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ORIGINAL RESEARCH OR TREATMENT PAPER

A Comparative Study of Bond Strength, Reversibility, and Projected Long-Term Durability of Lining Techniques for the Structural Stabilisation of Canvas Paintings

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ABSTRACT

Lining techniques for the treatment of structurally damaged canvas paintings have been in use since at least the seventeenth century, with on-going invention, development, and refinement. These systems can be categorised based on their adhesive component – natural or synthetic – or by their application procedure, such as water-based, hot-melt, cold-lining, nap-bond lining, or mist-lining. The choice of lining system is often influenced by geographical practice and individual expertise rather than purely material-technical considerations, as comprehensive data for benchmarking different systems is limited in both literature and practice. This paper aims to address this gap in knowledge by comparing various lining adhesives and their application techniques. The adhesives under examination include glue-paste, wax-resin, BEVA® 371, Plextol® B500, and Dispersion K360:Plextol® D512. Mock-linings were designed to reduce variables and ensure standardisation. Previously reported recipes and descriptions of studio application techniques were used where possible to create the mock-linings. These were subsequently subjected to stress/strain through exposure to cyclic fluctuations in relative humidity (RH) and temperature (T) to simulate mechanical-physical ageing. Both unaged and aged samples underwent lap-shear and T-peel tests according to ASTM standards, as reported in earlier studies. The data presented here can assist conservators and scientists in establishing requirements and making informed decisions tailored to the specific needs of each painting. Results indicate that each lining technique has its own limitations, and the suitability of a given technique will depend on the type of treatment necessary for stabilising individual paintings.

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Introduction

Lining, the process of adding a textile support to the reverse of a canvas painting, has significantly changed since the seventeenth century when it was first reported as a stabilisation method for painted textiles. Lining procedures serve a range of purposes, including providing structural reinforcement, addressing paint layer issues, and acting as preventive measures. Over the years, adhesives, approaches, methods, tools, and materials have evolved, with innovations regularly introduced and implemented by new generations of conservators, reflecting the ever-changing practice of structural treatment of canvas paintings. This progression is based on technical studies and an increasing understanding of the material-technical properties and chemical–physical-mechanical forces applied to (lined) paintings. While a comprehensive review of the history and use of different lining systems is beyond the scope of this paper, a summary is provided in the following sections that guided the methods used for creating mock-linings in this paper.

Today, the structural repair of canvas paintings is often carried out by specialists, resulting in a diminishing understanding and practice of this at times necessary technique. Contributing factors to this current state of affairs include the shift over the past half-century towards minimal intervention and avoidance of unnecessary treatments; a multitude of techniques and a scarcity of training in lining; and the lack of comparative data juxtaposing the different systems currently in practice. This paper aims to address the latter aspect, providing comparative data for conservators to evaluate traditional and modern lining systems used in stabilising degraded or damaged canvas paintings. Extracting such comparative data from existing literature has been challenging due to the lack of consistency across pre-existing studies – from different methodologies for obtaining data, including mechanical-physical tests of laminate structures and chemical

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ageing of constituent materials, to the use of different instruments and settings for testing samples, and divergent manners of reporting results.

To address these issues, for this first study the authors employed a consistent methodology to create mock-linings, minimising variables to yield both quantitative and qualitative results. Both historically practiced lining systems, such as glue-paste and wax-resin, as well as more modern ones utilising synthetic adhesives were selected. Current practices in application for each system were employed, specifically focusing on the adhesive's bonding strength to the canvas adherends, providing a clear comparison while keeping all other conceived variables constant. A custom prepared linen textile was used to simulate the original canvas painting, with a medium weave linen textile to replicate the lining canvas. Five commonly used adhesives in lining systems were chosen for comparison: glue-paste, wax-resin, BEVA® 371, Plextol® B500, and a 1:1 mixture of Dispersion K360 with Plextol® D512. All mock-linings were created by the same team of conservators, within the same time-frame, under the same environmental conditions to ensure consistency. Detailed descriptions of each mock-lining system are provided in dedicated sections of this paper. One set of mock-linings was retained as a reference, while a second set underwent stress–strain cycles to simulate the mechanical-physical behaviour of a restrained, mounted painting. Both aged and unaged samples were subjected to mechanical testing to assess differences in shear and peel strength of the adhesives. Identical instruments and settings were used to ensure comparability and produce a robust dataset. Additional sets for each lining system examined were created for future research.

While lining techniques and adhesives constitute a broad field of study, this research concentrates on a select few techniques and areas. The primary objective is to provide a set of standardised, comparable data previously absent within the existing literature, that can serve as a foundation for future studies encompassing additional lining techniques, adhesives, textiles, and variations. This new data will enable conservators to make informed decisions when selecting lining systems or evaluating existing linings. However, the results should not be considered definitive for making choices in the complex and nuanced practice of canvas painting conservation.

A brief history of lining systems

Glue-paste adhesives, using a mixture of collagen glue with flours, have been prevalent for lining since the seventeenth century. The system mitigates consolidation issues in the pictorial layers and improves surface deformations, in addition to providing additional support to the original canvas. This technique is most widely practiced by conservators in Europe but has found traction globally through both indigenous practice and dissemination (Hackney et al. 2012, 417). Although the precise origins of glue-paste linings are challenging to trace, they have stood as a fundamental practice in canvas conservation, significantly contributing to the protection of countless artworks over generations. Distinctive schools of glue-paste lining had emerged in countries such as Italy, France, Spain, Russia, and the UK by the mid-eighteenth century, leaving indelible marks in contemporary conservation literature (Calvo et al. 2023, 145; Cerasuolo 2023, 39; Massing 2016, 287; Newman 2003, 30; Reifsnyder 1995; Yurovetskaya 2023, 145). Each nation developed its unique approach to lining, characterised by nuanced differences in the proportions of collagen glue to flour, choice of flour (s), inclusion of additives, and selection of lining textiles. Application techniques can vary from region to region, country to country, and city to city. The technique remains widely practiced even today, in countries with well-established glue-paste lining traditions, underscoring its enduring importance in art conservation practices. However, the system is not without its challenges. The inherent use of moisture within the adhesive is seen as both beneficial and detrimental. Issues such as moisture-related shrinkage upon application, vulnerability to long-term mechanical changes, and infestation by insects or mould pose on-going concerns (Fuster-López et al. 2017, 9). Current research has shown that synthetic additions to the glue-paste adhesive mixture can mitigate application issues, reducing the amount of moisture used within the system (Rossi-Doria 2023, 81).[1] A more traditional, widely reported recipe was selected for experimentation within this study as this was considered more representative and had been studied extensively in previous studies (Ackroyd 1995, 84; Fuster-López et al. 2017; Poulis, Seymour, and Mosleh 2020, 8).

The pioneering introduction of *wax-resin linings*, employing a combination of beeswax and natural resin, by Nicolas Hopman (1794–1870) and his son Willem Anthonij Hopman (1828–1910) in The Netherlands marked a watershed moment in the practice of lining in Northern Europe (van Duijn and te Marvelde 2016, 813). This innovative technique quickly gained widespread recognition and adoption beyond Dutch borders. By the early twentieth century, linings utilising the so-called Dutch method had proliferated across continents, including in the UK, North America, Central America, Southern Africa, and Asia (te Marvelde 2001, 147; van Oudheusden 2014). Originally heralded as a comprehensive solution to moisture-related issues afflicting paintings in damp conditions, and applied often as a preventative measure, recent research has revealed limitations. Contrary to earlier beliefs, paintings lined with this system are not immune to moisture sorption, and lined paintings demonstrate significant tonal shifts (Andersen et al. 2019, 66; Bomford and Staniforth 1981, 58; Froment 2019, 407). The once-dominant lining system of the early to late twentieth century has gradually fallen out of favour in Northern Europe and North America although still prevalent in South and Central America (Paiva, Aguiar, and Vieira 2021, 87). A widely reported and previously published recipe was selected for testing within this study (Poulis, Seymour, and Mosleh 2020, 8; Young and Ackroyd 2001, 85).

In the early 1970s, Gustav Berger (1920–2006) introduced *heat-seal lining* with BEVA® 371, an ethylene vinyl acetate copolymer (Berger 1972; 2003, 49). Formulated specifically as an adhesive for conservation applications, BEVA® 371 was developed based on research funded by the Samuel H. Kress Foundation, carried out at the Conservation Center of New York University Institute of Fine Arts, in the late 1960s (Berger 1975). The original formulation was patented and is currently licenced to C.P.C (U.S.A.) and C.T.S (Italy) for sale and distribution. Since its introduction to the conservation field, BEVA® 371 in all its forms has found widespread use due to its availability and versatility, ease of use in various conservation processes, including lining, strip lining, consolidation, and facing in paintings conservation. It was designed to have different softening and melting temperatures which made it adaptable for various purposes (Ackroyd 2002, 4; Hackney 2020, 88). When used as a lining adhesive, typically, the softening temperature of the original formulation is 65–68°C. At this temperature, the adhesive should not liquify and remain between the original canvas, thus creating a 'nap-bond'. In practice, BEVA® 371 is often applied in liquid form (either heated or in solution) or as a pre-cast commercially available film to both the original canvas and the lining textile, and when used at higher temperatures will inevitably impregnate both canvases.

However since the 1970s, BEVA® 371 has been reformulated multiple times, leading to differences in the softening and melting temperatures due to the substitute ingredients from Berger's original formulation (Ploeger et al. 2014, 307; Ploeger, McGlinchey, and de la Rie 2014, 217). Since 2009 conservators have been using a commercialised version called BEVA® 371 O.F. (also known as BEVA® 371b) (Solution) produced in Europe by C.T.S. (Italy) and in North America by C.P.C (U.S.A.). A new formulation is being developed utilising funding provided by the Getty Foundation under its Conserving Canvas initiative (research is on-going at the time of writing this paper).[2] Within this study, BEVA® 371b (as produced and distributed by C.T.S., Italy) as well as BEVA® 371 Film were used as lining adhesives.

In the early 1970s, at the same time as Berger, Vishwa Raj Mehra (1931–2021) was researching a *cold-lining system* using Plextol® B500, a methyl methacrylate/ethyl methacrylate copolymer to combat issues related to heat, moisture, and/or pressure using nap-bonds (Mehra 1975; 2003, 121). In a cold-lining, bonds are typically achieved through the use of solvent to tackify the adhesive, allowing it to adhere the lining material to the original canvas without the need for heat, though under pressure. While Mehra's adhesive and lining process was far from simplistic, his approach to structural repair of paintings moved towards minimal intervention and placed emphasis on pre-treatments such as flattening, tear repair, and consolidation. This approach gained traction in Denmark and The Netherlands in the 1980s and became preferred among practitioners in these countries (Scharff 1995, 48; 2023, 18). Nap-bond linings, where the adhesive is restricted between the original canvas and the lining textiles began to be explored and developed. Plextol® B500 was also considered an essential inclusion within the current study. However, due to the complexity and scarcity of practice of Mehra's application process, the authors chose to apply the adhesive in the same manner as mist-lining within this study.

The *mist-lining system*, developed in The Netherlands in the 1990s, embodying the cold nap-bond lining philosophy, utilises Plextol® acrylic adhesives applied as a fine mist and regenerated with solvent vapours (van Och and Hoppenbrouwers 2003, 116). It simplifies the process of solvent regeneration introduced by Mehra through the utilisation of a solvent-vapour delivery cloth placed in contact with the already positioned lining canvas in an enclosed environment. This innovation eliminated the need to spray solvents to the adhesive and more importantly, reduced the volume of solvents used during activation. Furthermore, the application system used to apply the acrylic adhesive in the mist-lining system reduced the amount of adhesive required to achieve a bond between the two canvases. The spray application creates a volumetric network of adhesive tendrils that connect to the enhanced nap of the lining canvas to the reverse of the original. When tackifyed using solvent vapours, the two canvases are pressed together using low-pressure in an envelope. The adhesive tendrils create a point-to-point bond between the two canvases.

The mist-lining system was originally developed using two copolymer acrylic dispersions: Plextol® D360 and Plextol® D541. Both polymers contained the same copolymer resin but differed in molecular weight. This original binary system produced an adhesive mixture with a glass transition temperature (Tg) between the lower and higher molecular weight resins. However, these adhesives, along with their substitutes, are not manufactured anymore. The current formulation employs a mixture of Dispersion K360 and Plextol® D512. Recent research has shown that, despite the acrylic polymers not being based on the same copolymer, there is no adverse chemical interaction between these materials when mixed (Seymour et al. 2022, 146). On-going studies are assessing the long-term performance of these resins within the mist-lining system and results have confirmed the viability of these materials. For the study reported in this paper, the current mist-lining formulation was utilised.

After the momentous 1974 Greenwich Conference, there was a call for a moratorium on linings (though not imposed) to evaluate the consequences of linings on paintings, with alternative procedures such as strip lining, tear-mending, or loose linings being advocated (Ackroyd 2002, 8; Bustin and Caley 2003; Hackney 2004; Villers 2003). Despite evolving practices and criticisms, the tradition of lining structurally damaged canvas paintings endures into the twenty-first century as it is an indispensable treatment process. While certain traditions and practices are now approached with more caution, it is nevertheless important for conservators to understand traditional and modern lining techniques and their consequences on artworks. The 2019 *Conserving Canvas Symposium* at Yale University was the second conclave on the structural treatment of canvas paintings which sought to bring together conservators from all over the world and revisit these practices. A trend that could be inferred from the conference is that Southern European countries maintain the use of glue-paste linings, while South American practitioners favour wax-resin as the primary adhesive. In contrast, Northern European and Northern American conservators have transitioned away from wax-resin linings towards synthetic adhesives, such as BEVA® 371 or acrylic dispersions, applied to create a nap-bond. Information on past and current lining practices in Asia, Africa, Australia, and South America is scarce. Informal conversations with other conservators give mixed answers on what happens in other parts of the world; however, much information remains undocumented.

Establishing benchmarks for lining practice

The variety of historical and regional lining techniques has contributed to on-going uncertainty about the most effective approach to lining canvas paintings. Established literature from the latter half of the twentieth century suggests that both the lining material (textile and adhesive) should be stiffer than the canvas, priming, and paint layers to adequately support the imposed stress and strain over time (Ackroyd 2002, 7; Hedley 1981, 81.2.2–2; Michalski and Hartin 1996, 288; Young, Hibberd, and Ackroyd 2002, 377). Historically, lining was often performed not only to reinforce a failing canvas support, but also to consolidate ground and paint layers in one step. This was typically achieved through high temperatures causing the adhesive to melt and flow freely, often resulting in the adhesive impregnating the canvas threads and weave interstices of the original support as well as other layers in the painting. While this approach was intended to provide structural support, the unintended consequence was that the fluid adhesive could alter colour and saturation of the paint layers. Moreover, full impregnation of the adhesive often resulted in rigid structures, making it challenging to reverse such linings without damaging the original artwork. The advantage of transferring the load of the painting to the non-original textile, can be outweighed by the potential issues of removal or reversibility of the lining. Although theoretically the lining canvas could be removed by reactivating the adhesive and applying peel force, the adhesive that permeated the canvas threads and weave interstices of the original support remains difficult to remove.

In contrast, a nap-bond lining technique applies the adhesive only to the surface fibres of both the original canvas and the lining without penetrating the textile structure. This method goes further in preserving the integrity of the original structure facilitating easy removal and re-treatment, although resulting in a less stiff and therefore more flexible lining. This approach diverges from the rigid criteria outlined by researchers in the latter part of the twentieth century and suggests a need for a revised perspective on lining techniques (Seymour and van Och 2005, 103; Young 1999, 84). Linings utilising true nap-bonds may not effectively address planar distortions or cupped paint during the lining process. In such systems, deformations in the support or paint layers should be addressed separately before the lining is applied, through pre-treatments, strategically placed interleafs, or local reinforcements for a successful lining.

The field of conservation is characterised by divergent schools of thought regarding the selection of materials for lining, which profoundly impact decisions about bonding and rigidity. The complexities associated with lining canvas paintings raise fundamental questions about the ideal parameters for bond strength and rigidity. Key questions include: What constitutes minimal sufficient bond strength? How rigid should the lining be? Can reducing the amount of adhesive, whether through continuous or discontinuous application, still effectively secure both the lining and the original canvas while addressing planar deformations in the original support? Is there a universally applicable standard of excellence in lining systems? Does a superior or inherently 'better' lining system exist, or are there varying degrees of effectiveness among the systems practiced globally? Furthermore, which systems can be confidently recommended, and which should be approached with caution or avoided entirely? These questions continue to provoke debate and shape the on-going evolution of the structural treatment of canvas paintings.

The ambiguity surrounding lining techniques in conservation arises from a combination of divergent conservation philosophies and historical practices across different countries, as well as a lack of comparative data. This has led to certain lining techniques being more widely adopted than others. Conservators often rely on familiar methods and their own experience, partly due to scepticism about newer techniques and uncertainties regarding their long-term durability. Additionally, the specific requirements for each painting can vary widely, from simple reinforcement to more extensive mechanical and structural support. Factors such as the availability of materials, tools, and resources also significantly influence the choice of lining technique and adhesive. As a result, the selection of a lining method remains subjective and varies among practitioners.

Despite these challenges, some literature attempts to provide guidance on various aspects of lining, including adhesives, textiles, and the overall process. Several studies have compared the performance of different lining treatments and offered theoretical guidelines on bond strength (Hartin, Michalski, and Pacquet 1993, 132; Phenix and Hedley 1984, 84.2.38–44; Poulis, Seymour, and Mosleh 2020, 8; Young and Ackroyd 2001, 85; Young, Hibberd, and Ackroyd 2002, 377). However, these studies often differ in their testing parameters – such as peel rate, peel configuration, and the types of adhesives used – making direct comparisons difficult. Thus, while valuable, existing research does not offer a unified standard or conclusive recommendations for lining techniques. Additionally, a previous study conducted by the authors assessed samples of acrylic dispersions as a spray application (mist-lining) and mist-lined paintings over the last 30 years (Seymour et al. 2022, 149; Shah 2021, 72). Despite mist-lining being characterised as a weaker system with lower peel strengths, the examined paintings have remained intact and well-tensioned, without exhibiting planar deformations, across a range of controlled and uncontrolled environments, including museums, churches, and historic house interiors. This review raises questions about the adequacy of current baseline standards in the field. Could it be that weaker, more flexible linings are acceptable? Should a single rigid standard be replaced with a range of values that conservators can select based on the specific needs of each painting? Such flexibility would allow for a balance between rigidity and load transfer, reduced impregnation, and ease of removal, potentially offering more nuanced and adaptable conservation solutions.

A standardised, replicable study comparing the shear strength, resistance to peeling, and removability of different lining techniques for canvas paintings is long overdue. This research seeks to fill this knowledge gap by focusing on various lining techniques prevalent in current standard studio practice. It is essential to clarify that this study does not seek to identify the 'best' lining technique, as the most appropriate method depends on the specific requirements of each painting. Instead, the objective is to provide a thorough examination of the mechanical behaviour associated with several prevalent lining techniques. The aim is to equip conservators with detailed insights that will help them recognise trends and make well-informed decisions. Based on an exhaustive review of literature, the following lining techniques were chosen for investigation: glue-paste (*GP*), wax-resin (*WR*), BEVA® 371 O.F hot-seal adhesive (diluted with white spirits 1:1) (*B(Dil)*), BEVA® 371 Film (*BF*), Plextol® B500 (*PB500*), and acrylic dispersions (1:1 vol:vol Dispersion K360: Plextol® D512) (*ML*) applied using the mist-lining approach. The study employed well-established formulations for glue-paste and wax-resin adhesives.

There are four research questions posed here: What is the shear strength of the adhesives? What is the peel resistance of the adhesives? What is the ease of reversibility of the linings? What is the durability or (simulated) long-term performance of the adhesives?

Methods and materials

Sample preparation

Six lining systems and five adhesives were investigated using mock-linings designed to function as a physical model of a laminate canvas painting. The mock-linings are used to visualise and evaluate the design, structure, or functionality of the tested lining systems, which necessitate destruction during the testing phase. This prohibits using actual historical canvas paintings. They were made by the same team of conservators using identical equipment, adhering to typical studio practices for each specific lining procedure. The entire lining process was meticulously photographed and video-documented, and this documentation is available upon request for replication purposes.

- A custom-made primed canvas with a weave count of 20 warp x 20 weft per 1 cm^2 was specially ordered from Claessens Canvas, Belgium, and utilised to mimic 'the painting' in each mock-up. A similarly prepared canvas had been used in a previous study comparing the performance of glue-paste mixtures (Fuster-López et al. 2017). The primed canvas was prepared in 2021 and used in 2022 for the experiment. It was constructed using a medium weave linen that was sized with a natural hide glue (applied hot) and subsequently primed with a double ground, comprising two oil-bound layers: the lower layer containing zinc white and the upper layer containing titanium white. These specifications were chosen to closely replicate the typical mechanical-physical behaviours of linen canvas when subjected to mechanical-physical forces.

- The lining textile consisted of a medium weave lining canvas with a weave count of 17 warp x 17 weft per 1 cm^2 purchased from Claessens Canvas, Belgium. This textile was not de-crimped.
- For each mock-lining, the lining canvas was stretched on a working loom (90 × 120 cm). A standardised stretching system was implemented to ensure that all lining canvases were tensioned to the same degree (Seymour and Strombek 2022, 24). The primed canvas (75 × 105 cm) was lined untensioned with the warp and weft aligned with that of the lining canvas.
- While certain non-standard ingredients may have a role to play in the long-term behaviour of certain lining adhesives, it was not within the scope of this research project to be able to consider them. Therefore, all lining techniques were limited to one application technique to reduce variables and sample sizes.

To keep the samples as consistent as possible, with the lining adhesive being the only variable, it was decided not to face the paintings during the lining procedures.

Table 1 gives an overview of the lining adhesives, recipes, and procedures used for the mock-linings.

Glue-paste lining – A traditional hand-lining method was employed for this mock-lining. The adhesive comprised of 1 part animal glue, 6 parts wheat flour, and 36 parts water (weight) and the mixture was cooked to a thick paste consistency at 40°C as described in the study conducted by Fuster-López et al. (2017). The adhesive was applied cold to the reverse of the primed canvas and the lining canvas by hand. The excess adhesive was removed using a rubber squeegee. The two canvases were placed together with the adhesive surfaces facing each other and ironed face-up. An absorbent paper was placed beneath the two canvases on top of a sheet of siliconised Melinex® to absorb moisture while the front was ironed at 45°C, airing the structure at intervals until the moisture had evaporated. The Melinex® ensured that the canvas did not adhere to the table during ironing.

Wax-resin lining – A traditional wax-resin hand-lining method was employed for this mock-lining.[3] The adhesive consisted of natural beeswax, dammar, and gum elemi in the ratio 3:2:1 (weight). The mixture was melted in an *au bain-marie* pan and applied with a wide brush to the reverse of the primed canvas and the lining canvas in brick-like formation. Each canvas was ironed independently to achieve an even layer of adhesive. Both canvases became fully saturated with the adhesive mixture. The two canvases were then placed together, with the adhesive surfaces facing each other. A sheet of siliconised Melinex® was used to ensure the canvas did not adhere to the table surface. The painting surface was protected with sheets of paper and ironed on both sides until the wax-resin was seen to penetrate through to the front and then immediately cold-set under weights as the adhesive cooled.

BEVA® 371 lining – Two types of BEVA® 371 lining were carried out. BEVA® 371 Hot-sealing adhesive was diluted with white spirits (17% aromatic content) in a 1:1 ratio (weight: volume). Four applications of the diluted adhesive were applied on the lining canvas with a roller to ensure an even layer. The adhesive was applied only on the lining canvas and not to the back of the primed canvas. For the BEVA® 371 Film lining, the film was cut to the desired measurement and placed between the primed

Table 1. Lining adhesives, recipes, and procedures used in preparation of mock-linings.

Sample name and code	Adhesive recipe	Application	Reactivation of the adhesive
Glue-paste (GP)	1 part glue (rabbit skin glue from Kremer Pigmente) + 6 parts fine wheat flour (Grade 00)	Cold cooked glue-paste applied on both primed canvas and lining canvas	Heat (~45°C) – using hand-irons
Wax-resin (WR)	Natural beeswax, dammar, and gum elemi in the ratio 3:2:1	Melted wax-resin mixture applied in brick-like formation to both primed canvas and lining canvas	Heat (~60°C) – using hand-irons
BEVA® 371 (B(Dil))	BEVA® 371 (O.F from C.T.S. bought at Kremer Pigmente)	Four layers applied on the lining canvas	Vacuum hot table (68°C and 55 mbar)
BEVA® 371 film (BF)	BEVA® 371 Film, Thick (65 µm) (Kremer Pigmente)	Film sandwiched between primed canvas and lining canvas	Hot vacuum table (68°C and 55 mbar)
Plextol® B500 (PB500)	250 mL Acrylic Dispersion B500 (Deffner & Johann)	Sprayed on fluffed lining canvas	Reactivated with ethanol (99.8% HPLC grade) (Fisher Scientific) in a low-pressure envelope (20 mbar)
Dispersion K360/ Plextol® D512 (1:1 vol) (ML)	1 part Acrylic Dispersion D512 (Deffner & Johann) + 1 part Dispersion K360 (Deffner & Johann)	Sprayed on fluffed lining canvas	Reactivated with ethanol (99.8% HPLC grade) (Fisher Scientific) in a low-pressure envelope (20 mbar)

canvas and lining canvas. The activation of the adhesive for both linings was done on a heated vacuum table (Elkom GmbH) with a pressure of 55 mbar and a temperature of 68°C. The aligned canvases were first placed under vacuum before heat was applied and the pressure was retained until the heat had dissipated after lining.

Acrylic dispersions: Plextol® B500 and Dispersion K360/Plextol® D512 – The Plextol® B500 and the 1:1 ratio of Dispersion K360 and Plextol® D512 were applied using a spray application according to the mist-lining method practiced at SRAL (Seymour et al. 2022, 146). The lining canvas was stretched on a working loom, the dimensions of the primed canvas marked on it, the excess areas on the lining canvas were masked, the lining canvas lightly sanded to enhance its nap, and the lining adhesive (250 mL) sprayed onto it with a spray gun attached to a compressor. The dispersed adhesive droplets adhere only to the upstanding nap of the lining canvas and do not impregnate the textile weave. The water content of the adhesive was allowed to evaporate before lining. For lining, the two canvases were aligned, and a low-pressure envelope was prepared. The adhesive was reactivated with ethanol (99.8% HPLC grade) (60 mL/m^2), using solvent vapour via a solvent delivery cloth placed under the aligned canvases until the adhesive tackified (∼20 min) and removed. The two canvases are then kept under low-pressure (20 mbar) until the adhesive cured through solvent evaporation. Air is extracted from between two plastic sheets using an air extractor during the curing process. The plastic sheets conform to the surfaces providing light pressure, which is sufficient to bring the two canvases in close contact with each other so that the adhesive bridges the gap between the two textiles.

Following the lining process, the mock-linings were left on their working stretchers under tension for a period of four months. During this period, the mock-linings were maintained under studio environmental conditions, with relative humidity (RH) between 45 and 60% and temperature between 20 and 22°C. After four months, the mock-linings were removed from the working stretchers and divided into four sections (See Figure 1 Section A). Each section was designated for a specific purpose. One section was preserved for testing without exposure to mechanical-physical stress–strain forces. Another section was stretched on a smaller stretcher and subjected to cyclic fluctuations of stress–strain (as detailed in the section on mechanical-physical ageing below) to simulate mechanical-physical ageing. Sample strips for lap-shear and T-peel tests were cut from both sections (Figure 1(B and C)). The remaining two sections were retained as reference sets for natural ageing: one mounted under tension on stretchers and the other kept untensioned for future research. These reference sets continue to be stored under the same studio environmental conditions.

Mechanical-physical ageing

Chemical ageing of the adhesives through prolonged light / UV exposure was not chosen for this study because the adhesive is situated between two layers of canvas, making it inaccessible to light. Thermal ageing was also avoided because exposing adhesives to temperatures above their softening points can cause them to melt and even liquify, resulting in a failed lining. The glass transition temperature (Tg) of each adhesive was carefully considered when designing the artificial ageing parameters.[4]

Table 2 gives an overview of glass transition temperatures (Tg) and melting temperatures (Tm) of the adhesives used in this research from previously published studies by the authors (Poulis et al. 2022, 117; Poulis, Seymour, and Mosleh 2022, 114). All

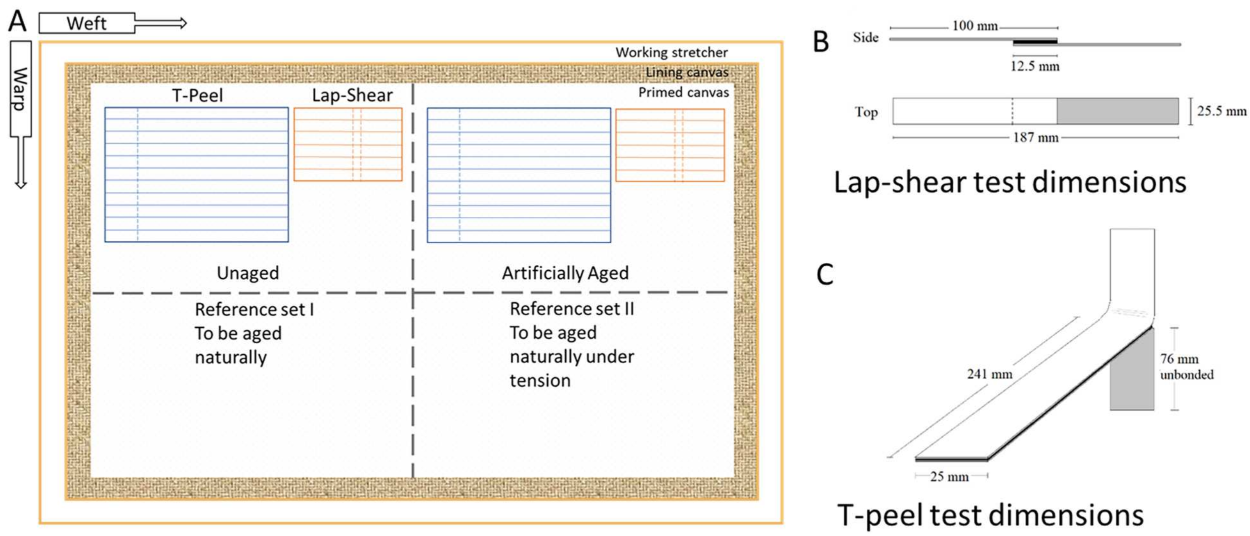

Figure 1. The mock-lining samples and how they were prepared for different tests.

Table 2. Glass transition (Tg) and melting temperatures (Tm) of the tested adhesives.

Adhesive	Glass transition temperature (Tg) (°C)	Melting Temperature (Tm) (°C)
Wax-resin (WR)	–	48.0 ± 0 and 60.0 ± 0
Glue-paste (GP)	47.5 ± 0.5	85.0 ± 0
BEVA® 371	−28.0 ± 0.5	56.0 ± 0 and 65.0 ± 1
Plextol® B500 (PB500)	−30.0 and 25.0 ± 2	55.0 ± 1
Dispersion K360	−31	–
Plextol® D512	26	–

temperature values are expressed in degrees Celsius. Tg and Tm values were obtained using differential scanning calorimetry (DSC) on a TA Instrument DSC 250 and were carried out by Yasmine Mosleh at TU Delft, The Netherlands. Some adhesives exhibit two temperature values for Tg and Tm, indicating that different components within the mixture behave differently. Melt temperatures for the acrylic dispersions were not identified.

Therefore, to introduce stress/strain cycles in the mock-linings and simulate mechanical-physical ageing, cyclic temperature and relative humidity conditions were selected. This protocol, designed to induce mechanical-physical stresses, was originally developed by a group of conservators for the International Lining Project and used in a study of glue-paste linings by Fuster-López et al. (2017, 2). It involves successions of 'warm and wet', 'warm and dry', 'cold and dry', and 'cold and wet' conditions to maximise mechanical stress on the adhesives and canvases, replicating the conditions real-world lined paintings experience in uncontrolled environments. The same protocol was replicated in this research, including not ageing the primed canvas before lining to reduce variables and focus solely on the behaviour of the lining adhesives. Within this paper, the authors use the term ageing to refer to the mechanical-physical forces applied to the samples. The authors are aware that the materials studied were not chemically aged and that chemical ageing will affect the performance of the adhesives.

The samples were subjected to mechanical-physical forces under tension to increase the stresses induced in each stratum of the laminate. This ageing process was conducted in an environmental chamber (Weiss Technik) at the Cultural Heritage Agency (RCE) in Amsterdam. Relative humidity (RH) extremes of 20% and 75% were sequenced with temperature (T) shifts between 15°C and 35°C. The ageing sequence comprised 50 cycles of a 16-hour programme consisting of four steps, each lasting 4 h, for a total duration of 800 h (Table 3). It is not possible to calculate an exact real-world ageing equivalent for the simulated conditions. However, noticeable differences were observed between the aged and unaged mock-linings and are described in the following sections.

Table 3. Overview of the mechanical-physical ageing sequence.

	Temperature (*T*)	Relative Humidity (RH)
Step 1 – Warm and wet	35°C	75%
Step 2 – Warm and dry	35°C	20%
Step 3 – Cold and dry	15°C	20%
Step 4 – Cold and wet	15°C	75%

Mass gain

Creep loading is a primary concern for adhesively bonded load-carrying structures that use viscoelastic polymers. Over time, constant or fluctuating stress can cause these materials to deform. In the context of lined canvas paintings, the weight of the lining canvas and adhesive contributes to the overall stress on the laminate structure. Consequently, a lighter load results in less strain and reduces the risk of long-term deformation due to creep. To establish the additional weight imposed by the lining materials, weight measurements were taken before and after lining. The first measurement after lining was taken as soon as the lining was complete (hour 0). The second measurement after lining was taken one week later. All weight measurements were taken in grams (g).

Lap-shear and T-peel tests

Lap-shear tests assess the shear properties of lining adhesives. Shear tests are invaluable for assessing the performance of laminate structures bonded with viscoelastic polymers, as they evaluate the adhesive strength between the adherends, thereby determining bond integrity and failure points under stress. These tests simulate real-world conditions, such as handling and environmental changes, by applying stress parallel to the canvas surface. This allows conservators to predict the longevity and durability of the lining treatment. Moreover, understanding the mechanical behaviour of adhesives through shear tests, including load-bearing capacity and elasticity, ensures that lined paintings can withstand mechanical stress. In this test, two strips of canvas of specified width are overlapped over a set proportion of their length and bonded with adhesive. One end of each adherend strip is fixed, while the overlapping bonded section is positioned in the centre. The instrument imposes stress incrementally by extending the fixed ends of the strip until adhesive failure occurs. The results are expressed as shear strength, which denotes the maximum load a material can endure in a direction parallel to its surface. Shear strength is calculated by dividing the force required to shear the specimen by the area of the sheared edge, with measurements reported in Megapascals (MPa), the SI unit for pressure. [5] (See Figure 1 Section B).

T-peel tests measure the resistance to peeling apart of original and lining canvases. T-peel tests are essential for evaluating the performance of lining canvases, as they measure the peel strength of adhesives used in lining treatments. These tests provide insight into the adhesive's ability to maintain a bond under peeling forces, which can occur during handling, transportation, and environmental fluctuations. Tacking margins and borders of tears are especially subjected to these forces. By applying a tensile force perpendicular to the adhesive bond, T-peel tests simulate the stress conditions that can cause delamination or failure in real-world scenarios. The results help conservators understand the adhesive's flexibility, strength, and durability, ensuring that the lining can protect the original canvas without compromising its structural integrity. A strip of canvas of given width is attached for a definite part of its length to a fixed vertical plate. The free end is bent down through 180 degrees (in the same direction as the fixed end) and weighted until the test strip peels away from the plate. The results are expressed as resistance to peeling. The measurements are given in Newtons (N) the SI unit of force. (See Figure 1 Section C).

The samples for lap-shear and T-peel tests were cut and pulled apart in the weft direction to minimise crimp extension. Lap-shear tests were done with a 1.3 mm/minute (ASTM International 2005) and T-peel tests were done with a 50 mm/minute separation rate (ASTM International n.d.). Tests were done on a Zwick 20 kN tensile test machine with a 1 kN load cell at laboratories of the Aerospace faculty at TU Delft, The Netherlands. The climatic conditions during the tests were 20°C and 60% RH. For all the tests, the primed canvas was always in the top clamp and the lining canvas in the bottom one. Five lap-shear tests and ten T-peel tests were done for each lining sample before and after ageing. The mean was calculated for each sample and test and the standard deviation is used as error bars in the graphs.

Digital photography and optical microscopy

Observations were made in visible and raking light and digital photographs were taken in photographic studio conditions of each mock-up before and after ageing. Additionally, cross-sections of each mock-up sample were taken using a clean, sharp scalpel. The sections measure 2 cm in length and 0.5 cm in depth and comprise the primed canvas, the lining canvas, and the adhesive layer. The cross-sections were mounted on glass slides using clay, examined with a Lietz Aristomet research microscope, and imaged with a Leica C3 digital camera. The same lighting conditions were utilised for all optical microscopic images.

One sample strip for each mock-up lining before and after ageing was partially hand-peeled, by keeping the sample face-down and gently pulling away the lining canvas. Photographs of the de-peeled intersection showing the reverse face of the original primed canvas and front face of the lining canvas were photographed using magnification. The photographs were used to quantify the amount of adhesive residue left after de-peeling on both canvases. Cross-sections and adhesive residue tests were done on samples that had not been subjected to the destructive lap-shear and T-peel tests.

Results and discussion

The samples are referred to in the discussion below by their given code names (see Table 1). Sample names are given in italics.

Mechanical-physical ageing

The cyclic 800-hour regime of low heat and RH fluctuations induces physical stresses and strains in the laminar structure of the mock-linings. It is not intended to induce significant chemical changes in the adhesives, although any change in the molecular structure of the adhesives will be reflected in their mechanical behaviour either in the form of delamination or higher T-peel or lap-shear values. Additionally, in this form of mechanical-physical ageing, it is not easy to determine ageing in the form of number of years and has not been attempted in this research. Instead, the second set of tensioned samples have been left in a dark ambient environment replicating museum conditions to naturally age and will be revisited in the future.

Visual observations of all the aged samples showed delamination at the edges and corners, except *B(Dil)*. Neither of the aged BEVA® 371 linings demonstrated the development of air-pockets[6] or deformations in the central section of the lined canvas, indicating that the bond remained stable in fluctuating heat and moisture conditions of the ageing sequence. These results conform to those discussed by Poulis, Seymour, and Mosleh (2020). On the other hand, the aged *WR* and *GP* samples did produce numerous air-pockets. This complies with their performance in actual case studies as they have been known to present problems when subjected to high and fluctuating RH conditions, especially under uneven tension (Andersen et al. 2014, 7; Fuster-López et al. 2017, 2; Poulis, Seymour, and Mosleh 2022, 114, 103119). The aged *WR* samples de-bonded with the slightest movement and this was especially noticed while preparing T-peel test strips. Aged *GP* samples were extremely rigid and brittle. Aged *PB500* and *ML* samples had air pockets in the edges of the lined canvas where peel forces are dominant, but they were fewer and smaller in size compared to *WR* and *GP* samples. These air-pockets were only visible from the reverse of the lined samples, suggesting that dimensional changes in the adhesive and the lining canvas did not transfer to the original primed canvas. This can be seen as an advantage wherein the integrity of the original is maintained, but also as a disadvantage because if the original canvas has major tears or planar deformations the lining adhesive and canvas may not be able to flatten those or prevent them over time. This emphasises the fact that if a painting has major tears or planar deformations, true nap-bond linings must be combined with pre-treatments and each problem addressed separately, possibly with interleafs to provide additional stiffness to local areas as required.

Mass gain

Figure 2 shows the average mass gained after lining. Three measurements were taken at each time and then averaged to get the final value. This test was performed to simulate the average weight gain that a lined painting would be subjected to.

Wax-resin linings have been known to contribute a significant increase in the mass of paintings; however, how much has not been well reported in the literature. The results demonstrated in this research show that 325 grams was added to a 75 × 105 cm *WR* mock-lining. The *B(Dil)* mock-lining also presented a significant increase in weight (160 grams), although not as much as *WR*. *GP* and *PB500* interestingly lose some of the mass gain, probably through the evaporation of the water in the former and the solvent/water in the latter in the week between measurements. The negligible amount of mass gain in the *BF* and *ML* system reinforces the idea of minimal application of adhesive. The increase of mass in *BF* over the week of measurement even though the samples were kept in a RH controlled environment needs to be further investigated.

The increase in the mass or weight of the whole lining composite should be taken into careful consideration when choosing a lining adhesive. The heavier the structure after lining, the more creep forces the system is subjected to, which can cause delamination or formation of air-pockets. Traditionally, paintings are displayed in a vertical position. Once stretched, the gradual extension of the lining canvas over time can lead to sagging of the painting under its new total weight. This is often referred to as a painting's 'belly' and is usually situated in the lower section of the tensioned painting. Ceiling paintings are displayed horizontally, causing the full weight of the painting to be centred on the middle of the canvas and, if lined, on the original canvas. This increases the creep forces acting on the painting putting additional strain on tacking margins. Especially for large-format paintings or ceiling paintings, the amount of extra mass that is being put into the system plays a considerable role in the structural stability of the whole.

Lap-shear and T-peel tests

Lap-shear

Figure 3 gives the average lap-shear data of all the samples before and after ageing giving information on the shear strength of the adhesive and indicating its resistance to creep stresses. All measurements are noted in Megapascal (MPa).

The lap-shear tests for all the aged samples, except *GP*, show that even though the adhesive bond failed, the canvases remained adhered to each other due to the thermoplastic nature of the adhesives. For *PB500* and *ML*, in addition to the tackiness of the adhesives, the fibre bridges (nap-fluff) also contributed to

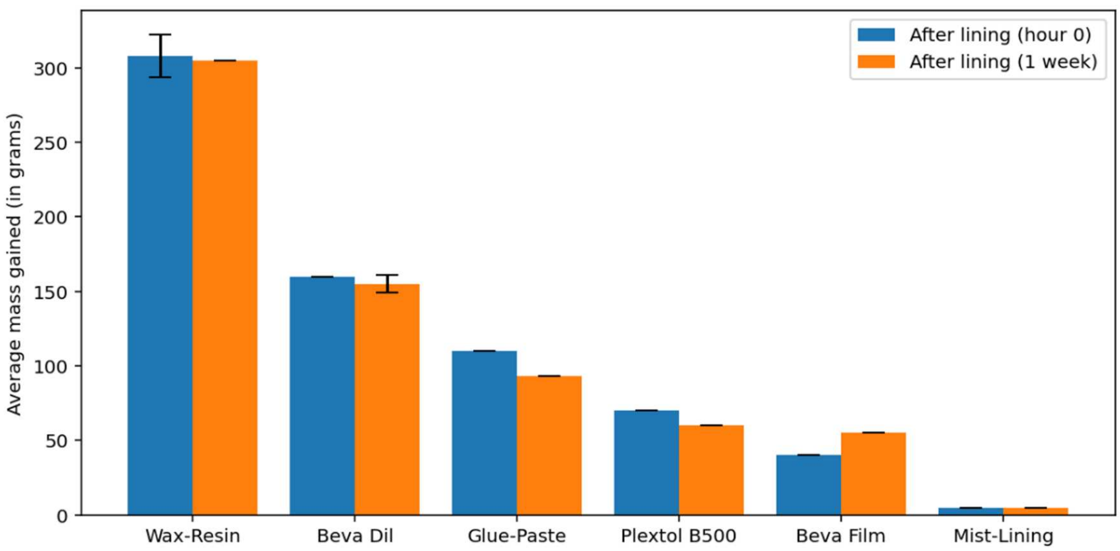

Figure 2. Average mass gain of the different mock-ups after lining.

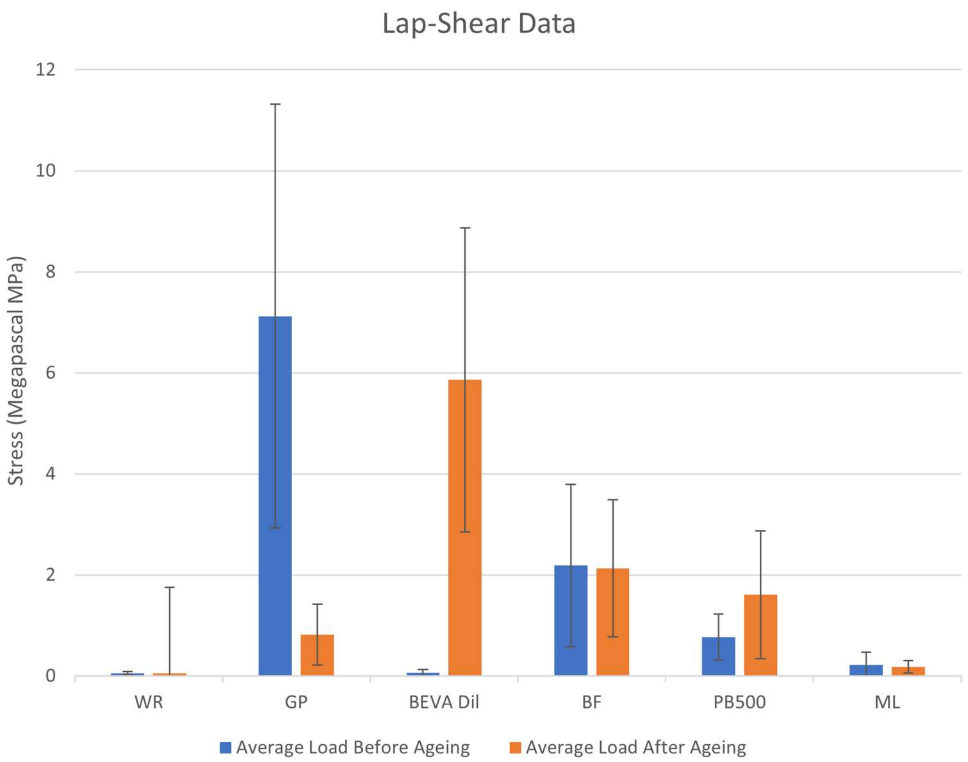

Figure 3. The average lap-shear load values before and after ageing of all the lining samples.

keeping the two canvases together through a mechanical interlocking mechanism. Nonetheless, an estimate of the force required to achieve the 'failure point' can be made and can help in understanding the adhesive strength in a laminate structure.

From the results, *WR* has negligible shear strength as expected, which does not increase after artificial ageing. The drastic lowering of the shear strength in the aged *GP* samples and the drastic increase in the *B(Dil)* samples, indicate that they are sensitive to the cyclic RH and T conditions. There is a slight increase in the strength of *PB500* on ageing, while *BF* and *ML* maintain their shear strengths upon ageing, thus far indicating that they are not as sensitive to the cyclic ageing that they were put through.

All the samples showed a cohesive failure inside the adhesive layer. A cohesive failure of an adhesive occurs when the adhesive material itself breaks apart, rather than detaching from the surfaces it is bonded to. In other words, the failure happens within the adhesive material, where it fractures or separates internally. This type of failure indicates that the adhesive's internal strength is weaker than its bond to the surfaces it is adhering to.

This test simulated the stress the laminate structure can withstand before undergoing sliding or rupture along a plane parallel to the direction of the force. Canvas paintings are typically displayed in a vertical position and are subjected to creep forces. The experiment suggests an understanding of how the weight, structural changes and environmental conditions impact the behaviour of the system.

T-peel

Figure 4 shows the average T-peel results for all the samples before and after ageing measuring the resistance in the separation of the bonded substrates to peel loading. All measurements are recorded in Newtons (N).

All samples showed a cohesive failure in the T-peel tests. The BEVA® 371 adhesives show considerably high peel strengths. *WR* and *ML* have very less resistance to peel. *GP* and *PB500* have similar peel strengths to each other. Post ageing there are changes in the resistance to peel of the adhesives. For aged *B(Dil)* and *PB500*, the peel force increased whereas for *WR*, *GP*, *BF,* and *ML* it decreased.

This test simulated the effect of removing the lining canvas from the reverse of the original support. The peel strength of an adhesive depends on the elastic modulus of the adherents, the peel angle, and the peel rate. In principle, high peel strength means more force is required to physically de-line the lining canvas. After ageing, if the peel force increases the lining will be more difficult to remove, and if the peel forces drop drastically the possibility of delamination increases. Finding the correct numerical value depends on many aspects – the condition of the original canvas and its state of degradation, the number of tears, the extent of deformations, and the environment the painting is going to be kept in.

Another significant finding from the mechanical testing conducted in this research is the variation in standard deviation values (STDV). Higher STDV indicates a greater dispersion of values from the

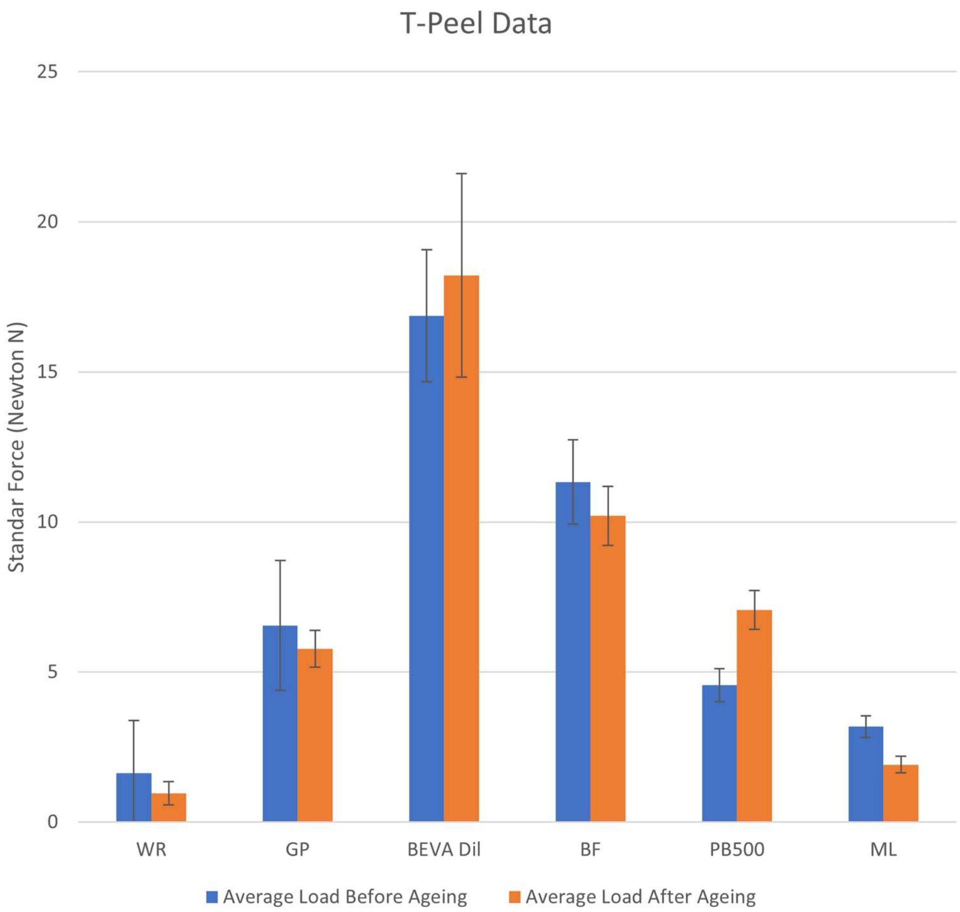

Figure 4. The average T-peel load values of the lining samples before and after ageing.

average, reflecting inconsistency in the adhesion strength across samples. Hand-lining techniques, such as glue-paste and wax-resin, exhibited higher STDV compared to linings performed on a hot table or in a low-pressure envelope, respectively the BEVA® 371 linings and acrylic dispersion linings. This suggests that hand-lining results in less uniform adhesion between the two canvases, likely due to delamination occurring during the lining phase. For effective bonding, the adherends must be kept in close proximity while the adhesive is still in a mobile phase. The use of hand-irons to heat local sections of the surface to activate the adhesive reduces the ability to apply even pressure during the lining process. Cold-setting blocks were utilised but especially in the case of the wax-resin mock-lining may have been applied too late. In contrast, the vacuum hot table and low-pressure envelope methods exert even and constant pressure on the mock-linings, ensuring that the adherends remain in close proximity during bond formation. Extensive research by our group over the past decade has consistently attributed this variability to the adhesive materials rather than the manual skills of the conservators. While hot tables and low-pressure envelopes seem to produce more uniform bonds and reduce variance, further investigation is needed to confirm this trend and understand the underlying mechanisms.

Optical microscopy and adhesive residue

Cross-sections of the mock-ups before and after ageing

The cross-sections show the primed canvas, the adhesive, and the lining canvas. They indicate the degree of penetration of the adhesive into the substrates (Figure 5, columns cross-section in visible light: before ageing and after ageing). While the fibre bundles of both canvases can be easily made out in all the cross-section images, they have been outlined in black to improve identification.

The cross-sections of the *WR* mock-lining (Figure 5, row (i) columns A and B) clearly show the impregnation of the adhesive into the original primed canvas support as far as the ground layer. Voids can be noted in the *WR* aged sample imaged at the interface between the two canvases. This delamination may have occurred due to stresses imposed during ageing.

Similarly, the cross-sections of the *GP* mock-lining (Figure 5, row (II), columns A and B) indicate that delamination has occurred after ageing. The adhesive also appears to have penetrated fully into the textile fibre bundles of both the original primed canvas and lining textile supports.

The BEVA® 371 linings seem remarkably similar to each other (Figure 5, rows (iii) and (iv), columns A

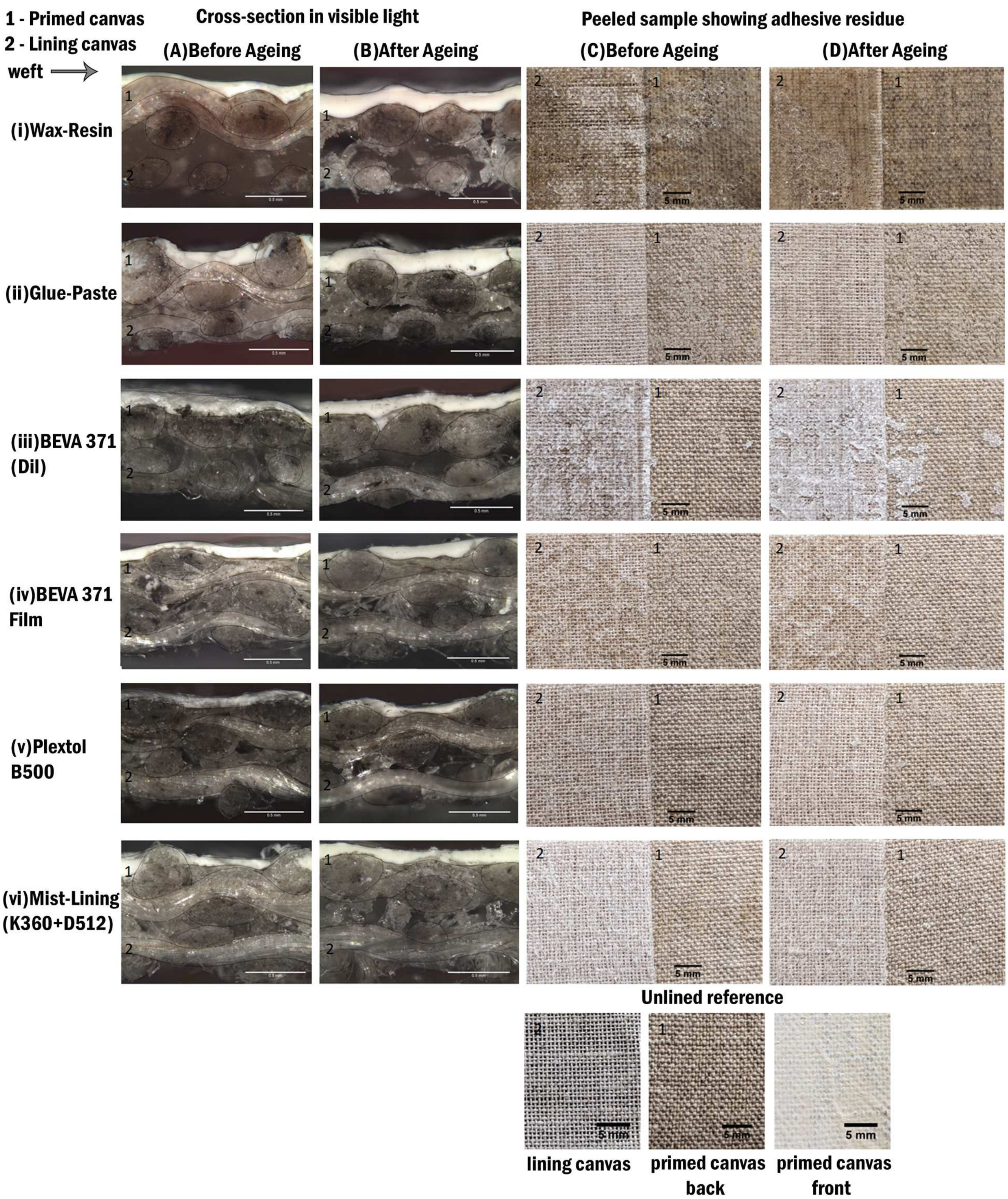

Figure 5. Cross-sections and adhesive residues of the mock-up samples before and after ageing.

and B), although the fibre bundles of the *BF* lining seem more distinct than those lined with the *B(Dil)*. While the adhesive appears to have saturated the lining canvases in both samples, penetration seems to be different for *B(Dil)* and *BF*. The film has perhaps retained its position between the two linings, migrating only into the lining canvas. Compared to the *WR* mock-lining cross-sections, it is clear that the colour change in the BEVA® 371 samples is less evident than for the *WR* mock-ups. The canvas appears lighter and 'greyer' in tone than the more 'yellow-brown' appearance of the *WR* samples. No voids or delamination are detected in either mock-lining. The amount of adhesive between the two canvases is more for the *B(Dil)* than for the *BF*.

The fibre bundles in both the acrylic dispersion adhesives of both the original primed canvas and lining textile are distinct (Figure 5, rows (v) and (vi), columns A and B). Both mock-linings *PB500* and *ML* used a spray application of the adhesive. The 'tendrils' of adhesive can be clearly seen bridging the gap between the two canvases in both cases. These tendrils do not seem disrupted after ageing. No impregnation of the adhesive into the canvas has occurred and no colour change can be observed.

Broadly, lining techniques can be divided into two categories: heat-seal and cold-lining. Both types of linings require the application of pressure to the adherends while the adhesive cures, transitioning from a liquid or tacky to a solid state. This is typically achieved by applying pressure either through weights or vacuum/low-pressure envelopes, ensuring that the two canvases bond as the adhesives cure. In heat-seal linings, the adhesive is made fluid by heat, which usually impregnates both the lining and the original canvases. This process can alter the nature and appearance of the materials. Common heat-seal adhesives include wax-resin, glue-paste, and BEVA® 371, all of which impregnate the lining textile and the original primed canvas, as shown in cross-sectional analyses. In contrast, cold-linings eliminate heat by using solvents to regenerate or swell the adhesives, making them tacky. The adhesive is not in a liquid state and thus linings are produced without significant impregnation of the original canvas. The application method – whether continuous, non-continuous, or spray/flocked – affects the stiffness of the lining as well as the degree of impregnation. Consequently, cold-linings are generally less stiff than hot-melt adhesives. Cold nap-bond linings with acrylic dispersions (in other words mist-lining) contain the least amount of adhesive compared to other methods, resulting in a lining that preserves the original materials' nature.

De-peeled samples before and after ageing

The optical microscopy images of the de-peeled strips indicate the degree of adhesive that remains on the front face of the lining fabric and the transfer of the adhesive onto the reverse of the original primed canvas. The de-peeled strips photographed in visible light show the adhesive residues (Figure 5, columns C and D – peeled sample showing adhesive residue, before ageing and after ageing). In all the samples, more adhesive residues were left on the reverse of the primed canvas after ageing.

The *WR* de-peeled strips clearly show that the adhesive has impregnated and saturated both the original primed canvas and lining textile (Figure 5, row (i), columns C and D). Compared to the images of the unlined reference textiles there is a significant degree of colour change of the canvas. The adhesive residues can be clearly seen in the interstices of both canvases and on the surface covering the canvas weave. This indicates that a cohesive break occurred when de-bonding. The adhesive appears slightly milky white in appearance in some areas due to the surface roughening of the adhesive as it cohesively breaks.

The discolouration of the textiles due to the penetration of the *GP* adhesive is less evident than for the *WR* mixture (Figure 5, row (ii), columns C and D). Considerable residues of the adhesive can be noted on both the reverse of the original primed canvas and the front face of the lining textile. However, the residues do not form a continuous layer as can be seen for the *WR* samples. Instead, corresponding voids can be detected, suggesting that the adhesive has bonded more significantly to one or the other textile.

A similar scenario has occurred with the *B(Dil)*, though more adhesive remains on the front face of the lining textile than on the reverse of the original primed canvas (Figure 5, row (iii), columns C and D). This suggests that the lining adhesive has remained as a discrete layer between the two textiles, bonding significantly to any raised nap of the original primed canvas. The adhesive remaining on the front face of the lining textile and the little residues present on the reverse of the original primed canvas have a whiter discolouration after ageing. This is likely due to the response to fluctuating relative humidity and to a phenomenon called stress-whitening which occurs due to micro-structural changes within a material caused by applied stress. When polymers are stretched or deformed, microvoids or microscopic cracks can form in the material's structure. These voids or cracks scatter light differently than the surrounding material, resulting in the whitened or hazy appearance. This phenomenon is commonly observed in plastic materials such as polyethylene, polypropylene, and polycarbonate, especially in applications where the material is subjected to repeated or prolonged mechanical stress, such as flexing, bending, or impact. While stress whitening may not necessarily indicate structural failure, it can affect the material's aesthetics and may be considered a sign of potential degradation or weakening of the material.

The weave on the reverse of the original primed canvas appears a little out of focus when compared to the reference sample. In fact, the photograph is in focus, the 'fuzziness' is a result of a disruption of the fibre bundles that have been pulled out of position during de-peeling. This correlates with the resistance to load that the *B(Dil)* shows when subjected to T-peel forces (see Figure 4).

The *BF* de-peeled samples show a similar situation to that of the *B(Dil)* (Figure 5, row (iv), columns C and D), although degree or thickness of adhesive residues is minimal in comparison. However, the degree of attachment of the adhesive to the reverse of the original primed canvas seems to be more than that of the more thickly applied *B(Dil)*.

The sprayed application of the *PB500* has remained bonded to the nap of the front face of the lining textile leaving little residues on the reverse of the original primed canvas pre artificial ageing. However, after ageing there appears to be more residues remaining (Figure 5, row (v), columns C and D). There is no penetration of the adhesive into the reverse of the original primed canvas and therefore no colour change of the textile.

A similar situation can be observed for the sprayed application of *ML* (Figure 5, row (vi), columns C and D), although there is less adhesive remaining after ageing on the reverse of the original primed canvas. Again, no discernible colour change can be detected which correlates to the lack of adhesive in the original primed canvas.

Quantifying adhesive residues is a complex process and residues differ due to a variety of factors. The direction, speed, and force of the peeling greatly influence where the residues remain. Empirical tests during sample preparation showed that if the lined sample was laid flat on a horizontal surface and one of the canvases (lining textile) pulled while keeping the bottom canvas (original support) in place with weights, more adhesive residues remained on the one that laid flat than the one being pulled away. When the two canvases were pulled apart vertically (T-peel) i.e. equal pulling force on both canvases, it was difficult to predict where the adhesive residues would be. In standard studio practice, a painting is secured face-down, and the lining canvas peeled away in a parallel direction to minimise damage to the ground and paint layers. Therefore, this method was preferred to document adhesive residues as it would replicate a hand de-lining used in standard studio practice rather than the sample strips subjected to T-peel and lap-shear forces.

Conclusion

The lining systems discussed in this paper represent only a fraction of the extensive modifications available within the conservation field, encompassing both historical and contemporary practices, for the structural repair of damaged or degraded canvases. Over the centuries, numerous variants have been introduced and subsequently abandoned. Conservation literature is filled with examples of seldom-used and outdated techniques, as well as regional practices not covered in this discussion (Lamers et al. 2020, 18). The field is ever-evolving, and as the mechanical and physical properties of laminate canvas structures become better understood, newer systems, textiles, and adhesives are likely to be introduced and modified (Hackney 2023, 6).

Choosing the appropriate lining technique depends on many factors including, but not limited to, the condition of the original painting, the integrity of the canvas, the degree of paint cupping, the number of tears present, the condition of the tacking margins, the adhesive strength required, resistance to peel, ease of reversibility, ageing/durability characteristics, adhesive residues, retreatability, access to materials, and the skill and knowledge of the conservator. This experimental research aims to compare different lining techniques most used in current studio practice around the world in terms of quantifiable data which can be used to qualify results. Mechanical aspects such as adhesive bond strength, resistance to peel, ease of reversibility, simulated long-term durability, and practical aspects such as weight gain and adhesive residue have been systematically evaluated for each of the chosen linings.

Each lining system discussed in this paper has its own strengths and weaknesses. Hand-lining versus lining on hot tables or in low-pressure envelopes shows significant differences in overall adhesive bonding in this paper and this trend needs to be investigated further. Wax-resin linings, as reported in the literature, do not perform well in fluctuating environmental conditions. Nevertheless, they have left a significant legacy that future conservators must address, and research now shifts towards reversing them and finding solutions that will retreat previously wax-resin lined paintings. Water-based lining adhesives remain popular and can mitigate or resolve more problems than just providing structural support. Their long-term performance remains questionable, but their durability, when performed with skill, is undeniable.

BEVA® 371 has proven to be a versatile lining adhesive that is easy to apply and produces high bond strengths, although its reversibility and removal from lined paintings is now being questioned, especially its performance in fluctuating RH conditions. Nap-bond linings with acrylic dispersions, although with lower peel and shear strengths than what has been suggested in the literature, have more potential when aspects of reversibility and retreatability are considered. Implementing them may present challenges, as it necessitates a comprehensive understanding of the physical and mechanical properties of the materials and textiles involved. Our research group has investigated these techniques for over a decade and has found that when executed correctly, paintings lined with the mist-lining technique have performed consistently with good results in different environmental conditions.

Ultimately, choosing a particular lining technique should be evaluated based on the needs of the painting being treated. While bond strength and peel strength values, along with the type of adhesive failure mode, are indispensable for designing a durable lining procedure, other factors such as adhesive performance in fluctuating environments, adhesive impregnation, and ease of reversibility should also be considered. In practice, unless conservators are trained in multiple structural treatment techniques, it remains likely that treatment choices will be made based on experience and expertise. Today, a wide range of adhesives and techniques is available to the conservator and through initiatives such as the Getty Foundation's *Conserving Canvas* project knowledge and dissemination of these techniques is becoming more widespread.

In conclusion, this research underscores the complexity and variability in lining techniques, emphasising the need for a nuanced approach tailored to the specific requirements of each painting. There is a pressing need for a more comprehensive understanding of the application, materials, and long-term behaviour of lined paintings. While this paper cannot fully address all knowledge gaps, it aims to contribute valuable data and comparative insights into adhesives and their interactions with textiles. By enhancing our understanding of these factors, the paper seeks to assist conservators in making informed decisions about both the re-treatment of existing lined paintings and the selection of appropriate techniques for future conservation efforts.

Notes

1. https://barberinicorsini.org/en/evento/water-based-adhesives-in-structural-painting-conservation-online-expert-meeting/ (Accessed 27 July 2024).
2. https://www.getty.edu/projects/conserving-canvas/grants-awarded/ (Accessed 16 March 2024).
3. see: https://www.rijksmuseum.nl/en/stories/operation-night-watch/story/relining (Accessed 16 March 2024).
4. Tg is the critical temperature range at which an amorphous material shifts from a rigid, glassy state to a softer, rubbery state without significant volume change. Below Tg, the material remains brittle, while above Tg, it becomes more flexible due to increased molecular mobility.
5. Definition taken from Glossary published in Schwarz, McClure, and Coddington (2023, 38–46).
6. An air-pocket is a partial delamination between the two canvases. These often occur due to differences in response of the two canvases to fluctuations in relative humidity (RH), which induces creep stress within the adhesive structure resulting in debonding.

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Suppliers

Product	Supplier
Primed Canvas Linen (20 warp x 20 weft per cm^2) sized with hide glue applied hot with two oil bound priming layers (raw linseed oil); Lower layer with zinc white and upper layer with titanium white	Claessens Canvas (Product made to order)
Lining canvas Linen (17 warp x 17 weft per cm^2)	Claessens Canvas Libeco Quality – OV10, Reference – 221.
Bleached Beewax Product Number #62200	Kremer Pigmente https://www.kremer-pigmente.com/en/shop/mediums-binders-glues/solvent-soluble-binders/62200-beeswax-natural.html
Gum Damar Product Number #60000	Kremer Pigmente https://www.kremer-pigmente.com/en/shop/mediums-binders-glues/solvent-soluble-binders/60000-gum-damar-best-quality.html
Gum Elemi Product Number #62050	Kremer Pigmente https://www.kremer-pigmente.com/en/shop/mediums-binders-glues/62050-gum-elemi.html
Rabbit Skin Glue Product Number #63025	Kremer Pigmente https://www.kremer-pigmente.com/en/shop/mediums-binders-glues/63025-rabbit-skin-glue-cubes.html
Wheat Flour Grade 00	Your Organic Nature https://www.ah.nl/producten/product/wi36783/ah-tarwebloem
BEVA® 371 Film Thick Product Number #87050	Kremer Pigmente https://www.kremer-pigmente.com/en/shop/linen-paper-foils/87050-beva-371-film-thin.html
BEVA® 371 (O.F) Product Number #87030	Kremer Pigmente https://www.kremer-pigmente.com/en/shop/mediums-binders-glues/87030-beva-371-hot-sealing-adhesive.html
Turpentine Substitute (White Spirit) Cat No T/4200/17	Fisher Scientific https://www.fishersci.nl/shop/products/turpentine-substitute-extra-pure-slr-4/10122690
Acrylic Dispersion B500 (formerly Plextol B500) B500 Product Number #2556100	Deffner & Johann https://deffner-johann.de/en/acrylic-dispersion-b-500-1-l.html
Acrylic Dispersion D512 (formerly Plextol D512) D512 Product Number #2555100	Deffner & Johann https://deffner-johann.de/en/acrylic-dispersion-d-512-1-l.html
Dispersion K360 Product Number #2558101	Kremer Pigmente https://deffner-johann.de/de/dispersion-k-360-nachfolgeprodukt-von-plextol-d-360-1-l.html
Ethanol, absolute, ≥99.8% HPLC grade Cat No E/0665DF/15	Fisher Scientific https://www.fishersci.nl/shop/products/ethanol-absolute-hplc-fisher-chemical-1/10542382?cid = WEB_INE_20231009_MJH50L