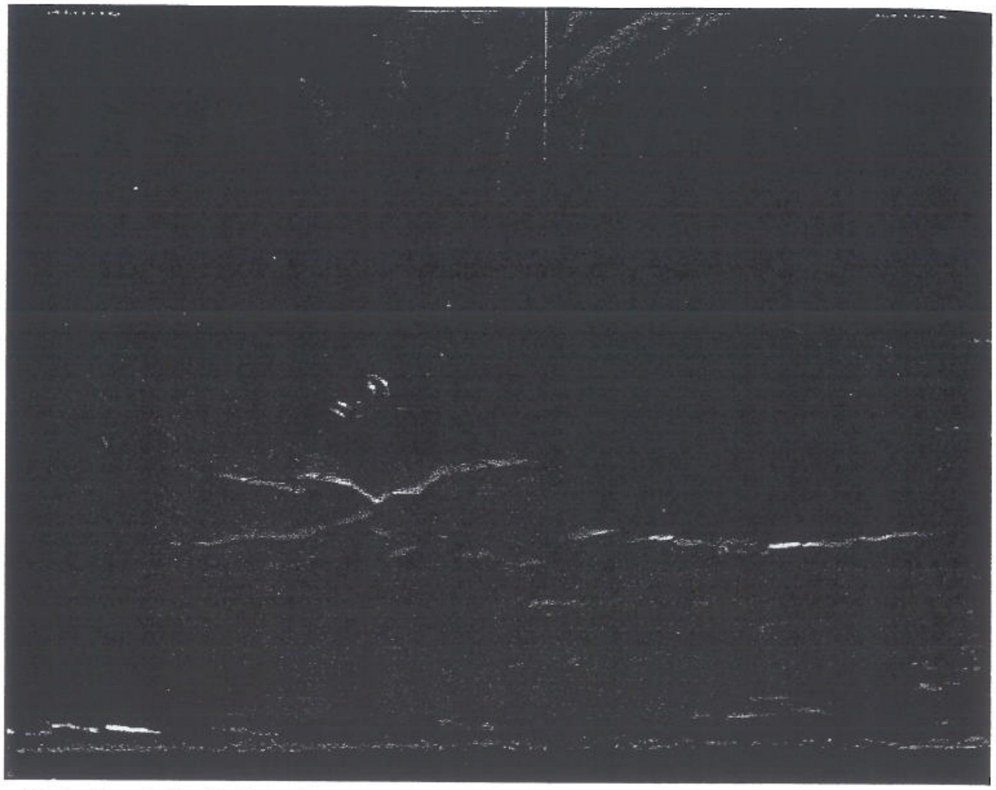


***Illustration 1**. Detail of a 19th century painting showing cleavage of the paint film resulting from moisture condensing on the reverse and collecting behind the lower stretcher bar. The mechanism is the shrinking of the canvas and the loss of strength of the glue size.*

OIL PAINTS

Oil paints are complex in that the different pigments cause paints to dry having very different mechanical properties. Figure 15 shows the stress strain results for different paints after drying for at least 12 years in a controlled environment of 40%-50% RH and 23° C. The paints tested here were cast on polyester film and removed for testing. All of the paints were allowed to equilibrate to an environment of 48% RH, 23° C prior to testing and the rates of the loading tests were identical. The paints made with the earth colors develop very little strength and stiffness even after 12.25 years of drying. The paints made with titanium white and basic lead carbonate have nearly the same modulus but the titanium white has little strength and its extension barely reaches the yield point of 0.005 (0.5% elongation). The titanium white can be considered a brittle paint. The paint made with the zinc oxide has developed a very high modulus and while it has developed a high strength, it is truly brittle having a breaking strain of only 0.003 (0.3% elongation). It is necessary to understand that

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while the strength of paint is important, its ability to elongate is of far greater importance. It doesn't take a great deal of force to crack thin paint films even though they have relatively high strength. The paint made with malachite is included to illustrate the effects of pigments containing copper. Another point to be made is that while a paint made with zinc oxide can become extremely brittle, it is a slow drier. On the other hand, paints made with the earth colors can become dry to the touch in three to five days yet remain quite flexible and never really develop significant strength. There seems to be little correlation between the drying time and the mechanical properties of paints [9, 10]. One of the questions that has often arisen is how long does it take paint to dry? The definition of drying is difficult to answer since it is normally associated with the "dry to the touch" concept. That concept is really a surface mechanism and not a through-the-thickness idea. Mechanical testing of paint films reveals that there are chemical processes continuing over very long times. Figure 16a shows the tensile stress-strain tests of a paint made by grinding basic lead carbonate in cold pressed linseed oil. This paint would be typical of a paint made several hundred years ago, without the addition of any modern driers, stabilizers, or inert bulking material. As shown in this figure, the paint is getting stronger (greater stress at break) as the time of drying continues, and there is a modest reduction in the strain (stretch) at the point of failure. The strain levels in these tests are fairly high and this paint is still quite flexible after 14.25 years of drying. One point of interest is that the paint shows a continual increase in strength over this time period. This means that whatever the chemical processes that affect the mechanical properties of this paint they are still continuing.

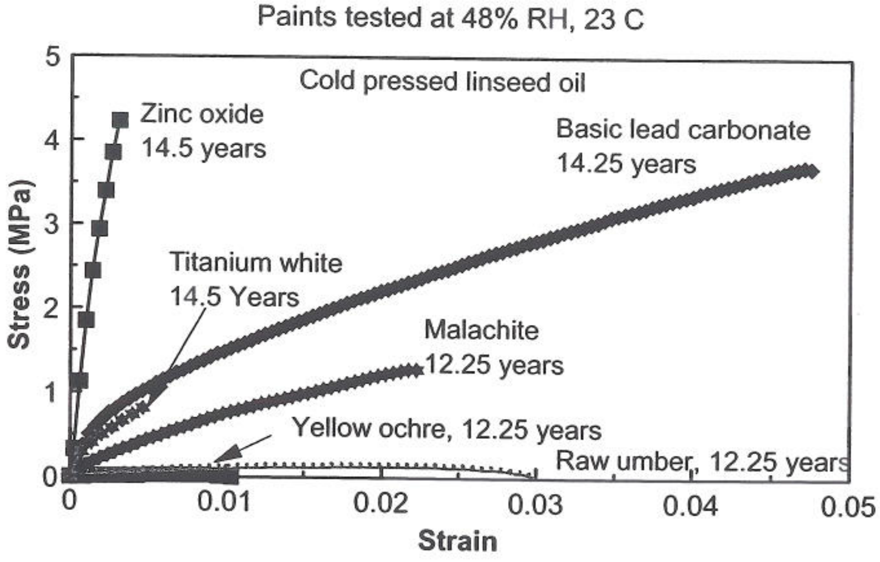
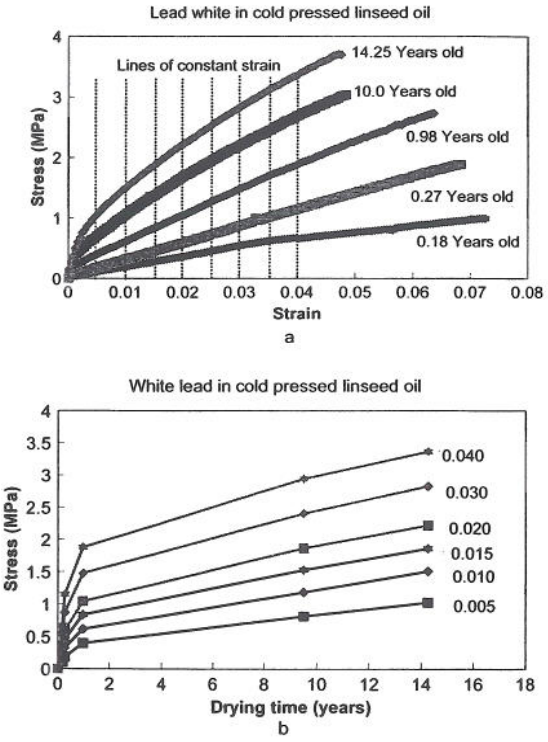


Fig. 15. *The results of stress strain tests conducted of paints made with different pigments. As can be seen the different pigments have a dramatic effect on the mechanical properties of oil paints. It must be noted that pigment volume concentrations can also have similar effects but these data are a result of the different pigments.*

In Figure 16a, the dashed vertical lines are lines of constant strain. Proceeding upward from the strain axis on any one of those lines shows how the paint is drying from another perspective. These lines show how the stress is increasing over time at a constant strain. This concept can be explored fully as shown in figure 16b.

Figure 16b shows the stresses at constant strains and how they increase with time. This is important since it shows that after the first year of drying, the stress increase is somewhat proportional with time elapsed. There is only a suggestion that the rates of stress increase are diminishing. It will take additional drying time to develop a better picture of the very long term behavior but it is quite clear that this paint is still undergoing changes in mechanical properties, even after 14 years. This paint is not unique in that the continued changes are occurring over a long period of time. Figure 17a shows the tensile test conducted over time of basic lead carbonate ground in cold pressed safflower oil. As with the lead white in cold pressed linseed oil, this paint shows a general increase in strength and a decrease in the strain to break. Figure 17b plots the stress increase at constant strain over the drying time for the lead white in safflower oil. This paint behaves in a nearly identical manner as the lead white in cold pressed linseed oil and shows considerable flexibility after 14.5 years.



Figs. 16a y b. *Figure 16a shows the stress versus strain plots of basic lead carbonate paint made with cold pressed linseed oil at different ages. Even after 14.25 years, the paint is still gaining in stiffness and strength. Figure 16b shows the stress at constant strains versus time for basic lead carbonate paint made with cold pressed linseed oil. These plots indicate that the processes that cause the increase in stiffness and strength show little indication of slowing down. This means that whatever chemical processes affect the mechanical properties of this paint are still continuing. If one uses a strain of 0.005 and extrapolates over time, it will take about 180 years for this paint to become as stiff and brittle as the zinc white paint shown in figure 15. However if the processes governing the changes in the mechanical properties slow down even a small amount then the paint will probably never become that brittle.*

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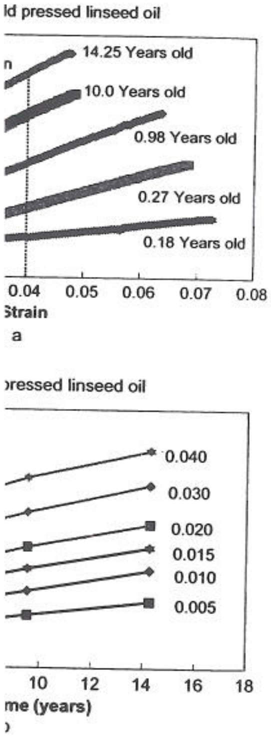
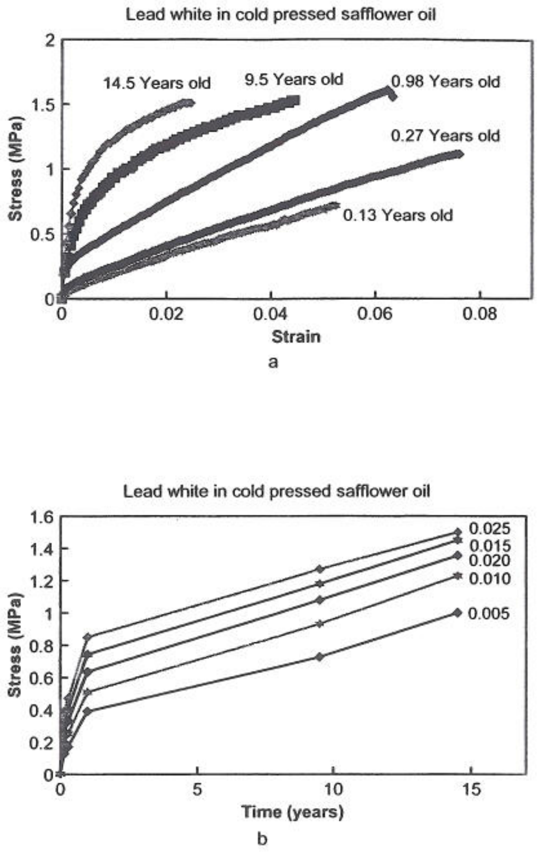
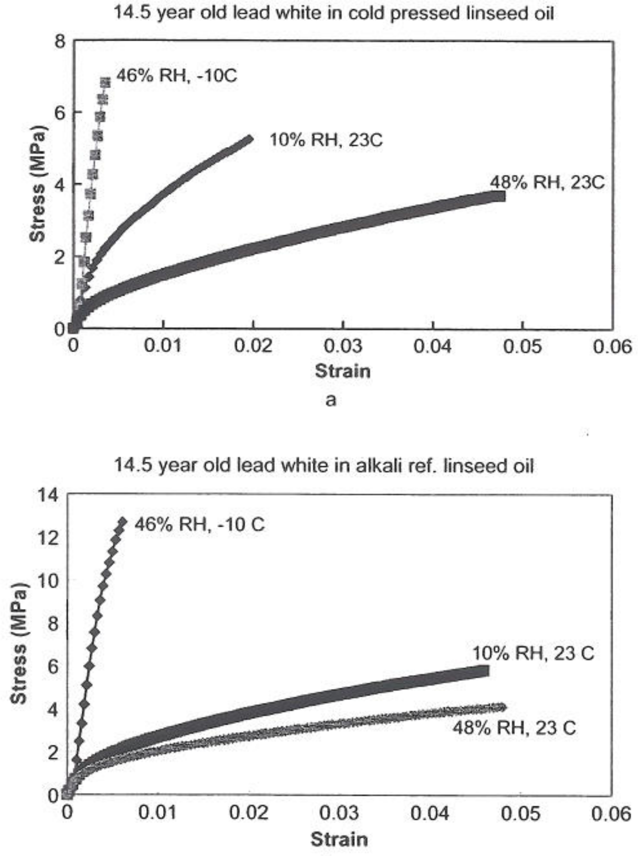




Figs. 17a y b. Figure 17a shows the stress versus strain plots of basic lead carbonate paint made with cold pressed safflower oil at different ages. Even after 14.25 years, the paint is still gaining in stiffness and strength. Figure 17b shows the stress at constant strains versus time for basic lead carbonate paint made with cold pressed safflower oil. These plots indicate that the processes that cause the increase in stiffness and strength show little indication of slowing down.

THE EFFECTS OF TEMPERATURE AND RELATIVE HUMIDITY

Relative humidity (RH) has been thought to cause paints to become brittle, yet the actual test data suggests that this is not completely true. Low temperature can have immediate consequences on the durability of paint films. Paint films are similar to many other polymers in that they pass through a phase change as the temperature is decreased. This is sometimes called the glass transition temperature or $T_{g,}$ with oil paints this region is between -10° C and -20° C, higher temperatures take longer to produce stiffening through different mechanisms. While low temperature embrittlement can be reversed by raising the temperature, high temperature alteration of the mechanical properties is permanent. Figures 18a, 18b and 19 show three oil paints tested at three different environmental conditions, 48% RH and 10% RH at 23° C and -10° C at 46% RH. Figure 18a shows the test results of basic lead carbonate in cold pressed linseed oil at these three environments. The first observation is that the paint tested at low temperature has become glassy and lost all flexibility. It is low temperature that causes much of the cracking that one observes in paintings and painted surfaces [11]. At 10% RH the lead white paint becomes somewhat stiffer and stronger, but still retains a considerable amount of flexibility. The effects of low temperature on the mechanical properties of oil paints are much more drastic than RH changes can ever cause.



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***Figs. 18a y b**. Figure 18a shows stress versus strain plots of lead carbonate paint made with cold pressed linseed oil. The tests were conducted at three different environments, 48% RH, 23° C; 10% RH, 23° C; and 46% RH, -10° C. While lower humidity did increase the stiffness and strength of the paint, it was the low temperature that caused the paint to become extremely brittle. Figure 18b shows the stress versus strain plots of lead carbonate paint made with alkali refined linseed oil. The tests were conducted at three different environments, 48% RH, 23° C; 10% RH, 23° C; and 46% RH, -10° C. While lower humidity slightly increased the stiffness and strength of the paint, it was the low temperature that caused the paint to become extremely brittle.*

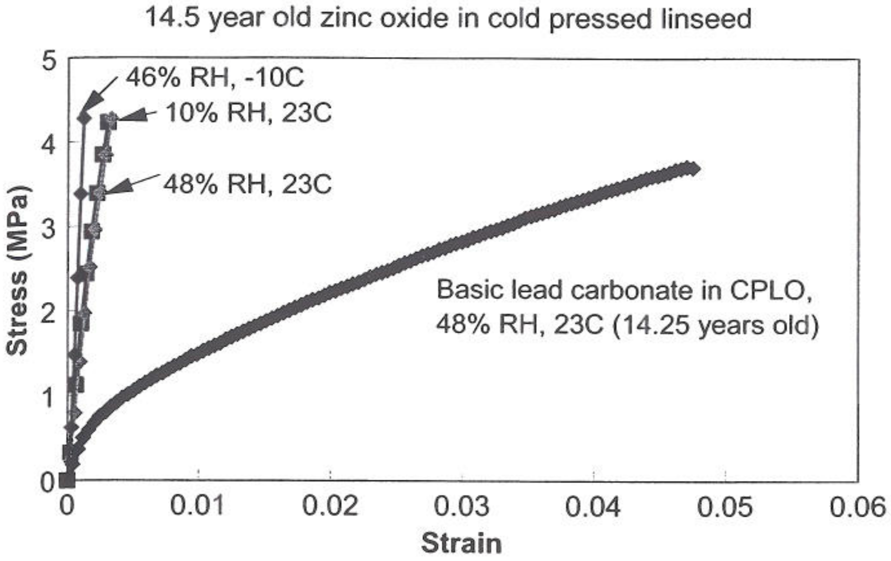


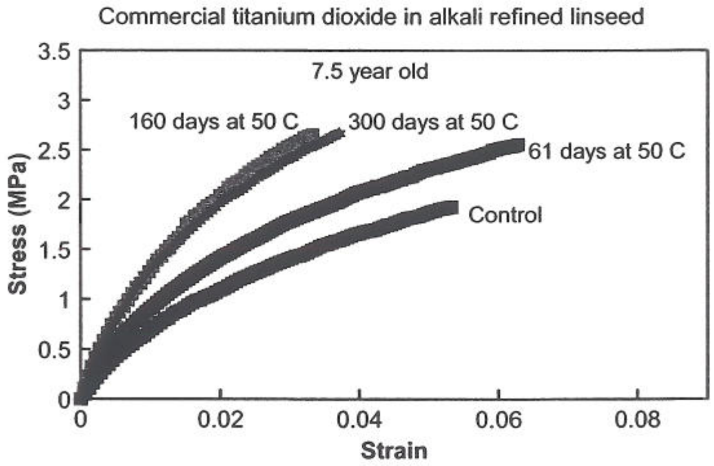
***Fig. 19** The stress versus strain plots of zinc oxide paint made with cold pressed linseed oil. The tests were conducted at three different environments, 48% RH, 23° C; 10% RH, 23° C; and 46% RH, -10° C. The zinc oxide paint is so brittle that neither the lowering of the RH or the temperature made a significant difference in the mechanical properties of this paint. The stress versus strain results of the lead carbonate paint made with cold pressed linseed oil are shown for comparison purposes.*

Figure 18b shows basic lead carbonate in alkali refined linseed oil tested in the same three environments as the lead white in the cold pressed linseed oil. Low temperature causes the paint to become quite brittle. On the other hand, low relative humidity seems to have only a small effect on the mechanical properties of this paint. It is worth commenting that alkali refined linseed oil is used extensively in the manufacture of today's artists' oil paints. Figure 19 shows the tensile tests of zinc white in cold pressed linseed oil in three different environments. Included in this figure are the test results of the lead white for comparison purposes. At 48% RH, 23° C the zinc white paint is already extremely brittle and the change in relative humidity to 10% has almost no effect at all. Cooling the paint down to -10° C increases the stiffness slightly without affecting the strength. It is possible that zinc white paint represents the extremes of physical properties that paint can achieve since it is so little affected by either low relative humidity or low temperature. It is simply extremely brittle as soon as it dries.

THE EFFECTS OF MODEST ELEVATED TEMPERATURES ON THE MECHANICAL PROPERTIES

Modest levels of heat can stiffen paints over time. Commercially prepared "titanium whites" ground in alkali refined linseed oil and alkali refined safflower oil were exposed to 50° C (122° F) for long periods of time. This is the temperature that one might find in an attic where there is no environmental control. Samples were periodically removed from the oven and allowed to equilibrate to 50% RH and 23° C after which they were mechanically tested. This particular paint is a successful mixture of titanium dioxide and zinc oxide that retained considerable flexibility at room temperature after 7.5 years of drying. Figure 20a shows the results of testing the "titanium white" ground in the linseed oil. The paint tends to stiffen with continued exposure to the heated environment. However, after 160 days of exposure there is no further increase in the stiffness. The 160 day sample and the 300 day sample show nearly identical results. Even after 300 days of exposure to 50° C this paint retains a considerable amount of flexibility. On the other hand the "titanium white" ground in alkali refined safflower oil showed continued stiffening over the duration of the heat tests. Figure 20b shows the mechanical test results of this paint. The results show that the longer the exposure (at tests up to 300 days in the study) the greater the stiffness of the paint. Nevertheless the paint still retained considerable flexibility.

While elevated temperatures can certainly increase the rate of whatever chemical processes are responsible for the increased stiffness of paints over time, unreacted fatty acids do act as plastizers to the paints and can be volatilized by the heat [12]. It is most likely a combination of this volatilization and other factors such as oxidation that cause the stiffening of the paints subjected to elevated temperatures.



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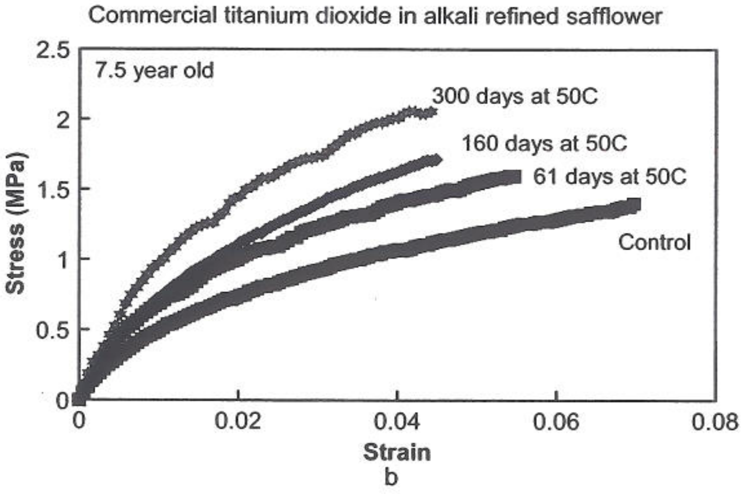
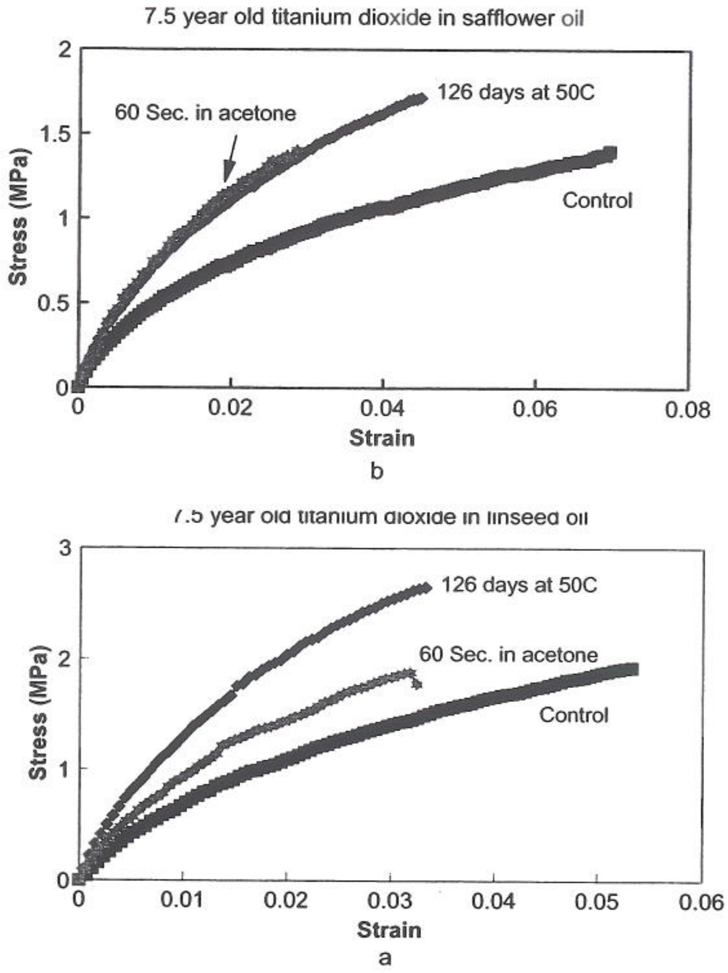


***Figs. 20a y b**. Figure 20a shows stress versus strain plots of commercially made "titanium white" paint made with alkali refined linseed oil. This paint contains a small proportion of zinc oxide pigment. The tests were conducted at 48% RH and 23° C after the paint had been exposed to 50° C for different periods of time. Figure 20b shows the stress versus strain plots of commercially made "titanium white" paint made with alkali refined safflower oil. This paint contains a small proportion of zinc oxide pigment. The tests were conducted at 48% RH and 23° C after the paint had been exposed to 50° C for varying periods of time. In both cases time at elevated temperatures increases the stiffness and strength of the paint.*

THE EFFECTS OF SHORT TERM EXPOSURE TO ACETONE ON THE MECHANICAL PROPERTIES

The same commercially mixed "titanium whites" used in the heat exposure tests were used to examine the effects of short term exposure to acetone. Acetone is a solvent that is commonly used in the removal of old varnishes from paintings. The paint films were 0.25 mm thick and can be considered "thick" films. The paint samples were exposed for 60 seconds, then dried and allowed to equilibrate to 50% RH and 23° C prior to conducting the mechanical tests. Figure 21a shows the difference in the mechanical testing results of the "titanium white" in linseed oil before and after the 60 second exposure to acetone. Included in the results for comparison purposes is the result of the test of heating for 126 days at 50° C. As can be seen, even a very short exposure to acetone increases the stiffness of the paint but not as much as the 126 days of exposure to the heat. Additional exposure to solvents results in further increases in stiffness [13]. Figure 21b shows the difference in the mechanical testing results of the "titanium white" in safflower oil before and after the 60 second exposure to acetone. Included in the results for comparison purposes is the result of the test after 126 days at 50° C. For this paint, the acetone increased the stiffness to the same degree as the paint sample that was heated to 50° C for 126 days. The acetone treated paint lost strength in comparison to the heated paint.



Figs 21a y b. *Figure 8a shows the stress versus strain plots of commercial "titanium white" paint made with alkali refined linseed oil. This paint contains a small amount of zinc oxide pigment. The tests were conducted at 48% RH and 23° C after the paint had been exposed acetone for 60 seconds and allowed to dry thoroughly. Figure 8b shows the stress versus strain plots of commercially made "titanium white" paint made with alkali refined safflower oil. This paint contains a small amount of zinc oxide pigment. The tests were conducted at 48% RH and 23° C after the paint had been exposed to acetone for 60 seconds and allowed to dry thoroughly. The short term exposure increased the stiffness and strength of both paints.*

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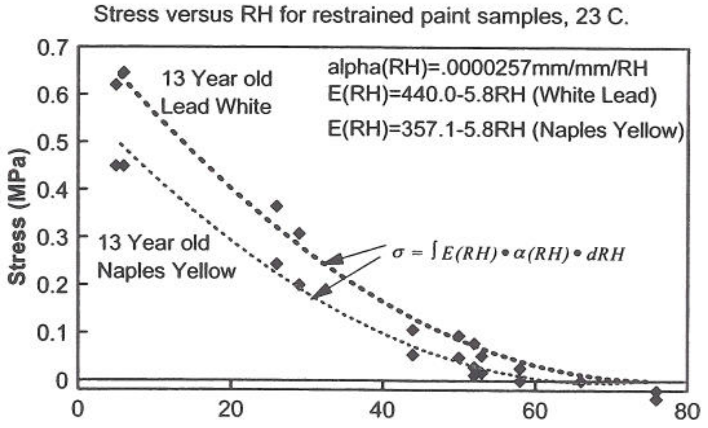
SUMMARY OF THE MECHANICAL BEHAVIOR OF CULTURAL MATERIALS

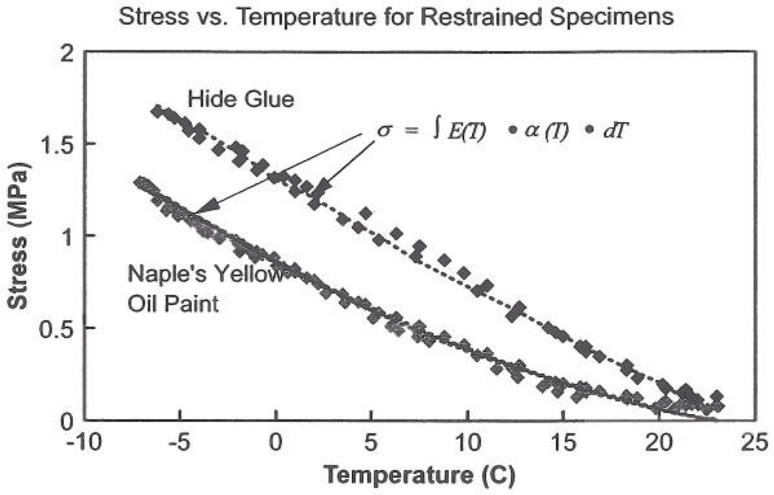
The mechanical properties of oil paints are affected by a number of factors. The properties of paint after it has initially dried (several years) are determined primarily by the composition of the paint, especially the type of pigment. Different pigments in the same oil can produce paints that range from weak and extremely extensible, to strong and flexible, to stiff and brittle even under "ideal" environmental conditions. If paints are aged under "normal" conditions, their properties change slowly over time. It is predicted that a typical paint such as lead white in linseed oil will require many centuries, if ever, to become "brittle" if it is not chemically or physically altered. Exposure to cold environments results in immediate embrittlement of the paint film though warming to room temperature reverses this. Solvents and elevated temperature can permanently embrittle the paint films.

The response of paintings as structures to the environment

UNIAXIAL TESTING AND THE COMPOSITE EFFECTS OF THE PAINTINGS' MATERIALS

If one restrains a material such as a paint film and desiccates it a stress will develop in the film. This is because the paint wants to freely contract but the restraint is preventing the contraction. The magnitude of the stress is a function of the moisture coefficient of expansion, alpha (RH) and the mechanical properties. In this particular case the modulus. For calculating the stresses in a restrained paint film the mechanical tests have to be conducted under full equilibrium conditions and not the faster 30 second interval tests previously shown [14-16].





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***Figs. 22a y b**. Figure 22a shows the tensile stresses measured in restrained samples of oil paint with decreasing relative humidity. The dashed lines show the calculated stresses using the moisture coefficient and the modulus of the materials [14-15]. Figure 22b show the tensile stresses measured in restrained samples of oil paint and hide glue with decreasing temperature. The dashed lines show the calculated stresses using the moisture coefficient and the modulus of the materials. Note that the stresses in the Naples yellow oil paint are higher when the temperature is decreasing than when the relative humidity is decreasing.*

Figure 22a shows the development of stress with desiccation for restrained samples of white lead and Naples yellow oil paints. Included in this figure are some of the data showing how the stress can be calculated as well as measured. Figure 22b Shows the stresses developed with cooling of restrained samples of oil paint and hide glue. It is worth noting that the stresses in the Naples yellow oil paint can reach higher levels when cooled than when desiccated. Cold temperatures and not low relative humidity causes the paint to become brittle.

Since it is possible to calculate stresses in materials using the physical and mechanical properties, it is possible to develop complex computer models of paintings and calculate their response to changes in different environments. It is also possible to gain insight into the response of paintings to changes in relative humidity using some fairly simple experiments.

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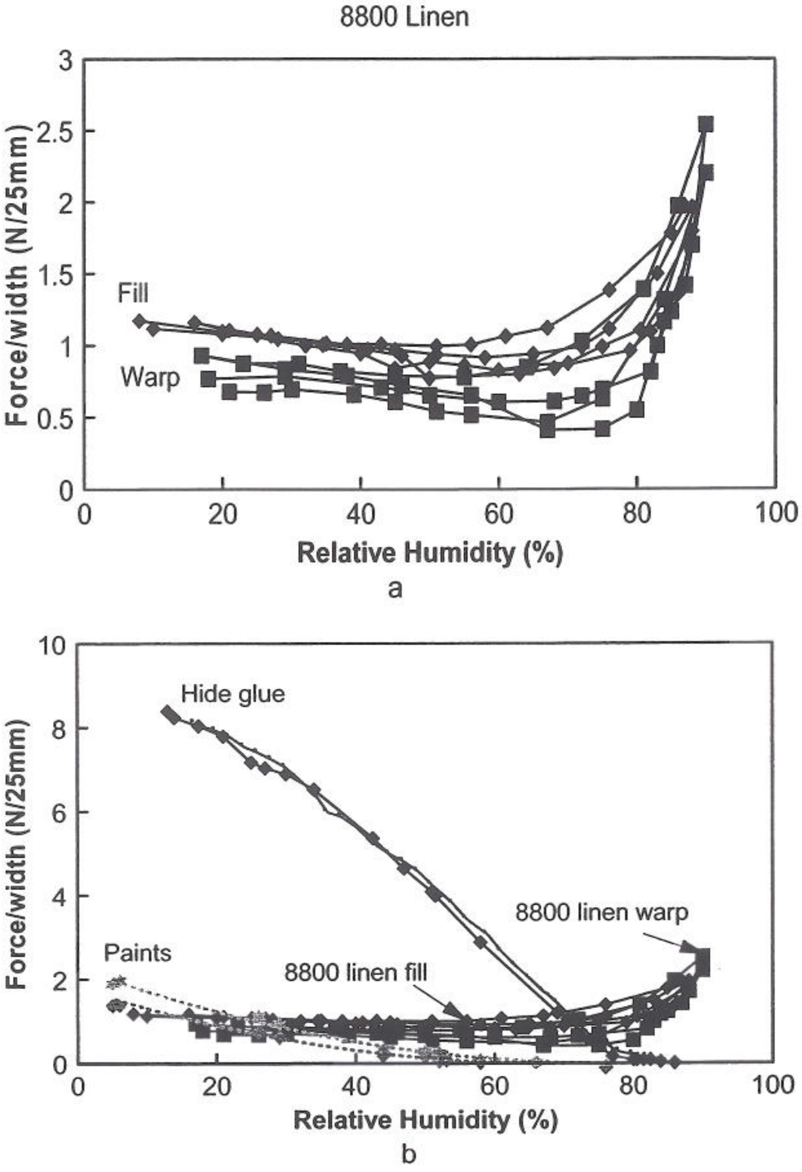

Figs. 23 a y b, *Figure 23a shows the tensile forces per width measured in individual restrained samples of the #8800 linen in the warp and fill directions with decreasing relative humidity. The greater forces develop when the relative humidity is above 80%. Figure 23b show the forces per width measured in individual restrained samples of oil paints and hide glue and linen with decreasing relative humidity. Note that the oil paints which have thicknesses of 0.12mm (the thickness of a typical 19th century painting) don't develop significant forces while the hide glue (0.012mm thick) develops very high forces when desiccated from 88% to 10% RH. The linen is included in this figure for comparison purposes.*

If one restrains samples of linen and allows the relative humidity to cycle up and down for several cycles, it is possible to measure the force per unit width of the specimens in both the warp and fill directions of the linen. It is also possible to measure each of the materials such as the hide glue and oil paint found in canvas supported paintings. Figure 23a shows the force per width developed in the warp and fill directions of restrained samples of the same #8800 linen shown in previous tests. The greatest magnitude of force is developed when the humidity is above 80% RH.

This is a direct result of the high stiffness (the modulus, E) and high degree of shrinkage shown in the free swelling and mechanical properties tests. Between 10% and 80% RH there is only a modest change in force. This is a result of the low stiffness and modest shrinkage of the linen in these RH ranges. Figure 23b shows the forces per width measured in individual restrained samples of oil paints and hide glue and linen with decreasing relative humidity. Note that the oil paints which have thicknesses of 0.12mm (the thickness of a typical 19th century painting) don't develop significant forces where the hide glue (0.012mm thick) develops very high forces when desiccated from 88% to 10% RH. At the higher levels of RH, the paints and glue sample have little strength or stiffness and thus develop little force. At low relative humidity it is the hide glue that develops significant force levels and at very low RH it is the linen. It is possible to compare these individual restrained tests to the restrained test of samples of an actual painting.

Figure 24 shows the force per width developed in restrained samples of a 1906 painting by Duncan Smith. This painting had a linen weave and weight very similar to the #8800 linen, a glue size layer, a thin white lead ground and raw umber as a design layer in the area the samples were taken. Samples were taken from each of the warp and weft directions of the support canvas. At very high relative humidity, above 80%, the force levels rise dramatically indicating that the linen is developing the forces in this RH range.

This can be said with high degree of certainty since no material other than linen is capable of developing forces at high relative humidity. On the other hand the most probable cause of the forces developed with desiccation is the hide glue size in the painting.

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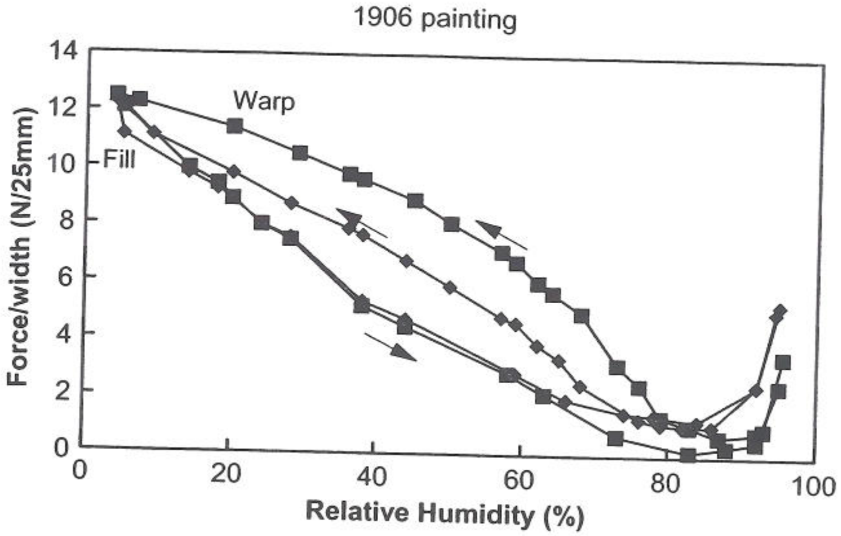

Fig. 24. Shows the force per width developed in restrained samples of a 1906 painting by Duncan Smith. At very high relative humidity, above 80%, the force levels rise dramatically indicating that the linen is developing the forces in this RH range. On the other hand the most probable cause of the forces developed with desiccation is the hide glue size in the painting.

Figures 22 through 23 shows that simple tests can give strong indications as to how each layer of a painting responds to changes in relative humidity. The more complex problem of determining how the entire surface of the painting responds to environmental change requires much more sophisticated research such a more detailed materials analysis and computer modeling. Never-the-less certain information has been developed.

Full scale experiments

It is not recommended to use cultural resources such as important paintings as experiments; never-the-less conservation treatments have actually done so for decades. Without fully understanding the consequences of some treatments, many have been recommended that can actually be detrimental. Measuring the properties of painting materials provides an opportunity to develop full scale "mock-up" paintings than can be used as experimental test paintings. For example, since one can control the pigment volume concentration of gesso, then one can create a gesso that has both the dimensional and mechanical properties of an old brittle oil paint. This allows one to bypass the long wait (centuries) for an oil to become dry and possibly brittle and use the gesso as a substitute for the oil design layer for experimental purposes. For example, a 500mm times 760mm experimental painting was made by first coating stretched linen with a hide glue size and then coating the sized painting with a gesso made with hide glue and calcium carbonate. The pigment volume concentration of the gesso was approximately 93%. This was a coating that was only minimally dimensionally responsive to changes in relative humidity but very weak and brittle. This gesso coating has very similar properties as the zinc oil paint discussed earlier in this paper with the exception that it has less strength. After the test painting was thoroughly dry, it was subjected to nine long term humidity cycles ranging from 90% to 35% RH. Illustration 2 shows the results of the cycling in relative humidity.

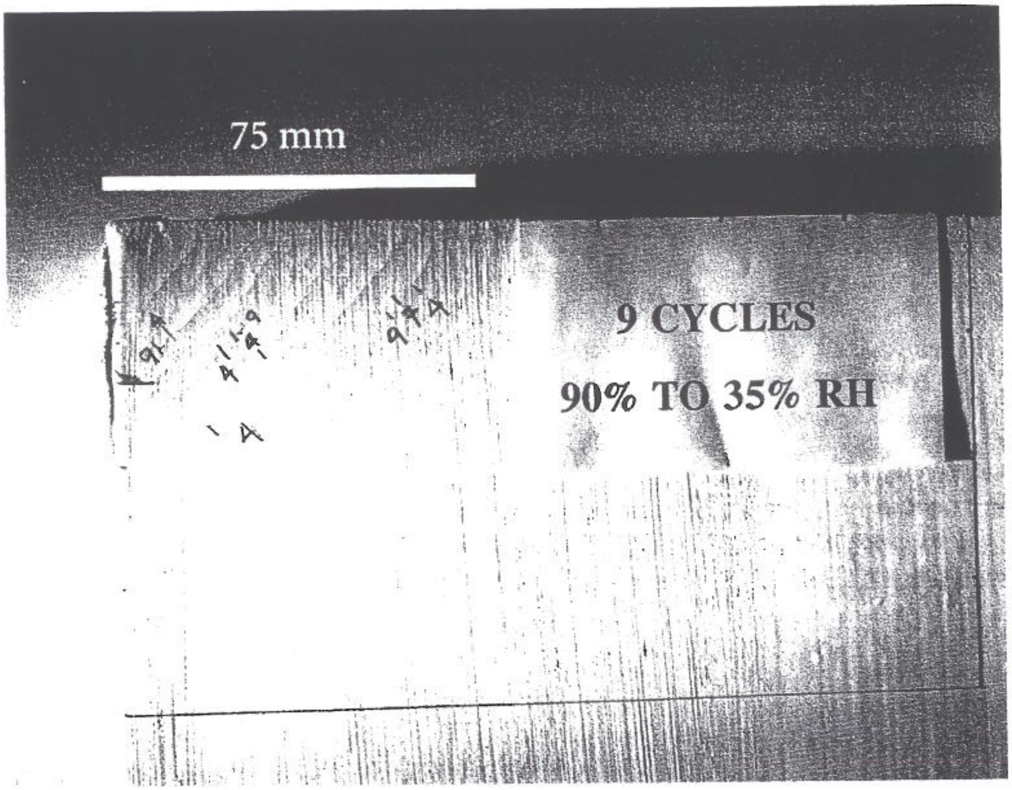

Illustration 2. *Crack formation resulting from exposing a test painting to severe cycles of relative humidity. What is of most interest is that even with the severe RH changes the damage is not more severe.*

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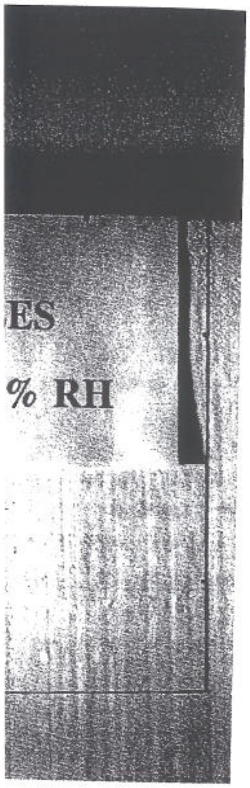

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he damage is not more

Cracking occurred at all four corners but the damage was localized to very small sections of the test painting. As can be seen in the illustration, the cracks are in the form that is often seen in actual paintings but not as extensive as might be expected. Also shown is the crack extension after some of the cycles. This suggests that severe humidity cycling, while causing damage is not as detrimental as currently thought.

Computer modeling

Computer modeling requires the most intensive effort in terms of materials characterization and programming capability. However, it has the capability of providing the user with the most comprehensive understanding of the behavior of paintings and their response to environmental change [16-17].

The method most commonly used is Finite Element Analysis (FEA) that subdivides a structure such as a canvas supported painting into a number of discreet elements. The elements are then assigned the proper materials properties such as the expansion coefficients and mechanical properties. The accuracy of the model largely depends on the accuracy of the materials properties and the number of elements used. The more elements used the more refined the model and the better the results achieved. Illustrations 3 and 4 give some insight into the capability of computer modeling. Illustration 3 shows the upper left corner of a painting that has been expanded on the stretcher (keyed-out) excessively.

Computer modeling generated the information that showed this to be the case [17]. In this illustration cracks are visible propagating from the corner towards the center of the painting. Equally important is the distortion of the painting often referred to as “drapes”. This distortion is actually also a result of the stretcher expansion causing plastic deformation of the design layer materials, prior to crack formation. When the keys become loose and the stretcher relaxes the distortion becomes quite pronounced as show in illustration 3. The effects of expanding a stretcher can also be generated using mock-up test paintings as described earlier.

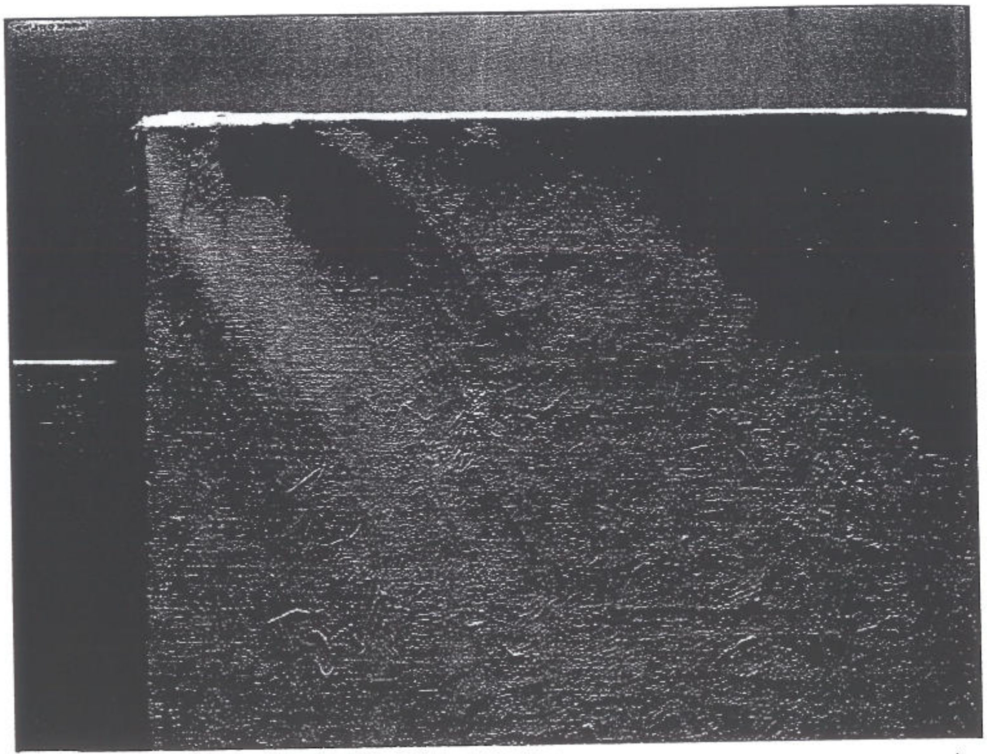

Illustration 3. *Shows the upper left corner of a painting subjected to excessive stretcher expansion. Both the cracks and the distortion are direct result of the expansion.*

Up to this point little attention has been given to the effects of very low temperature with the exception of showing that this environment causes paint to become quite brittle. All of the artists' materials expand and contract with heating and cooling in much the same way that they respond to moisture. If the data shown suggests that low temperature and not low relative humidity causes paint films to become brittle, then modeling the effects of low temperature on canvas supported paintings could reveal other effects. Illustration 4 shows a 19th century American painting (630mm x 760mm) with extensive cracking over its entire surface. This painting has a glue sized linen with a white lead oil ground. Computer modeling reveals that this was the result of low temperature and not low relative humidity. The data from Figures 22a and 22b shows that oil paint has the potential of developing higher stresses from low temperature than from low relative humidity. Low temperature will cause paint to be come brittle.

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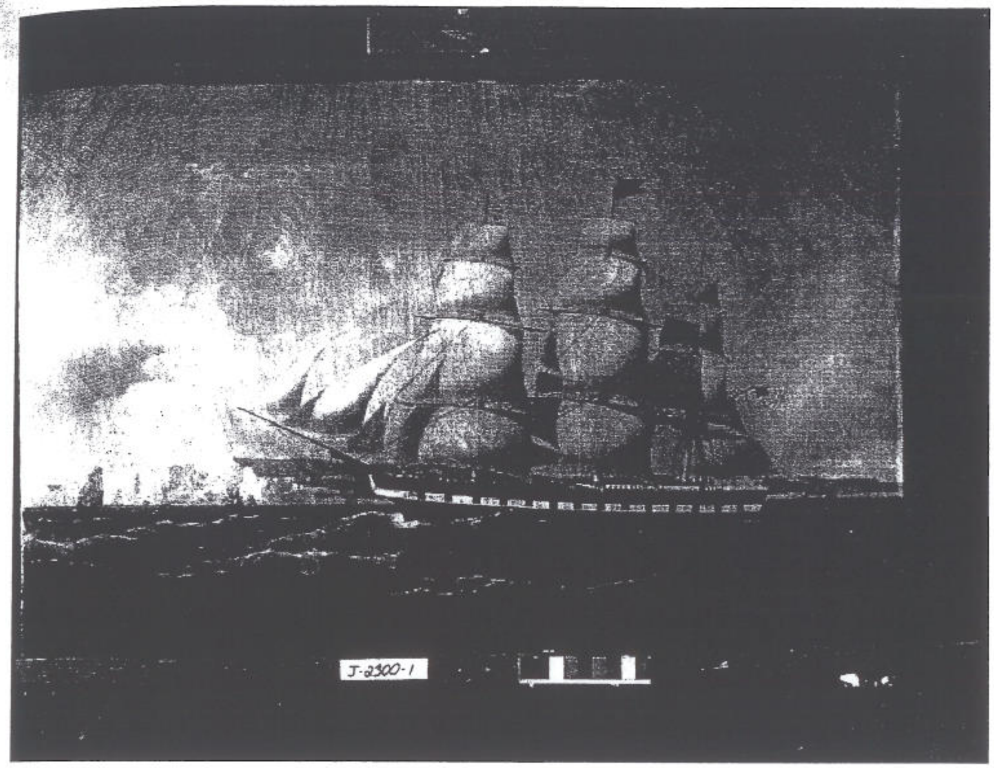

Illustration 4. *The crack damage caused by low temperature on a typical American painting. The cracking is far more extensive than seen on paintings subjected to low relative humidity.*

Conclusions

If one is to understand how paintings respond to environmental change, there are several systematic approaches that should be considered. Of primary importance is the physical and mechanical characterization of the materials themselves. There is considerable information to be gained from this exercise alone. As shown in this paper, relative humidity does not seem to cause the embrittlement of the materials as so often cited. Low temperature can certainly cause the oil paint to become brittle. Full scale mock-up model paintings can be created that can be used as experimental platforms for environmental studies as well as testing prototype conservation treatments. The key to mock-up paintings is to use materials such as gesso to mimic old brittle oil paint layers. By controlling the pigment volume concentrations of the gesso one can develop coatings that can reproduce both the dimensional and mechanical behavior of oil paints. Computer modeling is the most intensive type of analysis to perform but it yields the most comprehensive information regarding canvas supported paintings and their response to the environment. It is critical that the proper physical and mechanical properties of the materials are used in developing computer modeling.

One issue not covered in this paper is the chemical degradation of the materials over time. Research is currently in progress and there are some results that are of interest. The hydrolysis of oil paints over time makes them more flexible and not more brittle [9, 10]. It is uncertain as to what the effects of long term oxidation on the paints are. This is an area that needs considerably more research.

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