A look at the structural requirements of consolidation adhesives for easel paintings

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Introduction

Successful conservation treatments are a combination of a carefully planned action together with the accurate selection of materials and methods. Such an apparently obvious statement necessarily implies:

- Identifying the nature of the damage.
- Analysing what caused the damage.
- Understanding the failure mechanism that has taken place.
- Determining (and prioritising) the needs.
- Selecting the most appropriate methods and materials.

In this sequence chemical, physical, mechanical and biological processes are usually involved. In the case of paintings, in addition to the chemical reactions responsible for the ageing and degradation of artworks, the mechanical and dimensional properties of the different materials determine how paintings behave structurally, how the different materials of the composite structure interact with each other and how such properties change in time, both as the painting ages and as a function of environmental oscillations.

Polymers are used widely in many conservation treatments to strengthen, adhere and protect. Factors such as their composition, molecular weight, glass transition temperature (T_g), strongly determine their viscosity, film-forming properties and long-term chemical stability, which clearly influences their suitability for each specific treatment. This paper focuses on some structural issues of adhesives and consolidants in painting conservation as well as the cohesion and adhesion forces governing their performance. Also discussed are their mechanical properties, their interaction with environmental conditions and how their ability to penetrate determines their role in the context of the painting structure.

Consolidation treatments in easel paintings

Defining the concept

The term 'consolidation' may in one interpretation refer to any treatment consisting of the reinforcement and repair of a damaged support and in another to the re-adhesion of weak and flaking paint to an underlying substrate. Equally confusing is the fact that similar (if not the same) adhesives and solutions have been traditionally used, apparently indiscriminately,
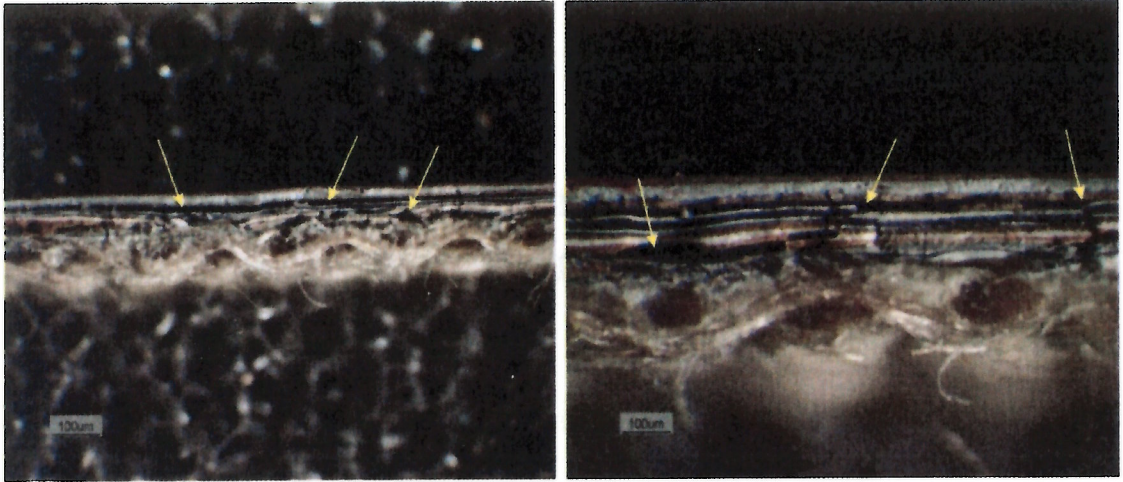
Figure 1 Cross-sections of a typical canvas painting showing evident delamination. The yellow arrows indicate the positions of the voids and, therefore, where the adhesive needs to penetrate. In general, adhesives must penetrate very small pore sizes. It is also clear that some difficulties will be faced to ensure that the adhesive reaches those voids as no cracks are observed on the surface. (Photos courtesy of Melvin J. Wachowiak.)

to line paintings, to consolidate powdery paint layers, to impregnate weak canvases from the reverse or simply to adhere locally delaminated paint fragments. At this point, several questions arise:

- Are the strength requirements for adhesives used to consolidate wood the same as for those used to reattach flaking paint and for those used to impregnate a canvas?
- What are the properties required of adhesives in each case? More specifically, what are the differences between adhesives and consolidants in terms of adhesive and cohesive forces?
- Can, therefore, any adhesive be used as a consolidant?

Examining the behaviour of each layer of a painting as a function of the forces acting inside the composite structure helps to understand that the requirements in each case are not the same.

For canvas paintings, for example, lining and consolidation adhesives have different requirements since they address different needs. Adhesives for lining must present cohesive and adhesive properties whereas consolidating adhesives require adhesion and penetration properties. In the case of linings it is obvious that adhesion is needed to bond a new canvas to a painting. But also, since the main forces acting inside the structure of a traditional painting are usually concentrated in the size layer which acts as the primary support, it becomes clear that cohesive properties are equally desirable in lining adhesives in order to confer cohesion, strength and proper stiffness. Consolidating adhesives also require adhesive strength since paint fragments need to be bonded together. However, it must be noted that the failure of some consolidation treatments may be the result of poor adhesive penetration as well as weak adhesive properties.

Cracks, cleavage, cupping, blisters, flaking and delamination correspond to different failure mechanisms as a consequence of multiple factors, such as the properties of the materials, their ageing, as well as their interaction with environmental agents. Different failure mechanisms determine the location of the damage and how much void any adhesives have to fill (Figure 1). Success also depends on how well adhesives penetrate through the design layers to reach the point where they are really needed.

Defining the structural requirements of consolidating adhesives

To determine the structural requirements of adhesives, a consideration of the cohesive and adhesive properties of materials is required to find answers to questions such as:

- How much strength is required to consolidate powdery paint?
- Should adhesives be stiffer than the paint film?
- Do different solvents determine different mechanical properties for adhesives?
- Why are adhesives that show lack of strength in experimental testing considered to work well in practice?
- What is meant when describing an adhesive as 'working well'?
- Are adhesives reaching the optimum position to be effective or are current consolidation adhesives forming separate layers on top of which paint fragments remain unsecured?

Tests run during the course of this research were devised to determine the cohesive and adhesive behaviour of some of the adhesives currently used as consolidants. The penetration of various adhesives was also tested.

Cohesion is a measure of the mechanical properties of the adhesive itself and reflects the ability of the adhesive alone to develop stiffness and strength. The cohesive test is an excellent way to examine the drying time and the effects of residual solvents. It is also extremely useful in determining the effects of different solvents on the properties of the material. For this purpose, the standard stress–strain test in tension was used.

Adhesion is the material's ability to bond together different materials. Simple 'peel' tests were used in this series of tests. Various materials were bonded together and the resistance in separating the bonded substrates or 'adherents' was used as a measure of the adhesive strength.

Penetration of adhesives is an essential prerequisite for bonding. Both penetration and adhesion rely heavily on several factors that depend on:

- The substrate
  - The substrate's porosity and composition
  - The substrate's surface uniformity
  - The existence of previous coatings applied to the substrate, etc.
- The adhesive
  - Type of polymer
  - Molecular weight and size
  - Glass transition temperature
  - Solvent used for dilution
  - Concentration
  - Adhesive and cohesive strength
  - Dry down, or the loss of volume of the adhesive during drying
  - Drying time
  - Adhesive wetting of the substrate surface
  - Viscosity
  - Thixotropy
  - Application methodology, etc.
- Environmental conditions

This research was intended to determine the pore size that each adhesive is able to penetrate as a function of the solvent and the concentration used. For this purpose, various filter papers with different pore dimensions were used. Alone the filter papers were easily peeled apart by attaching tape to the outer surfaces. If however the papers were first dipped into selected adhesives applied with various solvents at different concentrations, the increased force required to 'split' the paper became a measure of their effectiveness in penetrating different pore sizes.

Some other observations could also be made regarding:

- The effects of solvents on film forming.
- How solvents determine the mechanical properties of a polymer.
- How solvents determine drying times.
- The consequences of residual solvents in the polymer in terms of the strength and stiffness of the resulting film.
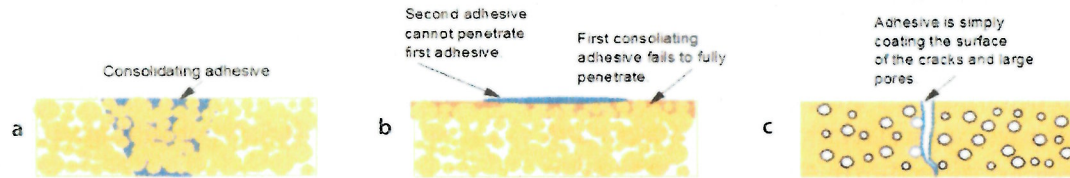
Figure 2 (a) This shows an adhesive that has fully penetrated a porous substrate; (b) this shows that the initial adhesive application can block any subsequent application; (c) this illustrates that the adhesive solution is able to penetrate the substrate but it simply coats the surfaces of the gaps and pores without bridging and bonding the material.

- The pore size that each adhesive can penetrate, depending on the resin, on the solvent and the concentration used.

Porosity, absorbency and penetration

Porosity is a measure of the number and size of pores/voids (empty spaces) in a material and it can also refer to how quickly a fluid can circulate through it: the lower the porosity, the slower the migration of the fluid through the pores. *Permeability* can be considered as a state where the small pores/voids are interconnected so that a fluid can pass from pore (or void) to pore. Both porosity and permeability determine the *absorbency* of a material. Absorbency is the ability of a material to retain a fluid. Generally the larger the particle size of the material, the more porous it is. Large particle-size substrates containing particles with a high surface area will absorb fairly well.

The aim of any consolidation treatment is to make the selected adhesive fully penetrate the paint layer and provide the lost adhesion. Most of the adhesives used in painting conservation set by evaporation of the solvent. Ideally the adhesive in solution or dispersion in water would penetrate the substrate only, the solvent or water would evaporate and the polymer (adhesive) would be left behind as seen in Figure 2a. It has to be taken into account, however, that canvas and the wood of panel paintings are extremely hygroscopic, porous and absorbent materials that tend to

rapidly absorb solvent, thereby increasing the concentration and viscosity of the remaining adhesive, which then tends to block the surface (Figure 2b). It is interesting to note that even though this effect takes place quickly and can be interpreted as a fast-drying adhesive, research has shown that some solvent is retained in the substrate materials for a considerable amount of time.

Many consolidation treatments are intended to bond paint fragments together. The problems to consider range from powdery substrates to big paint flakes. In all cases however, adhesive has to connect the gaps and/or pores that exist in the material. Figure 2c shows an adhesive solution in a concentration that is too low. The solution penetrates the substrate and coats the pore walls without bridging the materials that need to be adhered. The loss of volume of the adhesive during drying (known as 'dry down') also contributes to this effect. Several applications of the adhesive might be necessary in order to provide an effective bond.

Experimental

Materials

In 2007 a survey was conducted in order to collect information on the most common adhesives used for consolidation purposes. The answers received are shown in Table 1 and the substrates selected for bonding tests are specified in Table 2.

Table 1 Adhesives selected for the experimental testing.

Adhesive	Solvent	Solution	Comments
Hide glue	Water	5%	Natural animal glue
Hide glue	Water	10%	
Sturgeon glue	Water	5%	Natural animal glue
Sturgeon glue	Water	10%	
JunFunori	Water	6%	Seaweed (Gloiopeltis)
Acril AC33	–	Undiluted (46%)	Acrylic dispersion based on ethylacrylate + methyl methacrylate
Acril AC33	Water	1:1	
Plextol B500	–	Undiluted (50%)	Dispersion: ethyl methacrylate and ethyl acrylate copolymer
Plextol B500	Water	1:1	
Plextol B500	Xylene	40:60 (w/w)	Dispersion: ethyl methacrylate and ethyl acrylate copolymer
Klucel G	Water	20%	Hydroxypropylcellulose
Klucel G	Water	8%	
Plexisol P550	–	Undiluted (40%)	Hydrocarbon solution of an acrylic polymer
Plexisol P550	Toluene	1:1	Hydrocarbon solution of an acrylic polymer
Aquazol 500	Water	10%	Polyoxazoline: thermoplastic polymers formed by poly(2-ethyl-2-oxazoline)
Aquazol 200	Water		Polyoxazoline: thermoplastic polymers formed by poly(2-ethyl-2-oxazoline)
Beva 371	Toluene	1:1	Ethylenevinylacetate, paraffin, ketone resin
Beva 371	–	Undiluted	Ethylenevinylacetate, paraffin, ketone resin
Paraloid B-67	Acetone		Isobutyl methacrylate polymer
Paraloid B-67	Methanol		Isobutyl methacrylate polymer
Paraloid B-67	Toluene		Isobutyl methacrylate polymer
Paraloid B-72	Different solvents		Methyl methacrylate copolymer
Paraloid B-72	Toluene	25% (w/w)	Methyl methacrylate copolymer
Paraloid B-72	Toluene	50% (w/w)	
Gelvatol	Water	10% (w/w)	Poly (vinyl alcohol)
Gelvatol	Water	20% (w/w)	Poly (vinyl alcohol)
Vinavil 59	–	Undiluted (42%)	Vinyl acetate
Vinavil 59	Water	1:1	Vinyl acetate
Vinavil NPC	–	Undiluted (51%)	Vinyl acetate
Vinavil NPC	Water	1:1	Vinyl acetate
Fluoline HY	–	Undiluted	Copolymer of vinylidene fluoride-esafluoropropene
Fluormet A	–	Undiluted	Fluoroelastomers and acrylic polymers
Elvacite 2044	Toluene	25% (w/w)	N-butyl methacrylate polymer
Elvacite 2044	Toluene	50% (w/w)	N-butyl methacrylate polymer
Elvacite 2046	Toluene	25% (w/w)	Iso-butyl / n-butyl methacrylate copolymer
Elvacite 2046	Toluene	50% (w/w)	Iso-butyl / n-butyl methacrylate copolymer
Akeogard T35	–		Aliphatic polyether-urethane
Akeogard T35	Water	1:1	Aliphatic polyether-urethane
Akeogard T40	–	Undiluted	Aliphatic polyether-urethane
Akeogard T40	Water	1:1	Aliphatic polyether-urethane

Methods and sampling

Tensile tests

The cohesion tests were simple tensile stress–strain tests of samples of pure adhesive cast in thin films on polyester sheets. The rate of loading was 30 seconds between test points and all the samples were equilibrated to the test environment for at least 24 hours prior to testing. The test environments are indicated on the graphs. The testing equipment was a purpose-built group of small tensile devices for measuring thin films in controlled environments. The relative humidity (RH) was controlled using trays of buffered silica gel and monitored using two-stage chilled mirror dew-point meters.

Samples for cohesive testing were prepared by either diluting the adhesive in the solvents listed or using the adhesive as supplied and

Table 2 Substrates selected for the adhesive and penetration testing (original magnification 40×). (Photos courtesy of Melvin J. Wachowiak.)

Substrate	Characteristics		Maximum pore dimension (in μm)	Thickness (in mm)	Adhesive free splitting force (N/cm)
	– Whatman paper is nearly pure cotton and has a known porosity. – It has a fairly soft surface texture.	Whatman #1	11	0.178	0.43
	– It is used as a filter paper and stops particles 11 μm and greater.	Whatman #4	20–25	0.216	0.42
	– The biggest difference between the Whatman #1 paper and the Kraft paper was the fibre size and surface finish.	Whatman #5	2.5	0.216	0.58
	– Brown Kraft paper used for wrapping which has a fairly hard but smooth finish. – Used as a filter paper the brown Kraft paper would trap particles of about 5 μm or greater. – Compared to Whatman paper, Kraft paper had relatively large fibres and was much flatter with a somewhat harder surface.		~5	0.140	0.51
	– Reemay Grade 2250. – Non-woven mat made with spun polyester. – Weight of 19 g/m². – It can be used as an air filter.		–	0.127	–
	– Tara linen. – Medium weight fabric (180 g/m²). – Fine weave of 2.48 yarns per mm in both the warp and fill (weft) directions. – Used in the fill direction as it is stiffer.		–		

pouring it onto a flat and level sheet of polyester film. The concentration used was governed largely by the drying thickness of the film on the polyester. If too thin, the film was too fragile to handle or to be accurately measured for thickness. Increasing the adhesive concentration allowed an increase in the drying thickness of the film. Once initially dried, usually after 30 days or more, the adhesive films were removed from the polyester and cut into sample strips approximately 6–7 mm in width, 150 mm in length and typically 0.10–0.15 mm in thickness.

Peel tests

The basic adhesion test was a simple 'peel' test where the force to separate two adhered sample substrates is measured as illustrated in Figure 3a. The testing equipment was that used for the tensile tests. Since the speed of the peel test is one of the factors influencing adhesion, the tests were conducted at a load rate of 30 second increments between loadings. The displacement rate was 0.0043 cm/sec. All samples were air dried for a minimum of one week prior to testing and tested after equilibrating in the test environments for a minimum of 48
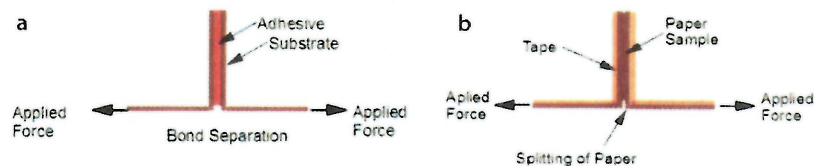
Figure 3 (a) The basic peel test and (b) the use of tape to assist in the splitting of the paper samples.

hours. The RH was controlled using trays of buffered silica gel and monitored using two-stage chilled mirror dew-point meters. Unless otherwise indicated, the test environments were 40–45% RH and 22–23°C.

The substrate materials were typically about 12 mm wide and 125 mm long, and bonded together by submerging them in the adhesive for half of their length and then joining them. Light pressure was used to join them and they were hung and allowed to air dry. For any given sample the length of the bonded substrates was about half of their total length or about 60–70 mm. To start the tests, the samples were peeled apart as far as the bonded section to ensure that only the bonded section was actually measured. For each test a total of about 6.5 mm was peeled apart. To conduct a second test, another section of the sample was used or an entirely new sample was tested. Considering that the substrate surfaces were rather uneven the test results are fairly consistent.

Penetration tests

It was possible to determine the maximum pore dimension that each adhesive was able to penetrate by splitting two papers internally. Figure 3b illustrates the use of tape in assisting in the splitting of the paper samples. Once started, the samples were installed into the micro-tensile testing equipment and the force applied at the same rate as described for the test protocols in the tensile testing section. The force required to separate the papers was measured and recorded in the same manner as that of the adhesive bond test.

Paper splitting controls were determined prior to the application of the adhesives. The range of pore dimensions of this study was

0.0 mm to about 0.025 mm (0–25 μm). For this purpose, different Whatman filter papers (almost 100% cotton and designed to trap particles of certain dimension or larger) and brown Kraft paper (made from pulp fibres) were used. The paper samples were cut in the same direction with dimensions of 6–7 mm in width and 150 mm long.

For testing adhesives, appropriate solutions were prepared and the papers were dipped into the solution for about half their length. Excess adhesive was wiped away and they were hung to dry for a minimum of seven days. Once dry, reinforced packing tape was applied to each side of the sample and the excess tape was cut away from the edges. It was necessary to completely remove the excess tape as any residual tape that stuck to itself at the edges of the sample would have adversely affected the test.

Results and discussion

For this research, natural and synthetic adhesives were tested (Table 1). It should be noted however, that whereas most of them could be tested for adhesion, it was not possible to run cohesive tests for some since no workable free films could be cast. Also, given the length constraints on this paper, results will focus only on some selected natural and synthetic adhesives.

Cohesive testing

This section illustrates the cohesive properties of adhesives, how some change as a function of RH, how solvents affect cohesive properties and how much time they need to evaporate. Figure 4a shows the tensile tests for a 10-year-old hide glue at different levels of RH. In
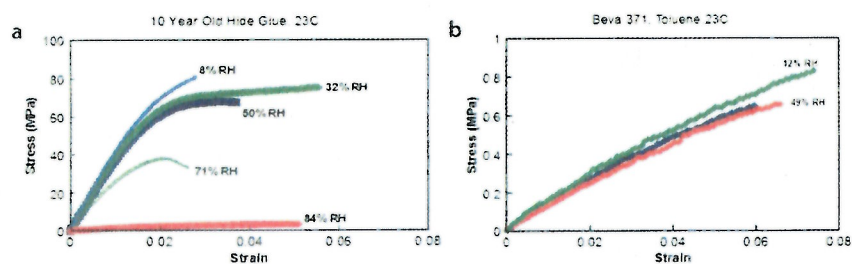
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Figure 4 (a) The stress–strain test results of 10-year-old hide glue (10% solution with water and tested at five different RH levels) and (b) the stress–strain test results of Beva 371 (as supplied) and tested at two RH levels.
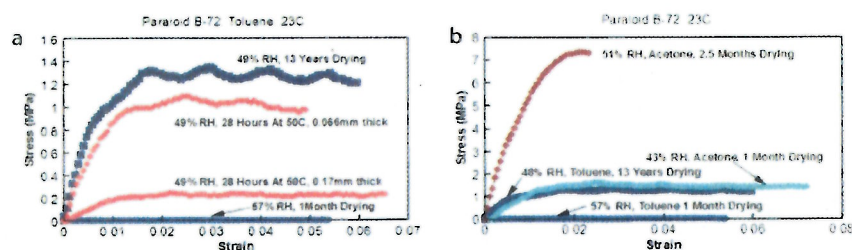

Figure 5 (a) The stress–strain test results of Paraloid B-72 dissolved in toluene after one month, 13 years of drying and being heated to increase the evaporation speed. Different films corresponding to different thickness were also evaluated. (b) The stress–strain test results of Paraloid B-72 dissolved in toluene and acetone after different drying times. In one month the B-72 becomes extremely stiff and brittle.

normal environmental conditions (± 24°C, ± 50% RH), animal glues develop the highest cohesive strengths and stiffness of any of the adhesives tested, far beyond all the synthetic polymers. However, they experience significant changes in their properties as a function of RH. In general, low RH levels make the adhesives become brittle, whereas higher RH (above 80%) cause them to lose nearly all their cohesive properties.

Regarding synthetic adhesives, some are extremely moisture sensitive, such as polyvinyl alcohols, whereas others are not affected by RH, for example, Beva 371 (Figure 4b). The strengths measured vary over two orders of magnitude: from 0.6 MPa in the case of Beva to 68 MPa for animal glues in the same environmental conditions (~50% RH). There are also some adhesives that developed no measurable cohesive strength in normal environmental conditions such as Akeogard T35 and Aquazol 500.

During this research it was also observed that the thickness of the sample had a dramatic effect on its drying time and that in most cases samples needed long drying times before solvents had completely evaporated (thus not influencing testing results). This can be observed in similar stress–strain curves for Paraloid B-72 (Figure 5a). Even after 20 months of drying, Akeogard T35 evidences no cohesive strength at 48% RH. However, it was observed that Akeogard T40 can develop some strength in a relatively short time but still needed around 29 months to allow for full strength development. Similarly, it took 20 months for the water to evaporate from the sample of Klucel G before a reliable stress–strain test could be completed. Independently of the solvent, Plexisol P550 did not develop much strength and still needed considerable time to dry. Interestingly, Aquazol 500 did not present cohesive strength at 52% RH but became brittle at 11% RH. This indicates that lowering the humidity induces a phase change in this material.

From a methodological point of view, it is quite usual to employ volatile solvents in order
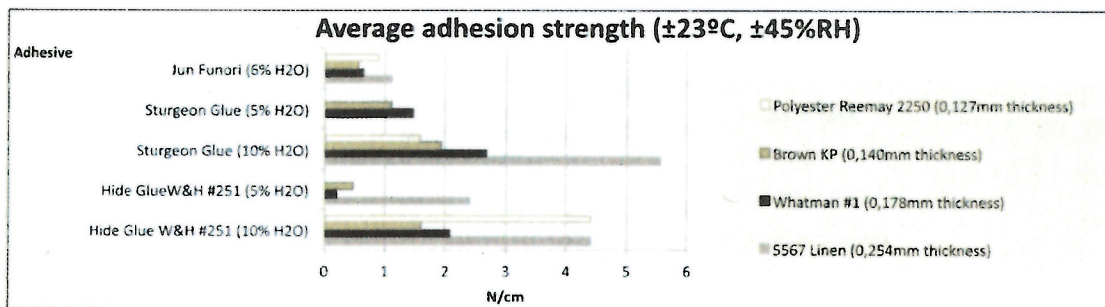
Average adhesion strength (±23ºC, ±45%RH)

Adhesive
- Jun Funori (6% H2O)
- Sturgeon Glue (5% H2O)
- Sturgeon Glue (10% H2O)
- Hide GlueW&H #251 (5% H2O)
- Hide Glue W&H #251 (10% H2O)

- Polyester Reemay 2250 (0,127mm thickness)
- Brown KP (0,140mm thickness)
- Whatman #1 (0,178mm thickness)
- 5567 Linen (0,254mm thickness)

N/cm

Table 3 The average adhesion strength of some natural adhesives diluted in water in different concentrations as a function of the different substrates bonded.

Adhesive	Solvent and solution	5567 Linen	Brown KP	Whatman #1	Polyester Reemay 2250
Substrate		N/cm	N/cm	N/cm	N/cm
Thickness		0.254 mm	0.140 mm	0.178 mm	0.127 mm
Hide glue W&H #251	10% , H O	4.39	1.60	2.06)	4.39
Hide glue W&H #251	5% , H O	2.40	0.49	0.19	–
Hide glue W&H #251	10% , H O 85% RH	1.60	–	–	
Sturgeon glue	10% , H O	5.57	1.94	2.68	1.58
Sturgeon glue	5% , H O	–	1.12	1.47	–
JunFunori	6% , H O	1.10	0.56	0.65	0.88

to speed up drying times. The experiments also showed that different solvents can have dramatic effects on the mechanical properties of a single adhesive. For example, Figure 5b shows the tensile test results of Paraloid B-72 dissolved in either toluene or acetone and allowed to dry for differing lengths of time. While a 13-year-old sample of Paraloid B-72 originally dissolved in toluene has a modest strength of around 1.5 MPa, a sample of Paraloid B-72 dissolved in acetone will reach a strength of about 7.5 MPa after drying for only 2½ months. Furthermore, this material when dissolved in acetone becomes extremely brittle.

Adhesion tests

The preceding section was intended to define some properties of the adhesives tested in terms of their stiffness and strength and how these properties change as a result of the solvents used or changes in ambient temperature and RH. The questions posed at the beginning of this paper also dealt with the fact that some of those adhesives that exhibited a lack of strength in the experimental cohesive testing seem to work well in practice. As has been seen, the levels of strength reached for natural adhesives such as animal glue are over a hundred times the strength development of Beva 371 in the same environmental conditions. Why then are both adhesives used to adhere flaking paint with similar apparent success? What needs to be considered to determine whether in both cases the cohesive and/or adhesive requirements are satisfactory?

The literature rarely refers to the strength required to bond fragments of paint to the underlying support and conservators rarely select adhesives based on their strength. Given that cohesive strength is not always a measure of the adhesive properties, adhesive testing is also required. The bar charts in Tables 3 and 4 clearly show the average adhesion strength of many of the adhesives tested (with a variety of concentrations and in different solvents) as a function of the substrates bonded.
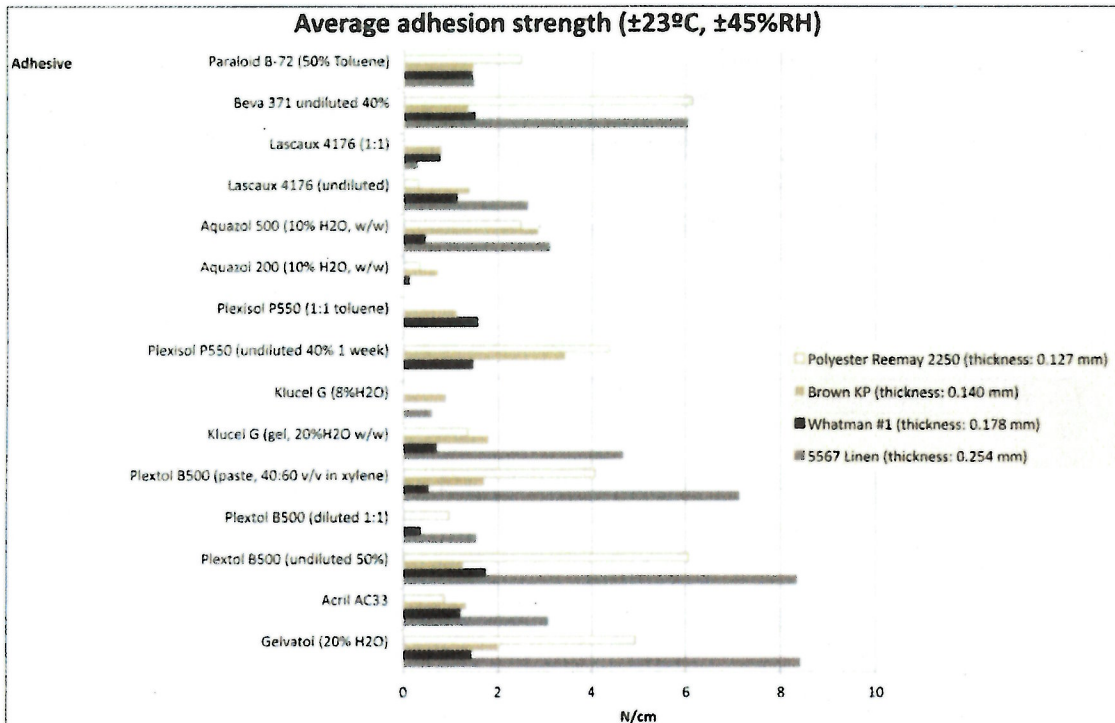
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Average adhesion strength (±23ºC, ±45%RH)

Adhesive

- Paraloid B-72 (50% Toluene)
- Beva 371 undiluted 40%
- Lascaux 4176 (1:1)
- Lascaux 4176 (undiluted)
- Aquazol 500 (10% H2O, w/w)
- Aquazol 200 (10% H2O, w/w)
- Plexisol P550 (1:1 toluene)
- Plexisol P550 (undiluted 40% 1 week)
- Klucel G (8%H2O)
- Klucel G (gel, 20%H2O w/w)
- Plextol B500 (paste, 40:60 v/v in xylene)
- Plextol B500 (diluted 1:1)
- Plextol B500 (undiluted 50%)
- Acril AC33
- Gelvatol (20% H2O)

☐ Polyester Reemay 2250 (thickness: 0.127 mm)
▨ Brown KP (thickness: 0.140 mm)
■ Whatman #1 (thickness: 0.178 mm)
▨ 5567 Linen (thickness: 0.254 mm)

N/cm

Table 4 The average adhesion strength of some synthetic adhesives diluted in different solvents according to different concentrations as a function of the different substrates bonded.

	5567 Linen (thickness: 0.254 mm)	Brown KP (thickness: 0.140 mm)	Whatman #1 (thickness: 0.178 mm)	Polyester Reemay 2250 (thickness: 0.127 mm)
Gelvatol (20% H₂O)	8.4	2.02	1.43	4.94
Acril AC33	3.06	1.32	1.19	0.86
Plextol B500 (undiluted 50%)	8.32	1.27	1.73	6.06
Plextol B500 (diluted 1:1)	1.55	0.73	0.35	0.96
Plextol B500 (paste, 40:60 v/v in xylene)	7.11	1.7	0.53	4.08
Klucel G (gel, 20%H₂O w/w)	4.67	1.8	0.7	1.36
Klucel G (8%H₂O)	0.58	0.88	–	–
Plexisol P550 (undiluted 40% 1 week)	3.09	3.42	1.45	4.39
Plexisol P550 (1:1 toluene)	0.70	1.13	1.58	–
Aquazol 200 (10% H₂O, w/w)	2.18	0.73	0.11	0.36
Aquazol 500 (10% H₂O, w/w)	3.08	2.85	0.45	2.49
Lascaux 4176 (undiluted)	2.63	1.4	1.14	0.32
Lascaux 4176 (1:1)	0.28	0.8	0.74	–
Beva 371 undiluted 40%	6.01	1.38	1.51	6.13
Micro wax	0.052	0.17	0.29	0.43
Paraloid B-72 (50% Toluene)	1.45	1.45	1.42	2.5

Hide glue

- *Linen to linen*: the average peel force per width required to separate linen when bonded with a 10% solution of hide glue is 4.39 N/cm. Considering that 1 newton (N)

corresponds to a weight of about 102 g, it takes a weight of about 448 g/cm to peel linen bonded with hide glue apart. The peel strength developed for that same sample at 85% RH is about 1.60 N/cm when it should have been expected to be a much lower

bond strength given the loss of all cohesive properties at levels of RH above 80% for hide glues. Similarly, the peel force per width for the same linen bonded with the same hide glue but in a 5% concentration is about 2.49 N/cm (slightly more than half of the peel strength of the 10% solution). This reinforces the idea that cohesive tests of an adhesive are not indicative of its bond strength.

- *Linen to polyester*: the average peel strength when using a 10% solution of hide glue to bond linen and polyester mat is identical to the linen even if the tests results show that there is a little more spread in testing. Again, this is surprising since the polyester is non-absorbent and therefore it must be concluded that the bonding mechanism for the hide glue is largely mechanical in that it is surrounding and entangling the textile fibres.

- *Linen to brown Kraft paper*: the force per width needed to split the brown Kraft paper with no adhesive application averages 0.45 N/cm. The 10% hide glue solution and the Kraft paper peel test show average strengths of 1.60 N/cm. This is considerably less than the bond strength of the linen of 4.39 N/cm. A higher paper bond strength might be expected since the paper has a very smooth and porous surface, however the bond strength of the paper is in all probability as high as the linen. In the case of the Kraft paper test with this adhesive (and many others) there were unforeseen results. Considering that the Kraft paper is only 0.140 mm (140 μm) thick, it is significant that the 10% solution is not fully penetrating it. If the adhesive were fully penetrating the internal fibres of the paper, it would require considerably more force to split it apart. On the one hand, the largest pore size of the Kraft paper is estimated to be about 5 μm, which suggests that pore size might be a limiting factor for the penetration of the 10% solution of hide glue. On the other hand, the solvent (water) is rapidly drawn into

the paper and away from the adhesive, increasing the adhesive concentration and causing 'blocking'. This has interesting implications since it allows an assessment of the adhesive concentration, depth of penetration of adhesives, and the effect of different substrate pore sizes. It is also noteworthy that the 5% hide glue solution and Kraft paper bond strength is shown to be extremely low. In this situation the original bond line between the papers failed, which was probably the result of 'dry down' where the contraction of the dilute adhesive fails to bridge the gaps between the two paper strips.

- *Linen to Whatman paper*: the Whatman #1 paper is 0.178 mm thick and has a filtering capacity of 11 μm or greater, so this paper is slightly thicker and has greater pore size than the brown Kraft paper. Furthermore, the splitting tests of the Whatman #1 paper with no adhesive gives an average peel strength of 0.43 N/cm, slightly less than the Kraft paper. The peel tests with the 10% solution result in an average splitting strength of 2.06 N/cm (higher than the same glue with Kraft paper) even though this paper is thicker. As with the Kraft paper, the Whatman paper split internally along one of the two paper strips. It is therefore safe to assume that the 10% solution of hide glue is penetrating a little further into the Whatman #1 paper than the Kraft paper. At the 5% glue solution the Whatman #1 bond line fails at a very low level of 0.19.N/cm. Again the glue is drying down during evaporation and not filling the gaps between the two paper strips.

Sturgeon glue

Bonding strips of linen together with a 10% solution of sturgeon glue results in higher (5.57 N/cm) bond strength than the hide glue (4.39 N/cm). Bonding papers together with sturgeon glue has a very similar result when compared to the hide glue and papers. As with the hide glue the papers split internally and
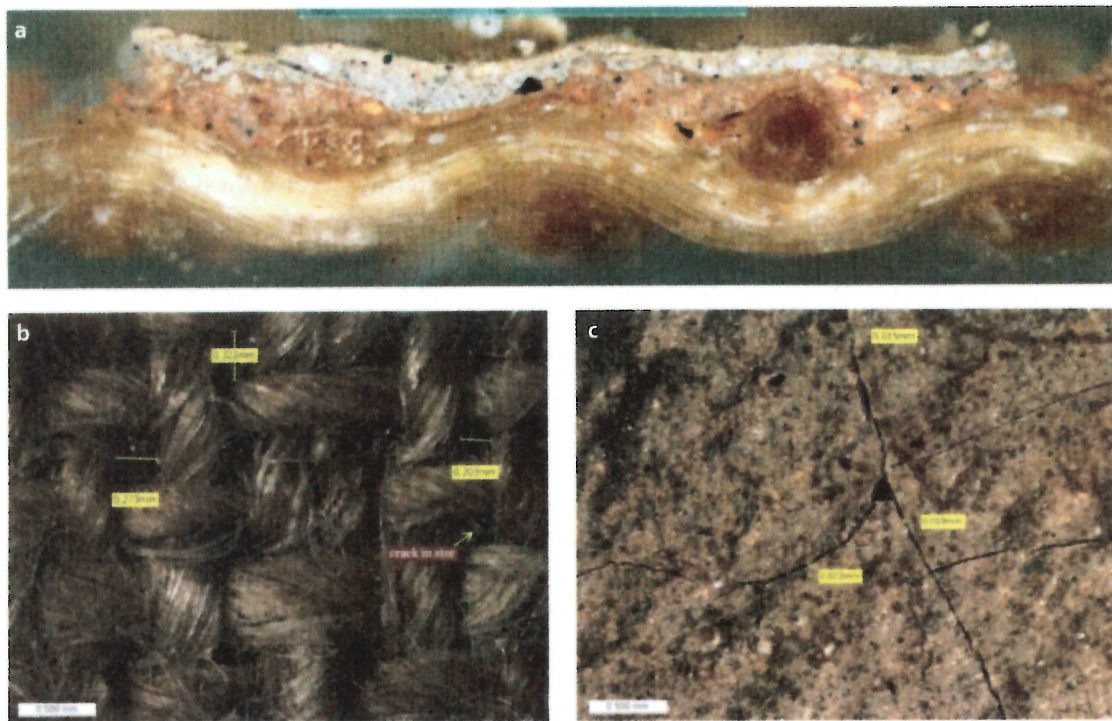
Figure 6 (a) Cross-section of a typical canvas painting; (b) the dimensions of some of the gaps between yarns of a canvas supporting an 18th-century painting; (c) the dimensions of some of the cracks in the paint layer of an 18th-century painting. (Photos courtesy of Melvin J Wachowiak.)

not along the adhesive bond line. Whatman #1 paper showed a higher splitting strength (2.68 N/cm) than the Kraft paper (1.94 N/cm). Again, this is perhaps due to the different pore sizes of the papers and the fact that the bonding strength of the 10% sturgeon glue is higher than the 10% hide glue.

JunFunori

JunFunori is a much weaker adhesive than the hide or sturgeon glue and all tests reflect this. The JunFunori was used in these tests as a 6% solution. The strengths of bonding linen and polyester together with JunFunori are considerably lower than those when using hide or sturgeon glue. Nevertheless the difference between the linen and polyester is small. The average peel strength is very low for both substrates and the linen strength is slightly higher than the polyester. On the other hand, the strength of bonding Whatman #1 and brown Kraft paper together with the 6% solution was very low and the papers split internally; the splitting strength was barely higher than the same paper when no adhesive was applied.

Beva 371

In the tests conducted here, the Beva 371 was applied undiluted and no heat was used. The sample substrates were simply pressed together and allowed to dry. The bond strength using the Beva 371 with linen and polyester substrates is very high, even higher than when using hide or sturgeon glue. As with other adhesives, Beva 371 did not fully penetrate the papers and resulted in internal splitting from the tests. However even though the Beva 371 was used undiluted and as a paste it did penetrate the papers sufficiently to develop moderately high splitting strengths.

Aquazol 200/ Aquazol 500

Aquazol 200 and 500 together with some of other adhesives tested (Acril AC33, Plextol
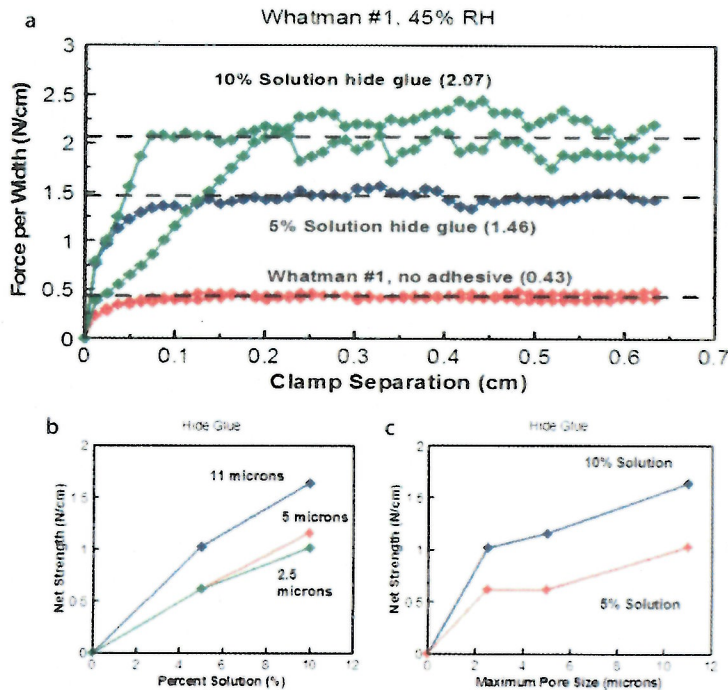
Figure 7 (a) Examples of the test results for splitting Whatman #1 paper with no adhesive and 5% and 10% solutions of hide glue; (b) and (c) summaries of the test results using 5% and 10% solutions of hide glue and the papers with different pore sizes.

B500, Plexisol P550, etc.) showed very little cohesive strength. The peel strength of linen bonded with a 10% solution of Aquazol 500 is slightly more than half that of hide glue and the peel strength of Aquazol 200 is 50% less than the Aquazol 500. Also, and with the exception of the Whatman #1 paper, the bond strength in all cases is fairly good and no internal splitting of either paper with the 10% solution was observed. Even if it is unclear why the Whatman #1 paper did so poorly in the tests, it is worth commenting here that modest adhesive properties can be developed even though there are no cohesive properties for that material. This again suggests that adhesion is largely a mechanical process with most of these adhesives.

Penetration test

Figure 6a shows the cross-section of a typical canvas painting. A scale showing 1 mm can be seen in the micro-photograph indicating that the thickness of a section of the ground and paint layers is only 0.125 mm (125 μm). Accordingly, any cracks, gaps and pores are going to be somewhere in this range. The gaps between the linen yarns of Tara linen 5576 can range between 0.028 mm and 0.212 mm. Older linens tend to have more open weaves with larger gap sizes (Figure 6b). The crack opening dimensions on paint films can range from the very small (0.015 mm) to larger sizes of 0.2 mm and upwards (Figure 6c). The significance is that the gap and pore sizes can vary from 0.001 mm to about 0.5 mm. Actual losses in paint films can become very large.

There are two concerns regarding adhesive penetration:

1. One major concern is whether adhesives will penetrate small gaps and pores with small dimensions in the range from 0.001 mm (1 μm) to about 0.025 mm (25 μm).

2. As the dimensions of pores and gaps get larger there is an additional concern as to the gap-filling capacity of the adhesive.

This section examines different adhesives, their solution concentrations and their ability to penetrate small pore dimensions. At the same time it will also be possible to estimate which adhesive concentrations are blocking, that is, not penetrating the pores at all or failing to fill the gaps in the pores. While Whatman and Kraft papers are not exactly the same thickness they are quite thin and, incidentally, the differences do not become a factor in this experiment. What will be assumed is that the maximum pore size of each paper is approximately that of the largest particle size the papers will retain when used as a filter.

Hide glue

The application of the different solutions of hide glue changes the splitting resistance of the Whatman #1 paper: the stronger the solution, the higher the splitting forces. The test results shown in Figure 7a also exhibit some interesting points. Clearly both solutions of the hide glue are penetrating the 11 μm pores in the paper and the force required to split the paper is actually fairly high. Remembering that the weight of 102 g is about equal to 1 N, the forces shown are the actual results but for the final analyses the paper control forces were subtracted from the measured adhesive–paper forces to give the net influence of applying adhesive to the papers. For example, the force needed to split the paper with the 10% solution of the hide glue is 2.07 N cm whereas the splitting force for the paper alone is 0.43 N/cm. The net increase in splitting force due to the adhesive is therefore 2.07 N/cm minus 0.43 N/cm or 1.64 N/cm. From this point on all results will be discussed in terms of the net force increase due to the adhesive. When using different papers and adhesives different bonding patterns emerge.

For example, Figures 7b and 7c show the results of testing 5% and 10% solutions of hide glue with papers of different pore sizes.

In Figure 7b, the net splitting strength of the papers is completely dependent on the solution concentration of the adhesive. For papers of the same pore size the splitting strength is seen to increase with the increased solution concentration. Also shown in this figure is that the increased pore size permits a larger amount of adhesive to penetrate. Consequently the splitting strength is greater for the 11 μm paper than for the 2.5 or 5 μm papers.

Figure 7c shows the splitting strength of the paper versus the pore sizes in greater detail. As with Figure 7b, the lower solution concentration yields lower splitting strengths for each pore size. But of interest here is that as the pore size increases, the splitting does not increase proportionally. At these low pore sizes the adhesive is not fully penetrating but as the pore size increases the bond strength increases somewhat. Keeping in mind that with a 10% solution of hide glue it took about 4.4 N cm to separate two pieces of linen and with a 5% solution it took 2.4 N/cm, the splitting strengths shown for the papers are still well below those values. If papers with greater pore size are used, the strength becomes so high that it cannot be determined, since it defeats the adhesive strength of the tape causing the tape to separate from the paper.

Sturgeon glue

Sturgeon glue has very similar penetrating properties as the hide glue but it shows much stronger splitting strengths. This can be a result of either greater penetration or a simple increase in the strength of the sturgeon glue when compared to the hide glue. Results show that the bond strength is almost proportional to both the pore size and the solution concentration with the highest splitting strength of 2.25 N/cm using the 10% solution and the 11 μm paper. This is an extremely high value and it was not possible to test this concentration of sturgeon glue with papers having greater pore sizes, since the strength of the bond was too high and there was tape failure. Results reveal another aspect of the sturgeon glue relating to the pore sizes discussed with respect to

actual artworks: when using the 5% solution of sturgeon glue, the splitting strength levels off rapidly after a pore size of 11 μm. What is occurring is that this concentration is not gap filling due to the increased pore size and the bond strength shows an upper limit of about 1.1 N/cm. Nearly all the gap and pore dimensions found in damaged works of art are greater than 11 μm and gap filling with a 5% solution of animal glues will present a problem. It will take multiple applications of the adhesive to assure full consolidation. It is also quite possible that with the 10% solution of animal glue, gap filling might be a problem when the pore size is greater than 40 or 50 μm. One further comment here is that the thickness of these papers is about the average thickness of a ground and paint layer found in typical canvas painting and the adhesives under discussion are not fully penetrating the papers.

JunFunori

JunFunori when mixed at a 6% concentration is still somewhat viscous. As a consequence it presents problems in both penetrating and gap filling as it dries down. Results show that initially a small amount of adhesive seems to penetrate using a 3% solution but the splitting force is low. As the concentration is increased there is very little penetration and the adhesive is blocking or left behind on the surface of the paper. On the other hand, as the pore size increases the 6% solution begins to both penetrate and fill the pore gaps. The 3% solution initially penetrates but as the pore size increases, it fails to fill the gaps. The splitting strength of this adhesive is fairly low when compared to either the hide glue or the sturgeon glue.

Beva 371

Beva 371 is a mixture of ethylene vinyl acetate, paraffin wax and ketone resin. Concentrated Beva 371 is reported to be around a 40% solution, but with evaporation it is sometimes not easy to be exact, which is the reason why it is very difficult to determine exact solution concentrations, therefore the information presented below is in dilutions. The tests were performed using a new can of Beva 371 diluted 1:4 with toluene by volume (1 part concentrated adhesive with 4 parts toluene), 1:2 with toluene by volume, and as supplied in its concentrated form (indicated as 1:0). These are not 10%, 20% and 40% solutions. Results show that when using small pore-size papers, it requires high concentrations of Beva 371 to achieve sufficient penetration to develop significant splitting strength. As the pore size of the paper increases, the splitting strength levels out and then decreases. This means that the adhesive is unable to fill gaps at larger pore sizes when using 1:1 and 1:2 dilutions. It is therefore best to use concentrated Beva 371 most of the time when trying to consolidate a painting in a fragile condition. In a way this is somewhat contrary to expectations and it suggests that the Beva 371 mixture is separating and that the lower molecular weight material, possibly the ketone resin, is the only component of the adhesive that is actually penetrating the papers and providing adhesive strength.

Aquazol

At a concentration of about 5%, Aquazol 200 has the ability to penetrate 5 μm pores and can be effective, but it cannot gap fill well at 11 μm pore sizes. At a concentration of 2.5% it does poorly in all pore sizes since it does not fill the gaps. For pore sizes greater than 5 μm it will require higher solution concentrations. Aquazol 500 can be a very effective consolidant at 5% solution concentrations in the pore size range from 2.5 μm to 15 μm. For pore sizes greater than 15 μm either higher solution concentrations are required or more than one adhesive application is needed. In general the strength of Aquazol 500 is greater than Aquazol 200.

Paraloid B-72

Paraloid B-72 has been used fairly extensively as a consolidant. For small pore sizes it is

reasonably effective at concentrations greater than 10%. It does not appear to penetrate very small pore sizes well. Results show that Paraloid B-72 does not fill voids at a 10% solution and pore sizes greater than 11 μm.

Plextol B500

Plextol B500 penetrates well at the lower concentrations (below 20%) and smaller pore sizes (5–11 μm). At these small pore sizes, higher concentrations tend to block significantly. As the pore size increases the lower concentrations have difficulty filling the voids and gaps. Above pore sizes of 5 μm it will require greater solution concentrations or multiple applications to develop strength. In general this adhesive develops good strength.

Conclusions

The aim of this study was to gain insight into the structural requirements of consolidation adhesives for easel paintings. Some issues regarding the adhesive and cohesive properties of adhesives have been discussed and questions such as penetration, influence of solvents and solvent retention have also been addressed.

As this research has shown, the strengths of the adhesives vary widely in normal environmental conditions (± 50% RH, ± 23°C). Natural adhesives have the highest cohesive strengths and stiffness (modulus) when compared with the other adhesives tested. Synthetic adhesives such as Acril AC33, Plextol B500, Akeogard T35, Aquazol 500 and Aquazol 200 develop no strength or stiffness regardless of how long they are allowed to dry. Many of the adhesives tested develop very little strength or stiffness including Paraloid B-67 in toluene and Plexisol P550 in any solvent tested. With the exceptions of Beva 371 and possibly Paraloid B-72 and Paraloid B-67, the adhesives are dramatically influenced by RH.

For some of the adhesives tested, modest adhesive properties can be developed even though they have scarce or no cohesive strength.

Even modest cohesive strength in a material is sufficient to enhance the adhesive properties. This suggests that adhesion is largely a mechanical process with most of these adhesives.

The concentration of the adhesives can also have a significant effect on adhesion: lower concentrations yield lower bond strengths. Critical solution concentrations might exist below which adhesives lose performance and this might also be influenced by porosity. The various types of polymer and their molecular weights are significant factors that require further systematic study. Some of the adhesives tested however appear not to penetrate most of the substrates studied, remaining on the surface and failing to act effectively. This could explain why most of the adhesive and paper tests showed splitting of the paper.

Finally, tests also showed that solvents can take a long time to evaporate from most of the adhesives tested and that the choice of solvent can dramatically affect the mechanical properties of some materials.
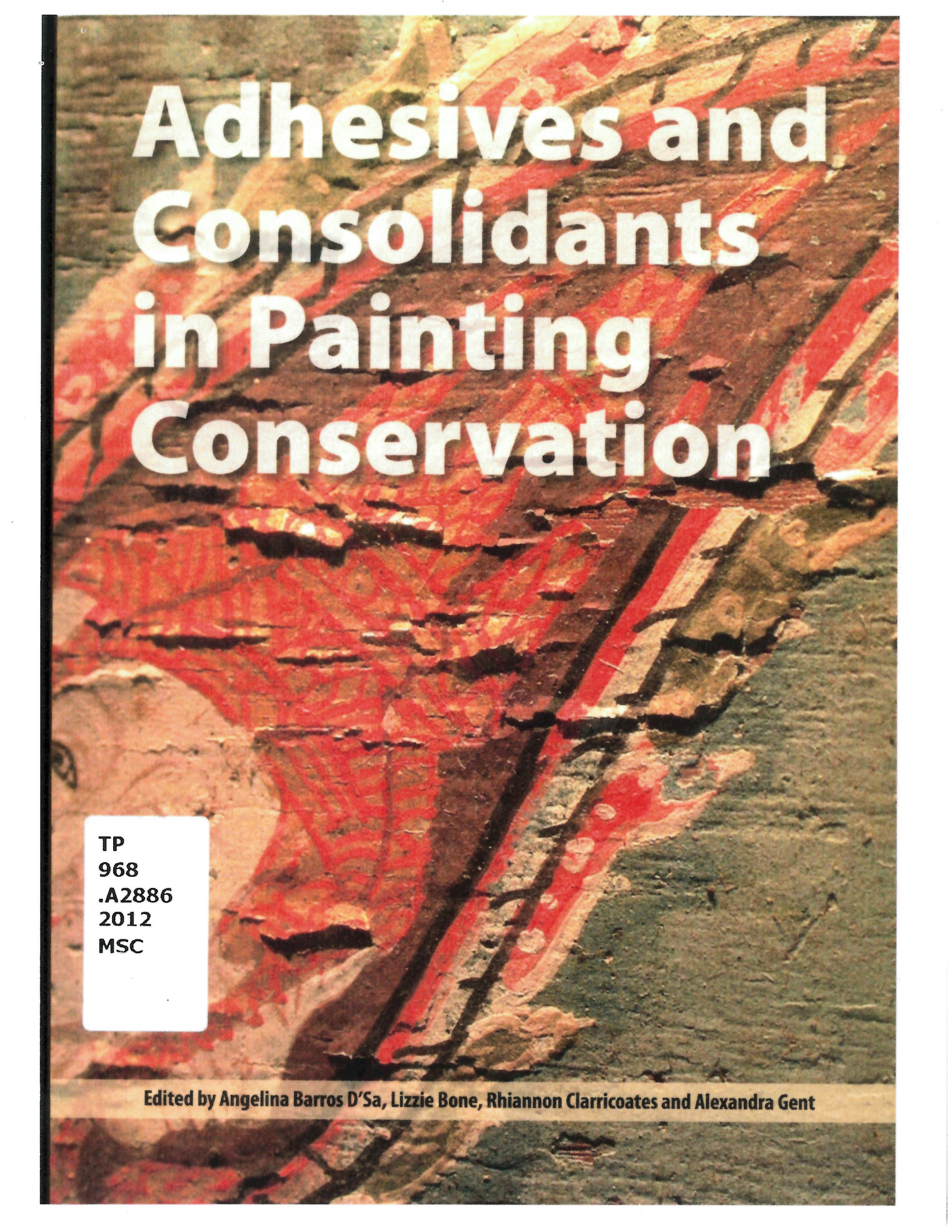
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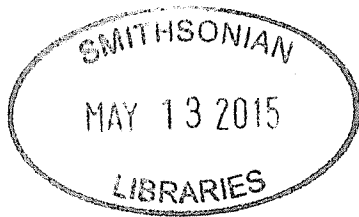
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Adhesives and Consolidants in Painting Conservation

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