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THE EFFECTS OF TEMPERATURE AND RELATIVE HUMIDITY ON THE MECHANICAL PROPERTIES OF MODERN PAINTING MATERIALS

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ABSTRACT

The mechanical properties of strength, modulus, and elongation to break were studied for artists' acrylic and alkyd paints under varying conditions of temperature and relative humidity (RH). In the ambient environment, 23° C, 50% RH, acrylic paints are very flexible and are able to sustain large deformations (>50%). Alkyd paints are much stiffer and stronger, and they cannot sustain deformations nearly as dramatic as the acrylics. Acrylic paints at 5% RH are stiffer and stronger than at 50% RH and their ability to stretch is lessened. At temperatures below 15° C at 50% RH, the strength and stiffness of acrylic paints begin to rise rapidly. Some were found to be brittle at 5° C, and by -3° C, all were brittle. At a lower RH, some acrylic paints became brittle at a temperature near 11° C. These temperatures and relative humidities may be found in the transport environment of art objects, and may render them subject to possible damage.

INTRODUCTION

The measured mechanical properties of oil paint films in different relative humidities (RH) and temperatures have recently been used to predict potential damage to oil paintings during transit. Two sets of mechanical properties are useful, those under rapid loading conditions, such as shock and vibration, and those under slow-loading conditions, in which the paintings stay equilibrated to environmental conditions. By using the experimentally determined mechanical properties of traditional oil paint, a structural analysis computer program accurately predicted cracking patterns due to vibration, edge, and corner impacts of oil paintings.[1] Stress fields and crack patterns in oil paint films subjected to dry and cool environments were also determined.[2]

Experimental techniques are being extended to determine the mechanical properties of other artists' materials, in particular modern acrylic and alkyd paints. Acrylic paints are pigmented polymer emulsions in water. In general, they are more flexible than traditional oil paints. Alkyd paints, on the other hand, are oil paints modified so that there is much more cross-linking in the paint film when dry. As a result, alkyd paints tend to be stiffer and stronger than traditional oil paints.

In this paper, the mechanical properties under rapid loading conditions of acrylic and alkyd paints in different relative humidities and temperatures are reported. These properties will be used in further studies of the sources of cracking and damage in modern paintings. Other experiments are currently being conducted to determine the mechanical properties of acrylic and alkyd paints under equilibrium conditions and will be reported at a later date.

TERMS

Strength, stiffness and elongation are measurable engineering properties and are defined as follows:

Stress (σ) = Applied force/cross-sectional area of material, (F/A)

Strain (ϵ) = Change in material length, L, in direction of deformation/undeformed length = $\Delta L/L$. $\epsilon \times 100$ = % elongation of material.

Modulus, E = Stress/strain (σ/ϵ). The modulus is a measure of a material's stiffness. The greater the modulus, the stiffer the material.

Strength = Maximum stress in a material before the material fails.

The method by which the mechanical properties of a typical paint are determined from its stress-strain curve is shown in Figure 1. The paint in this example is a sample of acrylic cerulean blue in an environment of 23° C, 50% RH.

TESTING EQUIPMENT

Stress-strain curves for the acrylic and alkyd paints were found by stretching samples on screw-driven tensile testers. Strain rates ranged from 0.001 in/in/sec to 0.01 in/in/sec. The testers were enclosed in plastic environmental chambers capable of maintaining constant temperature and relative humidity. Conditioned silica gel was used to maintain relative humidity. The tensile testers and environmental chambers were designed and constructed at the Conservation Analytical Laboratory (CAL) of the Smithsonian Institution.

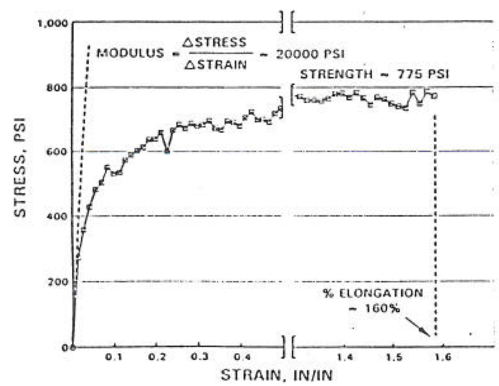


Figure 1. Stress-strain curve of acrylic cerulean blue at 23° C and 50% RH, showing its mechanical properties.

Test samples were taken from strips of paint cast between 1978 and 1982, making the youngest paint sample 10 years old. The samples were typical of commercially available acrylic paints. For testing purposes, each cast was cut into smaller strips approximately 0.2" wide and 3"-5" long. The different paint thicknesses varied from 0.005"-0.015".

MECHANICAL PROPERTIES OF ACRYLIC AND ALKYD PAINTS AT 23° C, 50% RH

Ten different acrylic paint samples from two different sources and eight different alkyd paints from a single source were tensile tested under ambient conditions, 23° C and 50% RH. Typical mechanical properties of these paints at this temperature and relative humidity are listed in Table 1.

Alkyd paints were found to be considerably stiffer and stronger than acrylic paints at 23° C, 50% RH. In this environment, the modulus of the alkyd paint samples ranged from 80,000 psi to 600,000 psi, while the modulus of acrylic paint samples ranged from only 10,000 psi to 45,000 psi. Alkyd paints were nearly twice as strong as acrylic paints. The strength of alkyd paints varied from 850 psi to 1600 psi, compared to a variation of strength in acrylic paints from 575 psi to 975 psi.

Table 1. Typical mechanical properties of acrylic and alkyd paint samples at 23° C, 50% RH

Paint Type	Modulus, psi	Strength,psi	Elongation to Break (%)
ACRYLIC PAINTS			
Burnt Sienna	40000	950	53%
Burnt Umber	11000	650	>293%
Cadmium Red	23000	800	174%
Cadmium Yellow	15000	625	195%
Cerulean Blue	20000	775	160%
Cobalt Blue	45000	975	54%
Iron Oxide Red	40000	900	60%
Ivory Black	12000	575	>363%
Raw Sienna	10000	865	279%
Titanium White	21000	819	255%
ALKYD PAINTS			
Alizarine Crimson	110000	850	2%
Burnt Umber	285000	1400	0.7%
Cadmium Yellow	190000	1000	2%
Iron Oxide Red	165000	1300	6%
Ivory Black	80000	1350	12%
Lead White	600000	1500	0.3%
Titanium White	275000	1600	1.4%
Yellow Ochre	140000	1050	3%

Interestingly, acrylic paints were able to withstand exceptionally large deformations at 23° C, 50% RH. All of the acrylic paint samples stretched at least 50% of their original length. Six of the samples stretched over 100%. The most flexible of the acrylic paints was a sample of ivory black, which stretched 363% of its original length before the test was stopped. The sample had reached the displacement limits of the tensile tester.

In the ambient environment, alkyd paints did not sustain elongations as large as the acrylics. An ivory black sample that stretched 12% was the only sample to stretch over 10% of its original length. The least flexible alkyd paint was a lead white, which stretched only 0.3% before breaking.

This same sample of lead white had the largest modulus (600,000 psi) of all the alkyd paints at 23° C, 50% RH. The acrylic ivory black sample that stretched 363% had the lowest modulus of the acrylic paints. In general, it was found that the higher the modulus, the less the acrylic and alkyd paints are able to stretch. Conversely, the lower the modulus, the more the paints are able to stretch.

The relative differences between the mechanical properties of acrylic and alkyd paints at 23° C, 50% RH indicate two different ways that these paints respond to shock. When force is applied, both kinds of paint initially deform and build stress. The rate at which stress builds with deformation during this period is determined by the modulus (modulus*$\Delta\epsilon=\Delta\sigma$). Once a maximum stress level is reached, acrylic paint films *plastically deform*. Rather than build more stress, they elongate. Alkyd paints plastically deform only slightly, if at all. Instead, they generally hold greater stresses. Some alkyd paints, in particular the lead white, did not plastically deform at all. This sample continued to build internal stress until it failed in a brittle manner, that is, without a plastic region in its stress-stain curve.

MECHANICAL PROPERTIES OF ACRYLIC AND ALKYD PAINTS AT 23° C, 5% RH

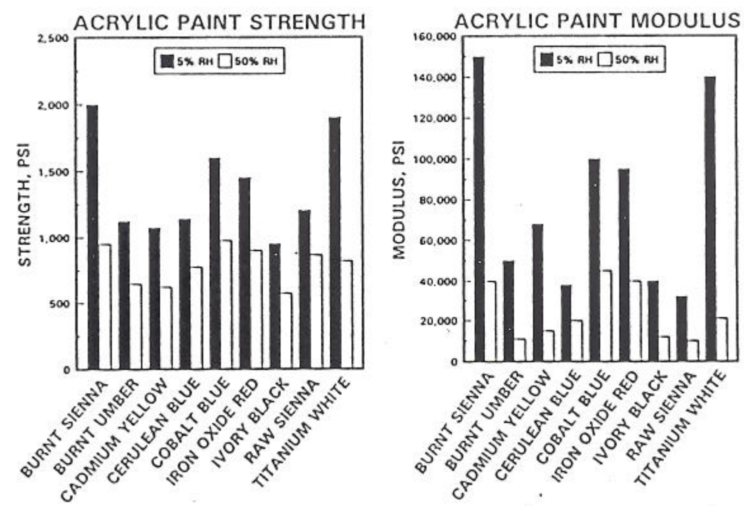
Nine types of acrylic paint and eight types of alkyd paints were tensile tested at 23° C, 5% RH. The mechanical properties of these paints at this temperature and relative humidity are listed in Table 2.

Desiccation to 5% RH at 23° C was found to stiffen all the acrylic and alkyd paint samples. In addition, their strengths rose and their ability to elongate decreased. The strengths and modulus of acrylic and alkyd paints at 5% RH and at 50% RH are compared in Figures 2 and 3.

The modulus increase of acrylic paints due to desiccation at 23° C is particularly dramatic. Titanium white, whose modulus rose from 21,000 psi to 140,000 psi had the largest relative stiffness increase of all the acrylic paint samples. The increase in modulus was accompanied by an increase in strength and a decrease in ability to stretch. Furthermore, when there were large increases in strength and modulus there were also large reductions in elongation ability. The maximum elongation of the acrylic titanium white sample mentioned above dropped from

Table 2. Typical mechanical properties of acrylic paint samples at 23° C, 5% RH

Paint Type	Modulus, psi	Strength, psi	Elongation to Break (%)
ACRYLIC PAINTS			
Burnt Sienna	150000	2000	14%
Burnt Umber	50000	1125	115%
Cadmium Yellow	68000	1075	80%
Cerulean Blue	38000	1140	113%
Cobalt Blue	100000	1600	17%
Iron Oxide Red	95000	1450	25%
Ivory Black	40000	950	>183%
Raw Sienna	32000	1200	>108%
Titanium White	140000	1900	40%
ALKYD PAINTS			
Alizarine Crimson	180000	1350	1.2%
Burnt Umber	400000	2400	0.7%
Cadmium Yellow	425000	1650	0.78%
Iron Oxide Red	300000	2000	2.8%
Ivory Black	180000	1930	7.5%
Lead White	850000	2400	0.3%
Titanium White	630000	2600	0.95%
Yellow Ochre	300000	2300	2.5%



a. b.

Figure 2. Strength (a) and Modulus (b) of acrylic paints at 23° C.

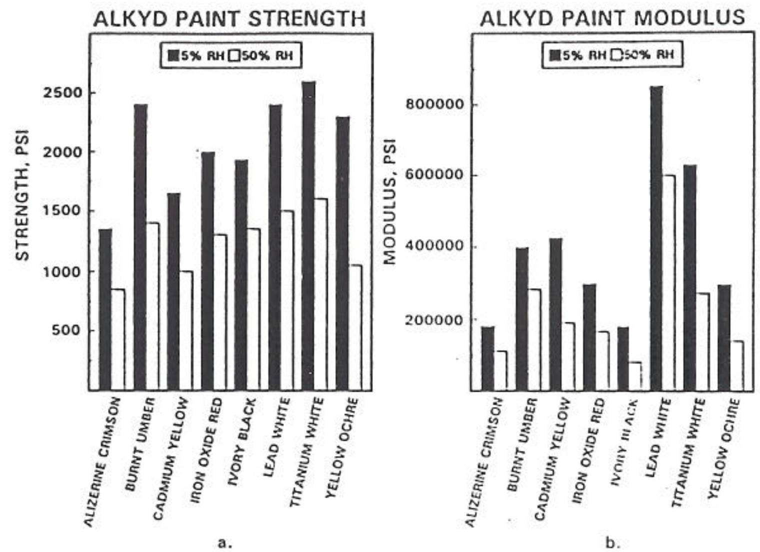


Figure 3. Strength (a) and Modulus (b) of alkyd paints at 23° C.

approximately 255% to 40%, which was also the largest relative drop in ability to sustain elongation seen in the acrylic paints.

Despite the large changes in strength, modulus, and ability to elongate during desiccation, acrylic paints still retained large abilities to stretch compared to alkyd paints. While at 23° C, 50% RH, no alkyd paint stretched over 12%, at 23° C, 5% RH all of the acrylic paints were still able to stretch at least 14% of their original length. Decreases in the ability of alkyd paints to elongate are losses of the ability to plastically deform when loaded. At 23° C, 50% RH, six of the eight alkyd paint samples stretched over 1% of their original length, but at 23° C, 5% RH only four of the samples were able to stretch that small amount. The loss of the ability to stretch in response to shock in desiccated environments at 23° C is more dangerous to alkyd paint films than to acrylic paint films.

MECHANICAL PROPERTIES OF ACRYLIC PAINTS AT DIFFERENT TEMPERATURES IN 40-50% RELATIVE HUMIDITY

The variation of strength, stiffness and ability to stretch versus temperature was studied for three acrylic paints in relative humidities of 40-50% RH. The paints were burnt umber, ivory black and cobalt blue. The cobalt blue used for testing was a relatively stiff acrylic paint, and the ivory black and burnt umber were relatively flexible acrylics. The strength and modulus of these acrylic paints at different temperatures in 40% to 50% RH is shown in Table 3. Table 4 shows the elongations to break of these paints at low temperatures.

Table 3. The mechanical properties of three acrylic paints at different temperatures, with relative humidity between 40% and 50%.

	Burnt Umber		Ivory Black		Cobalt blue	
Temp, °C	*Modulus (psi)*	*Strength (psi)*	*Modulus (psi)*	*Strength (psi)*	*Modulus (psi)*	*Strength (psi)*
-8.1	570000	3650	------	----	930000	4200
-4.3	485000	4050	450000	3850	720000	3200
-2.9	360000	2830	285000	2830	------	----
-1.4	340000	3740	275000	2700	560000	2700
3.4	260000	2730	260000	1950	360000	2550
5.6	225000	2250	210000	2200	290000	2020
8.5	200000	1450	80000	900	230000	2100
15.1	40000	620	13000	>220	58000	775
23	11000	650	12000	600	45000	950
33.4	2500	220	680	50	3300	>120

Figures 4 and 5 show the rise in the strength and the modulus of burnt umber, ivory black, and cobalt blue acrylic paints with decreasing temperature. Above 15° C, the modulus and also the strength of each acrylic paint is small, and the paints have a large ability to deform in response to shock. As the temperature dropped below approximately 15° C, the strength and modulus of all the acrylic paints rose rapidly. Associated with this rise was a similarly sharp decrease in the ability of these paints to stretch when rapidly loaded.

In 40% to 50% RH, all the acrylic paints were found to become extremely brittle at low temperatures. At -2.9° C, none of the tested paints exhibited the ability to deform plastically in response to rapidly applied force. Often, samples shattered when breaking. At temperatures below -2.9° C, samples of ivory black and burnt umber often broke eary, although their modulus generally kept increasing. This suggests that the paint films prematurely broke before a stress equal to their strength was developed in the entire sample. This may be due to very high stresses localized in areas of defects or impurities, a phenomenon called *fracture sensitivity*. It must be assumed that there will be defects present in actual paints and that this form of brittle behavior must be considered.

Table 4. The elongation to break of three acrylic paints at low temperatures and 40% to 50% RH

Paint Type	Temperature, °C						
	-8.1	-4.3	-2.9	-1.4	3.4	5.6	8.5
Burnt Umber	0.76%	1.28%	1.12%	1.86%	6.82%	>27.0%	>24.1%
Ivory Black	0.67%	1.63%	1.95%	7.35%	>30.2%	>50.0%	>16.7%
Cobalt Blue	0.52%	0.51%	-----	1.12%	1.43%	2.37%	6.46%

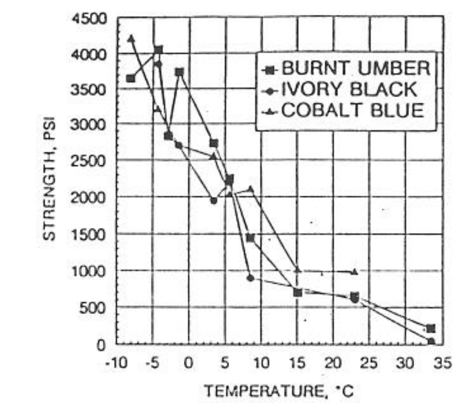


Figure 4. The variation of strength with temperature for three acrylic paints in environments near 50% RH.

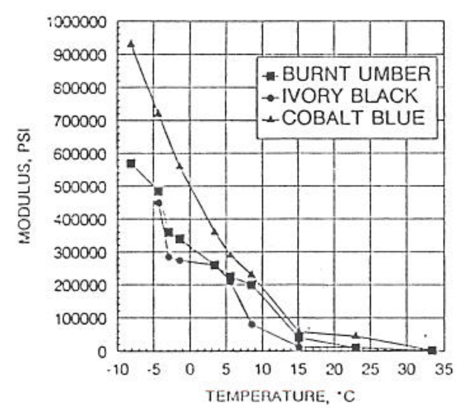


Figure 5. The variation of modulus with temperature for three acrylic paints in environments near 50% RH.

As temperatures increase from -2.9° C, with relative humidities between 40% and 50% RH, acrylic paints demonstrate the ability to plastically deform. More flexible acrylic paints have the ability to plastically deform at -1.4° C. For example, an ivory black sample stretched 7.35% at this temperature. However, stiff acrylics, like the cobalt blue, do not have a substantial ability to deform without shattering unless the temperature is over 5.6° C.

The bar charts in Figure 6 shows that the relative rise in strength and modulus in acrylic paints with desiccation to 5% RH at 23° C is much less severe than the strengthening and stiffening due to cooling to -2° C, maintaining 40% - 50% RH. If the reaction of these paints to rapid shock are compared, not only will stress build up faster in the cooled paint (because the modulus is higher), but the paint film will not hold the maximum stress through any plastic deformation. Once the maximum stress is reached, the paints will crack. At -2° C, all the paints tested exhibited brittle behavior. However, some acrylic paints, like the cobalt blue, exhibited brittle behavior at temperatures as high as 5° C.

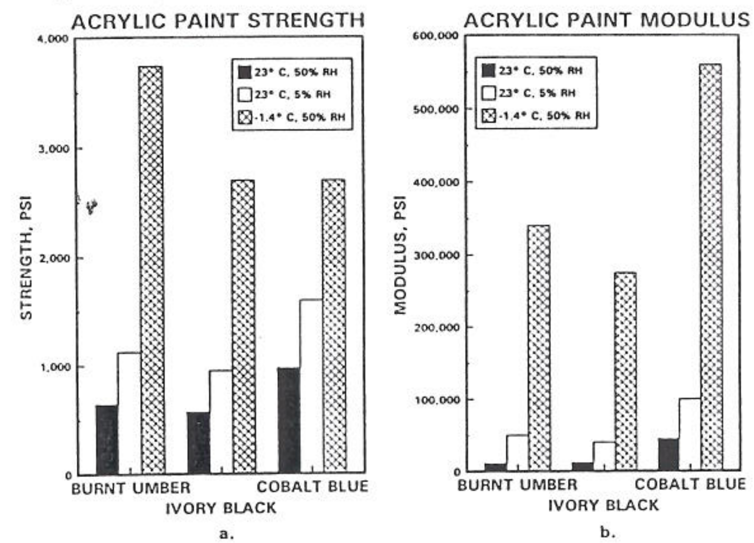


Figure 6. Strength (a) and modulus (b) of three acrylic paints in different temperatures and RH.

MECHANICAL PROPERTIES OF ACRYLIC AND ALKYD PAINTS IN ENVIRONMENTS WHICH COMBINE LOW TEMPERATURES AND LOW RELATIVE HUMIDITIES

The data so far presented indicates that alkyd paints in desiccated environments are brittle, and that acrylic paints are brittle in temperatures below 5° C in 40% to 50% RH. Acrylic paints in 5% RH at 23° C are stiffened, but they retain a substantial ability to stretch.

The combination of desiccation and cooling was found to embrittle severely acrylic and alkyd paints. Tables 5 and 6 list the mechanical properties of three acrylic and three alkyd paints in different temperatures at 5% RH. Figure 7 shows the modulus and strength of these three acrylic paints at 23° C 50% RH, 23° C 5% RH, 5° C 5% RH, and -6.5° C 5% RH.

Desiccation sharply raises the temperature at which acrylic paint exhibit brittle behavior. If the relative humidity is maintained between 40% and 50% RH, acrylic paints become brittle and fracture sensitive when their modulus nears or passes approximately 400,000 psi, usually under 5° C, as shown above. In 5% relative humidity, titanium white and burnt sienna samples each developed a modulus over 400,000 psi at 11° C. Furthermore, the burnt sienna sample was decidedly brittle at this temperature, breaking at an extension of only 1.44%. The titanium white sample showed a slight amount of plastic deformation.

Table 5. The mechanical properties of three acrylic paints at different temperatures, in 5% relative humidity.

Temp, °C	*Modulus (psi)*	*Strength (psi)*	*Modulus (psi)*	*Strength (psi)*	*Modulus (psi)*	*Strength (psi)*
ACRYLIC PAINTS	**Titanium White**		**Cadmium Yellow**		**Burnt Sienna**	
-6.5	1500000	5060	790000	4460	920000	3280
-5.2	1000000	3600	------	----	------	----
5.0	900000	6090	640000	3760	875000	4800
11.1	570000	3450	------	----	400000	2440
23.0	140000	1900	68000	1100	150000	1900
ALKYD PAINTS	**Alizarine Crimson**		**Lead White**		**Iron Oxide Red**	
-5.0	650000	1700	1250000	2500	1300000	4000
23.0	180000	1300	850000	2400	300000	2000

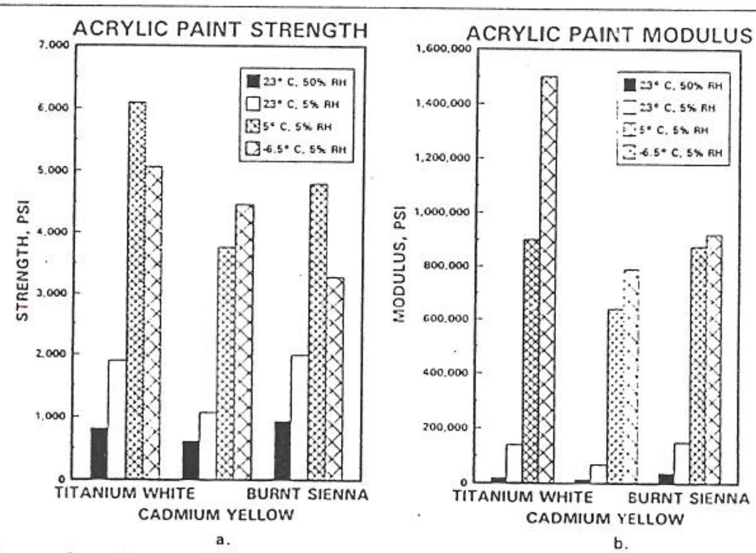


Figure 7. Strength (a) and modulus (b) of three acrylic paints at various temperatures and relative humidities.

Table 6. The elongation to break of three acrylic paints and three alkyd paints at 5% RH in different temperatures.

Paint Type	**Temperature, °C** -6.5	-5.0	-5.2	5.0	11.1	23
ACRYLICS						
Titanium White	0.46%		0.38%	1.01%	4.78%	40.2%
Cadmium Yellow	0.63%		-----	0.63%	-----	76.0%
Burnt Sienna	0.38%		-----	0.61%	1.44%	13.2%
ALKYDS						
Alizarine Crimson		0.25%				12.0%
Lead White		0.15%				0.3%
Iron Oxide Red		0.5%				2.5%

At low temperatures, very brittle samples tested in 40%-50% RH tended to shatter prematurely. Extreme fracture sensitivity was also exhibited by acrylic paint samples tested at temperatures below -5.2° C in 5% RH, as shown in Figure 6(a). At 5° C, the acrylic paint samples all were extremely brittle, with high strength and modulus, but they did not seem to be fracture sensitive.

The combination of desiccation and cooling also greatly increased the strength and stiffness of the alkyd paint samples. However, the extraordinarily large rises in modulus and strength seen in acrylic paint samples in desiccated and cold environments were not seen in alkyd paint samples. Indeed, although alkyd paints are stiffer than acrylics at 23° C, 50% RH and at 23° C, 5% RH, acrylic paints are stiffer than alkyds at -5° C, 5% RH. The modulus of the titanium white at this temperature, 1,500,000 psi, was the largest modulus of any paint, including alkyds in all environments, seen in this study. Alkyd paints, however, still could not sustain as much elongation as acrylic paints even at -5° C, 5% RH. The alkyd lead white sample that failed after only 0.15% had the least amount of deformation before it shattered of all the tested samples.

CONCLUSION

The strength and stiffness of acrylic and alkyd paints become greater as relative humidity changes from approximately ambient RH to 5% RH. Acrylic paints were found to be extremely flexible at 23° C, 50% RH. At 5% RH, their ability to stretch is smaller, but remains substantial. Alkyd paints, in comparison, stretch significantly less than acrylic paints at 50% RH, and many can deform only small amounts at 5% RH.

As acrylic paints are cooled in 40-50% RH, their stiffness and strength rise as the temperature drops below 15° C. In this RH, some acrylic paints were brittle at 5° C. That is, they lost their ability to plastically deform after developing a maximum stress. At -3° C, many of the acrylic paints exhibited drops in strength although their modulus continued to increase. This may indicate fracture sensitivity in acrylic paints at very low temperatures.

Desiccation effectively increases the temperature at which acrylic paints become brittle when cooled. At 50% RH, some acrylics were brittle at 5° C, but at 5% relative humidity many were brittle at temperatures as high as 11° C. Alkyd paints are also very brittle at low temperatures and low relative humidities.

The experiments presented here indicate that cold transport environments are potentially dangerous to acrylic and alkyd paint films because their ability to respond to force by deforming is diminished, thus making them susceptible to shattering. Aircraft holds, for instance, generally have a temperature of approximately 10° C, although some holds have temperatures as low as 5° C.[3] Acrylic paint in 5% RH is brittle at both of these temperatures, but if its environment were buffered to a higher relative humidity the chance of it breaking due to shock or vibration would be lessened.

ACKNOWLEDGEMENTS

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DETECTION OF DELAMINATIONS IN ART OBJECTS USING AIR-COUPLED ULTRASOUND°

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Abstract

The possibility of using air-coupled ultrasound to find delaminations between layers in paintings was investigated. Simulations of modern paintings were constructed with hardboard as the support layer, and a layer of gesso, an animal hide glue and chalk, as the upper layer. Delaminations were introduced between the two layers. Scanning the samples using air-coupled ultrasound clearly showed these flaws. A transmitting transducer, which was 25 mm in diameter and had a focal length of 51 mm, was placed 11 mm from the back surface of the sample and an identical receiving transducer was placed 51 mm from the front surface. The transducers were operated in a tone burst mode at a center frequency of 475 kHz. Signal enhancement techniques were used to improve the contrast of the data.

Introduction

The care of wooden art objects is rendered more difficult by the presence of cracks, voids, and delaminations. Computer analysis shows that cracks in wood promote severe stress concentrations that are aggravated by environmental and other stresses.[1] Unfortunately, many of these internal anomalies are not easily visible, making assessment of the various risks to art works difficult. In the case of a panel painting, its structural condition can be mapped using nondestructive testing techniques, in order to predict how it will respond mechanically over time in different environments. It can then be decided whether the object can be safely shipped to special exhibitions, and what plans can be made for proper display, storage, and conservation.

Various nondestructive methods for detecting voids, hidden cracks, and fine fractures in paintings have been investigated.[2] These methods have been incorporated into the repertoire of techniques from which conservators draw, to prevent the premature failure of objects.

Investigations of wooden panels and paintings have shown that xeroradiography has the advantage over x-ray radiography as xeroradiography's edge enhancement property enables flaws to be displayed prominently. It also uses equipment compatible with that typically found in conservation laboratories.

Research has shown that air-coupled ultrasound, a non-contact, nondestructive testing technique, can detect delaminations and cracks at certain angles that radiography cannot. Unlike radiographic techniques, ultrasound is not a health hazard for the user. The need for a non-contact ultrasonic method for use in the art conservation field has been discussed before.[3]

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