Understanding Microcrystalline Waxes

for the Seismic Protection of Art Objects

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ABSTRACT—Use of microcrystalline waxes for the protection of ceramic art objects from seismic events is an inexpensive and relatively popular technique. This paper presents performance results for three commercial, microcrystalline waxes based on anchoring requirements of resisting seismic-induced tensile and shear forces, while exhibiting a ductile failure mode to prevent objects from suddenly detaching themselves from their display units and becoming sufficiently mobile to fall off stands or collide with other art objects. As many of the testing techniques described in this paper are not easily accessible to the average museum conservator, and some of the products may not be readily available, emphasis is placed on establishing an expected range of strengths, and correlations are suggested for predicting the general performance of any microcrystalline wax in a specific application arrangement, based on easily performed, simplified tests that were found to be able to predict tensile capacity within 10%. Distinctive performance trends were found amongst various products with capacity being as much as 183 kPa in tension and 42kPas in shear. The pre-application of a methylacrylate copolymer to the bonding surface consistently improved performance, while increasing wax thickness did not.

1. INTRODUCTION

Protecting art objects from ground movements has long been a concern for art collections located in earthquake-prone regions (Benuska 1990, Cornu and Bone 2001, Ginnell 1995, Harold 1995, Hascall 2001, Lever 2000, Mashlakian n.d., Podany 1988, 1991, 1995, 1997, Podany and Leavengood, 1992). The potential financial losses under such circumstances are significant. A survey following the 1989 Loma Prieta earthquake of 8 museums in the San Francisco Bay Area found 150,000 damaged items corresponding to $10 million in losses. Of that, the Asian Art Museum in San Francisco alone suffered $3 million in damage, representing 1% of the total market value of its collection (FEMA 1994).

Despite the identified risk, protection solutions have been slow to emerge. A major reason for this is that unlike other vulnerable, high-value, building contents [e.g. computer equipment, hospital equipment, and laboratory items (Benuska 1990)], art objects are almost by definition unique. Thus, a single collection may be comprised of tens of thousands of objects of varying sizes, weights, geometries and materials. Consequently, pioneering widely applicable intervention methods has been difficult. One such method to resist vertical and horizontal seismic acceleration is anchoring through the application of wax to the bottom of ceramic and glass objects (Benuska 1990, Cornu and Bone 2001, Ginnell 1995, Podany 1991). The approach is popular, because it is thought to meet the physical response requirements of resisting seismic-induced tensile and shear forces, while exhibiting a ductile failure mode to prevent objects from suddenly detaching themselves from their display units and becoming sufficiently mobile to fall off stands or collide with other art objects. The method is also popular, because it is considered to meet other anchoring requirements of being non-corrosive, reversible, simple to use, easy to handle,

inexpensive, applicable without special equipment, undetectable to visitors (fig. 1), and possessing post-peak, residual strength (resistance capacity after the maximum load has occurred). The testing regime presented in this paper concentrates on exploring physical response capabilities, as other issues (e.g. reversibility) have been explored elsewhere [Podany 1995(a) and (b)].

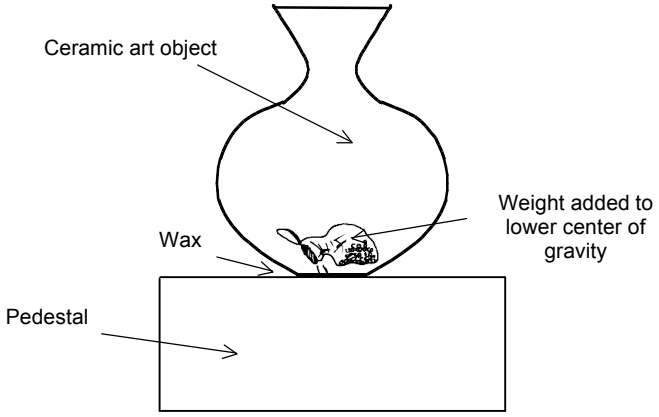


Fig. 1. Typical Application Arrangement of Microcrystalline Wax to an Art Object

Understanding performance capacities is important, because despite the documented success of wax against seismic activity (Benuska 1990), there are risks associated with its application. The high porosity of some ceramics and the composition of various glazes and paints make some art objects vulnerable to surface damage from the wax [Podany 1991, 1995(b)]. As a direct reflection of the multitude of ceramic materials and finishes involved, prediction of such vulnerability to wax-generated damage is not easily predetermined. Consequently, there needs to be a conservative approach in wax application – minimizing the quantity applied to match the calculated, anticipated need.

To date there is no independent or manufacturer-provided guidance as to the required quantity of wax needed to resist a specified amount of tensile and/or shear force (main components during earthquake loading). Without such information, conservators face the near impossible task of selecting a quantity of wax to correlate to an anticipated seismic level. A similar dilemma exists as to efficacy of application methods (hot versus cold and with or without a barrier resin coating). To address these issues, a wide variety of physical tests were conducted to begin to establish clear performance expectations, with regards to establishing anchoring capabilities in terms of the potential tensile and shear capacities, the reliability of such load capabilities, the extent of ductility, and the efficacy of application methods. Furthermore, because of the complexity and equipment requirements for many of these tests, consideration was given not only to establishing which of the tests generated the most reliable prediction of performance but to determining reasonable correlations with simplified methods – ones that could be easily conducted by regular museum personnel.

2. STRUCTURE AND PROPERTIES OF MICROCRYSTALLINE WAXES

Waxes are distinguished from other substances by their composition of esters and higher alcohols and by their freedom from fatty acids. Microcrystalline waxes are a subset of these. They are adhesive waxes and like paraffin waxes are by-products of petroleum processing. Used in a wide range of applications and in the manufacturing of inks, coatings, asphalts, and binders (Mansoori 2003), microcrystalline waxes are marketed for seismic protection. They have molecular structures similar to polymers, where a large molecule is constructed from the repetition of small, simple chains of carbons, which are side-bonded to various atoms (Billmeyer 1984). Polymer molecules are characterized in terms of their size, shape, and structure (Treloar 1958).

Size is specified by molecular weight, shape is qualitatively described by the degree of twisting, coiling, or bending of molecular-level chains (fig. 2), and structure is depicted by the manner in which the structural units are joined together: linear, branched, cross linked, networked, or a combination of these (fig. 3). Microcrystalline waxes can be characterized in these terms. Of particular importance is the microstructure, as it controls the maximum degree of crystallinity.

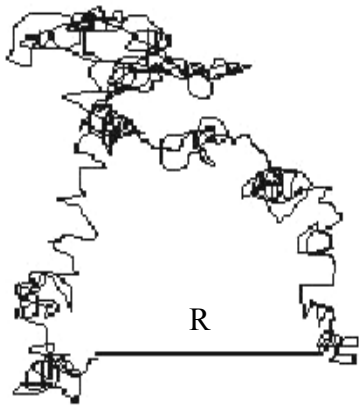


Fig. 2. Schematic representation of a single polymer chain molecule that has numerous random kinks and coils (Treloar 1958)

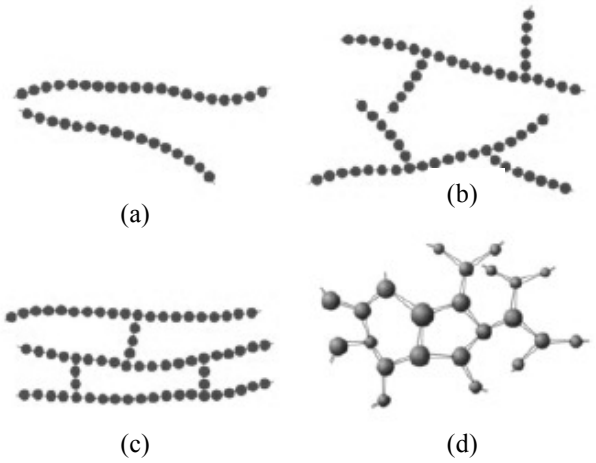


Fig. 3. Schematic representations of (a) linear, (b) branched, (c) cross linked, and (d) networked structures (Billymer 1984)

Crystallinity refers to the extent to which a three-dimensional order exists on the level of atomic dimensions, based on definite and ordered chemical and geometrical structures (Billymer 1984), and it is from this that the microcrystalline wax derives its name. The degree of crystallization depends on the molecular chain structure and on the cooling rate during solidification. Chains within a viscous liquid must have adequate time to align themselves in an ordered configuration when solidifying for crystallization to occur. Linear polymers crystallize easily, while those with

side branches interfere with extensive crystallization. The extent of crystallization influences physical properties. The more crystalline a wax is the greater its degree of hardness and brittleness (Agrawell and Joshi 1981, 1983, 1985 and Ratnasamy et al. 1973). Tests done by Agrawell and Joshi (1981, 1983, 1985) on microcrystalline waxes sampled from different petroleum tank processing areas (i.e. tank bottom, sucker rod, and residual) showed that higher branching levels resulted in softer and more plastic waxes, thus reflecting a lower level of crystallinity.

Microcrystalline waxes are also adhesives, which allow them to join dissimilar materials, improve stress distribution across a joint, and impart good dynamic-fatigue resistance (Kinloch 1987); all of which are attractive characteristics for seismic protection. Microcrystalline waxes mainly adhere because of interatomic and intermolecular forces, primarily Van der Waals forces (Kinloch 1987). Unfortunately, because of the niche market of seismic protection for which these microcrystalline waxes are now being marketed and applied, relatively little testing data is available that is directly relevant towards performance prediction for art object protection. The experiments in following sections were conducted to begin to bridge this gap by conducting static tests, which provides essential prerequisite information for subsequent dynamic testing.

3. TESTS METHODS AND EXPERIMENTAL PROGRAMME

Four waxes were studied: paraffin wax (P) and three microcrystalline waxes, Multiwax (M), Secure Wax™ (S), and Quake Hold™ (Q). The microcrystalline waxes were commercial products obtainable in the United States (Adhesives and Consolidants 2004 for the first two and Quake Hold Products 2004 for the last). Paraffin, a non-microcrystalline wax was included as a point of comparison.

Supplementary testing was conducted to investigate the possibility of identifying a simple test that could serve as a rough, first indicator of tensile and shear performance for new or untested products, thereby allowing a quick comparison to published data of known products, where more sophisticated testing apparatus might not be readily or quickly available to a conservator.

To begin to establish the actual range of physical performance that can be expected for microcrystalline waxes, pseudo-static tensile and shear testing were conducted as the critical first step for ultimately quantifying dynamic capabilities. Determining specific tensile and shear capacities was problematic as no standards for testing wax existed, and cross-application of other material tests could not be done without procedural modification, mostly due to the difficulty in manufacturing a consistent sample. As will be explained below, to this end, standardized procedures for tensile tests on metal (BS 2001, ASTM 1999) and shear tests on soil (BS 1990, ASTM 2004a) were altered to develop reliable testing procedures for wax.

As a wax's crystalline structure is fixed, melting imparts mobility to the molecules, which allows them to more readily respond to external stimuli. Therefore, melted waxes more easily generate consistent samples and adhere better than those applied at room temperature (Kinloch, 1987). A major difficulty with this approach is that in practice the waxes are applied cold; conservators hand place small balls of microcrystalline wax, at room temperature, to the underside of art objects.

Additionally, although the wax can be applied directly to the art object, conservators often pre-apply a thermoplastic, acrylic resin as a protective coating. Under limited testing conditions, the

resin has been shown to prevent both wax-generated staining and accidental detachment of any of the art object itself (Podany 1995[a]). The preferred product is Paraloid B-72, a methylacrylate copolymer (Acryloid 2000). Paraloid B-72's advantages over traditional polyvinyl acetate resins include reversibility, improved durability, and strength and hardness without brittleness (Podany et al. 2001, Koob 1986). As such, the following sections describe tensile tests and shear tests conducted to reflect various preparation and application methods (Table 1).

Table 1. Testing variables

Wax Type	Application	Preparation
Paraffin (P)	Cold (C)	No Resin Coating (N)
Multiwax (M)	Hot (H)	Resin Coating (R)
Secure Wax ™ (S)		
Quake Hold ™ (Q)		

3.1 TENSILE TESTING

Critical was the creation of repeatable test specimens, in terms of full platen coverage and consistent thickness, both across a single platen and between specimens.

3.1.1 Specimen Preparation

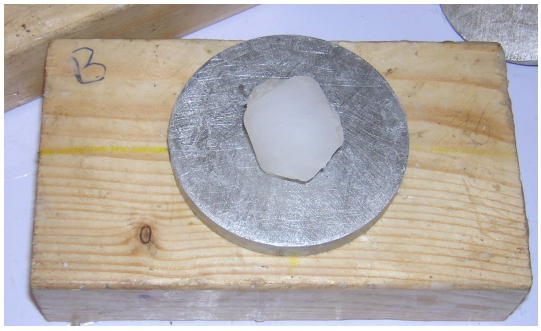
Tensile tests specimens were prepared using both compacted and melted preparation methods (described below) to attain cold and hot application, respectively and were tested both with and without the application of the Paraloid B-72 coating.

Museum personnel typically apply the microcrystalline waxes by pressing small balls of hand-rolled wax to the underside of an art object, which in turn is pressed against a display case. Un-

fortunately, such an approach did not produce repeatable specimens, both in terms of platen coverage and with respect to specimen thickness. As an alternative, a mechanized method was adopted for cold wax application. Five balls, of 2 g of wax each, were hand-rolled at room temperature and then placed on a bottom platen (fig. 4a). The wax was then compressed between two platens using a compression machine, which employed a screw mechanism (fig. 4b), until the height was reduced to 2 mm. The 10 g of wax generated full coverage of the platen, with little excess material emerging from around the platens' sides. The platens were made as a specialty item in the machine shop of the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign. The platens were of stainless steel and machine finished so that the adhesion surface was smooth and highly polished. The platens were 12.5 mm high and 37 mm in radius. All testing was conducted at room temperature to reflect actual industrial usage.

For the hot application, an aluminum receptacle was placed in a double boiler and 14 g of wax were melted over a medium heat until liquefied. The liquefied wax was poured across the entirety of a bottom platen [using a collar of modeling clay to prevent wax overflow and to ensure a consistent specimen height (fig. 4c)]. After pouring, the top platen was immediately placed on top of the hot wax. Unlike the compacted samples that were ready for testing immediately after wax application, the melted and cast specimens were left to solidify for a minimum of 16 hours prior to testing. The quantity of 14 g of wax was established experimentally, as the minimal amount needed to repeatedly achieve full platen coverage for the 4300 mm^2 plate, and was larger than the experimentally established amount required in the compaction method, as a small amount of loss occurred in the wax's transfer from the melting container to the platen. The sam-

ples were subjected to a constant loading rate (typically referred to as the crosshead speed) of 0.5 mm/min in the testing apparatus.



4a Cold application

4b Compression machine

4c Hot application

4d Modified Instron 4411Machine™

Fig. 4. Tensile testing

The Paraloid B-72 coating was prepared in a screw top beaker using 100 g of acetone, 0.1 g of silica, and 8.5 g of Paraloid B-72 granules, which were suspended in a cotton gauze bag. The quantities corresponded to a 17% weight:volume ratio. The Paraloid B-72 was dissolved overnight. The lid was then removed, and the acetone was left to evaporate in a fume cupboard, until a 1:1 resin:solvent ratio was achieved. The step-by-step preparation of this coating followed that described by Koob (1986), except for the weight:volume ratio. Using a paintbrush, the coating was applied over the entirety of the bottom platen and left for an hour for complete drying. Otherwise, coated samples were prepared as described in the above sections.

3.1.2 Testing Equipment

To determine a worst-case scenario for the tensile capacity, the wax was tested against the stainless steel platens (fig. 4d). The platens provided low frictional resistance and prevented the development of shear keys between the testing apparatus and the wax. An electromechanical Instron 4411 Machine^{TM} was altered with specialty connecters to accommodate these platens (fig. 4d).

3.1.3 Testing Protocol

To create a tensile testing procedure, two standards were considered: the European Standard Metallic Materials – Tensile Testing – Part 1: Method of Test at Ambient Temperature (BS 2001) and the ASTM Standard Practice for Verification of Specimen Alignment Under Tensile Loading (ASTM 1999). Table 2 summarizes the differences between the specified and the developed procedures. The focus of this study was to find ultimate tensile capacity. Therefore, the testing protocol adopted emphasized this goal and was reported in the form of stress versus strain.

Table 2. Tensile testing procedure comparison

Testing Parameter	BS 2001	ASTM 1999	This Study
Properties obtained	Percentage elongation Tensile strength Yield stress	Axial strain Maximum bending strains Percentage bending	Tensile strength
Reported information	Graph of load versus Extension	Estimation of precision and bias	Maximum failure load Graph of stress versus strain

3.2 INHERENT SHEAR TESTING

Inherent shear tests were devised to determine the shear strength of the material within its own mass, as opposed to its capacity when interfacing with a different material. Critical to this outcome was the creation of repeatable test specimens that could be used for determining the wax's inherent shear capacity, as well as its interface shear capacity.

3.2.1 Specimen Preparation

To accommodate constructability issues and facilitate sample production, a mold was created in which to cast all melted wax samples. The mold had to be sufficiently rigid, removable, and reusable, as well as being impermeable to prevent seepage of melted wax, easy to make, and cheap to construct. A cardboard mold covered in Clear Seal™ (a plastic wrap) proved effective (fig. 5).

For the inherent shear specimens, all samples were melted and cast into the molds, allowed to solidify, and then tested. To achieve this, 50 g of wax were melted and cast, as previously described. The liquefied wax was then poured into a cardboard, shear mold (fig. 5). The cast wax

was left to solidify for 16 hours, after which time the mold was removed, and the wax was cut into 5 individual 20 x 20 x 25 mm samples.

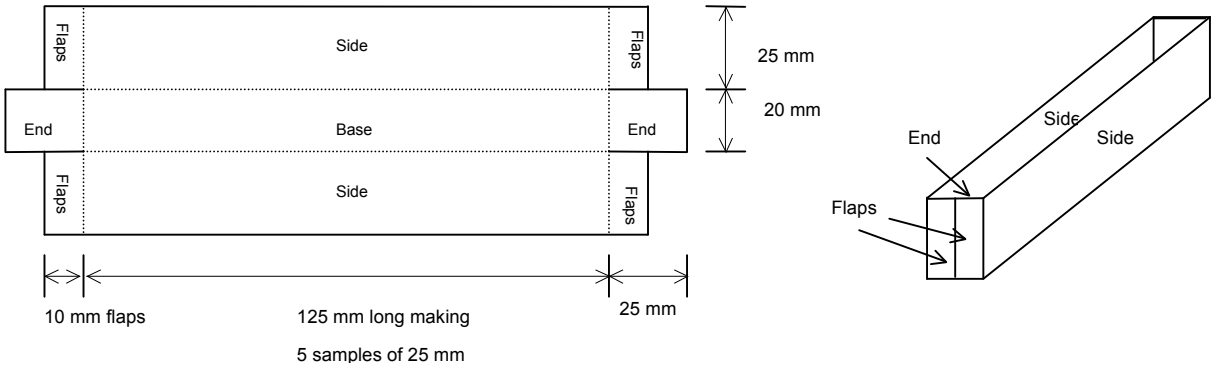
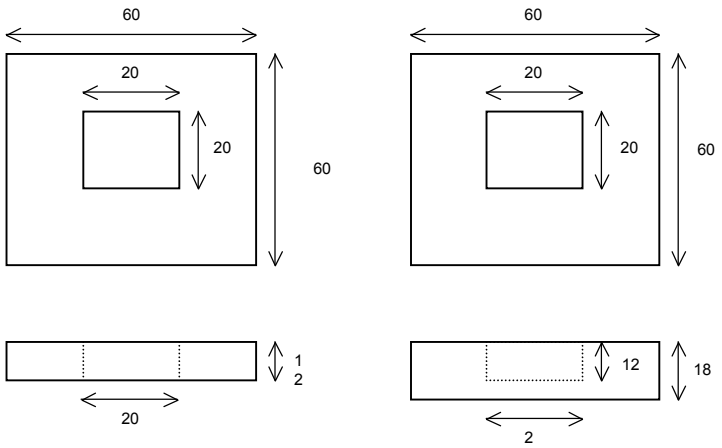


Fig. 5. Shear mold

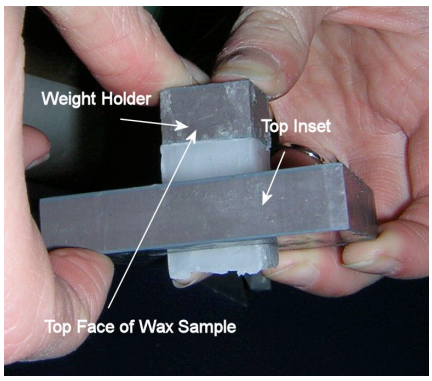
3.2.2 Testing Equipment

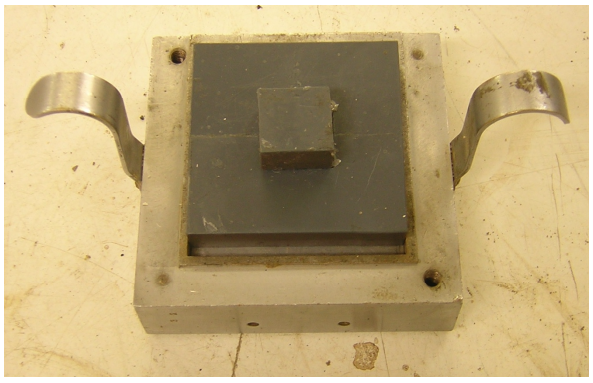
Inherent shear tests were conducted in a standard shear box apparatus, according to the British standard (BS 1990). The only equipment modification was to the shearing area. This was done to accommodate a limited amount of material available for testing of one of the waxes. The shearing area was reduced from the standard 60 mm x 60 mm to a surface area of 20 mm x 20 mm, thus the sample sizes listed in the above section. There was no change in the pre-specified depth of the testing apparatus. The contact area was decreased through means of a polyvinyl chloride (PVC) plastic inset that consisted of two pieces (fig. 6a). As the surface area reduction was necessary to accommodate a highly limited amount of some other waxes that are not featured here, other researchers should not find this alteration necessary, although the dimensions related to the specimen preparation steps would need to be altered to reflect the larger testing area.

Samples were pushed through the top inset of the shear box and then placed in the bottom inset (fig. 6b), and finally inserted into the apparatus (fig. 6c). Horizontal displacement, perpendicular to the sample, was applied at the rate of 0.025 mm/s. The rate was considered by the authors as sufficiently slow to not introduce unintended, dynamic response characteristics, yet rapid enough to preclude creep. Resistance readings were recorded at every 0.01 mm increment of horizontal displacement. As described below, as part of the testing, there was a vertical force applied as a constant normal load on the wax, to represent the art object's mass (fig. 1).



6a PVC insets for the shear box apparatus (all dimensions in mm)





6b Inserting the wax through the top inset 6c Insets placed in shear box apparatus

Fig. 6. Shear testing

3.2.3 Testing Protocol

For an inherent shear testing protocol, the British Standard Methods of Test for Soils for Civil Engineering Purposes – Part 7: Shear Strength Tests (Total Stress) [BS 1990] and the ASTM Standard Test Method for Direct Shear Tests of Soils Under Consolidated Drained Conditions [ASTM 2004(a)] were considered. Table 3 highlights the differences between the standards and the shear testing employed. One major difference was the normal load. Forces of 50 kPa and 235 kPa were selected to represent two classes of art objects: small ones and medium ones. The forces were selected based on extensive consultation with conservation staff of the J. Paul Getty Museum to reflect typical weights of small to medium sized objects for which the wax is predominantly used. The waxes were tested at both normal loads. The other difference in procedure was a halving of the reading intervals, to reflect the fact that the wax fails at a faster rate than soil.

Table 3. Shear testing procedure comparison.

Testing Parameter	BS 1377	ASTM D 3080	This Study
Vertical load/normal force	Approximately 222 kPa, 444 kPa or 888 kPa applied for different rates of consolidation	Approximately 7 kPa	50 kPa and 235 kPa
Reading intervals per interval of horizontal movement	0.02 mm	2% of specimen's diameter or width	0.01mm

3.3 INTERFACE SHEAR TESTING

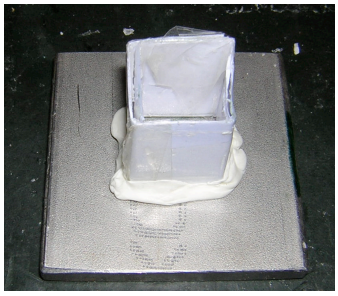
Although the inherent shear capacity of the wax was important to establish, the wax to surface interface capacity was considered more likely to control the failure in the actual application. To this end, samples were tested in an arrangement that was designed to represent a lower bound capacity, by employing a steel plate against which to shear the wax, as the materials used for the actual display cases are highly varied and in many scenarios are smooth or highly polished.

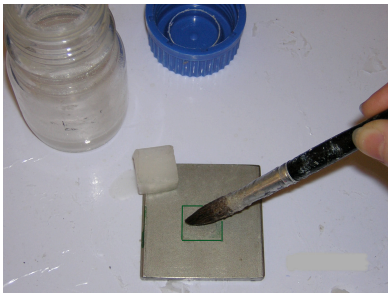
3.3.1 Testing Equipment

As with interface testing, interface shear tests were conducted in the same basic shear box apparatus (fig. 6). The shear box was, however, modified to allow the wax to shear against a smooth, steel plate. To achieve this arrangement, two porous plates were added on top of the retaining plate in the shear box to increase the height of the bottom of the shear box. Then a smooth, steel bond plate was added in lieu of the bottom portion of the shear box (18 mm). The top inset (fig. 6a) was placed over the sample, while avoiding displacement of the sample from its position on the shear plate. The shear box was then placed in the apparatus. The rate of horizontal displacement, the frequency of displacement readings, and the applied normal load were identical to those applied for the inherent shear tests.

3.3.2 Specimen Preparation

All hot applied interface tests required 60 g of wax, which were melted and cast as previously described. For those that were hot applied without coating, the wax was poured into the modified shear mold, which was placed directly onto the steel plate; modeling clay was used at the mold/plate interface to create a barrier to prevent wax outflow (fig. 7a). The specimen was left to solidify for 16 hours, after which the mold was removed, and the sample was ready for testing.





7a Hot applied wax mold 7b Cold applied wax placement 7c Coating the shear plate

Fig. 7. Shear testing preparation

For cold applied samples, the specimens were prepared using the same procedure as for the inherent shear test (fig. 5), except that the wax samples were taller -- cut into 10 separate 20 x 20 x 15 mm sized samples. The samples were pressed firmly onto the steel plates (fig. 7b) and were ready for immediate testing. For all samples tested with a resin coating, a layer of Paraloid B-72 was prepared as previously described. The coating was spread onto the surface using a paintbrush, over the entirety of the marked area (fig. 7c). The coated plates were left for an hour for complete drying of the resin prior to wax application. Otherwise, coated samples were prepared as described in the above sections.

3.3.3 Testing Protocol

The testing protocol was adapted from the standards BS 1377 (BS 1990) and ASTM (D3080). Applied forces were those as described for the inherent shear tests. Like the inherent shear tests, specimens were tested for each of the waxes at both normal forces.

3.4 SUPPLEMENTAL PHYSICAL TESTS

To identify procedures that would be accessible to most conservators, a supplemental set of physical tests were conducted using methods that are both well-documented and employ simple equipment. These tests were explored to determine, if a relatively simple and easy procedure could be identified to establish a qualitative response for a new and/or unknown wax by comparing the results of the simplified outcomes to those for which rigorous and extensive shear and tensile testing has already occurred. The tests included relative hardness (employing a needle penetration test), contraction, density, softening point, and melting point.

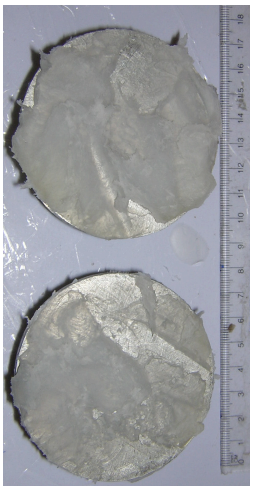
Needle penetration tests are prevalent in the petroleum industry to obtain relative hardness values of petroleum products and were conducted according to British Standard EN1426 (BS 1999b) by measuring the distance that a standardized needle will penetrate a sample vertically, under specified temperature, load, and duration [BS 1999(b)]. Density measurements were obtained by pouring melted wax into containers with identical internal diameters (55 mm) and heights (35 mm). As contraction occurred in some of the waxes during solidification, after approximately one hour, samples were refilled to generate a consistent volume of material to test. All samples were left to solidify over night, and density was calculated based on the volume divided by the mass. The same containers and initial procedures were used to determine contraction, however, no material was added, once the original sample was poured. Instead, after solidifying over night, water was added to each container using a graduated, milliliter dropper, until the container was refilled. The amount of water added established the volume change.

Softening point is the temperature at which an adhesive attains a degree of softness under specified conditions, which in this case was the temperature at which the sample was sufficiently soft to allow a metal ball to pass through a ring of wax of a fixed thickness (BS 1999a). The wax was melted into two open-ended molds (6.4 mm high by 15.9mm in internal diameter) and left to solidify overnight. The samples in their molds were then placed in a heated water bath apparatus with a pair of 3.5g steel balls atop the samples. The apparatus was heated at a rate of 5˚C per minute. According to the standard, failure is defined as the temperature when the ball passes through the bottom of its respective mold. This is considered the softening point temperature. The temperature at failure of the two samples must be within 5% of each other, for the test to be valid[(BS 1999(a)]. In contrast to the softening point, the melting point is the temperature at which the substrate liquefies (BS 1970), as indicated by the formation of a definite meniscus. To achieve this, a ground sample of the wax was placed in a test tube, which was then put into a 20˚C water bath whose temperature was increased by 3˚C per minute, until a meniscus was observed in the liquid wax.

4. TEST RESULTS

4.1 TENSILE TEST RESULTS

Three tensile failure modes were observed: adhesion (fig. 8a), mixed (fig. 8b), and cohesion (fig. 8c). The microcrystalline waxes experienced cohesion or mixed failures (fig. 8), while the paraffin wax exhibited adhesion failure. The adhesion failure was sudden, as opposed to the progressive nature of the others.



8a Adhesion failure 8b Mixed failure 8c Cohesion failure

Fig. 8. Tensile failures modes

As summarized in Table 4, when the microcrystalline waxes were applied cold without coating, Multiwax had the highest tensile strength, and resin coating application improved strength by an average of 30% for the microcrystalline waxes.

Table 4. Tensile test results

Wax Type	Application	Coating	No. of Tests	Average kPa	SD kPa	COV %	Max kPa	Min kPa
Paraffin	Cold	No resin	0					
Multiwax			6	156	38.6	24.7	209	107
Secure Wax™			6	89.6	17.6	19.7	123	76.0
Quake Hold™			6	133	26.0	19.5	169	107
Paraffin	Cold	Resin	0					
Multiwax			6	183	32.6	17.8	242	158
Secure Wax™			6	122	10.0	8.20	140	113
Quake Hold™			6	185	46.0	24.8	259	125
Paraffin	Hot	No resin	6	60.0	14.2	23.7	82.0	44.0
Multiwax			6	194	52.0	26.8	265	139
Secure Wax™			6	183	39.9	21.9	229	128
Quake Hold™			6	236	37.7	16.0	277	179
Paraffin	Hot	Resin	6	79.0	59.8	75.7	192	30.0
Multiwax			6	293	28.4	9.72	336	254
Secure Wax™			6	289	74.1	25.7	390	209
Quake Hold™			6	317	23.8	7.52	350	293

The strongest microcrystalline wax tested hot applied with no resin was Quake Hold™, with a narrower performance range of only 9.2% difference was shown for the coated, hot applied microcrystalline samples. Typical coefficient of variations (COVs) were in the 15-25% range.

Without any coating, the hot applied, microcrystalline samples gave on average a 90% increase in tensile strengths over the cold applied samples (fig. 9), which was caused by the superior molecular contact achieved by employing a melted preparation for the application method (Kinloch, 1987). The difference between the performance of the hot and cold applied samples with the resin coating was nearly as great, with the hot providing an average increase of 83% more capacity.

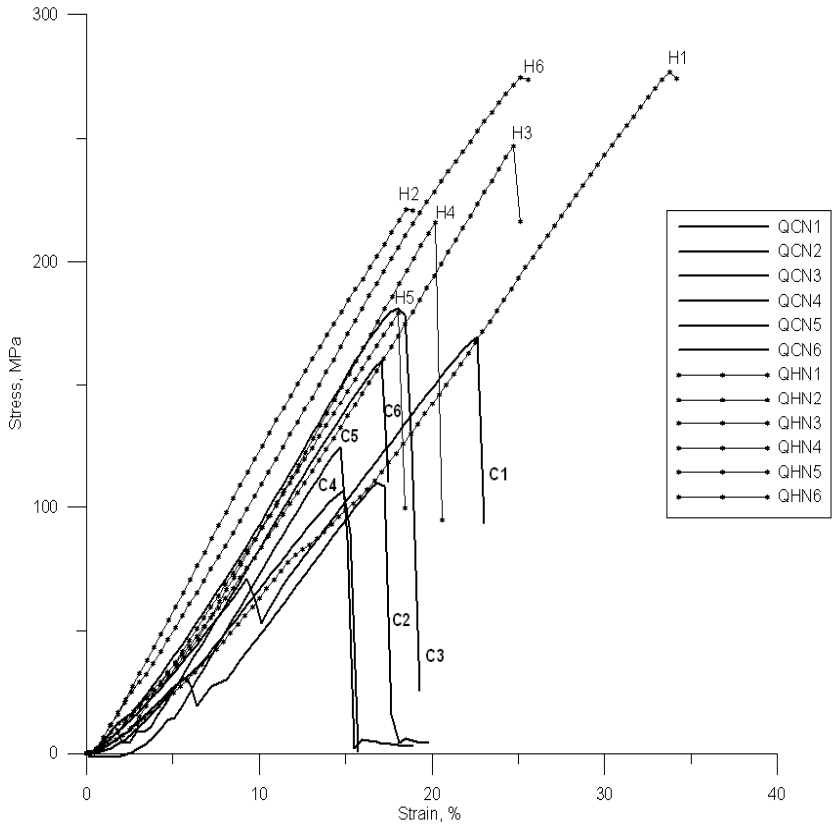


Fig. 9. Stress-strain curves of Quake Hold™ hot applied (QHN, dotted line) versus cold applied with no resin coating (QCN, smooth line)

On average, the microcrystallines waxes with coating had a 38% increase in tensile capacity over those without coating (46% for hot applied samples and 30% for cold applied ones) [fig. 10]. Additionally the COV was typically halved with resin application, although results were not uniformly favorable (Table 4). The inconsistency may be a function of the resin's application method: the clear coating was applied with an acrylic brush, and thus a consistent covering was hard to verify.

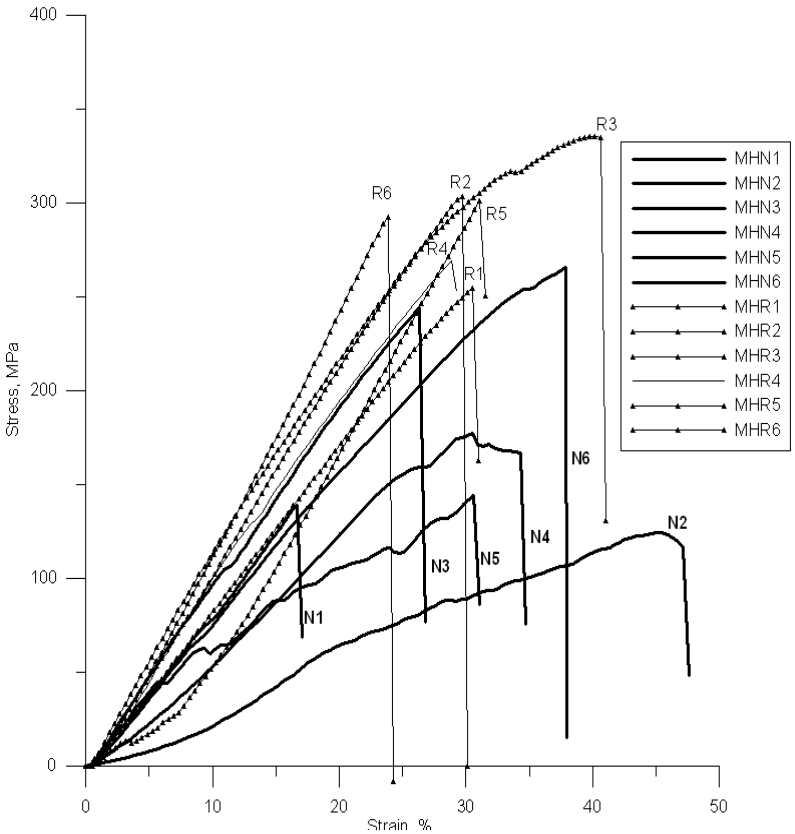


Fig. 10. Stress-strain curves of Multiwax hot applied with no resin (MHN, smooth line) coating versus resin coating (MHR, dotted line)

4.2 INHERENT SHEAR RESULTS

Inherent failure types were classed as brittle or plastic (fig. 11). The microcrystalline waxes experienced plastic failures, while the paraffin wax exhibited brittle failure. The brittle failures were sudden, as opposed to the progressive nature of the plastic failure.

a Brittle b Ductile

Fig. 11. Inherent shear failure modes

Five samples were tested under two normal loads (50 kPa and 235 kPa). As summarized in tables 5 and 6, of the microcrystalline waxes, Multiwax exhibited the highest inherent shear strength, on average 5-8 times stronger, than the Secure Wax™, the poorest performing microcrystalline wax. There was an average of a 14% increase in shear strength with a 4.7 times increase in normal load – a nearly 25% increase in capacity, as a function of additional normal load.

Table 5. Inherent shear results for 50kPa normal stress

Wax Type	Average kPa	SD kPa	COV %	Max kPa	Min kPa
Paraffin	776	180	23.2	1040	599
Multiwax	321	65.8	20.5	415	250
Secure Wax™	39.7	10.1	25.4	55.8	31.0
Quake Hold™	279	45.2	16.2	349	229

Table 6. Inherent shear results for 235kPa normal stress

Wax Type	Average kPa	SD kPa	COV %	Max kPa	Min kPa
Paraffin	874	68.0	7.78	981	795
Multiwax	347	75.6	21.8	409	240
Secure Wax™	73.9	23.0	31.1	99.1	47.5
Quake Hold™	310	63.4	20.5	397	219

Of note was the increased COV of the microcrystalline waxes under the heavier load (up 18%). What is unclear is whether a heavier load impedes or otherwise damages the intricate network of branching and, thus, makes performance less consistent.

4.3 INTERFACE SHEAR RESULTS

The failure mechanisms for interface shear results were similar to those displayed in the inherent wax testing, with the paraffin wax showing brittle failures and the microcrystalline ones being plastic. Results are based on 5 samples for each of the 2 normal loads selected (50 kPa and 235 kPa, see rationale above). Of the cold applied samples with no resin, Multiwax had more than twice the capacity of the lowest performing wax, Secure Wax™. When the resin was applied to the cold samples, capacity increased by a average of 91%, and the Multiwax remained the best performer and the Secure Wax™ the worst (Table 7).

Table 7. Interface shear results at the lighter stress of 50kPa

Wax Type	Application	Resin	No. of Tests	Average kPa	SD kPa	COV %	Max kPa	Min kPa
Paraffin	Cold	No Resin						
Multiwax			5	29.7	6.94	23.3	37.2	22.7
Secure Wax™			5	11.5	1.45	12.6	13.4	9.91
Quake Hold™			5	19.6	3.10	15.8	24.8	16.5
Paraffin	Cold	Resin	5	31.3	17.8	56.9	63.0	21.7
Multiwax			5	41.7	9.17	22.0	55.8	33.0
Secure Wax™			5	32.6	7.40	22.7	42.3	22.7
Quake Hold™			5	31.8	8.98	28.3	43.4	19.6
Paraffin	Hot	No Resin						
Multiwax			5	47.9	3.39	7.08	53.7	45.4
Secure Wax™			5	19.6	2.31	11.8	22.7	16.5
Quake Hold™			5	29.7	8.08	27.2	43.4	22.7
Paraffin	Hot	Resin						
Multiwax			5	94.6	20.8	22.0	115.6	72.3
Secure Wax™			5	44.6	8.83	19.8	55.8	33.0
Quake Hold™			5	47.4	8.31	17.5	58.3	37.2

This product ordering with respect to the capacity was repeated for the hot applied waxes. With no resin, Multiwax was the highest capacity, at more than twice that of the lowest, Secure Wax™. The increase in capacity gained by the coating was on average 94% better. The hot applied waxes had a 66% average increase over those cold applied (59% increase with no resin and 73% increase with resin). These patterns were not seen at the higher normal load of 235 kPa. In cold applied samples with no resin, Quake Hold™ was 2.4 times the capacity of the lowest performing wax Secure Wax™ (Table 8). When the resin was applied to the cold samples, it increased the capacity by an average of 56%, with the Quake Hold™ exhibiting the highest capacity and the Secure wax™ the lowest.

Table 8. Interface shear results at the heavier stress of 235 kPa

Wax Type	Application	Coating	No of Tests	Average kPa	SD kPa	COV %	Max kPa	Min kPa
Paraffin	Cold	No Resin						
Multiwax			5	58.5	9.49	16.2	67.1	42.3
Secure Wax™			5	29.9	6.02	20.1	39.2	22.7
Quake Hold™			5	73.3	8.88	12.1	88.8	67.1
Paraffin	Cold	Resin	5	9.42	1.29	13.8	11.4	8.26
Multiwax			5	61.8	9.14	14.8	75.9	53.7
Secure Wax™			5	70.8	12.8	18.1	90.9	60.9
Quake Hold™			5	92.1	16.0	17.4	110	72.3
Paraffin	Hot	No Resin						
Multiwax			5	60.9	9.00	14.8	71.2	49.6
Secure Wax™			5	31.8	8.31	26.1	43.4	22.7
Quake Hold™			5	58.4	14.0	23.9	72.3	35.1
Paraffin	Hot	Resin	2	64.0	2.92	4.56	66.1	62.0
Multiwax			5	91.8	19.2	20.9	116	71.6
Secure Wax™			5	67.1	12.0	17.8	84.7	56.8
Quake Hold™			5	93.8	24.6	26.3	134	70.2

For hot applied waxes with no resin, Multiwax exhibited the highest capacity and Secure Wax™ the lowest. The increase in capacity gained by the coating was on average of 73% more, how-

ever the addition of the coating to these hot applied samples changed the capacity leader to Quake Hold™ (but only 3% over the Multiwax).

When comparing the results of hot applications to cold, the hot applied Multiwax and Secure Wax™ without resin were stronger than those similarly cold applied, but the Quake Hold™ experienced a decrease in shear capacity and a higher COV. In the resin case, hot application produced a broader range of results than with the cold, from a 48% increase (Multiwax) to a 5% decrease (Secure Wax™).

4.4 SUPPLEMENTAL PHYSICAL TEST RESULTS

Further testing was undertaken in an attempt to find a simple and readily executable test that could be performed by museum personnel to predict wax capacity of unknown products. Relative hardness, failure mode (plasticity and brittleness), contraction propensity, density, softening point, and melting point were all considered.

Hardness is the measure of a material's rigidity and resistance to pressure and can be measured through a needle penetration test [BS 1999(b)]. Based on this procedure, microcrystalline waxes were found to be softer than the paraffin (Table 9). Of the microcrystalline waxes, Multiwax was the hardest and Secure Wax™ the softest, with a 200% difference in penetration.

Table 9. Physical properties

Characteristics	Waxes			
	Multiwax	Secure Wax™	Quake Hold™	Paraffin
Needle Penetration At 25 °C (dmm)	22	67	56	12
Relative hardness[b]	Medium Hard	Soft	Medium soft	Hard
Failure mode	Mildly Plastic	Plastic	Plastic	Brittle
Contraction ($mm^3 \times 10^{-6}$)	14	10.5	12.1	24.1
Density (kg/m^3)	395.82	401.24	441.66	471.1
Softening Point (°C)	79.40	78.10	75.20	52.40
Melting Point (°C)	80.00	79.30	75.90	53.70

[a] Insufficient material to conduct tests

[b] Results based on physical observations

Plasticity is the property of a solid body, whereby it undergoes a permanent change in shape and size, when subjected to a stress exceeding its yield value, whereas brittleness is the condition when the material breaks prior to any appreciable plastic deformation. Plasticity and brittleness observations were based on the failure mode noted during the tensile (fig. 8) and inherent shear tests (fig. 11). Agrawell and Joshi (1985) found brittle waxes to have a higher degree of contraction during solidification than microcrystalline ones. In the tests conducted as part of the current study, the paraffin wax had the greatest degree of contraction at 24.1 x 10^6 mm^3, which was 141% more than that the smallest recorded contraction of 10.5 x 10^{-6} mm^3 by the Secure Wax™, which was also the softest and most ductile wax. Contraction is heavily influenced by crystallization structure. The linearity of a paraffin's molecular structure allows it to crystallize more effectively, thereby occupying less volume upon solidification. Wax densities ranged from 395 kg/m^3 to 471 kg/m^3, with the Multiwax being the lowest and the Secure Wax™ the next lowest. There was only a few degrees difference between the melting and softening points, which ranged from 52 °C to 80°C.

5.0 ANALYSIS

Because of their plastic failure behavior, microcrystalline waxes are attractive for seismic protection of museum objects. Their gradual breakage lengthens the failure time-cycle, thereby allowing for the potential of objects to display displacement prior to complete failure of the wax anchoring. Additionally, their residual capacity decreases the likelihood of an object falling to the ground or crashing into another object or the exhibition case. In both tension and shear, paraffin fails suddenly and brittlely, thus showing itself to be inappropriate as a seismic anchoring material.

Another requirement is having a predictable capacity. Despite, extensive repetitive testing the results still generated high COVs, which seem to be indicative of the performance and/or composition of the material and not the testing arrangement as relatively low COVs, which indicate data consistency, were achievable with some materials under certain application conditions.

Because wax removal is difficult and ceramic surfaces, glazes and paints can be harmed, a major objective in wax selection is obtaining maximum capacity, which in turn minimizes the needed quantity. Of the microcrystalline waxes, the Secure Wax™ consistently had the lowest capacities in tension, inherent shear, and interface shear (Tables 10, 11 and 12), irrespective of application configuration and was found to be the softest wax from the needle penetration test. This simple test finding directly reflects the material's inability to efficiently transfer energy. If a substrate is hard and brittle and the wax is soft, energy will be dissipated by the deformation of the wax until failure occurs (Russell and Kim 1999). If, on the other hand, the wax has a hardness level similar to the substrate, energy dissipation is more evenly distributed between the wax

and substrate, which results in a higher ultimate capacity. The Secure Wax™ was, thus, the worst performer of the waxes.

In tensile tests, cold applied, without resin coating, Multiwax was the best performer. In all other tensile testing configurations, however, Quake Hold™ was superior by 1% to 15% (Table 10). In inherent shear tests, Multiwax was the best performer overall, achieving the maximum inherent shear strength at both applied normal loads (Table 11).

Table 10. Performance range tensile tests

Application		Maximum Wax	kPa	COV	Minimum Wax	kPa	COV
Cold	No Resin	Multiwax	156	24.7	Secure wax™	90	19.7
	Resin	Quake Hold™	185	24.8	Secure wax™	122	8.20
Hot	No Resin	Quake Hold™	236	16.0	Secure wax™	182	21.9
	Resin	Quake Hold™	316	7.52	Secure wax™	289	25.7

Table 11. Performance range inherent shear tests

Normal Load	Maximum Wax	kPa	COV	Minimum Wax	kPa	COV
50 kPa	Multiwax	321	20.5	Secure wax™	39.7	25.4
235 kPa	Multiwax	347	21.8	Secure wax™	73.9	31.8

Average inherent shear capacities were over 660% higher than average interface capacities, therefore, failure can be expected at the object/wax interface or the pedestal/wax interface (fig. 12). Inherent shear strength results cannot be used to predict interface shear strength, and the poor correlation between the inherent and interface shear tests [fig. 13(b)], demonstrated that increasing the thickness layer of the wax provides no additional protection to the art object.

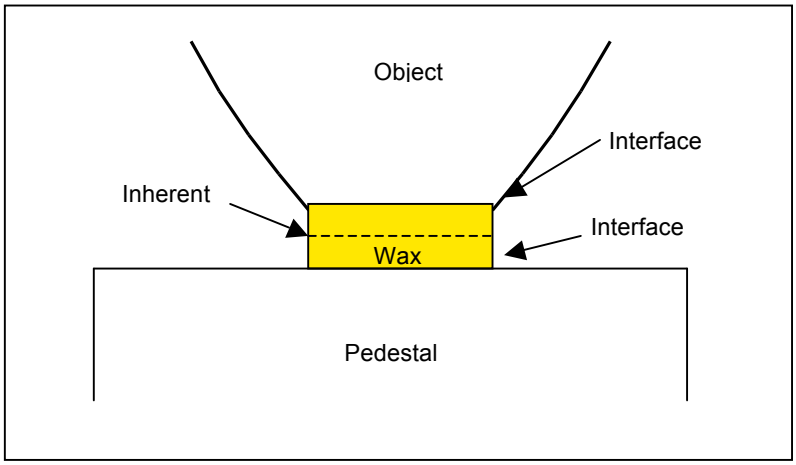
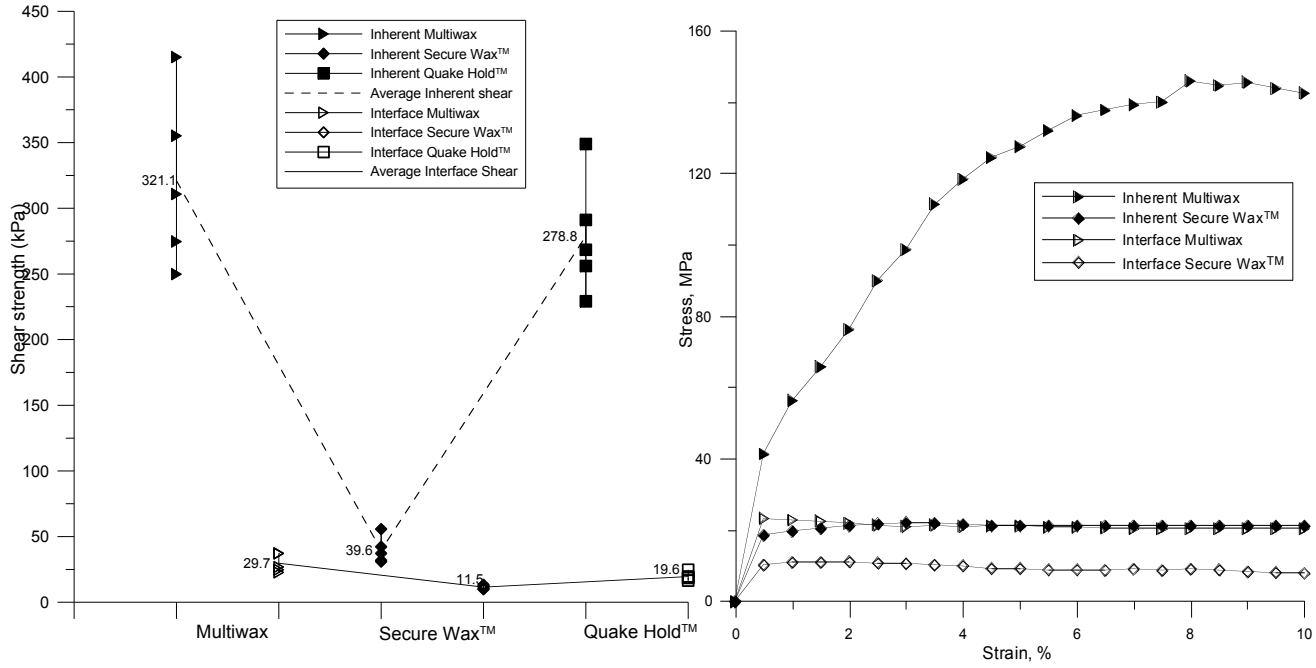


Fig. 12. Inherent versus interface failure planes



(a) Average results (five tests) (b) Average comparative failure pattern

Fig. 13. Inherent versus interface results for the microcrystalline waxes cold applied with no resin coating at normal load of 50 kPa

For the interface shear, at a normal load of 50 kPa (representing the weight of a small art object), Multiwax was the best performer with the maximum interface strength under all applications (Table 12), but at the higher normal load of 235 kPa (for a medium sized art objects), Multiwax and Quakehold™ were virtually indistinguishable in the hot applications (within 2-3%) [Table 13], but the Quake Hold™ outperformed the Multiwax in the cold applications by approximately 30%.

Table 12. Performance ranges for interface shear strength at 50 kPa

Application		Maximum			Minimum		
		Wax	kPa	COV	Wax	kPa	COV
Cold	No Resin	Multiwax	29.7	23.3	Secure wax™	11.5	12.6
	Resin	Multiwax	41.7	22.0	Secure wax™	31.8	28.3
Hot	No Resin	Multiwax	47.9	7.08	Secure wax™	19.6	11.8
	Resin	Multiwax	94.6	22.0	Secure wax™	44.6	19.8

Table 13. Performance ranges for interface shear at a normal load of 235 kPa

Application		Maximum			Minimum		
		Wax	kPa	COV	Wax	kPa	COV
Cold	No Resin	Quake Hold™	73.3	12.1	Secure wax™	29.9	20.1
	Resin	Quake Hold™	92.1	17.4	Secure wax™	69.0	13.7
Hot	No Resin	Multiwax	60.9	14.8	Secure wax™	31.8	26.1
	Resin	Quake Hold™	93.8	26.3	Secure wax™	69.1	15.0

Globally speaking, the B-72 resin coating increased the capacity of the waxes in all configurations: an average of 38% in tension, 93% in inherent shear at 50 kPa and 64.5% at 235 kPa. In general, hot application generated more capacity than cold. Only in the interface shear tests under the heavier load (235 kPa) did this trend vary, and then there was a 15% average decrease accompanied by a 100% increase in COV. This result would indicate that there may be a threshold normal load at which point capacity begins to deteriorate, and the results become less consistent; establishing such a threshold falls outside the purview of this study and may be at a differ-

ent level during dynamic loading than in pseudo-static loading. Overall, microcrystalline waxes generated 92% higher shear strengths under a 370% increased normal force (an approximate 25% capacity increase as a function of additional load).

A variety of simplified testing techniques proved relatively effective at qualitatively predicting performance, under specific application arrangements (Table 14). A conservator would use Table 14 to compare the performance of an untested microcrystalline wax with ones that have been presented in this paper. First, the conservator would determine the expected application method (e.g. Hot, no resin) and then look to see which test had the best correlations for tensile and shear loading. In this case it would be the Contraction test. A sample of the untested wax and a sample of the waxes presented in this paper would be subjected to the simple test and the relative capacity of the unknown wax could thus be established.

These values were obtained by normalizing the individual results of the simplified tests by the smallest (lowest) reading for that particular test, taking the average of those results, and then dividing them by the similar average for either the tensile or shear outcomes. Those results shown in Table 14 with numbers closest to a value of 1.0 most accurately correlated with the tested capacity. Those within 10% are demarcated in bold to show the best correlations.

Table 14. Correlation of simplified measures to tensile and interface shear capacities*

Test	Application	Contraction	Needle penetration	Density	Melting Point	Softening Point
Tensile	CN	1.21	0.81			
	CR	1.15	0.77			
	HN	**0.96**				
	HR	0.89		**0.99**	**1.01**	**1.00**
Shear Interface at 50kPa	CN		**1.01**			
	CR	**0.93**		**1.04**	**1.05**	**1.05**
	HN		**0.95**			
	HR	1.20	0.80			
Shear Interface at 235kPa	CN		**1.03**			
	CR	0.79		**1.07**	**1.08**	**1.08**
	HN		**0.91**			
	HR	**0.99**		**1.07**	**1.07**	**1.07**

* Values not shown exceeded 20% variation from ideal correlation and thus should not be employed

Since cold application is the preferred option by the conservation community, establishing a test to correlate to this was the priority. Correlation for tensile results was poor except in a hot applied, resin configuration (Table 14). In contrast, the needle penetration test correlated extremely closely for the cold applied, no resin shear tests at both normal loads, but density, melting point, and softening point were all better contenders for predicting results for the cold applied, resin testing configuration. As shown in Figure 14, even though tensile tests have a poor correlation with the simplified tests, there is a clear trend between tensile and shear capacity, particularly for

the shear results at the lower applied normal load.

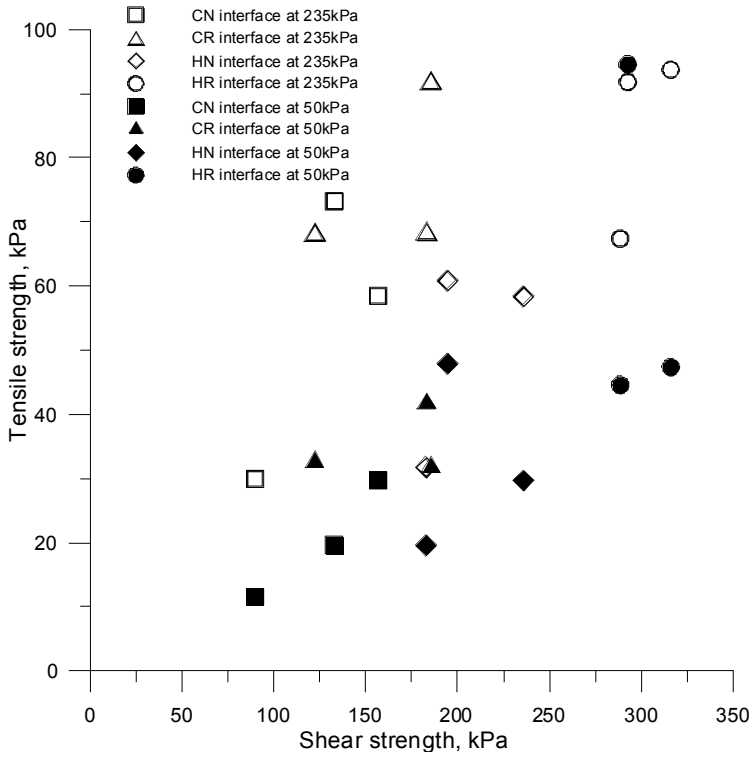


Fig. 14. Average capacities of tensile tests versus interface shear tests

6.0 DISCUSSION AND CONCLUSIONS

The above study was designed to provide conservators with a sense of performance expectations for microcrystalline waxes, with regard to establishing anchoring capabilities in terms of ductility, potential tensile and shear capacities, reliability and application method efficacy. Conclusions to date are as follows: (1) microcrystalline waxes fail in a ductile manner that is preferable to other waxes, (2) there is a wide variety of possible performance levels in both tension and shear, depending upon brand and application method. Generally, hot application provides a superior load carrying capacity and a more consistent result, but is not adopted presently by the conservation community because of logistical matters with respect to wax placement, particularly since it is often used for during the rapid deployment associated with temporary exhibits.

Amongst the tested products, Multiwax consistently gave the highest tensile (183 kPa) and shear results (42 kPa under 50 kPa normal load), except under the higher load normal load, when the wax was cold applied with the resin; failure to generate significantly higher shear capacities under substantial increases in normal load is a phenomenon identified in this study as a potential difficulty that needs further investigation. What was definitively shown in the tests conducted was that coating improves wax capacity, which should encourage the use of the resin in conjunction with microcrystalline waxes as an anchor material, to prevent staining and damage to art objects, as well as to increase capacity.

Because of the wide range of results between products and the various application methods, a product should not be used without some testing and without a clear understanding of how it will be applied. Adoption of a simplified testing regimen can be useful as an indication of relative capacity with respect to the above-published results. A comparison of these simplified tests in this study show that simplified tests can predict shear results within 10%. Although not as successful in predicting tensile capacity, these tests can provide a good basis for a preliminary assessment, when conservators are confronted with a new commercial wax.

Despite the acknowledged success of microcrystalline waxes in the protection of art objects from seismic events, these products are used presently with little guidance as to the optimal application method and expected capacities. The results presented herein begin to fill a gap in conservation knowledge as to the behavior of these waxes based on physical criteria of tensile and shear capacity, reliability, and ductility, irrespective of application method. The results give a higher level of confidence in the use of microcrystalline waxes for the seismic protection of art collec-

tions and supports continued usage, but further study is required to establish a definitive correlation between static tests and actual dynamic loadings.

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