Failure Mechanisms in Canvas Supported Paintings: Approaches for Developing Consolidation Protocols

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Introduction

If one is to discuss the consolidation of deteriorated and damaged paintings on canvas, it might be useful to explore why the damage occurred initially. In this way it is possible to take preventative steps to stop damage in the first place and better understand the methods and materials that might be most appropriate in the consolidation and repair of the painting. The damage that does occur can result from accidents in handling, excessive change in ambient moisture, excessive changes in temperature, conservation treatment, chemical deterioration, and biological attack.While all of the sources of damage may be different, the consequence is that it ismost likely will be the need for structural intervention at different levels. In this case structural intervention means that the mechanical properties of the painting materials will need to be considered as well as adhesion and cohesion of the consolidating adhesives used to reinforce the damaged painting. Even though they may look entirely differently, paintings by different artists have a considerable amount in common. Many used linen canvasses, hide glue sizing, oil grounds, and oil paints in their construction, and this is true for a large number of artists' paintings in the 18th, 19th and 20th centuries in America and even earlier painting in Europe. The typical construction of a painting might be described as shown in Figure 1. The principal differences among artists, that is to say 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. While it can be said that the there is little difference between the varieties of animal glues used in paintings, the quality and strength of those glues can vary widely. This depends on the freshness and "shelf life" of the glue and the strength of the glue can have a profound effect on the durability of the painting. To some degree this can even be said of oils used in the paint 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 making the painting surface of the canvas somewhat smoother and reducing the texture of the canvas.

The design layers are then applied over the ground. There are an infinite variety of these combinations of materials and it can be shown that the way a material is applied can affect the fundamental structural properties of the painting and how that painting responds to environmental changes. What can have an even greater effect is the choice of the materials used in the painting. For example, it will be shown later in this paper that the choice between a white lead ground and an earth color ground can result in significantly different degrees of damage. One of the things rarely considered is whether a drier was used in the paint. If one is concerned about the preservation and conservation of canvas supported paintings then it is useful to first focus on the fundamental similarities, and this includes the focus on the materials used. 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 and the response of the painting to different external stimuli can be explored.

The Moisture Absorption of Some Artists' 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. Many materials such as wood and plant fibers absorb a considerable amount of moisture from the atmosphere and for this reason have large dimensional changes with changes in ambient relative humidity. It might be useful to look at the absorption properties of some of the materials typically found in paintings. Figure 2 shows the change in moisture content of samples of pigment free cold pressed linseed oil and the same oil containing a low percentage (1.6%) of the drier litharge, PbO. They had been allowed to dry for ten years in a controlled environment (40%-50% RH, 20o-23oC). These samples gain and loose about 6%-7% of their weight in moisture over a wide range of relative humidity. Naturally this will have some effect on the swelling properties of artists' paints. The important point here is that if a material absorbs moisture from the environment, it is likely to swell. If it looses moisture with a reduction in the ambient relative humidity, then the materials will shrink. If a restrained material is desiccated then it will cause an increase in the stress in the material.

Three important material aspects need consideration. One is the dimensional response to changes in relative humidity. The second is the mechanical properties of the materials and how the properties are affected by changes in relative humidity and the third aspect is the development of stress in the materials when restrained. Understanding these three fundamental behaviors assists in understanding why paintings are damaged and provides insight into the necessary properties needed for consolidating the damaged paintings. This paper focuses on the development of stress at different environments and how the painting is affected.

Restrained Testing of Artist's Materials

It is possible to demonstrate the development of stress (or force) in restrained materials subjected to changing relative humidity. The reason for doing this is to determine the magnitude of the forces and stresses developed in the different layers of paintings since any consolidation adhesive used in consolidation will need to have similar properties. It also shows the levels of RH when the most stresses occur and in this way one can find methods of avoiding the same adverse environmental conditions.

Another reveling feature of this form of testing shows that the high stresses occur at the time that the materials develop high dimensional response and high stiffness at the same level of relative humidity. For example, linen has both a high stiffness as shown by the mechanical tests and a high dimensional response as shown by the swelling isotherms at the same high levels of relative humidity, above 85%. Consequently, it demonstrates high force development at those RH levels when restrained. Similar behavior can be shown for all of the materials with the important exception that high stresses develop at different humidity levels..

The restrained testing of linen

Since linens are stretched on stretchers and not free to expand or contract it becomes of interest to determine the level of forces developed by the canvas as the relative humidity in the environment changes. Figure 3 shows the changed in the force per width of Ulster #8800 linen as the relative humidity changes. What is important here is that first, the forces are fairly high and second that they develop at high levels of relative humidity. The force per width is used since it is not readily possible to measure the cross-sectional area of the fibers in the linen that is normally used to calculate stresses. The important point here is that the linen is fairly unresponsive at RH levels from 10% to 80%. Above 80% RH, the force development is significant and if the fabric is loose at all it will shrink, and cleave the design layer away from the canvas.
On the other hand, different linens behave differently. Figure 4 shows heavier 248 linen where only the warp direction yarns develop forces at high humidity. In all probability the fill yarns in this linen have little crimp. It was reported by Headley that only restrained machine woven textiles seem to exhibit stress increases at high humidity [1]. This suggests that the more loosel y woven hand made textiles are less prone to this behavior.
A final comment here is that canvases can only develop tensile stresses, never compression stresses. This limits their active contribution to the mechanical deterioration of paintings to the high RH levels..

The restrained testing of hide glue

Of all of the materials used in canvas paintings hide glue is the strongest and nearly the stiffest. It is also the one material that develops the most force when restrained and desiccated. It is because this material is both stiff (and strong) and has a high dimensional response at low humidity that it develops so much force. Figure 5 shows both the force per width (and stress) a thin film of the glue will develop when restrained and desiccated from 85% to 15% RH. The thickness of the film shown in this plot is about the same as that found as a size coating on a painting.

The restrained testing of oil paint

In general, the force per width (and stress) developed in restrained and desiccated oil paint is considerably less than the other materials found in paintings. One of the reasons is that with the exception of some of the paints made with the earth colors, the dimensional response to humidity changes is low. On the other hand while the earth colors tend to have a higher dimensional response they have relatively low stiffness. Figure 6 shows two paint samples restrained and desiccated from around 75% to 5% RH. Even with this large change in relative humidity, the forces and stresses developed are low. So the likely hood that low humidity alone damages the oil paint layer is low. It takes a combination of materials and their individual responses to changes in humidity to cause deterioration. This can be demonstrated by superimposing all of the layers of a painting together and comparing the results with an actual painting.

Superposition of the different paint layers

It is possible to plot the information from figures 3, 5, and 6 on the same graph as shown in figure 7. The thickness of these films are the same shown in their respective figures and would be typical of a common painting. In this figure it is possible compare the responses of the individual layers of a canvas painting and to determine the different forces occurring different levels of RH. For example the fabric is developing high forces only at high RH levels and staying relatively constant at humidity levels below 80%. The hide glue is developing high forced at very low RH levels but looses all force at levels above 80%RH. Also note that the paint films are developing relatively low stresses and that is only at very low levels of RH.

The restrained testing of samples from an actual painting

Figure 8 shows forces developed in a restrained test of samples of an actual painting in a changing environment of relative humidity. These painting samples were constructed with a medium weight machine woven fabric, a hide glue size, a lead white ground and a design layer of raw and burnt umber. It is important to note that there are two areas of high force development, one at the very low levels of RH and the other at the very high levels of RH. This is comparable to the force development of hide glue and the canvas as shown in figure 33. When look at figure 34, it is easy to see which layers are developing the highest forces at different levels of relative humidity.

When looking at both Figures 7 and 8, it also becomes apparent which materials are loosing all of their strength. For example it is safe to say that the hide glue is no longer acting as the secure bond between the ground and linen canvas. From 80% RH and above the paint layer is clearly at risk of delaminating from the canvas. At this same RH the paints films are the most flexible but are also in their weakest state. From 80% RH and below the forces in the fabric is changing very little. Above 80% RH, the fabric will shrink if loose and certainly delaminate the design layer attached to it. This will be explored in more detail in later sections..

Effects of Cycling in Large Ranges of Relative Humidity

If a painting as described in this discussion is exposed to cycling of large changes in relative humidity then another form of corner cracks can occur. This can be demonstrated by constructing a "mock" painting of canvas, a size layer of hide glue and a "design layer" composed of a hard gesso film having the mechanical properties of an old brittle oil paint film.

The gesso layer was a hide glue and calcium carbonate mixture [3]. Figure 9 illustrates the results of such an experiment. These cracks can be sources of delaminating of the paint layers if the environmental changes get excessively worse such as actual wetting with water.

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Moisture Induced Damage to Paintings

One of the most frequently encountered types of damage to paintings, both on canvas and on wood is a result of exposure to high moisture levels. In old historic buildings, the moisture can condense on the inside of exterior walls from a variety of reasons. One of those reasons is the excessive humidification if the interior spaces of the building in the wintertime. At such times the exterior walls of older building can get quite cold to the point where the interior surfaces reach the dew point. The dew point is the ambient temperature where moisture condenses out of the air. Behind paintings, which act as insulation, hanging on the inside of exterior walls moisture condenses on the cold walls. Conversely in the summertime, the exterior walls get hot and the space behind the painting is warmer than the interior space of the gallery where the painting is exhibited. In such cases the relative humidity drops and can get as low as 35%. The microclimate behind paintings hanging in the inside of interior wall is entirely different than the central gallery space.

Another reason that condensation can occur is that in old stone buildings, the masonry walls are cooled during the wintertime. These massive stone walls, due to their high thermal mass, are slow to warm up with the changing seasons and in the spring time warm moist air enters the building along with visitors through open doors. This results in extensive condensation of not only the walls but paintings hanging on those walls. This occurs on many of the monuments in Washington, D.C. in the United States.

One of the less frequently considered conditions occurs on very hot, humid days in the summertime. In July in Rome for example, the outside temperature can easily reach 32o C (90o F) and the relative humidit y can reach 65% or higher. Inside a building such as St. Peter's Basilica it is considerably cooler where the temperature can be around 27o C (80 o F) but the relative humidity can be as high as 90%. This is a result of open doors and the outside air cools at it enter the building. The air in such large building can stratify and the cooler air remains at the lower levels of spaces where it can be even cooler and the humidity even higher, even approaching the dew point.

Existing environmental conditions are not the only source of high moisture levels. Many of the traditional lining techniques using hide glues and pasta lining adhesives contribute to increasing the moisture content of the painting. This increases the potential for causing massive shrinkage of the original painting canvas and weakening the original glue size.

Water condensing on paintings often tends to run to the bottom of the painting and typically causing damage along the bottoms of the paintings as shown in figures 11 and 12. In the case of the painting shown in the figures 11 and 12, there was sufficient water to leave a "tide line" on the canvas and actually totally disrupt the adhesive bond of the anima l glue size layer. Hence the canvas shrank, the glue size lost all of it adhesive strength and the paint and ground layerscompletely separated from the canvas in the areas as shown in figure 12.

Se un dipinto venisse sottoposto a forti variazioni di umidità relativa, diciamo tra il 95% o più e il 35%, allora ci si aspetterebbe un degrado degli strati pittorici dello stesso. Elevati valori di umidità possono facilmente essere l'effetto della condensa della parete esterna in edifici storici. Viceversa, dove le pareti esterne possono diventare fredde, possono anche assorbire calore nel periodo estivo. Pareti calde fanno effettivamente diminuire l'umidità relativa dell'aria ambientale vicino ai muri. I dipinti appesi alla parte interna delle pareti esterne possono così essere facilmente esposti ad ambienti sia freddi e umidi, che caldi e secchi.

Behavior of Possible Consolidation Adhesives Behavior of Possible Consolidation Adhesives

Since consolidation of damaged paintings is ultimately one of the major goals of the fine arts preservation, it might be worth while to take a look at the properties of some materials that have been used or considered as consolidating adhesives. Curiously, adhesives often selected as consolidants are rarely tested to see if they have sufficient cohesive or adhesive strength. It is also true that they are rarely tested to see if they are excessively responsive to RH fluctuations.

Even traditional hide glues can have a wide variability in mechanical performance when they show no indication of deterioration.

Some adhesives that might be possible candidates for consolidants include more modern materials. In the case of Mowiol adhesive as shown in figure 13, it is excessively dimensionally responsive to RH and might not be considered a suitable adhesive. It is even more dimensionally responsive than hide glue. Equally important is whether the consolidating adhesive has sufficient strength.

If a conservator is asked to reconstruct a damaged painting and hang in it original place then one necessarily needs to ask whether the micro-climate of its installation location was responsible for the damage in the first place. It makes no sense to reinstall the painting without correcting the factors inducing the damage in the first place. On the other hand there are conditions where the environment cannot be easily adjusted and needs to taken into consideration. For example, let's assume that the relative humidity in the environment typically swings from 25% to 75% on an annual basis. The stresses induced in the glue size layer of a typical painting range from about 5 MPa to 27 MPa (see figure 5).

Figure 14 shows the mechanical properties of several different resins and adhesives including Acryloid B-67 and Acryloid B72 which have been used as consolidating adhesives in the past.

The important point is that none of the materials shown in figure 14 develop the strength of 27 MPa which is actuall y needed as a consolidant in some cases where the environment is not even moderately controlled. It the humidity levels go higher than 75% then even the hide glue will have problems as a consolidant since it looses all strength at high RH levels. The important point here is that it is not enough to just consider the properties of the material used in consolidation but the environment existing where the painting is installed..

Conclusions: Relative Humidity Control

If one examines the research data on the dimensional and mechanical properties there are some significant conclusions to be drawn.

- The most obvious one is that high relative humidity and exposure to water can have a serious effect on the all of the textiles, the hide glues, the gessoes and most of the paints made from the traditional pigments identified as the earth colors. This includes raw and burn umber, ocher, raw and burnt Sienna, and some of the iron oxides. The sources of these high RH levels are condensation on cold exterior walls, high interior humidity on hot, humid, summer days and excessive moisture from lining adhesives in conservation treatments. These moisture levels cause a significant proportion of the damage seen on both canvas supported and wood panel paintings. There is a direct correlation between the measured properties of artists' materials and the damage observed in the paintings. It is also clear that keeping the humidity levels below 75% will diminish the amount of damage done to paintings.
- With the exception of the hide glues, very low relative humidity does not seem to have as dramatic an effect on the artist's materials as high relative humidity. At very low humidity, the hide glue had the potential for developing extremely high stresses in a painting. This is because there is considerable shrinking of the

glue as well as the development of very stiff and strong mechanical properties. Also at low RH the stiffness of the linen canvas is considerably reduced forcing the upper layers of the painting to act as more and more of the support of the painting.

- It may not always be possible to change the environmental conditions in a church or building but there are some measures that can be taken to reduce damage to the paintings. One of the recommendations is the attachment of stable backing boards to the reverse of the paintings. These act both as buffers and barriers, separating the painting from the source of the moisture. In addition, it is possible to install spacers between the painting and the walls such that ambient air in the exhibition space can more easily circulate behind the painting. If the ambient RH behind the painting can be lowered to around 75% or lower there will be a considerable reduction in damage.
- It is necessary to consider all of the mechanical and dimensional properties of all of the materials found in paintings when considering a consolidating adhesive. While the materials in paintings act together to form the "structure" of the painting, they in fact act to a large degree independently as materials when subjected to changes in the environment.
- The addition of a linen lining canvas serves to make the painting somewhat more sensitive to high humidity since the canvas lining material will act in the same manner as the original canvas. While textiles with synthetic fibers are often used as linings, they still need to be tested systematically to see if they have the capacity to act as true supports for paintings.
- The use of hide glue as the lining adhesive or consolidant will make the painting more responsive to low humidity conditions. It is very clear that there needs to be a concerted effort in identifying, developing and testing materials considered as consolidants for paintings.
- In the case of paintings exhibiting interlayer cleavage as shown in figure 43, the penetration of adhesives will be the problem. The bond between layers (which are extremely weak) that have not yet separated will prevent any adhesive penetration. In these cases other structural support considerations will need to be considered.

References

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Mecklenburg, M.F., McCormick-Goodhart, M., and Tumosa, C.S., *Investigation into the Deterioration of Paintings and Photographs Using Computerized Modeling of Stress Development*, "JAIC" 33(1994) 153-70.

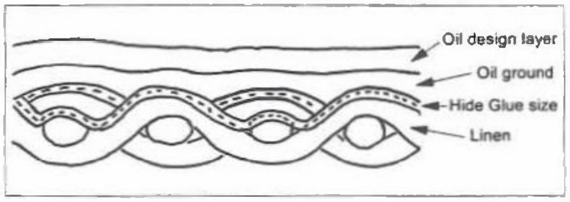

Fig 1. The construction of a typical canvas supported painting.

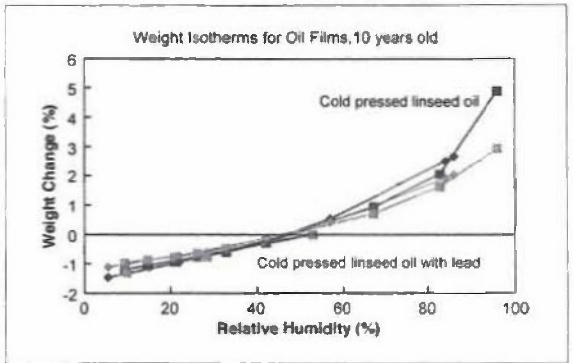

Fig 2. The weight change of un-pigmented linseed oil with changes in relative humidity. The oil with the lead is slightly less responsive to moisture changes and this can possibly be the result of the drying effect of the litharge.

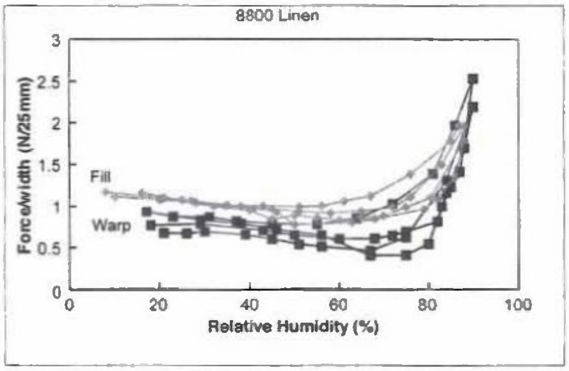

Fig 3. Shows the force per width of both the fill and weft directions of Ulster #8800 linen when it is restrained from movement and the ambient humidity is changed. This fabric would be considered "shrinker."

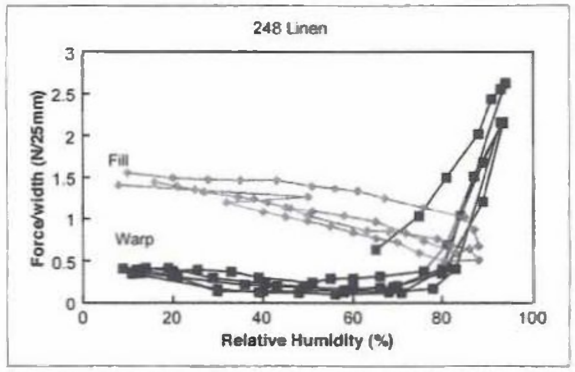

Fig 4. Shows the force per width of both the fill and weft directions of type 248 linen when it is restrained from movement and the ambient humidity is changed. This fabric would be considered "shrinker" but only in the warp direction.

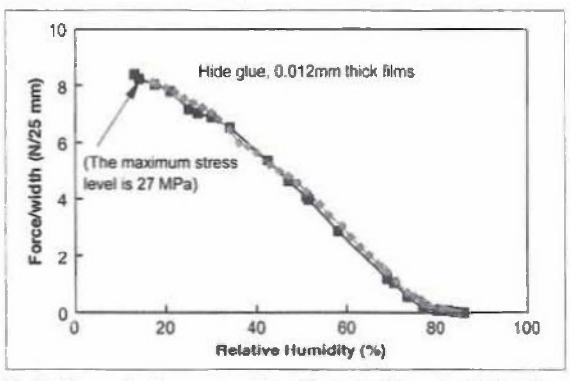

Fig 5. Shows the force per width of both the fill and weft directions of type 24 linen when it is restrained from movement and the ambient humidity is changed. This fabric would be considered "shrinker" but only in the warp direction.

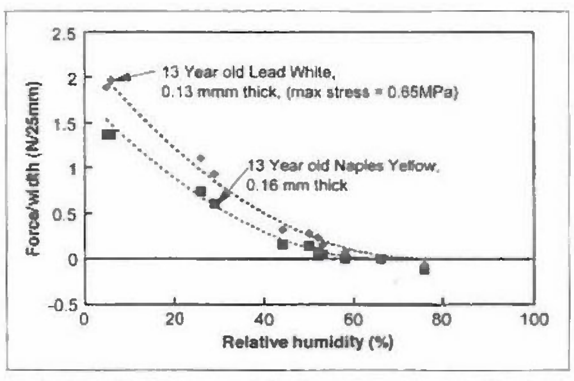

Fig 6. shows the force per width of restrained samples of lead white and Naples yellow oil paints. The stress of the white lead paint at the maximum force per width of this sample was only 0.65 MPa. The force per width of the paints is considerably lower than the hide glue and a bit lower than the #8800 linen shown in figure 3. The thicknesses indicated for the paint samples is typical of those found in paintings.

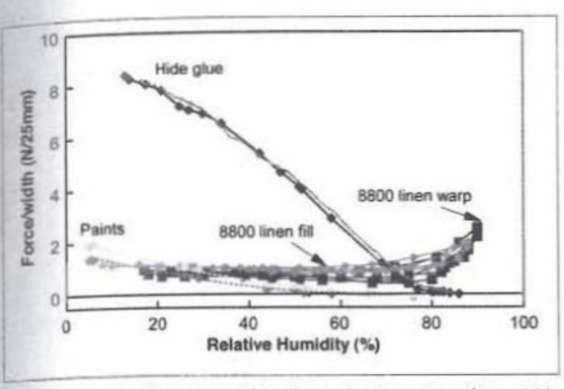

Fig 7. Shows the force per width of restrained samples of linen, hide glue, and lead white and Naples yellow oil paints. The thickness of these films are the same shown in their respective figures and would be typical of a common painting. In this figure it is possible compare the responses of the individual layers to that of an actual canvas painting and to determine the different forces occurring at different levels of RH. For example the fabric is developing high forces at high RH levels and the hide glue is developing high forced at very low RH levels..

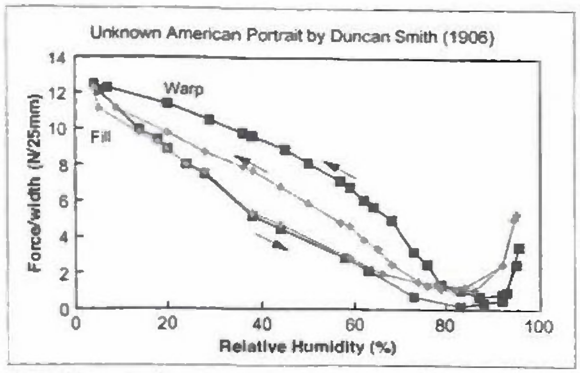

Fig 8. Shows the forces per width of restrained samples of an actual painting in both warp and fill directions. These painting samples were constructed with a medium weight machine woven fabric, a hide glue size, a lead white ground and a design layer of raw and burnt umber. It is important to note that there are two areas of high force development, one at the very low levels of RH and the other at the very high levels of RH. This is comparable to the force development of hide glue and the canvas as shown in figure 7.

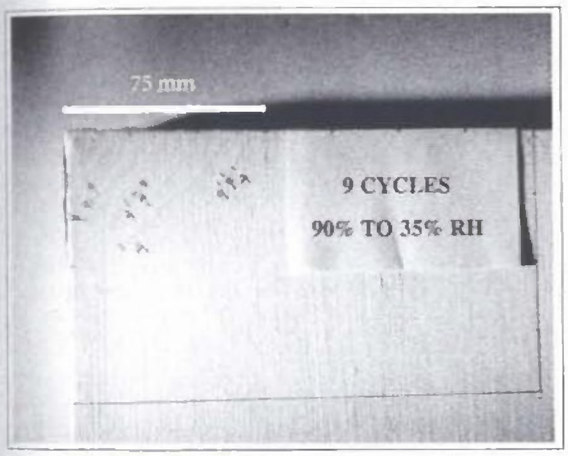

Fig 9. Shows the results of cycling and experimental "mock" painting to cycles of large changes in relative humidity. Additional cycling beyond the initial 9 cycled did no further damage as the cracks that occurred relieved the stresses due to the initial RH cycles. This model painting was constructed with a stretched canvas, a hide glue size and a stiff gesso acting as a design layer.

Fig 10. Shows the combination of crack patterns from stretcher expansion and cycling in large changes in relative humidity.

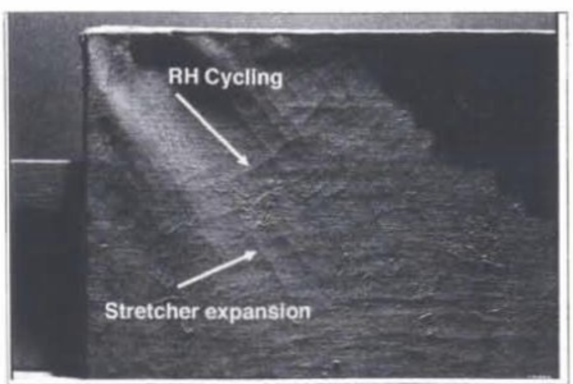

Fig 11. Shows the front and reverse of a painting where condensation has run to the lower edge of the painting and caused damage. On the front view of the painting the red arrow shows the damage and on the reverse view, the red arrow shows the "tide line" left by the water (*Photos by Matteo Rossi Doria*).

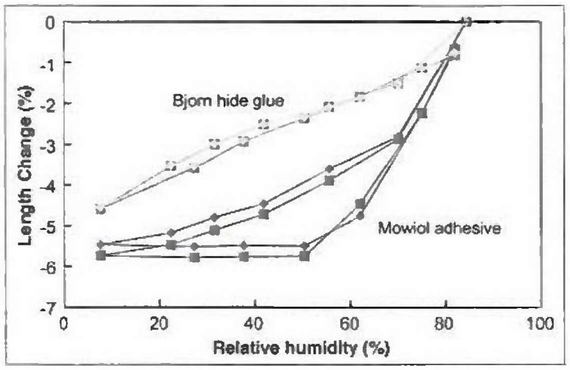

Fig 13. Show the dimensional response of Hide glue and Mowiol adhesive to changes in relative humidity. The Mowiol adhesive is considerably more responsive to RH and it has a very high hysteresis behavior.

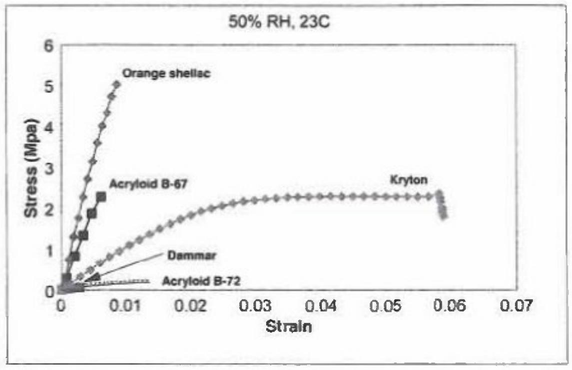

Fig 14. Shows the mechanical properties of some materials potentially used as consolidating adhesives. Acryloid B67 and Acryloid B-72 have been used as consolidants in the past.

THE CARE OF PAINTED SURFACES.

Materials and methods for consolidation, and scientific methods to evaluate their effectiveness

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