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**PAPER TYPE: Testing and Evaluation Journal**

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## **Sample Preparation and Testing Methods for the Evaluation of 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. Unfortunately, because of the high porosity of some ceramics and the fragility of their glazes and paints, the surface of many art objects may be vulnerable to damage from the microcrystalline wax. Thus, a conservative application approach is needed – applying only as much as is actually required for predicted levels of ground movement. Determining this quantity and verifying the best application technique (e.g. hot versus cold) has yet to be established. This paper presents the development of testing techniques to optimize the application of microcrystalline waxes, specifically, the pioneering of tensile and shear sample preparation. These procedures were applied to 70 tensile and 175 shear tests on paraffin wax, beeswax, and 4 microcrystalline waxes. Static testing methods demonstrated the clear superiority of certain products and average performance capabilities of up to 167kN/m<sup>2</sup> in tension and 89 kN/m<sup>2</sup> in shear under light loading.

**KEYWORDS** Seismic Protection, Art Objects, Museums, Microcrystalline Wax, Tension, Shear, Thermoplastic Acrylic Resin

### **Introduction**

Protecting art objects from ground movements has long been a concern for art collections located in earthquake-prone regions.<sup>1-12</sup> The potential financial losses under such circumstances are significant. A survey following the 1989 Loma Prieta earthquake of 8 museums in the San Fran-

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cisco 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.<sup>13</sup> 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),<sup>1</sup> 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 a widely applicable intervention method has been difficult. One popular method is the application of wax to the bottom of ceramic and glass objects.<sup>1-3,9</sup> The approach is attractive, because the wax is inexpensive, theoretically reversible, and does not impede the visitor's view (Fig.1). The most common materials used for this purpose are microcrystalline waxes.

Microcrystalline waxes, like paraffin waxes are by-products of petroleum processing. The crystal structure of the microcrystalline waxes is needle-like and smaller than that of paraffin, which has a plate-like crystal structure. The microcrystalline waxes also contain higher proportions of iso- and cyclo-alkanes than paraffin waxes, which causes the microcrystalline waxes to be more malleable and adherent than the paraffin ones.<sup>14</sup> Paraffin and other candle waxes are not regularly used for this application. As will be demonstrated as part of the testing results, they do not possess the requisite ductility.

Despite the documented success of microcrystalline wax against seismic activity,<sup>1</sup> there are risks associated with its application. The high porosity of some ceramics and the composition of some glazes and paints make certain ceramics vulnerable to surface damage from the wax.<sup>9</sup> The

high porosity of some ceramics and the level of adherence of some glazes and paints make certain ceramics vulnerable to surface damage from the wax through a number of mechanism including staining due to the physical embedding of wax into a porous surface or its migration into the porous substrate (like oil, or silicone, etc.) or physical damage due to the loss of surface material. As a direct reflection of the multitude of ceramic materials and finishes conditions involved, prediction of such vulnerability to wax-generated damage is not easily assessed. Consequently, there needs to be a conservative approach in the application of the wax – minimizing the quantity applied to match the calculated, anticipated need. To date there is no independent or manufacturer-provided guidance as to the most effective method of wax application or the required quantity of wax needed to resist a specified amount of tensile and/or shear force. The methods described in this paper were essential for an initial determination of such guidance. This work was done at the behest of the J. Paul Getty Museum, Department of Antiquities Conservation.

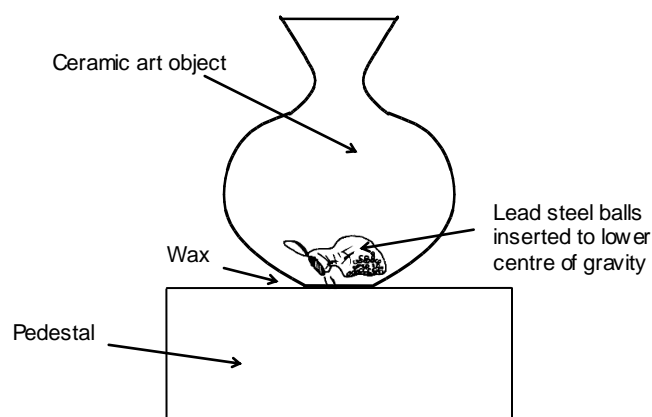


FIG. 1— *Typical set up of wax protection*

## Background

The San Francisco Bay-area survey of 8 museums taken 4 days after the 1989 Loma Prieta earthquake concluded, “The first and most striking observation was that prevention does work.”<sup>1</sup> This statement was made with respect to a wide variety of prevention methods including the use of microcrystalline wax, which was generally considered highly effective, although some failures occurred.<sup>1</sup>

The current state of practice employs the hand placement of small balls of wax, at room temperature, to the underside of an art object. Although the wax can be applied directly to the art object, there is often the pre-application of a thermoplastic acrylic resin, also known as an acrylic copolymer (often used in a solvent solution), as a protective coating. The resin has the functions of acting as a consolidant, a protective coating and as an adhesive. Under some limited testing conditions, the resin has been shown to prevent both wax-generated staining and loss of surface material.<sup>9</sup> The preferred product is Paraloid B-72, a methylacrylate copolymer.<sup>15</sup> Paraloid B-72’s advantages over traditional polyvinyl acetate resins include reversibility, strength and hardness without brittleness, and improved durability.<sup>16</sup>

In studying Paraloid B-72 as an adhesive for Sivic marble, Podany and associates<sup>16</sup> tested bar- and rod-shaped butt-joints in accordance with ASTM Standard Test Methods for Tensile Strength of Adhesives by Means of Bar & Rod Specimens (D 2095) and for Pentellic marble with ASTM Standard Test Methods for Apparent Shear Strength of Single-Loop-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal to Metal) [D 1002]. Podany and associates<sup>16</sup> concluded that the application of a Paraloid B-72 acetone barrier provided sufficient tensile and

shear capacity for most self-weight loading, if the barrier is thin and fully dried, before the application of a second adhesive.

The above investigation established the probable beneficial role of applying Paraloid B-72, but determining the specific tensile and shear capacities for the microcrystalline waxes themselves was problematic: no standardized tests for 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 testing sample. To this end, standardized procedures for tensile tests on metal and shear tests on soil were altered to develop reliable testing procedures for the waxes.

### **Experimental Program**

To develop good practice guidelines for the application of microcrystalline waxes for the protection of art objects from ground movements, a series of 70 tensile and 175 shear tests were conducted. Six waxes were studied. Beeswax (B) and paraffin (P) were considered, in addition to four microcrystalline waxes: Multiwax (M), Secure Wax<sup>TM</sup> (S) Quake Hold<sup>TM</sup> (Q), and Earthquake wax (E). The first three of the microcrystalline waxes were commercial products obtainable in the United States, Multiwax and Secure Wax<sup>TM</sup> from Adhesives and Consolidants<sup>17</sup> and Quake Hold<sup>TM</sup> from Conservation Tools, Equipment & Supplies.<sup>18</sup> The fourth was provided by the J. Paul Getty Museum, Department of Antiquities Conservation as a product being used in Dolmabahce Place in Istanbul, Turkey (Table 1). The non-microcrystalline waxes were included as points of comparison to enhance the understanding of the importance of specific industrial processing and chemical composition on wax behavior.

In addition to the tensile tests, two sets of shear tests were conducted: one to shear through the material and the other to assess a wax/display case interface, shear capacity. As described in the following sections, samples were prepared by two means, except the inherent shear tests which had no interfaces in need of multiple preparation methods. The first involved casting melted wax into the desired form. The other employed compaction (as described in the sample preparation section below), to achieve the desired specimen geometry. For the tensile tests, the melted specimens were cast directly onto testing the platen, which had wax removed by heating and was degreased using liquid soap. For the interface shear tests, some of the melted specimens were cast directly onto the testing face, while others were melted into a mold and cold applied. Surfaces were cleaned according to procedures developed for the tensile tests. The Paraloid B-72 resin coating was applied to some of the tensile and shear interface specimens (Fig. 2).

TABLE 1—Testing variables

Wax Type	Preparation	Application	Coating
Beeswax	B Compacted	C Hot	H Resin Coating R
Paraffin	P Melted	M Cold	C No Resin Coating N
Multiwax	M		
Secure Wax <sup>TM</sup>	S		
Quake Hold <sup>TM</sup>	Q		
Earthquake	E		
All	A		

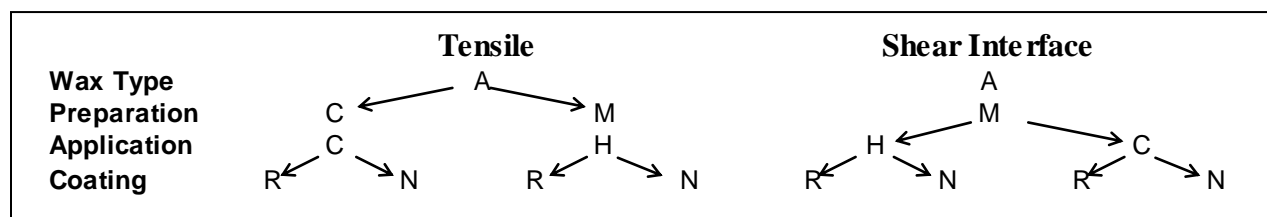


FIG. 2—Testing regimen

## Tensile Testing

A total of 70 tensile tests were performed. Critical to this outcome was the creation of repeatable test specimens in terms of full platen coverage and consistent thickness, both across the platen and between specimens.

### *Specimen Preparation*

Tensile test specimens were made using both compacted and melted preparation methods and were tested both with and without the application of the Paraloid B-72 coating.

*Compacted Preparation*—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. Unfortunately, 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. A 10g ball of wax was hand-rolled at room temperature and placed on the bottom platen (Fig. 3b). The wax was then compressed between the two platens using a compression machine (Fig. 3c), until the height was reduced to 2mm. The 10g of wax generated full coverage of the platen, without excess material emerging from around the sides of the platens. Unfortunately, due to the higher stiffness of most of the waxes, consistent sample preparation using this compaction method was only achievable with Secure Wax<sup>TM</sup>. The other waxes failed to produce even coverage across the platen, irrespective of the quantity of force applied or the quantity of material used.



*3a Compaction preparation*



*3b Compression machine*



*3c Melted preparation*



*3d Modified Instron 4411 Machine™*

FIG. 3— *Tensile testing*

*Melted Preparation*— Using an aluminum receptacle in a double boiler, 14g of wax were melted over a medium heat until liquefied. The liquefied wax was poured across the entirety of the bottom platen [using a collar of modeling clay to prevent wax overflow and to ensure a consistent specimen height (Fig. 3d)]. 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 specimens were left to solidify for a minimum of 16 hours prior to testing. The quantity of 14g of wax was established experimentally, as the minimal amount needed to re-

peatedly achieve full platen coverage (with a 2mm thickness), as a small amount of loss occurred in the transfer from the melting container to the platen.

*Coating*— The Paraloid B-72 coating was prepared in a screw top beaker using 100g of acetone, 0.1g of fumed silica, and 8.5g of Paraloid B-72 crystals, 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,<sup>19</sup> except for the weight:volume ratio. Using a paintbrush, the coating was applied over the entirety of the bottom platen and left for 5 minutes for complete drying. Otherwise, coated samples were prepared as described in the above sections.

### *Testing Equipment*

To determine a worst-case scenario for the tensile capacity, the wax was tested against a pair of specially machined 74mm diameter stainless steel platens (Fig. 3d). 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<sup>TM</sup> was altered with specialty connectors to accommodate these platens (Fig. 3d).<sup>20</sup> The samples were subjected to a 50N load at a crosshead speed of 0.5 mm/min.

### *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 (EN 10002-1)<sup>21</sup> and ASTM Standard Practice for Verification of Specimen Alignment Under Tensile Loading (E 1012). Table 2 summarizes the differences between the specified and the developed procedures.

TABLE 2—Tensile testing procedure comparison

Testing Parameter	EN 10002-1	ASTM E 1012	Wax Procedure
Properties measured	Load Extension	Strain	Load
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

### *Major Results*

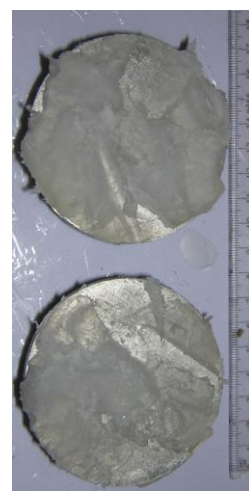
Three failure types were observed: adhesion (Fig. 4a), mixed (Fig. 4b), and cohesion (Fig. 4c). The microcrystalline waxes experienced cohesion or mixed failures (Fig. 4), while the beeswax and paraffin wax exhibited adhesion failures. The adhesion failures were brittle failures, thus emphasizing the superior characteristics of microcrystalline waxes for seismic protection of museum objects over paraffin wax or beeswax.



*4a Adhesion failure*



*4b Mixed failure*



*4c Cohesion failure*

FIG. 4— *Tensile failures*

As summarized in Table 3, the microcrystalline waxes tested using the melted preparation procedure without a resin coating exhibited a wide performance range – ranging from an average low of 37.67 kN/m<sup>2</sup> (Secure Wax<sup>TM</sup>) to an average high of 167.33 kN/ m<sup>2</sup> (Multiwax) [a 344% difference]. When the Secure Wax<sup>TM</sup> was tested using a compacted (instead of melted) preparation method, the results were more than twice as strong, but still at least 30% less than that of any of the other microcrystalline waxes prepared with the melting method. Since only the Secure Wax<sup>TM</sup> could be tested using a compacted preparation method, the question remains unanswered, whether the performance trend for this wax is indicative of the other products. If so, the results from the melted preparation method samples could be considered as a lower bound for performance. What was, however, clear was that in tests without the resin coating, the Multiwax was the best performer. Not only did it exhibit the highest tensile strength, it also had a coefficient of variation of only 0.02 for these tests, which was more than an order of magnitude less than all other products.

Similar trends were shown for the resin-coated samples. The Multiwax had an average tensile strength of 193.50 kN/m<sup>2</sup> (a 187% increase over the lowest strength microcrystalline wax), but the coefficient of variation was an order of magnitude higher and now similar to the other materials; the transparency of the coating may have contributed to lower quality control during sample production. The microcrystalline waxes with coating had on average 7% more tensile capacity than those without coating, except the Earthquake wax, which experienced a 58% decrease in strength. As such, the capacity related benefit of the Paraloid B-72 in tensile loading was only marginal.

TABLE 3—Tensile results

Wax type	Preparation	Application	Coating	Average <sup>a</sup> kN/m <sup>2</sup>	SD kN/m <sup>2</sup>	COV %	Max. kN/m <sup>2</sup>	Min. kN/m <sup>2</sup>
Beeswax	Melted	Hot	Resin	61.00	3.16	5.18	66	57
			No resin	47.50	14.45	30.42	59	21
Paraffin	Melted	Hot	Resin	79.00	59.78	75.67	192	30
			No resin	60.00	14.21	23.68	82	44
Multiwax	Melted	Hot	Resin	193.50	40.37	20.86	239	136
			No resin	167.33	3.67	2.19	172	161
Secure Wax <sup>TM</sup>	Melted	Hot	Resin	108.00	20.39	18.88	129	79
			No resin	37.67	15.23	40.43	64	21
	Compacted	Cold	Resin	121.50	10.09	8.30	140	112
			No resin	89.17	17.59	19.73	123	76
Quake Hold <sup>TM</sup>	Melted	Hot	Resin	142.00	33.05	23.27	164	104
			No resin	111.00	50.41	45.41	155	56
Earthquake	Melted	Hot	Resin	68.00	32.53	47.84	91	45
			No resin	160.00	80.61	50.38	217	103

<sup>a</sup> The results in this table are all based on 6 tests, except for Quake Hold<sup>TM</sup> wax for which there were only 3 tests and Earthquake wax for which there were only 2.

## **Inherent Shear Testing**

A total of 55 inherent shear tests were performed. These determined the shear strength of the material within its own mass. Critical to this outcome was the creation of repeatable test specimens that could be used for determining the inherent shear capacity of the material, as well as the shear capacity of the material at its interface with a display case.

### *Specimen Preparation*

To accommodate constructability issues and facilitate sample production, a mold was created in which to cast all melted wax samples (both those used for inherent shear capacity testing and those for the interface tests – see below). The mold had to be sufficiently rigid, reusable, and easy to remove, 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<sup>TM</sup> (a plastic wrap) proved effective (Fig. 5).

For the inherent shear specimens, all samples were melted and then tested when at room temperature. To achieve this, 50g of were melted as previously described. The liquefied wax was then poured into the cardboard, shear mold (Fig. 5). The cast wax was left to solidify for 16 hours, after which the mold was removed, and the wax was cut into 5 individual 20 x 20 x 25mm samples.

As the microcrystalline waxes are applied cold in practice, another set of inherent shear capacity tests were conducted. These specimens were achieved by compacting the wax into the mold as follows. At room temperature, 50g of wax were taken and evenly divided into 20 pieces of 2.5g each. One at a time, each piece was compressed by hand and then by hammer into the mold, to minimize seam development. This procedure was repeated until the mold was full; the compacted pieces were placed perpendicular to shearing plane. The mold was then removed, and the wax was cut into 5 individual 20 x 20 x 25mm samples, identical in appearance to those that were cast. The samples were ready for immediate use.

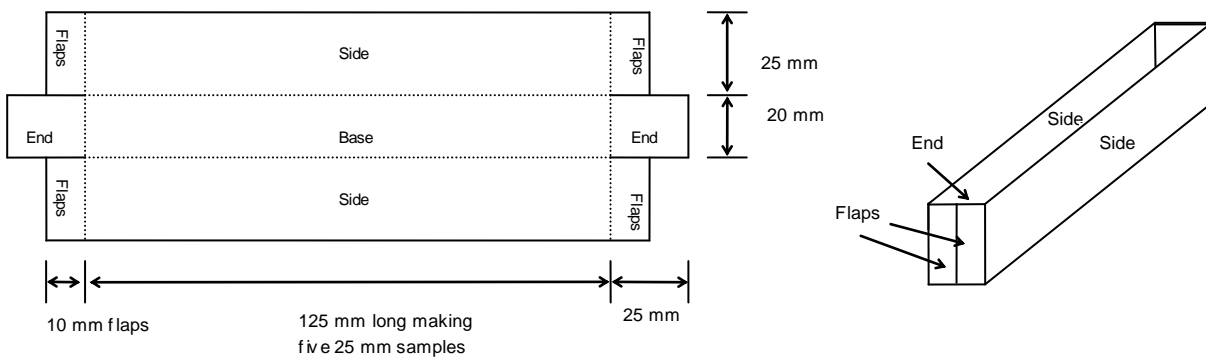


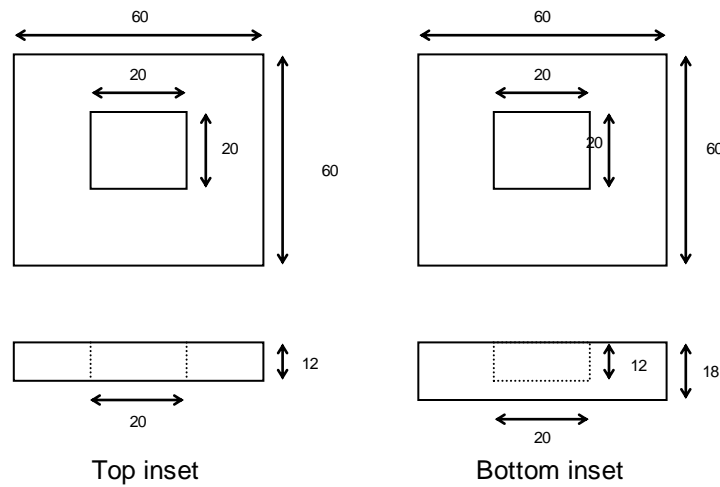
FIG. 5— *Shear mold*

### *Testing Equipment*

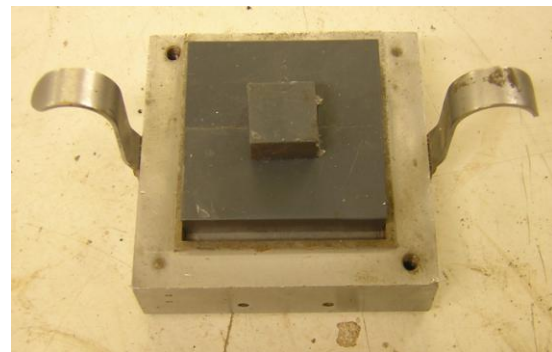
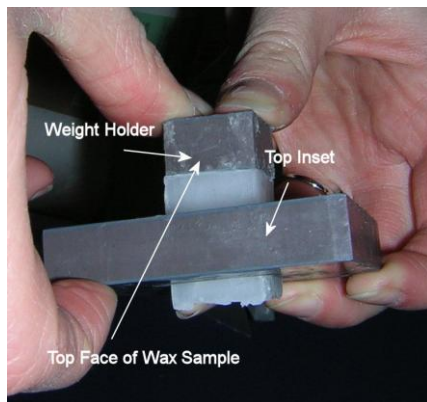
Inherent shear tests were conducted in a standard shear box apparatus according to British standard BS 1377:Part 7:1990.<sup>22</sup> The only part of the equipment that was modified was the shearing area. This was done to accommodate the limited amount of material available for testing. The shearing area was reduced from the standard 60mm x 60mm to a surface area of 20mm x 20mm, thus the sample sizes listed in the above section. There was no change in the original 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). The surface area reduction was necessary to accommodate a highly limited amount of one of the samples. For other testing regimens, this alteration should not be 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 and then placed in the bottom inset (Fig. 6b) and then inserted into the apparatus (Fig. 6c). The rate of horizontal displacement was 0.025mm/s. Readings of vertical displacement and loads were recorded at every 0.01m increment of horizontal displacement.



6a PVC insets for the shear box apparatus



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

FIG. 6— Shear testing

### Testing Protocol

For inherent shear testing protocol the British Standard Methods of Test for Soils for Civil Engineering Purposes – Part 7: Shear Strength Tests (Total Stress)[BS 1377]<sup>22</sup> and ASTM Standard Test Method for Direct Shear Tests of Soils Under Consolidated Drained Conditions (D 3080) were considered. Table 4 highlights the differences between the standards and the developed shear

testing. One major difference was the change in vertical force (50kpa and 235kpa). These forces were selected to represent two classes of art objects: small ones and medium ones. Five specimens of each of the waxes were tested at both normal loads.

TABLE 4—Shear testing procedure comparison.

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

### *Major Results*

The inappropriateness of paraffin wax and beeswax for the seismic protection of art objects wax was again confirmed. Despite their ability to withstand 400% more inherent shear stress than the microcrystalline waxes, they regularly exhibited the same brittle failure mechanism as demonstrated under tensile loading (Fig. 7).



*7a Brittle*

*7b Ductile*

FIG. 7— *Failure modes in inherent shear tests*

Of all the microcrystalline waxes, Multiwax exhibited the highest inherent shear strength – 150.54 kN/m<sup>2</sup> at 50kpa normal force (Table 5) and 182.96kN/m<sup>2</sup> at a 235kpa normal force (Table 6). At 50kpa, the Multiwax was 336% stronger than the Secure Wax<sup>TM</sup>, the poorest performing microcrystalline wax. At 235kpa the difference was similar, 400% between Multiwax and Secure Wax<sup>TM</sup>, the poorest performing microcrystalline wax. The Multiwax also had the lowest COV of the microcrystalline waxes.

In a trend that deviated from that of the tensile results, the inherent shear strength of the compacted form of Secure Wax<sup>TM</sup> was 58% less than its melted form under a 50kpa normal force and 13% less under a 235kpa normal force. Theoretically, the two sample preparation methods should have generated the same results in the inherent testing arrangement. The difference in results would indicate that there may be uncertainties introduced into the testing scheme by the use of a compacted sample. Microcrystalline waxes generated an average of a 126% increase in shear strength with a 470% increase in normal load.

TABLE 5—Inherent shear results for 50kN/m<sup>2</sup> normal force

Wax Type	Preparation	Application	Coating	Average kN/m <sup>2</sup>	SD kN/m <sup>2</sup>	COV %	Max. kN/m <sup>2</sup>	Min. kN/m <sup>2</sup>
Beeswax	Melted	Cold	No resin	254.41	107.56	42.28	437.78	169.33
Paraffin	Melted	Cold	No resin	775.61	180.10	23.22	1042.83	598.85
Multiwax	Melted	Cold	No resin	150.54	27.79	18.46	175.53	104.28
Secure Wax <sup>TM</sup>	Melted	Cold	No resin	23.75	6.77	28.51	30.98	16.52
	Compacted	Cold	No resin	9.95	1.72	17.29	11.98	7.23
Quake Hold <sup>TM</sup>	Melted	Cold	No resin	94.16	40.48	42.99	140.42	47.50
Earthquake	Melted	Cold	No resin	61.54	35.83	58.22	98.09	16.11

TABLE 6—Inherent shear results for 235kN/m<sup>2</sup> normal force

Wax Type	Preparation	Application	Coating	Average kN/m <sup>2</sup>	SD kN/m <sup>2</sup>	COV %	Max. kN/m <sup>2</sup>	Min. kN/m <sup>2</sup>
Paraffin	Melted	Cold	No resin	873.91	67.96	7.78	980.88	795.03
Multiwax	Melted	Cold	No resin	182.96	56.56	30.91	239.54	88.80
Secure Wax™	Melted	Cold	No resin	35.93	33.92	94.41	94.99	8.26
	Compacted	Cold	No resin	31.39	29.40	93.66	82.60	8.26

## Interface Shear Testing

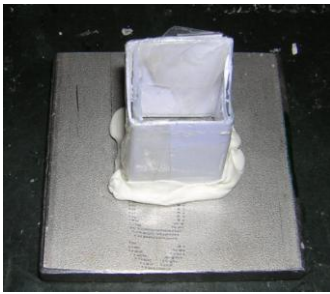
Although the inherent shear capacity of the wax was important to establish, the wax to surface interface capacity was considered more likely to control the failure in the actual application. To this end, 120 samples were tested in an arrangement that was designed to represent a lower bound solution by 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 smooth or highly polished.

### *Testing Equipment*

As with interface testing, interface shear tests were conducted in the same basic shear box apparatus. 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 part 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 and readings of vertical displacement and the load were identical to those applied for the inherent shear tests.

### *Specimen Preparation*

All melted interface tests required 60g of wax, which were melted as previously described. For those that were melted and then hot applied without coating, the liquid wax was poured into the modified shear mold, which was then placed directly onto the steel plate; modeling clay was used at the mold/plate interface to create a barrier to prevent wax outflow (Fig. 8a). The specimen was left to solidify for 16 hours, after which the mold was removed, and the sample was ready for testing.



*8a Hot wax mold*



*8b. Cold wax/shear plate placement*



*8c Coating the shear plate*

**FIG. 8— *Shear testing preparation***

For compacted, cold applied samples, the specimens were prepared using the same procedure as for the compacted specimens for the inherent shear test (Fig. 5), except that the wax samples were larger -- cut into 10 separate 20 x 20 x 15mm sized samples. The samples were pressed firmly onto the steel plates (Fig. 8b) and were ready for immediate testing.

For all samples tested with a resin coating, a layer of Paraloid B-72 was prepared and applied as previously described (Fig. 8c). In this testing regimen, the combination of a hot applica-

tion with coating was not pursued because of the ability to successfully generate cold applied samples.

### *Testing Protocol*

Testing protocol was adapted from the standards BS 1377 (TC 1990) and ASTM (D3080) as described for inherent shear testing with one additional adjustment to the apparatus, shear box height was reduced from the standard 32mm to 18mm by methods explained above in testing equipment. Applied forces were those as described in the inherent shear tests. Like the inherent shear tests, five specimens were tested for each of the waxes at both normal forces.

### *Major Results*

The failure mechanism were similar to that displayed in the inherent wax testing, with the paraffin wax and beeswax showing brittle failures and the microcrystalline ones being ductile. Of the non-coated samples tested at the lower 50kpa of applied normal force, the highest average interface shear capacity of the microcrystalline waxes was with a melted preparation, hot application. This was Multiwax at 88.8 kN/m<sup>2</sup>. The result was 357% stronger than the weakest microcrystalline wax (Quake Hold<sup>TM</sup> at 19.41 kN/m<sup>2</sup>) and 261% stronger than the Multiwax, when cold applied (Table 7). Unfortunately the COV was the highest at 0.54. Of note is that this high COV was generated in a no coating testing arrangement. Of the melted, cold applied samples, the Multiwax was the best at 24.57 kN/m<sup>2</sup>, a 213% increase over the poorest performing wax, Secure Wax<sup>TM</sup>. This melted, cold applied arrangement was felt to most closely represent the current state of practice.

TABLE 7—Interface shear results at the lighter force of 50kN/m<sup>2</sup>

Wax Type	Preparation	Application	Coating	Average kN/m <sup>2</sup>	SD kN/m <sup>2</sup>	COV %	Max kN/m <sup>2</sup>	Min kN/m <sup>2</sup>
Beeswax	Melted	Cold	Resin	21.87	12.41	56.74	42.33	10.02
Paraffin	Melted	Cold	Resin	31.31	17.82	56.91	62.98	21.68
Multiwax	Melted	Hot	No resin	88.80	47.85	53.89	148.68	49.56
		Cold	Resin	35.81	33.32	93.05	94.99	14.87
			No resin	24.57	10.67	43.43	38.20	9.29
Secure Wax™	Melted	Hot	No resin	19.62	2.31	11.77	22.72	16.52
		Cold	Resin	32.63	7.40	22.68	42.33	22.72
			No resin	11.54	1.45	12.56	13.42	9.91
Quake Hold™	Melted	Cold	Resin	54.78	9.60	17.52	65.78	40.01
			No resin	28.70	6.75	23.52	38.20	20.65
		Hot	No resin	19.41	8.43	43.43	28.91	7.23
Earthquake	Melted	Cold	Resin	31.80	8.98	28.24	43.37	19.62
			No resin	19.62	3.10	15.80	24.78	16.52
		Hot	No resin	59.68	26.12	43.77	99.12	29.94
		Cold	Resin	22.92	12.14	52.97	41.30	7.23
			No resin	24.86	9.10	36.60	37.17	12.39

Secure Wax™ compacted and applied cold had an average interface shear strength 150% higher than when melted and applied cold, however, compacted samples also had nearly double the coefficient of variation (0.24 versus 0.13) [Table 7].

What differed significantly in the interface shear tests, compared to the tensile ones, was the impact of the resin. The final performance of the three American microcrystalline waxes in the melted, cold applied arrangement with the coating became nearly identical. The Multiwax was the leader at 35.81 kN/m<sup>2</sup>, but the other two were within 10%. The COV of the samples, however, on average nearly doubled. Also, the improvement trend did not hold true for the Earthquake wax, which experienced an 8% decrease, similar to that seen in the tensile testing. The probable cause of this divergent trend is a negative chemical reaction between the Earthquake wax and the Paraloid B-72 coating.

As shown in table 8, under a 235kpa normal force, Multiwax also had the highest interface shear capacity, when hot applied without a coating—108.21kN/m<sup>2</sup>, a 240% increase in strength from the poorest performing microcrystalline wax (Secure Wax<sup>TM</sup> 31.8kN/m<sup>2</sup>). Also, Multiwax again had the highest coefficient of variation (0.39), when melted and cold applied with coating), although this variability was directly comparable to that of the other materials. Overall microcrystalline waxes generated 138% higher shear strengths under a 470% increased normal force. As a final observation, the average inherent shear capacities of the microcrystalline waxes were over 300% higher than their average interface shear capacities (Fig. 9).

TABLE 8—Interface shear results at the heavier force of 235kN/m<sup>2</sup>

Wax Type	Preparation	Application	Coating	Average kN/m <sup>2</sup>	SD kN/m <sup>2</sup>	COV %	Max kN/m <sup>2</sup>	Min kN/m <sup>2</sup>
Beeswax	Melted	Cold	Resin	13.66	4.96	36.31	19.88	8.05
Paraffin	Melted	Cold	Resin	9.42	1.29	13.69	11.36	8.26
Multiwax	Melted	Hot	No resin	108.21	48.09	44.44	161.07	51.63
		Cold	Resin	76.01	29.77	39.17	123.90	42.33
			No resin	58.47	9.49	16.23	67.11	42.33
Secure Wax <sup>TM</sup>	Melted	Hot	No resin	31.80	8.31	26.13	43.37	22.72
		Cold	Resin	16.44	5.36	32.60	24.78	10.33
			No resin	7.43	4.22	56.80	12.39	3.10

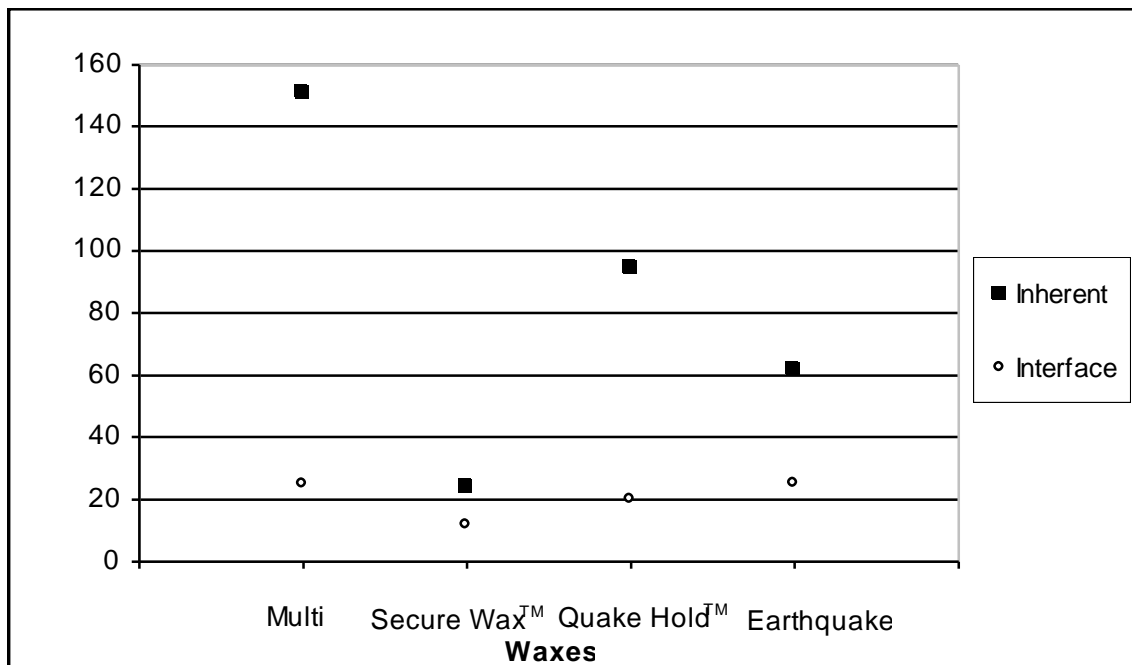


FIG. 9— *Inherent versus interface results for the microcrystalline waxes*

## Conclusions

By modifying traditional tensile and shear tests for other materials, experimental procedures to establish fundamental tensile and shear behavior of wax could be established. Although the testing procedures developed did not fully reflect the current application methods in industry, consistent specimens could be generated and the tests could reliably be conducted in a manner that a superior product was identifiable and its expected performance largely quantified (up to 164 kN/m<sup>2</sup> in tension and 89 kN/m<sup>2</sup> in shear). As the tests conducted under this program were static, the results should be indicative of performance expectations, but definitive values should be applied directly to dynamic loading conditions with care.

The other major findings were that paraffin wax and beeswax were confirmed to be inappropriate for seismic protection of art objects due to their brittle failure mechanisms. Hot (versus

cold) application with no coating of microcrystalline waxes resulted in a 261% higher interface shear capacity in most waxes. Compacted shear samples produced inconsistent results compared to those that were melted. Across all shear testing, capacity increased at a rate of 65% of the applied normal force. Although the application of the resin prior to the introduction of the microcrystalline wax had only a marginal effect on tensile strength (7% average increase) of the microcrystalline waxes, it had a substantial effect on the interface shear strength (50% average increase), along with an affiliated increase in the coefficient of variation of 77%. Therefore, selection of design capacity levels needs to be considered in relation to these two competing factors.

The specimen production methods for tensile and shear testing presented in this paper proved effective in establishing clear performance trends and ranges of capabilities amongst six different waxes. The establishment of these procedures permit the future development of full dynamic testing methods to definitively establish expected performance capabilities for the seismic loading of art objects being protected by microcrystalline waxes.

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