Some Mechanical and Physical Properties of Gilding Gesso

Marion F. Mecklenburg

Abstract

The gesso layers typically used in gilding are a mixture of a hide glue and an inert filler such as calcium carbonate. Since relative humidity has a dramatic influence on the mechanical and physical properties of the glue, mixtures of gessoes containing the glue will be similarly affected. This paper examines some effects of environmental moisture on the mechanical and physical properties of rabbit-skin glue alone and gesso mixtures containing this glue and calcium carbonate. The mechanical effects of an initial single relative humidity (RH) cycle are compared to the effects of several consecutive RH cycles.

The cracking and flaking of the gilded gesso surfaces found on picture frames, furniture, and decorative objects are a major concern. The repair of these surfaces is costly and time consuming, and the continuing degradation of these artifacts represents a persistent decay of our cultural heritage. If one includes the preventive maintenance of collections as an important component of good conservation practice, it is necessary to establish sound procedures for long-term storage, for proper exhibition conditions, and for appropriate transportation of the objects. The development of systematic, rational approaches to the prevention of the cracking and flaking of gilded surfaces requires an understanding of the degradation processes involved.

Deterioration may be the result of chemical processes or, equally important, of mechanical processes. The interaction of environmental fluctuations with the mechanical properties of the artifact's constituent materials results in forces that produce dimensional changes and material "failure." The environmental changes referred to here include oscillations in both ambient temperature and atmospheric moisture, and this paper will discuss some aspects of the influences of environmental moisture on the mechanical and physical properties of gesso and the hide glue adhesive used in making this material.

Research Objectives

To understand the gesso and the behavior of its mechanical properties and their relationship to environmental conditions, certain objectives were established. These were (1) to examine some mechanical properties of gesso with respect to the chalk-to-glue ratio and the pigment volume concentration (PVC, the ratio of the volume of the chalk to the total gesso volume); (2) to examine the effect of relative humidity (RH) on the dimensional stability of rabbit-skin glue in several gesso mixtures; (3) to examine the stress developed in restrained samples of hide glue and selected samples of gesso mixtures with respect to changes in RH; and (4) to determine, if possible, those mechanisms that might lead to a more complete understanding of the environmental effects on the mechanical deterioration of gesso.

The research relied on the following basic definitions. The mechanical properties of a material are those that define the strength and stiffness (or flexibility) of the material. Specifically, strength is the maximum stress or force per unit area that can be applied to a material before it breaks and is usually referred to as the ultimate strength. Strain, the change in length per unit length, is a measure of the material's ability to deform when subjected to stress. Stiffness is the ratio of stress to strain, called the modulus of the material, and is normally determined from the linear portion of the stress-strain plot.

For this study, the physical property of a material that was of most concern was the swelling of the gesso associated with the uptake of water. The amount of water absorbed increases with the increase in ambient RH—that is, the amount of water vapor available to react with the gesso. It seems obvious that RH influences the physical properties, but it also has a marked effect on the mechanical properties.

Sample Preparation

The gilded surface prepared for a wood substrate has many layers of gesso, some of which have different chalk-to-glue ratios. The strength of hide glues in each layer can vary considerably. Both the strength of the glue and the ratio of chalk to glue in the gesso mixture can affect the mechanical properties of the gesso layers. Deborah Bigelow's "Gold Leaf on Furniture" records the variety of gilding mixtures used by artists to prepare gesso coatings.[1] Besides using different animal sources and preparation methods for their glues, artists have relied on an assortment of fillers or bulking materials: calcium carbonate, burned gypsum (calcium sulphate), and clay boles. This means that there have been many permutations in the making of gesso. From an experimental point of view, this presents difficulties. For this research project, considerably fewer gesso sample mixtures were tested to delineate some factors that seem relevant.

Bigelow also has provided a record of historic recipes for mixing the stock-glue solution and for the various gesso layer mixtures.[2] While these are somewhat vague and not very quantitative, at worst the recipes provide a guide for examining various combinations of chalk and glue mixtures that we can use in our tests. (This vagueness in the cited recipes indicates the degree of personal experience needed by a craftsman to reproduce the gesso mixtures consistently.)

For this study, a 10% (by weight) stock solution of rabbit-skin glue was prepared and used throughout the tests. The glue was granular, and the normal precaution against exceeding 52°C was observed. From this stock solution, all the gesso mixtures were made using ground calcium carbonate and deionized water, and these are listed in table 1 in ascending order of chalk-to-glue ratios. Those labeled clearcole, softwhite, and hardwhite refer to the specific mixtures referenced in Bigelow's dissertation. In the same table are the pigment volume concentrations. The equation used to calculate these values was

Table 1. Gesso Mixtures

Gesso type	Parts by weight			Chalk-to-glue ratio†	PVC
	RSG*	Water	Chalk		
Stock glue	1.00	0.00	0.00	0.00	0.00
Clearcole	2.00	1.00	0.63	3.15	58.30
Hardwhite	2.00	1.00	2.00	10.00	81.60
a. Intermediate	1.50	1.50	2.00	13.50	85.50
b. Intermediate	2.00	1.00	3.00	15.00	86.90
Softwhite	1.50	1.50	3.00	20.00	89.90
c. Intermediate	1.00	2.00	3.00	30.00	93.00
d. Intermediate	0.50	2.50	2.00	40.00	94.70
e. Intermediate	0.50	2.50	3.00	60.00	96.40

SOURCES: Robert C. Weast, ed., *Handbook of Chemistry and Physics* (54th ed.; Cleveland: CRC Press, 1973–74), p. B-77; K. H. Gustavson, *The Chemistry and Reactivity of Collagen* (New York: Academic Press, 1956), p. 67. Gustavson reports a theoretical density of 1.38 and a measured value of 1.41 for pure collagen. I have assumed that we are dealing with less than pure collagen and estimated the specific gravity as 1.2.

* 10% stock glue solution by weight.
† Specific gravity of chalk = 2.7; specific gravity of glue = 1.2.

$$PVC = (W_c/\gamma_c)/(W_c/\gamma_c + W_g/\gamma_g) \tag{1}$$

Where PVC = pigment volume concentration,
W_c = weight of the chalk
W_g = weight of the glue
γ_c = specific gravity of the chalk
γ_g = specific gravity of the glue.

(These values are useful in presenting some data graphically.)

Once mixed, the fluid gesso was poured on a Mylar sheet that had been stretched tightly on a level Plexiglas surface. Upon drying, the gessoes were cut with a sharp scalpel into strips approximately 0.25" wide. The cut edges of the strip samples were then sanded with 400-grit sandpaper to eliminate any edge defects that might precipitate premature rupture during the testing of the specimens. The sample sizes typically were 7.00" long by 0.25" wide by 0.014" thick. Samples of the stock glue solution were prepared similarly except that thickness of the dried glue film was 0.006". The glue and the films of the first six gesso mixtures listed in table 1 dried

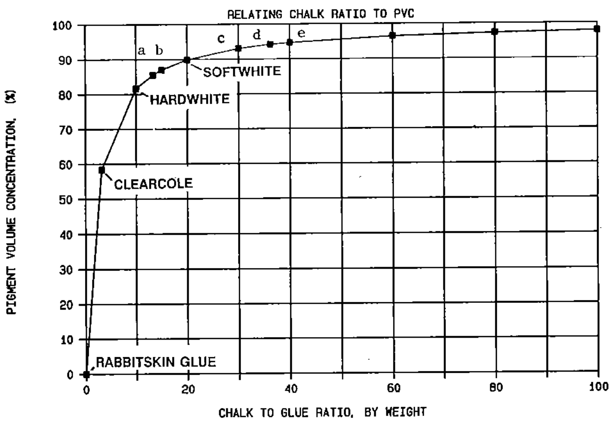

Fig. 1. Pigment volume concentration versus the chalk-to-glue ratio.

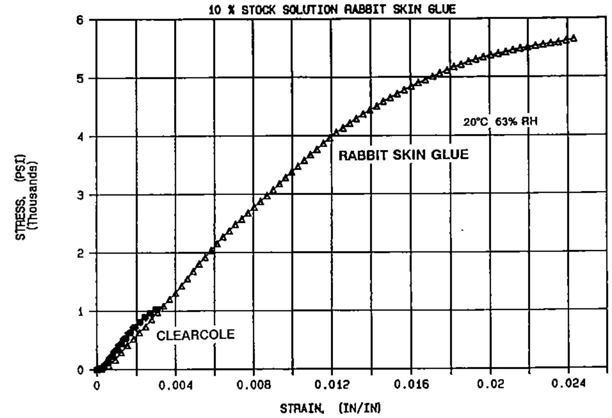

Fig. 2. The stress-strain plots of a typical rabbit-skin glue and three samples of the clearcole gesso mixture. Note the significant difference in the strength of the materials.

crack free and flat. Severe drying cracks formed in the last two mixtures (PVC = 94.7% and 96.4%). A plot of the gesso mixtures in relation to the chalk-to-glue ratio versus the PVC is presented as a conceptual aid in figure 1.

Mechanical Testing

Strip specimens of the glue and uncracked gesso films were subjected to tensile tests using small screw-driven tensile testers. The increments of strain were approximately 0.0003"/". The stress and strain values were recorded after allowing a stress relaxation time of 1 minute for each loading increment. At least three samples were tested from each gesso mixture. Figure 2 presents a typical stress-strain plot of the dried stock glue. The glue reached a strength of 5700 lbs. per square inch (psi) without failing. This is typical of the strengths attainable of hide glues in general.[3] The duration of the test was 72 minutes. For comparison purposes, the data for the clearcole tensile tests are shown on the same figure. Clearcole was the strongest of the gesso mixtures and reached an average breaking strength of only 1050 psi, less than one-fifth the glue strength. The tests demonstrated that increasing the proportion of the chalk in the gesso mixtures affected both the strength and the stiffness of the material. The strain at the time of failure is also greatly reduced, indicating an increasing embrittlement. Tensile test data of some other gesso mixtures are presented in figures 3, 4, and 5.

Figures 6, 7, and 8 summarize the important aspects of the tensile test results. In figure 6, the mean ultimate strength is plotted against the chalk-to-glue ratio, and the data points define a nearly linear descent. A line defining the data will pass through zero psi at a chalk-to-glue ratio of about 36 (PVC = 94%). The two gesso mixtures that failed to dry without severe drying cracks had chalk-to-glue ratios of 40 (PVC = 94.7%) and 60 (PVC = 96.4%) respectively, both exceeding the zero strength value of 36 that emerges from the data in figure 6. This suggests that there is a minimum amount of glue required for the drying strength of the gesso to exceed the stresses developed in gesso as it shrinks on drying. The gesso strengths are also low with respect to the strength of the pure glue, which in turn suggests any degradation of the stock glue solution will seriously affect the strength of the gesso. This was borne out by another set of tests. After casting all the gesso films needed for this study, the remaining stock solution was allowed to sit in a closed container at room temperature for four days, at which point the stock glue gel had severely degraded and was no longer a firm gel but a liquid-gel combination. Attempts to form gesso films with this glue resulted in extensive drying cracks in mixtures that had previously dried crack free.

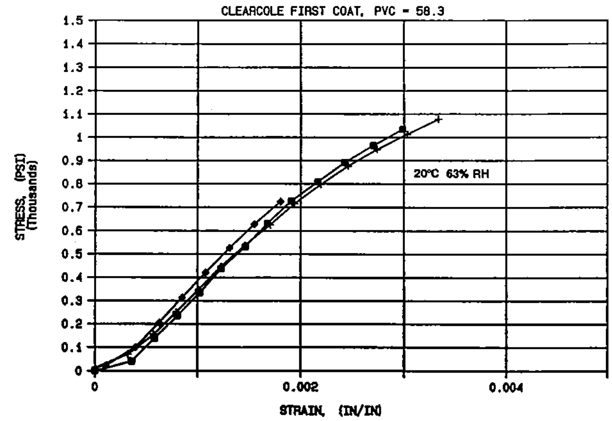

Fig. 3. The stress-strain plots of the clearcole samples.

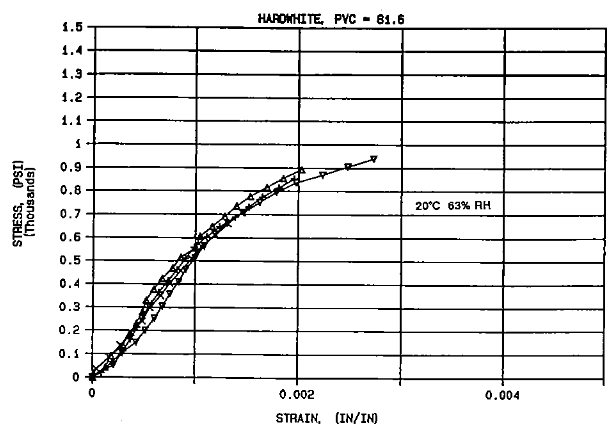

Fig. 4. The stress-strain plots of the hardwhite samples.

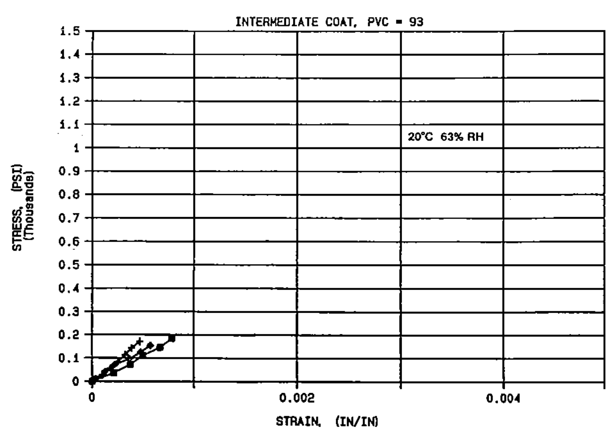

Fig. 5. The stress-strain plots of a set of intermediate gesso mixtures. This set with the high pigment volume ratio has very little strength.

Degradation of the original glue solution led to weak gesso films. Figure 7 shows the dramatic effect of the strength loss when increasing the chalk volume beyond the hardwhite mixture. Figure 8 shows the mean initial modulus (the steepest slope of the stress-strain curve) plotted against the pigment volume concentration. The initial modulus, a measure of the stiffness of the gesso, is somewhat analogous to the brittleness of the gesso. In many other materials, there is even a correlation between the modulus and the hardness, and although this has yet to be demonstrated for gesso, it is most likely true for this material as well. Also of note in this figure, the gesso has a well-defined maximum stiffness when the PVC reaches nearly 86%, a figure that falls between the hardwhite and the softwhite gesso mixtures. Increasing the chalk ratio beyond a PVC value of 86% results in a rapid loss of stiffness, yet it is in this less stiff region that the gesso is sufficiently soft to accept a burnish for laying highly polished gold leaf.

Dimensional Response to Relative Humidity

There are two factors to consider when discussing the dimensional responses of glue and gesso to relative humidity. The first is the response of either material when it is subjected to a single "cycle" of RH. (A cycle consists of first exposing the sample to very high RH, desiccating the environment, and then returning the sample to a high RH.) The second is the cumulative effect of several such consecutive cycles on the material.

Figure 9 presents the percent change in length of three test materials (stock glue, clearcole, and hardwhite) versus the ambient RH for the initial RH cycle. For this test the materials were allowed to equilibrate to a RH for 48 hours before recording the length of the specimen. The ambient temperature was a constant 20°C. Specimens then were exposed to extremes of RH ranging from 95% to 8%. The resulting plots, figure 9, exhibit a response typical of many polymers—that is, a dramatic swelling at high humidity levels. What is significant is the effect of PVC on the magnitude of the dimensional response. The greater the PVC, the less total change in length.

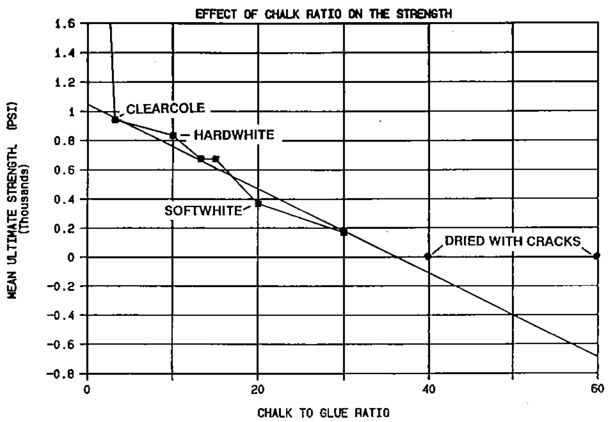

Fig. 6. The mean ultimate strength of the gesso mixtures versus the chalk-to-glue ratio.

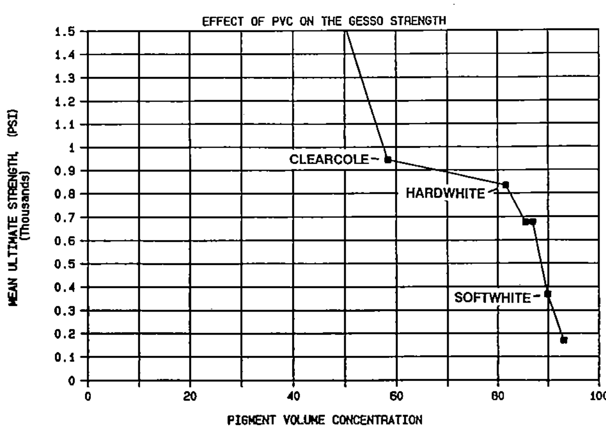

Fig. 7. The mean ultimate strength of the gesso mixtures versus the pigment volume concentration.

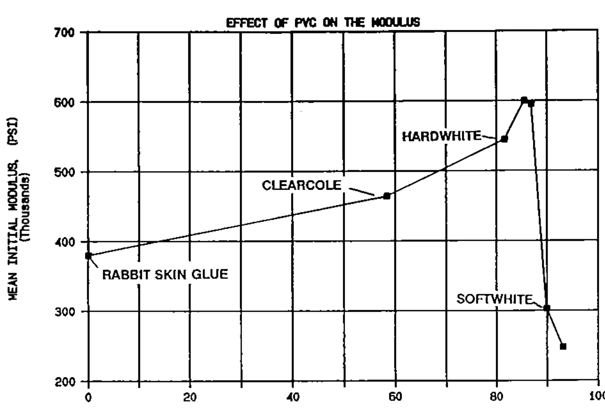

Fig. 8. The mean initial modulus of the rabbit-skin glue and the gesso mixtures versus the pigment volume concentration. The gesso mixtures rapidly lose stiffness after a PVC of about 86%.

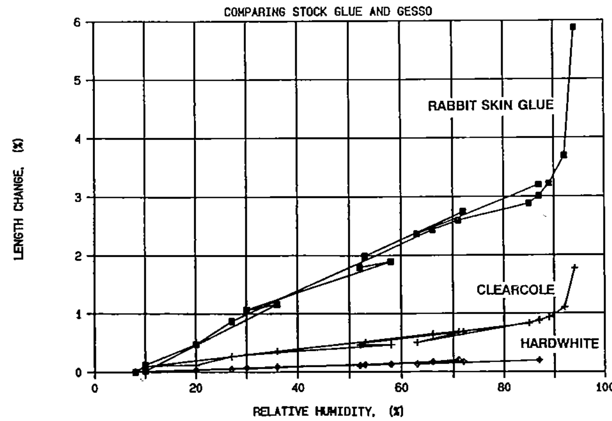

Fig. 9. Percent length changes versus the first cycle of relativity humidity changes for rabbit-skin glue, clearcole, and hardwhite gesso mixtures. Increasing the percentage of chalk dramatically reduces the dimensional response to changes in relative humidity.

On the first cycle, the total length change for the stock glue specimen was almost 6.0%, while the hardwhite changed only about 0.3%.

Of greater interest was the response of the material to consecutive cycles of RH. Figures 10, 11, and 12 demonstrate the dimensional response of the glue and gessoes when exposed to four RH cycles. All specimens exhibited an initial permanent shrinkage after being subjected to a second exposure to 95% RH. The stock glue and the clearcole continued to exhibit additional, but smaller, permanent shrinkage after being subjected to subsequent high RH levels. The hardwhite seemed to exhibit no further permanent contraction after the second cycle but did lose a full percent in length between the first and second cycles. Further, this specimen broke during the third cycle.

Figure 13 summarizes the dimensional responses of the materials when subjected to multiple humidity cycles. The stock glue demonstrated a nearly 5.0% permanent loss of length, and the clearcole lost nearly 2.5% after four cycles. This behavior suggests that if a specimen were restrained and not free to expand and contract with changes in RH, a permanent increasing stress would develop that could be associated with the desiccated periods of the humidity cycles.

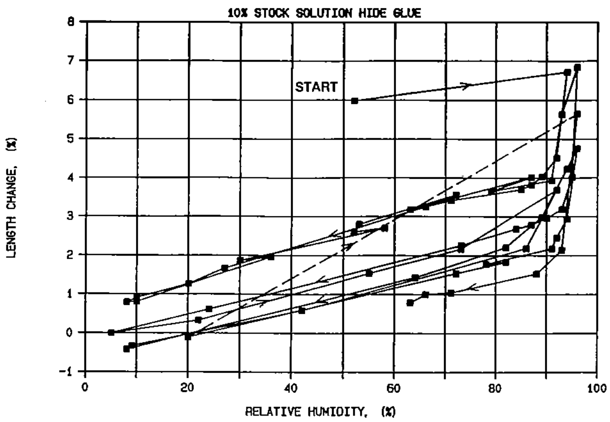

Fig. 10. Percent length change versus relative humidity for several consecutive RH cycles. The material is a sample of the stock rabbit-skin glue. The length is permanently decreasing with each subsequent cycle.

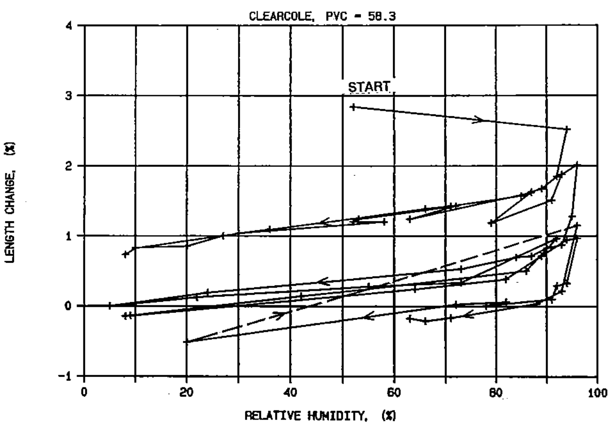

Fig. 11. Percent length change versus relative humidity for several consecutive RH cycles. The material is a sample of the clearcole gesso. The length is permanently decreasing with each subsequent cycle.

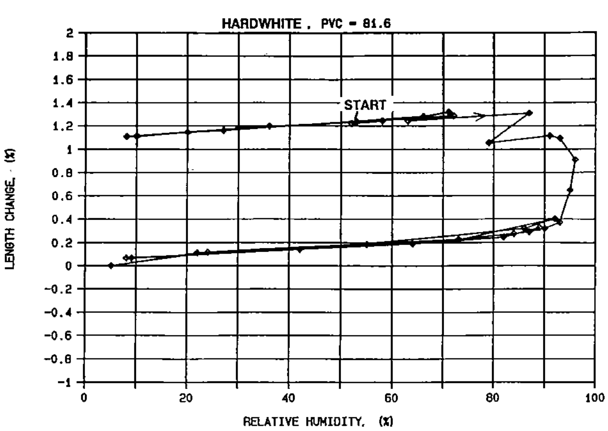

Fig. 12. Percent length change versus relative humidity for several consecutive RH cycles. The material is a sample of the hardwhite gesso. The length is permanently reduced only after the first cycle.

Restrained Specimen Testing

Next, specimens of the stock glue, clearcole, and hardwhite were installed in the tensile testing equipment used in the above experiments and a small restraint applied. The initial conditions were 20°C, 63% RH, and an applied equilibrium stress of about 300 psi. This stress value was considerably less than the ultimate strength attained during the tensile testing of any of these materials. The environment was allowed to desiccate, and stress levels were recorded after the specimens had come to equilibrium with the new environment. This took about 48 hours. After reaching about 5% RH, the humidity was incrementally increased to 93% RH and then recycled to 5% in steps. This cycling of the environment was continued for three complete cycles. Figures 14, 15, and 16 illustrate the stress development of the restrained specimens versus the RH.

All specimens showed a rise in stress with increasing desiccation and a loss in stress with a humidity increase during any single cycle. In the stock glue and clearcole specimens, however, there was a permanent stress increase every time these specimens were subjected to a high RH level and then subsequently desiccated (see figs. 14, 15). On the other hand, the hardcoat showed a permanent loss of stress after the first period of high RH and no permanent changes after that (see fig. 16). Nevertheless, both the

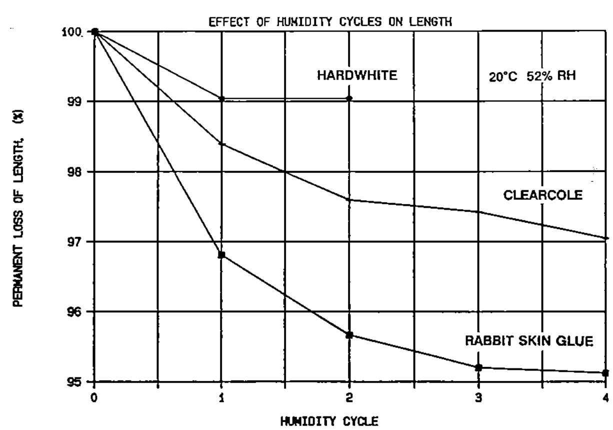

Fig. 13. The permanent loss of length of glue and two gesso samples versus the number of full RH cycles. Data points are taken at 20°C and 52% RH on the moisture regain paths shown in figures 10, 11, and 12.

clearcole and the hardwhite specimens failed because of their stress development during desiccation in the third cycle. The permanent stress changes in the specimens are summarized in figure 17.

It is unclear why the hardcoat gesso failed, even though it demonstrated a permanent loss of total stress. It is possible that this specimen demonstrated a partial failure during the test, hence the initial stress drop. What is important is that the materials experience dramatic and permanent changes when exposed to very high RH values (above 90%) and are subsequently desiccated. Any substrate to which gesso is applied provides at least a partial gesso restraint if the substrate does not expand and contract in response to RH. If the substrate is completely unresponsive to RH, it provides full restraint to the gesso layer. If the substrate response is the same as the gesso layers, there is no restraint. Wood, most often the substrate for gesso, is anisotropic in that the grain direction is considerably less responsive to changes in RH than the cross grain direction. Under these circumstances the grain direction provides considerable restraint to the gesso layers above and provides an opportunity for full stress development in the direction parallel to the grain. Cracks in the gesso, when they form, occur perpendicular to the direction of stress development and thus would form perpen-

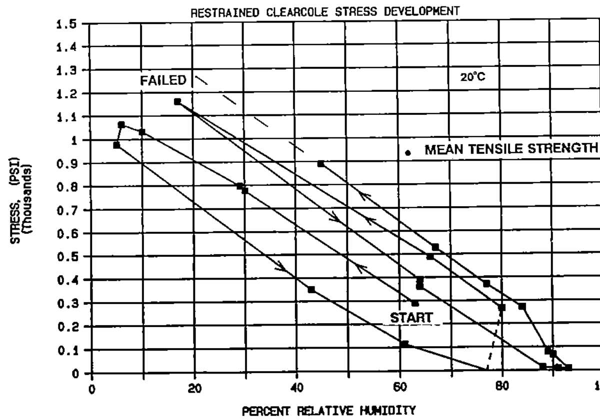

Fig. 15. Restrained specimen stress versus consecutive cycles of relative humidity. The specimen is a sample of the clearcole gesso. Stress is increasing with subsequent cycles of RH.

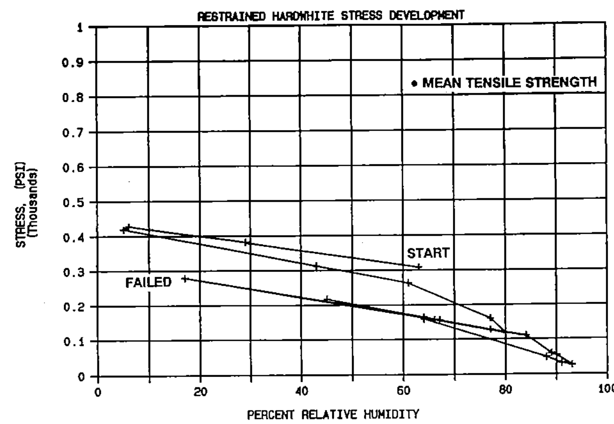

Fig. 16. Restrained specimen stress versus consecutive cycles of relative humidity. The specimen is a sample of the hardwhite gesso. Stress has decreased with the subsequent cycles, and the specimen still failed in the third cycle.

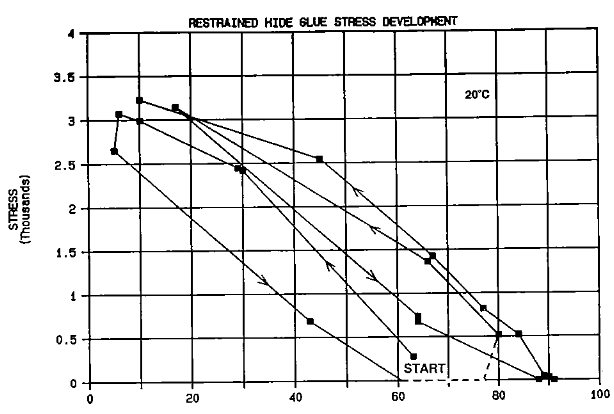

Fig. 14. Restrained specimen stress versus consecutive cycles of relative humidity. The specimen is a sample of the stock rabbit-skin glue. Stress is increasing with subsequent cycles of RH.

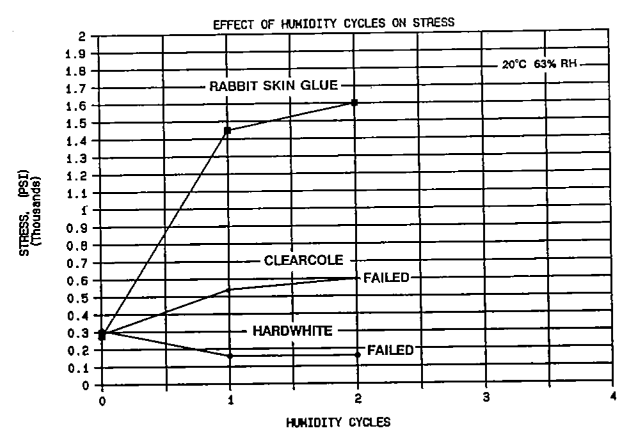

Fig. 17. Permanent stress changes versus humidity cycles for the stock glue, clearcole, and hardwhite specimens. The data were taken at 20°C and 63% RH on the desiccating paths as shown in figures 14, 15, and 16.

dicular to the grain of the wood. This is the case on nearly all gilded frames exhibiting cracks.

Research is needed to determine if this behavior is limited to these very wide RH changes or if any changes in RH produce such permanent alteration to the glue and gesso films. Another research problem is whether other materials demonstrate similar behavior. The Conservation Analytical Laboratory of the Smithsonian Institution is undertaking several programs to try to determine the effect of RH changes on the mechanical and physical properties of many materials found in artistic and cultural objects.

Conclusions

A systematic investigation of some responses of gesso to environmental conditions has led to several conclusions.

The ultimate tensile strength of gesso is considerably lower than the hide glue from which it is made and is inversely proportional to the chalk-to-glue ratio. Using rabbit-skin glue, crack-free gessoes could not be prepared if the chalk-to-glue ratio exceeded about 36 (PVC = 94%). If the glue had a lower initial strength or if the glue was spoiled, this number was considerably lower.

The stiffness, as measured by the initial modulus, increases with a higher proportion of chalk to a chalk-to-glue ratio of about 13.3 (PVC = 85.5%). Further addition of chalk decreases the modulus rapidly. Additionally, the breaking strain of the gesso decreases with the increasing chalk content. An excess of chalk can produce premature cracking upon drying, a very soft gesso, a very weak gesso, or all three of these conditions.

For any single RH cycle, rabbit-skin glue can exhibit a total dimensional change of about 6%. The gesso mixtures exhibit considerably less change. The greater the proportion of gesso, the less the dimensional change.

Progressive cycling of the unrestrained glue and gesso samples over a wide range of relative humidity results in progressive and permanent shrinkage. The amount of permanent shrinkage decreases with each RH cycle, but the total loss can be substantial: rabbit-skin glue can lose 5.0%, clearcole nearly 2.5%, hardwhite about 1.0%.

When restrained, the glue and gesso samples exhibit a permanent change in stress development during RH cycling. The glue and the clearcole showed a progressive increase in developed stress. The clearcole and hardwhite samples failed on the desiccating path (increasing stress) of the third RH cycle.

If the glue and gesso mixtures are applied to a substrate that has less dimensional response to RH than the applied layers, the substrate provides at least partial restraint. Under these conditions, the potential for failure and cracking exists if the object constructed in this manner is subjected to severe ranges in RH.

NOTES

1. Deborah Bigelow, "Gold Leaf on Furniture: Its History, Application, and Conservation" (Advanced diploma course diss., London College of Furniture, London, 1982).

2. Bigelow, "Gold Leaf," pp. 64–66.

3. Marion F. Mecklenburg, "The Role of Water on the Strength of Polymers and Adhesives" (Ph.D. diss., University of Maryland, 1984); Marion F. Mecklenburg, "The Effects of Atmospheric Moisture on the Mechanical Properties of Collagen under Equilibrium Conditions," in *Preprints of Papers Presented at the Sixteenth Annual Meeting* (New Orleans: American Institute for Conservation, 1988), pp. 231–44.

Biography

Marion F. Mecklenburg is assistant director for conservation research, Conservation Analytical Laboratory, Smithsonian Institution, Washington, D.C.

Gilded Wood

Conservation and History

SOUND VIEW PRESS
Madison, Connecticut
1991