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Mechanical and physical characterization of natural and synthetic consolidants

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ABSTRACT

The mechanical behavior of adhesives is strongly influenced by a large number of variables, relating to a complex interaction of mechanical-physical-chemical factors, such as its loading direction (shear, peel), the temperature and the environmental relative humidity (RH). These variables can have a large influence on the durability of restored art objects where thermoplastic adhesives have been used as a consolidant. This study aims to characterise the mechanical and physical behavior of some adhesives commonly used polymers by conservators as consolidants to restore cultural objects such as canvas paintings or historic wooden furniture. Twelve commercially available natural and synthetic adhesive materials were tested. The influence of RH at room temperature on the mechanical and physical properties of the adhesives was investigated. Shear and peel experiments were performed on adhesively bonded wood and canvas coupon to establish mechanical characterisation. The physical properties of the adhesives were determined by performing moisture adsorption measurements and Differential Scanning Calorimetry (DSC). The results of this study demonstrate that synthetic adhesive products are able to resist higher shear and peel loads than natural types. Moreover, the influence of important changes in RH on the mechanical properties of the adhesives was demonstrated. Reflecting on the combined data derived from shear and peel tests with the adhesive's sensitivity to moisture will help conservators to select the most suitable adhesives for their applications to achieve optimal durability and the best mechanical performance in versatile environmental conditions.

1. Introduction

An adhesive is described as a substance capable of joining materials by surface attachment in ASTM D907-05 [1]. Consolidants can be considered as a sub-group of adhesive materials that have to make up for the loss of binding media and often needs to penetrate into a surface [2]. The most typical behavior for an adhesive as a consolidant when used in art conservation was established by Berger and Zeliger [3], who stated that an adhesive acts as a consolidant, when it is fully compatible with the art object (e.g. a painting) and also fulfils three other requirements, as described below:

- It must be reversible or at least be re-workable and leave no trace when removed from the object;
- Not damage the object as a result of chemical interactions;
- It must be mechanically and chemically stable in time in the exposed environment.

An overwhelming variety of adhesive products are available to art conservators to choose from, all of which show specific mechanical, chemical and physical characteristics [4–7]. There is a lot of knowledge in art and cultural heritage conservation, despite this, there is little scientific understanding regarding the performance of these adhesives

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[7]. Art conservators often choose an adhesive based on their experience and 'empirical feel'.

A good adhesive bond is a result of the optimal combination of the right surface treatment of the adherend, the intrinsic properties of the adhesive (chemical stability, surface tension, viscosity), temperature and the adhesive application method [6,8]. These should be tuned to the use requirements such as the extent and the direction of the mechanical loading that the adhesive bond undergoes, and the environment and forces to which it will be exposed. If not, the adhesive bond may fail prematurely.

The exposure to (combinations of) light, temperature, and relative humidity (RH) might lead to substantial changes in the chemistry and mechanical performance of an adhesive, generally referred to as ageing [8–10]. If moisture is absorbed into the adhesive polymer structure, a weight change might be measurable, as well as this moisture uptake may cause plasticizing leading to a decreased glass transition temperature and the modulus of elasticity, reduced hardness, strength to failure and strain to failure. Moisture ingress in the adhesive layer may lead to an overall reduction in mechanical performance [6,9,10], often combined with a shift in the failure mode and durability [11]. At elevated temperatures this effect may be amplified [12]. Most consolidation materials, such as examples researched here, are thermoplastic polymers. They are more vulnerable to moisture than thermosets which contain a larger number of chemical crosslinks, resulting into a higher resistance to moisture penetration [13].

A comprehensive research into the mechanical behavior of different art and cultural heritage consolidants under the influence of RH is scarce, as even small changes in materials, pre-treatment, environment, loading or test speed lead to different test results. The existing literature provides a limited source of scientific data of the environment on the mechanical, physical, and chemical these consolidants [14–16], and many are linked to specific case studies [9,17–19]. The literature results are tested by different researchers in different laboratories in different environments referring to different applications and making use of different test and evaluation methods. This makes it nearly impossible to select an adhesive based on available literature, and was the motivation for this comprehensive study of the behavior of consolidating adhesives.

This paper investigates the physical and mechanical characteristics of twelve well-known commercially available adhesives commonly used for the consolidation of cultural objects such as (panel) paintings, antique furniture, and sculptures after the exposure to three different RH conditions. Differential Scanning Calorimetry (DSC) and moisture absorption tests were performed to assess the moisture sensitivity on their thermal properties. Lap shear experiments on wooden substrates were performed to compare the mechanical performance, while T-peel tests on canvas were done to determine the failure type (cohesive, adhesive, or mixed failure), giving valuable information on the adhesive bond performance [4,5]. The generated data will assist conservators in making more informed choices of the adhesive type in terms of their mechanical properties and their moisture sensitivity.

2. Materials and methods

2.1. Materials: adherends

2.1.1. Wood

Wooden substrates were cut from laminated Triplex wooden birch tree sheets (Gamma, The Netherlands) with dimensions: 200 × 25 × 3 mm (length × width × thickness). Substrates were cut in such a way that the outer wood fibres were oriented in the longitudinal direction of the substrate loading.

2.1.2. Canvas

Canvas substrates (300 × 25 mm, length x width) were used as the flexible substrate material for peel tests. It consists of a standard preground medium rough (pure) canvas linen (density: 18 × 19 threads per 2 cm^2), Claessens Canvas (Belgium). One side of this canvas was covered by a ground layer material (calcium carbonate with an acrylic binder, as determined by FTIR-ATR) while the other side is just the bare pure natural linen material.

2.2. Adhesives

Table 1 summarises the researched 12 different natural and synthetic adhesives commonly used in the art and cultural heritage conservation area.

2.2.1. Natural adhesives

- Gelatine (from porcine): A photographic grade gelatine (protein) with Bloom strength of 100 g, sourced from Talas, USA. Made available as granulate.
- Rabbit skin glue: Sourced from Kremer Pigments Inc., USA. Made available as granular pellets soluble in water (Bloom strength of 340–360 g) [9].
- Isinglass (sturgeon glue): Kremer Pigmente & Co.KG, Germany (Bloom strength: 575–625 g).
- Funori: Talas, USA, a dried Japanese seaweed.

2.2.2. Synthetic adhesives

- Klucel® G: Sourced from De Labshop, the Netherlands.
- BEVA® 371b: Conservator's Products Company (CPC), Flanders, New Jersey. Sold from 2010 onwards after substituting the main tackifier from Berger's Original Formulation released in 1971 [20]. (T_m: 61 ± 1 °C, Table 3).
- BEVA® 371OF: Talas, USA. Sourced from Talas, USA The manufacturer had substituted the main tackifier a second time in 2018, obtaining a whitish paste, called "NF" by the authors as "New Formulation" to indicate that the newest formulation was used, but it is sold as BEVA 371 OF [20]. (T_m: 58 ± 0 °C, Table 3).
- BEVA® D8:. Sourced from C.T.S. Spain, Europe.
- Evacol R: De Labshop, the Netherlands.
- Mowilith® 20: De Labshop, the Netherlands.
- Jade® 403: Talas, USA.
- Paraloid® B72: Talas, USA.

2.3. Methods

2.3.1. Surface preparation wooden substrates

The wooden substrates were first cleaned using compressed air, then degreased with a cotton cloth wetted by PF-SR (a high flash point

Table 1
An overview of the tested adhesives including their chemical base, origin and main constituents. (PVA; Polyvinyl Acetate, EVA; Ethylene Vinyl Acetate).

Type	Origin	Chemical base
Gelatine	Natural	Animal collagen
Rabbit Skin Glue	Natural	Animal collagen
Isinglass	Natural	Animal collagen
Funori	Natural	Polysaccharide
Klucel® G	Synthetic	Hydroxypropyl cellulose
BEVA® 371b	Synthetic	2 EVA-copolymers, 2 tackifiers, paraffin wax, organic solvents
BEVA® NF	Synthetic	3 EVA-copolymers, 2 tackifiers, paraffin wax, organic solvents
BEVA® D-8	Synthetic	EVA-copolymer water-based emulsion
Evacol R®	Synthetic	EVA copolymer emulsion
Mowilith® 20	Synthetic	PVA solution in ethanol/acetone (7:3)
Jade® 403	Synthetic	PVA emulsion in water
Paraloid® B-72	Synthetic	Copolymer of ethyl methacrylate and methyl acrylate in acetone

Aerospace commercial surface cleaner fluid from PTI Technologies, Cork Ireland) to remove organic contaminations such as finger prints. Then it was lightly sanded with 80 grit sandpaper (KL 361 JF, P80, Klingspor, the Netherlands) and cleaned again by a cloth soaked with PF-SR. The substrates were prepared 2 h in advance of the bonding process in order to let the PF-SR evaporate.

2.3.2. Surface preparation canvas substrates

The surface of the canvas fibres was prepared by removing dust using (oil-free) compressed air. No further treatment was done before the adhesive was applied.

2.3.3. Adhesive application

The individual procedures for the preparation of the adhesives and their application in the bonding process are shown in Table 2.

The adhesive for the lap shear substrates was applied (at RT) to both wooden parts by a brush (25 mm wide) and then after being assembled, clamped by a metal paper-clamp (30 mm wide) in a mould. The adhesive bonds were cured for at least 7 days.

The T-peel substrates were made from two canvas strips bonded together on the canvas fibre side. Adhesive blends were applied to both sides (at RT) by brush (25 mm wide). The bonded parts were pressed with a 500 g steel-weight wrapped with Aircap 1 (polyimide) tape from Airtech Europe, and cured for at least 7 days.

2.3.4. Moisture conditioning and weight measurements

For the moisture uptake experiments adhesive substrates (around 2–3 mg each) were prepared by drying them at room temperature in a desiccator filled with silica gel where a flow of nitrogen gas maintained 6% RH. Substrates were kept in this environment for 3 weeks until the weight stabilized, after which the weight measurements were performed. Weight measurements were done on a Mettler Toledo XSR204DR balance. The solvent-based adhesives like the BEVA® 371 types and the Paraloid® B-72 have been corrected for losing weight as a function of time due to solvent evaporation.

This procedure was followed by an exposure during 7 days at 25 °C at respectively medium (55%) and high (85%) RH in a Weiss WK11 340 climate chamber to evaluate the moisture uptake of the adhesives. The RH was separately measured by a Europe Supplies LTD WS 9400 electronic portable device.

Table 2
The Adhesive preparation and its application to the adherend's surfaces. RT: room temperature, n.a.: not applicable.

Type	Adhesive preparation	Adhesive application for bonding
Gelatine	Solution of 1:10 w/w% dissolved in distilled water (47 °C)	Adhesive solution (47 °C) applied. Drying 7 days at RT
Rabbit Skin Glue	Solution of 1:10 w/w% dissolved in distilled water (57 °C)	Adhesive solution (57 °C) applied. Drying 7 days at RT
Isinglass	3 w/w% solution in distilled water at 47 °C.	Adhesive solution (55 °C) applied. Drying 7 days at RT
Funori	3w% solution prepared by soaking the seaweed in distilled water overnight at a temperature of 55 °C.	Adhesive solution (47 °C) applied
Klucel® G	Solution of 1:10 (w/w%) dissolved in distilled water.	Adhesive solution (RT) applied. Drying 7 days at RT
BEVA® 371b	Prepared as a 40 w/w% solution in toluene	*Adhesive solution applied, the solvent evaporated by heat (70 °C) under vacuum (*200 mbar*) during 7 days.*
BEVA® NF	n.a. Applied directly from the can	*Adhesive applied, the solvent evaporated by heat (70 °C) under vacuum (*200 mbar*) during 7 days.*
BEVA® D-8	n.a. Applied directly from the jar	Adhesive applied at RT. Drying 7 days at RT
Evacol-R®	Applied directly from the bottle.	Adhesive applied at RT. Drying 7 days at RT
Mowilith® 20	Diluted as 1:1 w/w in ethanol with 5 w% water.	Adhesive solution applied at RT. Drying 7 days at RT
Jade® 403	n.a. Applied directly from the bottle	Adhesive applied at RT. Drying 7 days at RT
Paraloid® B-72	Prepared as a 1:1 w/w solution in acetone.	Adhesive solution applied at RT. Drying 7 days at RT

Table 3
The thermal transitions obtained from DSC experiments. "–": no thermal transition identified.

Adhesive Type	RH	T_g (°C)	T_m (°C)	Melting enthalpy (J/g)
Gelatine	6%	–	–	–
	50%	54 ± 0	105 ± 0	28 ± 1
	85%	36 ± 1	71 ± 3	20 ± 0
Rabbit Skin	6%	–	–	–
	50%	54 ± 1	84 ± 0.6	23 ± 1
	85%	30 ± 1	63 ± 3	24 ± 1
Isinglass	6%	–	–	–
	50%	62 ± 1	94 ± 0	28 ± 1
	85%	47 ± 0	55 ± 0	25 ± 0
Funori	6%	Above 150	Above 150	Above 150
	50%	98 ± 0	–	–
	85%	42 ± 0	–	–
Klucel G	6%	–	–	–
	50%	–	–	–
	85%	–	–	–
BEVA® 371b	6%	−27	65 ± 0	8 ± 0
	50%	−22 ± 1	61 ± 1	31 ± 1
	85%	−24 ± 0	61 ± 0	31 ± 1
BEVA® NF	6%	−27 ± 0	56 ± 0	28 ± 1
	50%	−28 ± 0	58 ± 0	30 ± 1
	85%	−28 ± 0	58 ± 0	32 ± 0
BEVA® D-8	6%	0 ± 0	–	–
	50%	−1±0	–	–
	85%	−13 ± 0	–	–
Evacol R	6%	−9±0	–	–
	50%	−10 ± 1	–	–
	85%	−11 ± 0	–	–
Jade® 403	6%	6 ± 0	–	–
	50%	3 ± 0	–	–
	85%	−7±1	–	–
Paraloid® B-72	6%	38 ± 0	–	–
	50%	37 ± 1	–	–
	85%	37 ± 1	–	–
Mowilith 20	6%	39 ± 0	–	–
	50%	31 ± 0	–	–
	85%	14.5 ± 0.5	–	–

2.3.5. Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry was employed to investigate the influence of the moisture ingress on the thermal behavior of the adhesive when subjected to different environmental RHs. The measurements provided information on the thermal transitions such as glass transition temperature (T_g), melting temperature (T_m) and melting enthalpy (ΔH_m) using a TA DSC 250 instrument. For sample preparation, approximately 11 mg of casted and dried adhesive film was hermetically sealed in Tzero aluminium pans (TA instruments, New Castle, USA); an empty pan was used as a reference. Substrates underwent three subsequent thermal cycles. In the first heating cycle they were heated from room temperature to 120 °C at 10 °C/min and maintained at 120 °C for 5 min. They were then cooled in the second cycle to −100 °C at 10 °C/min and maintained for 10 min. at −100 °C. They were finally heated again from −100 °C to 120 °C at 10 °C/min. All measurements were performed in triplicate.

The T_g was measured as the midpoint of the heat flow change. The melting temperature (T_m) is reported as the minimum point of the endothermic melting peak in the first heating scan. The enthalpy of melting (ΔH_m) is calculated as the area of the endothermic melting peak in the first heating scan. The crystallization temperature (T_c) is

identified as the maximum point of the exothermic crystallization peak in the cooling scan.

2.3.6. Mechanical tests

All mechanical tests were done on a Zwick 10 kN tensile test machine using a 1 kN load cell for improved accuracy at laboratory conditions (20 ± 2 °C and 55 ± 5% RH).

Lap shear tests, based on ASTM D1002 [21] (at least 5 substrates per test, with an overlap of 12,5 mm), were performed to obtain the mechanical shear stress of the adhesives. Tests were performed at a test speed of 1.3 mm/min.

T-peel tests were performed to determine the peel resistance of adhesively bonded flexible adherends and the failure type, based on the ASTM D-1876-01 standard [22]. At least 10 substrates of each type were conditioned for 7 days before testing. The resistance to bond failure was measured at a test speed of 254 mm/min in which at least 127 mm was peeled off.

2.4. Bond failure types

An overview of the failure types is given in Fig. 1. It is generally accepted in adhesive bonding technology that bond failure should preferably be cohesively inside the adhesive layer or inside either substrate (the adherends), but never at the interface, which can be considered as the most complex and unpredictable failure part of the adhesive bond, the so-called adhesive failure as clearly described by Kinloch and Petrie [5,6].

In contrast, for art conservation purposes, the adhesive bond should preferably occur either cohesively inside the adhesive layer (Fig. 1A) or inside the added part (Adherend 2, Fig. 1D), as a cohesive failure at the interface or inside the art object itself is unwanted. As such, the adhesive bond should preferably be prepared in such a way, that the cohesive strength of the adhesive is weaker than that of the adherend, but still strong enough to withstand external forces.

The failure types were determined by identifying adhesive traces on the tested substrates through a combination of visual observation, microscopy (Zeiss Discovery V8 stereo microscope) and spectroscopic analysis through Fourier Transform Infrared Spectroscopy (FT-IR), using a Perkin Elmer Spectrum 100 Spectrometer equipped with a universal attenuated total reflectance (ATR) sampling accessory and a ZnSe crystal. Data were collected at 16 scans with a resolution of 4 cm^{-1}. To take into account any surface heterogeneity, a minimum of three spectra in different areas were measured per sample.

3. Results and discussion

3.1. Moisture uptake of the adhesives

Fig. 2 shows the moisture uptake of the adhesives after the exposure to the different RHs compared to the initial weight at 6% RH, when stabilized. The standard deviation (STD) is not shown as it is smaller than 0,01 mg. The graph clearly shows that natural adhesives, and specifically Funori and Isinglass, are in general more sensitive to moisture uptake than the synthetic ones.

3.2. DSC

Table 3 summarises the measured thermal transitions of the adhesives i.e. T_g, T_m and ΔH_m of substrates exposed to different RHs. The identification of thermal transitions is important, since they affect the mechanical performance of adhesives.

As observed in Table 3, the glass transition and melting temperatures of natural adhesives such as gelatine, rabbit skin glue, isinglass, and Funori are very sensitive to environmental RH. This is in line with the moisture uptake experiments (Fig. 2), indicating that the absorbed water acts as a plasticiser, reducing the T_g more than 20 °C in some cases, which can influence their mechanical performance. It must be noted that in all tested environments the T_g of the natural adhesives remained above room temperature.

Conversely, (Table 3), the majority of the synthetic adhesives such as BEVA® 371b, BEVA® NF, Paraloid, and Evacol R demonstrate minimal changes in their thermal transitions. This is again in accordance with the

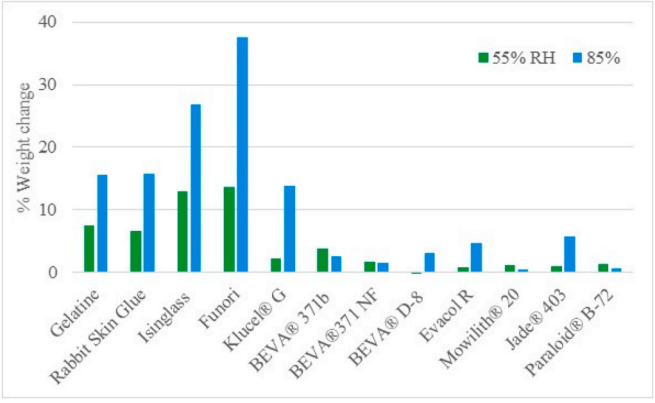


Fig. 2. The percentage of weight change due to moisture uptake, referenced to 6% RH, 25 °C.

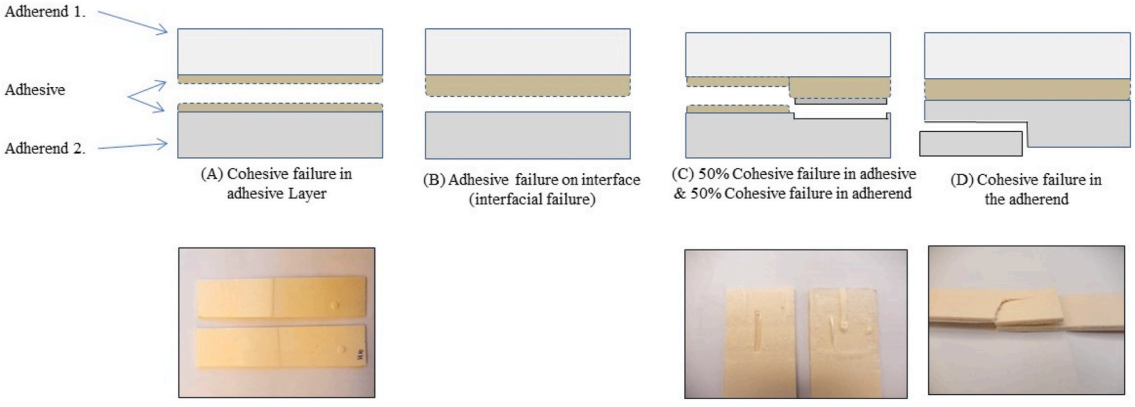


Fig. 1. Examples of (A) cohesive failure in the adhesive, (B) interfacial failure, (C) mixed-mode failure, (D) cohesive failure in the adherend, including photographs of such failure types as found at the lap shear tests.

moisture uptake results, showing low moisture absorption from the environment by these adhesives. Only BEVA® D8 and Evacol R demonstrated moderate reductions in their glass transition temperature in humid environments. In both adhesives, their glass transitions are substantially below room temperature which is clearly visible on their mechanical performance when tested at room temperature at different RHs (Fig. 4).

3.3. Influence of RH on lap shear strength

Fig. 3 shows the load - displacement curves of the lap shear tests of the wooden substrates after a week of exposure to 25 °C, 55% RH. The presented curves are averaged from five tests. They clearly show the large differences in individual mechanical behaviors, such as stiffness and strain to failure.

The average lap shear stress of all of most tested adhesives was found to be below 2 MPa (with the exception of Evacol R (2,2 MPa) down to 1.1 MPa (Mowilith® 20), characterizing the tested materials more as sealants rather than structural adhesives when the maximum shear failure load of 2 MPa is taken as the criterion as suggested by Petrie [6].

The moduli of elasticity of the tested adhesives are low and ranges from roughly 1.0 E-4 GPa (Klucel G) to 1.0 E-3 GPa for BEVA® 371 NF, which was found to be a far tougher and stronger than the BEVA® 371b. However, this might very well be the effect of the amount of xylene still present in the adhesive during testing, as the average adhesive bond strength was found to be up to 20% higher after one extra week exposure to 50 °C at vacuum (results not shown).

Evacol R, BEVA® 371NF and gelatine showed the highest deformation capacity, due to their large elastic behavior.

The bar graphs of Fig. 4 show the averaged test results of at least 5 lap shear substrates wood - wood conditioned at the different hygrometric values. Evacol R and Paraloid® B-72 showed the highest average lap shear stress at laboratory conditions (23 °C and 55% RH). Fig. 4 should also show the relation between the Bloom strength (or gel rigidity), which is strongly related to the average molecular weight, and the measured shear stress of gelatine rabbit skin glue and isinglass as described by Schellman [9]. Indeed, Fig. 4 clearly shows that gelatine generated the weakest adhesive shear strength at 55% RH, but no significant difference between Isinglass (1) and rabbit skin glue could be found. Most possibly the result of the interfacial failure type of the Isinglass (Table 4).

The influence of the two extreme values of environmental moisture became visible in the mechanical behavior, as gelatine and Beva® D8 seemed to be mechanically sensitive to the environmental moisture content, with Beva® D8, showing an increased cohesive failure with increasing moisture content (Table 3). This is in line with the DSC experiments, showing a reduction of the T_g and hence further softening of the adhesive at room temperature. Klucel® G became very weak after a week of moisture exposure. Though overall it can be seen that, within the large STD, the moisture does not show much influence on the lap shear stress of the natural adhesives. This is in agreement with the findings of the DSC experiments, since the T_g of these adhesives is above room temperature (even at higher humidity conditions). This means that at room temperature (at which mechanical properties are tested) the adhesives are in their glassy state. Hence, the mechanical performance is less affected by humidity.

The more often a batch of Isinglass is heated, the lower its modulus. For this reason, this study evaluated the sensitivity to peel stress of an Isinglass batch at room temperature at three different moisture conditions after being heated three consecutive times (Isinglass 1, 2 and 3). It was observed that the peel strength decreased, while the sensitivity to moisture remained equal.

The comparison of the moisture uptake and the measured average lap shear stress of natural adhesives to synthetic ones, revealed that the difference in their performance is likely related to the intrinsic properties of the adhesive, as well as the environmental humidity. Some remarkable variation of the shear strength in different environmental conditions can be observed, particularly for the adhesives with T_gs that are well below the mechanical testing temperature and also the adhesives that demonstrate high moisture uptake.

The effect of moisture on the failure mode is related to both the adhesion to the substrate and the sensitivity to moisture uptake of the adhesive (and adherend). Moisture uptake by adhesives leading to increased plasticity and the tendency to an increased cohesive failure mode is demonstrated in the case of Klucel® G and Gelatine. Though after a prolonged exposure to very high humidity moisture ingress might lead to interfacial failure, visible with BEVA® 371 b and Isinglass.

3.4. Influence of RH on T-Peel strength

Testing the bonded canvas substrates revealed that after a week of exposure no measurable changes in the T-peel strength occurred within the STD, with the exception of rabbit skin glue and Jade®. This is partly due to the large STD found. The data of Isinglass 2 and 3 as well as

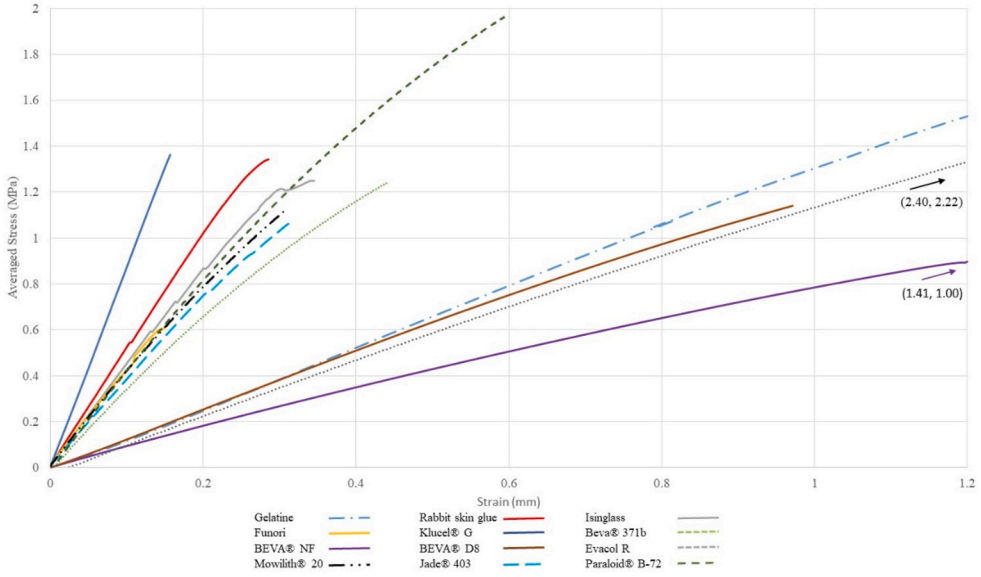


Fig. 3. The averaged stress - strain curves of the tested adhesives (55% RH, 25 °C).

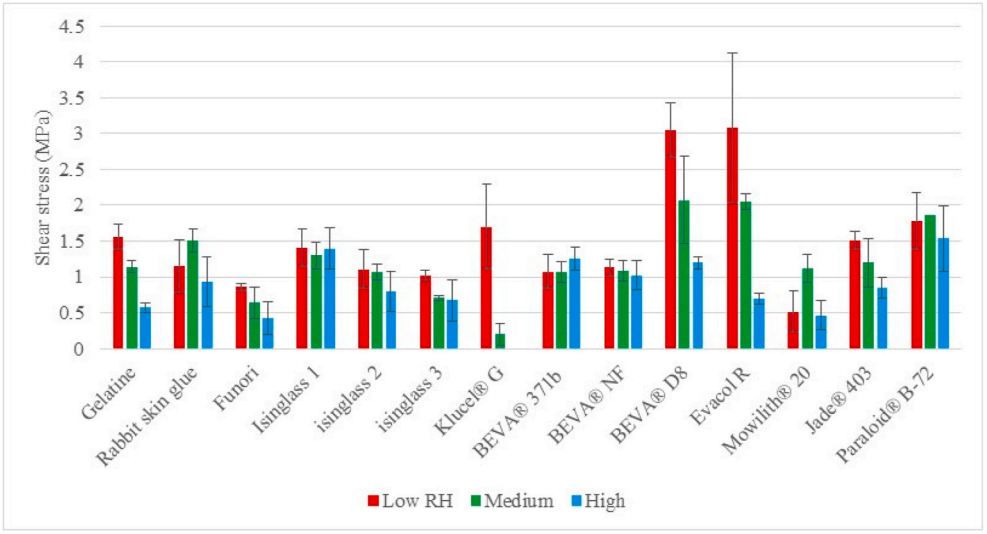
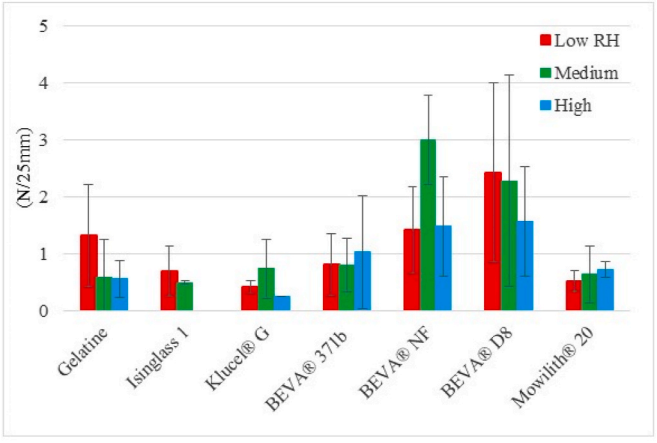


Fig. 4. Averaged lap shear test results (wood – wood) after exposure to three different humidity environments (6%: low, 55%: medium, 85%: high).

Funori are not shown in Fig. 5, as they failed cohesively as a result of brittleness before testing.



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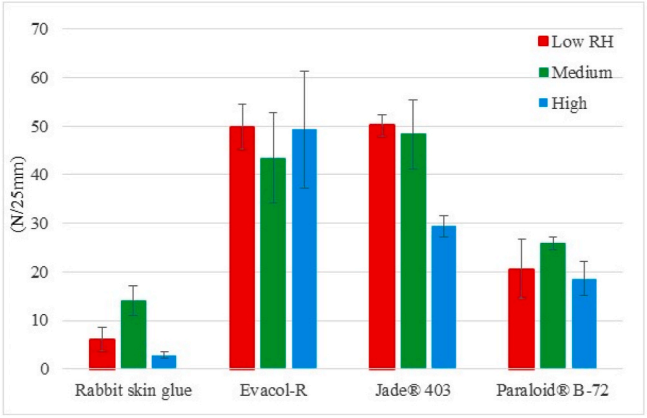

B

Fig. 5. A, B, Averaged T-peel test results (canvas-canvas) after exposure to different RH environments (6%: low, 55%: medium, 85%: high) for synthetic and natural adhesives with the lower values in Fig. 5A and the higher values in Fig. 5B (bottom).

Some adhesives like Jade® showed a clear change in T peel strength (Fig. 5) but not as much in failure type (Table 5) as a result of the moisture exposure. Within the very large STD the average peel values of most adhesives did not show dramatic changes, though the failure types (Table 5) indicate that the loss of peel strength of the natural adhesives is the effect of a loss of cohesive strength. An increasing interfacial failure of the synthetic adhesives was visible due to moisture ingress on the interface. In general, the uptake of moisture showed some loss of the average failure load. However, the extremely dry environment also showed a loss of strength of the animal glues as the lack of water molecules between the polypeptides of the triple helices lead to a loss of interactions and thus embrittlement.

Mowilith® 20, was found to be the only tested adhesive that showed a 100% cohesive failure throughout.

3.5. Adhesive selection

The DSC and moisture uptake data, along with mechanical test results, demonstrated that moisture sensitivity often changed the thermal transition temperatures, especially in the case of natural adhesives. Moreover, it was shown that moisture can affect the mechanical performance of synthetic adhesives, particularly the ones with glass transitions well below the room temperature such as BEVA® D-8 and Evacol R.

Table 6 enables one to quickly compare the tested adhesives based on their measured mechanical properties at room temperature but at different RHs. Please note that this table only gives a global indication of the tested adhesives, as their behavior depends strongly on many variables such as: adherend type, surface preparation, batch type, concentration, solvent or water content, exposure time, etc. It is meant to help give conservators some guidance when choosing an adhesive, if they are aware of the type of forces (shear and/or peel) working upon the bond as well as the environment it will be exposed to.

It can be concluded that rabbit skin glue, Jade®, Evacol R, and Paraloid® B-72 can withstand the highest shear and peel forces. and Klucel® G and Isinglass being the most sensitive to moisture.

4. Conclusions

This research linked the mechanical performance of lap shear and T peel loading of a number of commonly used natural and synthetic commercially available adhesives for the conservation of art and cultural heritage to their physical properties determined by DSC and

Table 4
Indicative percentage of failure type of the lap shear wood – wood substrates. Cohesive inside the adhesive, interfacial, or of the (wooden) adherend, as a function of the exposure to an environment of low (6%), medium (55%), or high (85%) RH.

Environment	Dry environment			Lab condition			Moisture exposure		
Failure Type (%)	Adhesive	Interface	Adherend	Adhesive	Interface	Adherend	Adhesive	Interface	Adherend
Gelatine	30		70	40		60	100		
Rabbit skin glue	20		80	100			100		
Isinglass 1	60	40		40	60		80	20	
Isinglass 2	60	40		40	60		80	20	
Isinglass 3	60	40		40	60		80	20	
Funori	80		20	100			100		
Klucel® G	60	40		80	20		100		
Beva® 371b	45	15	40	50		50	90	10	
BEVA® NF	100			100			100		
BEVA® D8	20		80	20		80	90		10
Evacol R	10		90	50		50	100		
Mowilith® 20	100			100			100		
Jade® 403	80		20	100			100		
Paraloid® B-72			100	40		60	60		40

Table 5
Indicative percentage of failure types of the canvas-canvas T-Peel substrates as a function of the exposed environments. Cohesive inside the adhesive, interfacial, or cohesive inside the canvas adherend, as a function of the exposure to an environment of low (6%), medium (55%), or high (85%) RH. Adherend failure indicates fibres torn out of the canvas surface layer.

Environment	Dry environment			Lab condition			Moisture exposure		
failure Type (%)	Adhesive	Interface	Adherend	Adhesive	Interface	Adherend	Adhesive	Interface	Adherend
Gelatine	90	10		90	10	5	100		
Rabbit skin glue	90	10		90	10		100		
Isinglass 1	95	5		95	5		100		
Funori	90	10		90	10		100		
Klucel G	90	10		90	10		100		
Beva® 371b	100			100			100		
BEVA® NF	90		10	90		10	90		10
BEVA® D8	90		10	90		10	100		
Evacol R	90		10	100		10	100		10
Mowilith® 20	100			100			100		
Jade® 403	85		15	85		15	90	10	
Paraloid® B-72	100			95		5	90		10

Table 6
Test results combining lap shear (wood to wood) and peel (canvas to canvas) strength showing the optimum performance of the tested adhesives when either loaded in shear or peel stress and their relative sensitivity to RH. (legend: ++: very good, – –: very poor).

Adhesive	Wood - Wood	Canvas - Canvas	Resistance to moisture ingress
Gelatine	+ +	– –	–
Rabbit skin glue	+ +	++	+/–
Isinglass	+	– –	+/–
Funori	+	– –	–
Klucel® G	–	– –	– – –
Beva® 371b	+ +	–	++
BEVA® NF	+ +	+	++
BEVA® D8	+ +	+	–
Evacol R	+ +	++	– –
Mowilith® 20	+	–	–
Jade® 403	+	++	–
Paraloid® B-72	++	++	–/+

moisture adsorption at room temperature and at three different RHs.

Evacol R, Paraloid® B-72 and rabbit skin glue were found to obtain the overall strongest average adhesive bonds in both shear and peel loading at 55% RH. At peel loading Evacol R, Jade® 403 and Paraloid® B-72 were found to be stronger than the natural adhesives, though rabbit skin glue showed the overall best mechanical performance of all tested natural adhesives at 55% RH.

It was shown that moisture affects the mechanical performance of the tested natural adhesives, and can affect the mechanical performance of synthetic adhesives, particularly the ones with glass transitions well below room temperature such as BEVA® D-8 and Evacol R.

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