Heritage Science

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Evaluation and modelling of the environmental performance of archival boxes, part 1: material and environmental assessment

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Abstract
Archival boxes are used as a preventive measure to control the microenvironment in museums and archives storages. However, their efficiency in protecting valuable artefacts from fluctuations in relative humidity (RH) is not yet fully understood. In this study, the environmental performance of different archival boxes with different configurations (size, design, presence of holes/paper material, cardboard types, surface modification) was included in the evaluation of internal environment (RH). The effectiveness of archival boxes on reducing relative humidity fluctuations was investigated by testing various properties of boxes and boards, such as air exchange rates (AER), moisture sorption and water vapour transmission rates (WVTR). While most cardboard boxes showed only a limited buffering against the humidity ingress, strategies such as surface modification limited the interaction of a box with the external environment, resulting in a more stable internal environment. Material and box properties, such as moisture sorption, AER and WVTR proved to be useful quantitative tools for assessing the environmental performance of the selected archival boxes.

Keywords Archival boxes, Microenvironments, Relative humidity, Moisture sorption, Moisture transfer, Air exchange rates, Water vapour transmission rates

Introduction
Proper storage of archival collections is a critical conservation measure to ensure a longer lifespan for objects with minimal degradation [1]. Indeed, most of archival objects, such as paper and plastic artefacts, are stored in cardboard boxes and kept in climate-controlled storage rooms [2, 3]. In preventive conservation, archival boxes are a valuable tool as they can protect archival materials and provide additional insulation of the microclimate in the storage spaces by cushioning the fluctuations in relative humidity (RH) and increasing in absolute humidity, both inside and outside of the box.

RH fluctuations can damage archived paper material by making it more susceptible to mechanical damage [4, 5] while high temperatures can increase the rate of

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degradation for both paper and plastic [6, 7]. Relative humidity can also create a favourable environment for mould growth, which can cause irreparable damage to archival materials [8]. In most archival storage environments, pollutant emissions, such as by e.g., wood products, are catalysed by high relative humidity and the presence of oxidants [9, 10]. Research has also reported the negative impact of RH fluctuations on writing inks [11] and paper support [12]. When exposed to fluctuating humidity, these materials expand, which can lead to physical deformation, warping, and weakening [13]. In addition, moisture can weaken the fibres in paper and board causing physical damage. Variations in RH can directly affect the moisture content of archival materials, which can absorb or release moisture, resulting in dimensional changes that can affect its structural integrity [14]. In addition, moisture can trigger chemical reactions in archival materials. For example, metals can corrode in the presence of higher RH values, leading to the degradation of artifacts and documents that contain metal components [15].

However, the RH in the archival box is influenced by a variety of processes that interact with the environment and the contents of the box. The materials used for the construction of the archival box, such as paper, cardboard, or plastic, can have different permeabilities and allow moisture to pass through [16]. Paper and cardboard, as hygroscopic materials used in archival boxes, have the ability to absorb and release relative humidity from the environment, which moderates the RH fluctuations inside the archival box. In addition, the degree to which the archival box is sealed or encapsulated can affect the exchange of air, volatile organic compounds (VOCs) emissions, and moisture between the inside of the box and the external environment [17]. A tightly sealed box can limit exchange, while a less sealed box might allow more airflow and moisture exchange. Rapid temperature fluctuations can also lead to changes in RH levels inside the archival box. The heritage materials and contents of the archival box, such as papers and photographs, can also affect RH fluctuations through moisture desorption and reabsorption. External environmental conditions, such as the climate in the storage room, can affect RH levels in the box. Studying moisture interaction is important for selecting appropriate archiving materials and predicting their effects on microenvironment stability. However, the interaction of moisture with archival materials such as historical paper materials, has been studied in the past [18–22]. However, the interaction of moisture and storage materials, such as archival paperboards, have been investigated by a limited number of studies [21]. Furthermore, the effect of these interactions on internal RH of archival boxes has not been explored.

There are three processes that could have an influence on the RH levels inside a archival box. The first two processes describe the interaction between the archival boxes and moisture, namely the measurement of moisture sorption and water vapor transmission rates (WVTR) [23, 24]. The third process is the air exchange between a box and the external environment, which has been extensively studied for display cases [25–27]. Moisture sorption refers to the ability of a material, such as paperboard material from a box and stored paper and wood material, to absorb or release moisture from its surroundings (moisture sorption isotherms show a relation between the moisture content in the material and air RH at stable temperature). While moisture sorption doesn't provide specific information about the actual RH levels within an archival box, it offers a general idea of how an archival box material might behave [28]. Water vapor transmission rate is a quantitative measure of how much water vapor passes through a material over a given period. It's a critical factor in assessing how effectively a material can allow moisture to move in and out of an enclosed space. Both methods are relatively standard, easy, cheap, straightforward, and non-specific methods that can be used to describe the behaviour of archival boxes in regard to RH fluctuations.

Understanding the moisture sorption properties and WVTR of archival boxes' materials can help determine how effectively the box buffers RH fluctuations and help select materials that allow for even moisture distribution, minimising the risk of localised RH extremes. Past research papers have found that the air exchange rates and/or material sorption properties can affect the microenvironments within an enclosure [23, 29, 30]. In the packaging industry, moisture sorption isotherms are commonly used to study the interactions between archival materials and moisture [26, 30–34]. In addition to moisture sorption, WVTR is a standard method to study moisture transfer through the archival material. Furthermore, the measurement of air exchange rate is a standard method used in preventive conservation [2, 29, 30, 35]. In the past, air exchange rates and their influence on humidity ingress in rigid enclosures, such as display cases, microchambers and wooden boxes, have been researched [28, 36, 37]. The exchange of air between an enclosure and the external environment importantly affects the air quality in the enclosure through exchange of gases (oxygen content, concentrations of emitted compounds), water (humidity equilibration), energy (temperature distribution) and particulates (dust ingress) [38]. Higher AER can help reduce the accumulation of harmful gases that can accelerate decay and distribute the temperature inside the box more evenly. If the external environment has lower humidity than the enclosure, the exchanged air can help reduce moisture build-up in the box and the formation of localised zones of high humidity zones where mould can from. On the other hand, lower AER allows the box to act as a buffer between the contents and external environmental conditions such as rapid temperature and RH changes, as well as externally generated pollutants [39]. Furthermore, it is not clear if the air exchange in an archival box happens mostly through the box openings or also through the board material. The majority of air exchanges in display cases happen through cracks and edges, as glass is a less permeable material than paper [27]. However, due to their porosity, archival boxes could exchange air through both their holes and surface.

Archival boxes can be made with different constructions, consisting of different types of cardboard, coatings, adhesives, and enclosure mechanisms. Monitoring of these boxes over an extended period to capture variations over time is particularly important to observe how the different packaging constructions react to seasonal changes and daily RH fluctuations. To protect objects in stored archival collections from environmental fluctuations, it is important to monitor both the external environment and microenvironment within the archival boxes with different materials and designs [5]. Research into the microenvironmental conditions inside storage enclosures, for example archival boxes, and parameters which influence those microenvironments is often overlooked [33, 40, 41]. Previous scientific studies focused on the investigation of microenvironment inside different archival boxes, such as phase and Solander boxes [5, 27, 33, 43, 44]. Some of their conclusions were that the paper material inside the archival boxes acts as a buffer and stabilises the internal RH values by adsorbing excessive moisture, and that the humidity inside an archival box is highly influenced by the external humidity.

However, as far as the authors are aware, a method to assess the environmental performance of archival boxes for paper collections, as a conservation priority, had not been developed before this study. This paper presents the results of the experimental investigations of a new methodology for monitoring the microenvironments inside selected paper archival boxes of different constructions (size, design, presence of holes and/or paper material, board type, and surface modification). Selected archival boxes for the storage of historical paper were subjected to fluctuations in RH and their microenvironment was monitored and compared to external RH values. The results were evaluated against the properties of box material (WVTR, moisture sorption) and construction (AER) to establish how these properties affect the microenvironments of archival boxes.

Materials and methodology

Archival boxes samples

25 different archival boxes of different manufacturers with different constructions/designs (e.g. board type, size, thickness, presence of holes and/or paper material and surface treatment) were studied (see Table 1). The boxes were evaluated in order to investigate how these boxes parameters influence the microenvironments of an archival box. These boxes were subject to microenvironmental monitoring, air exchange rates, and boards moisture sorption measurements.

Microenvironmental monitoring

The monitoring experiment was performed in an isolated room with a controlled temperature and relative humidity (20 ± 2 °C and 50 ± 5% RH). Before each monitoring cycle, the boxes were left to equilibrate with the room environment for approximately 24 h. Humidity in the room was controlled with a dehumidifier (Eva II Pro, Inventor, UK, capacity 20 L/24 h) and wet towels. There were four changes of relative humidity during the experiment, approximately 50 ± 5%, 35 ± 5%, 70 ± 5% and 50 ± 5% RH. Air velocity inside the room was controlled with a fan (0.02 m/s). The fans (FTF300W, Futura, UK, intended for domestic use, 2 kW heating power) were placed about 2 m away from the boxes in a room measuring 2.5 × 3 × 2.8 m and were not pointing directly into the direction of the boxes. The boxes were placed about 30 cm from the walls in a non-air-conditioned room. The fans were placed about 2 m away from the boxes and not pointing directly into the direction of the boxes. The air velocity was measured in front of the boxes at three heights and the average is provided. One T/RH HOBO MX1101 data logger (Onset Computer Corporation, USA) was placed inside each box (on the base of an empty box or on top of the paper stack in a filled box, see Fig. 1). One external HOBO logger was placed on a shelf, and it measured the environmental conditions in the room. Data was collected every five minutes for 4–5 days in the case of empty boxes and 16 days for the boxes filled with paper material. These boxes were filled with a commercial print paper, and they were filled up to the top. The accuracy of the data logger's humidity measurement is ± 2.5% RH.

Air exchange rates (AERs)

The air exchange measurements were performed on the boxes which were used in the monitoring experiment. A CO_2 tracer gas decay method was employed. A small amount of CO_2 gas was injected through the holes into

Table 1 The boxes used in the microenvironmental monitoring and AER experiments

Box No	Box configuration	Abbreviation (Size, box design, board type, holes/empty)	Supplier
1	Clam/short side, JPP 1 mm, hole, empty	A4 CLAMss JPP1 H E	JPP[a]
2	Clam/short side, JPP 1 mm, empty	A4 CLAMss JPP1 E	JPP
3	2-part glued, JPP 1 mm, hole, empty	A4 2-P GL JPP1 H E	JPP
4*	2-part glued, JPP 1 mm, empty	A4 2-P GL JPP1 E	JPP
5	2-part glued, JPP 1 mm, coated with tape, empty	A4 2-P GL JPP1 coated E	JPP
6	2-part glued, JPP 1 mm, slits sealed with tape, empty	A4 2-P GL JPP1 sealed E	JPP
7	A3 clam/short side, JPP 1 mm, empty	A3 CLAMss JPP1 E	JPP
8	A3 clam/short side, JPP 1 mm, hole, filled	A3 CLAMss JPP 1 H F	JPP
9	A5 clam/short side, JPP 1 mm, empty	A5 CLAMss JPP1 E	JPP
10	A5 clam/short side, JPP 1 mm, hole, filled	A5 CLAMss JPP1 H F	JPP
11	Clam/long side, JPP 0.65 mm, empty	A4 CLAMls JPP.65 E	JPP
12	Clam/long side, JPP 0.65 mm, hole, filled	A4 CLAMls JPP.65 H F	JPP
13	Clam/long side, JPP 1.3 mm, empty	A4 CLAMls JPP1.3 E	JPP
14	Clam/long side, JPP 1.3 mm, hole, filled	A4 CLAMls JPP1.3 H F	JPP
15	clam/long side, CXD fluted 2.2 mm, empty	A4 CLAMls CXDflut E	CXD[b]
16	Clam/long side glued, recycled board 1.5 mm, empty	A4 CLAMls GL Recy E	CXD
17	Clam/long side glued, recycled board 1.5 mm, empty, hole	A4 CLAMls GL Recy H E	CXD
18	Clam/short side, JPP 1 mm, Moistop wrapped, empty	A4 CLAMss JPP1 Moistop E	JPP
19	Clam/short side, polyethylene, empty	A4 CLAMss PE E	CXD
20	Clam/short side, Kraft paper wrapped polyethylene, empty	A4 CLAMss Kraft wrap PE E	Matija Strlič[c]
21	Clam/short side, Kraft paper wrapped, empty	A4 CLAMss Kraft wrap E	Kraft paper
22	Clam/short side, textile wrapped, empty	A4 CLAMss Textile wrap E	Matija Strlič
23	Clam/short side, JPP 1 mm, EVA coated, empty	A4 CLAMss JPP1 EVA E	JPP
24	Clam/short side, JPP 1 mm, Paraloid coated, empty	A4 CLAMss JPP1 Paraloid E	JPP

[a] JPP: John Purcell Paper, https://www.johnpurcell.net/arcbox.html

[b] CXD: Conservatio By Design, https://www.cxdinternational.com/

[c] Matija Strlič: made by Matija Strlič, professor of Heritage Science, University College London, UK

[*] Control box used to evaluate the effect of coating and wrapping on the box environmental performance

a closed box, so that the initial concentration of CO_2 in the box was above 5000 ppm. One CO_2 logger (HOBO MX1102A, Onset Computer Corporation, USA) was placed inside an empty box and the second logger was measuring the background concentration of CO_2 in the room. Data was collected every minute for one hour. Temperature and relative humidity in the room were stable during the experiment (20 ± 2 °C, 50–60% RH). The air velocity in the room was 0.02 m/s. The measurements were repeated three times for each box. The air exchange rates for each box were calculated from the plots of the natural logarithm of the decay curves against time. The slope of the linear regression line represents AER value[46].

Board moisture sorption properties

The moisture sorption isotherms of the uncoated (solid and recycled board) and coated boards (EVA, Paraloid and Moistop) and Kraft paper were determined using a dynamic vapor sorption instrument (DVS Adventure, Surface Measurement Systems, UK), whose accuracy of the mass measurements is ± 0.1 µg. The moisture sorption behavior of the selected boards, namely solid and recycled boards and Kraft paper were tested at 20 °C for the range of RH from 0 to 90–0%. This was done to see how different archival boards absorb moisture and what are the moisture contents of these boards at specific environmental conditions. Prior to the analysis, the instrument was calibrated with the standard weights. Approximately 20 mg of the board samples were loaded into the metalized quartz pans and analyzed at three different temperatures (10, 20 and 30 °C). The samples were exposed to increasing/decreasing RH for a specific period of time and their weight changes were measured in five second intervals. The absorption cycle was conducted in a range of 0% (chamber exposed to dry nitrogen) to 90% RH and the desorption cycle from 90% back to 0% RH, both in 10% RH steps. Progress to the next RH was made after the weight change was less than 0.0001% in a period of 120 min as this allowed the board samples

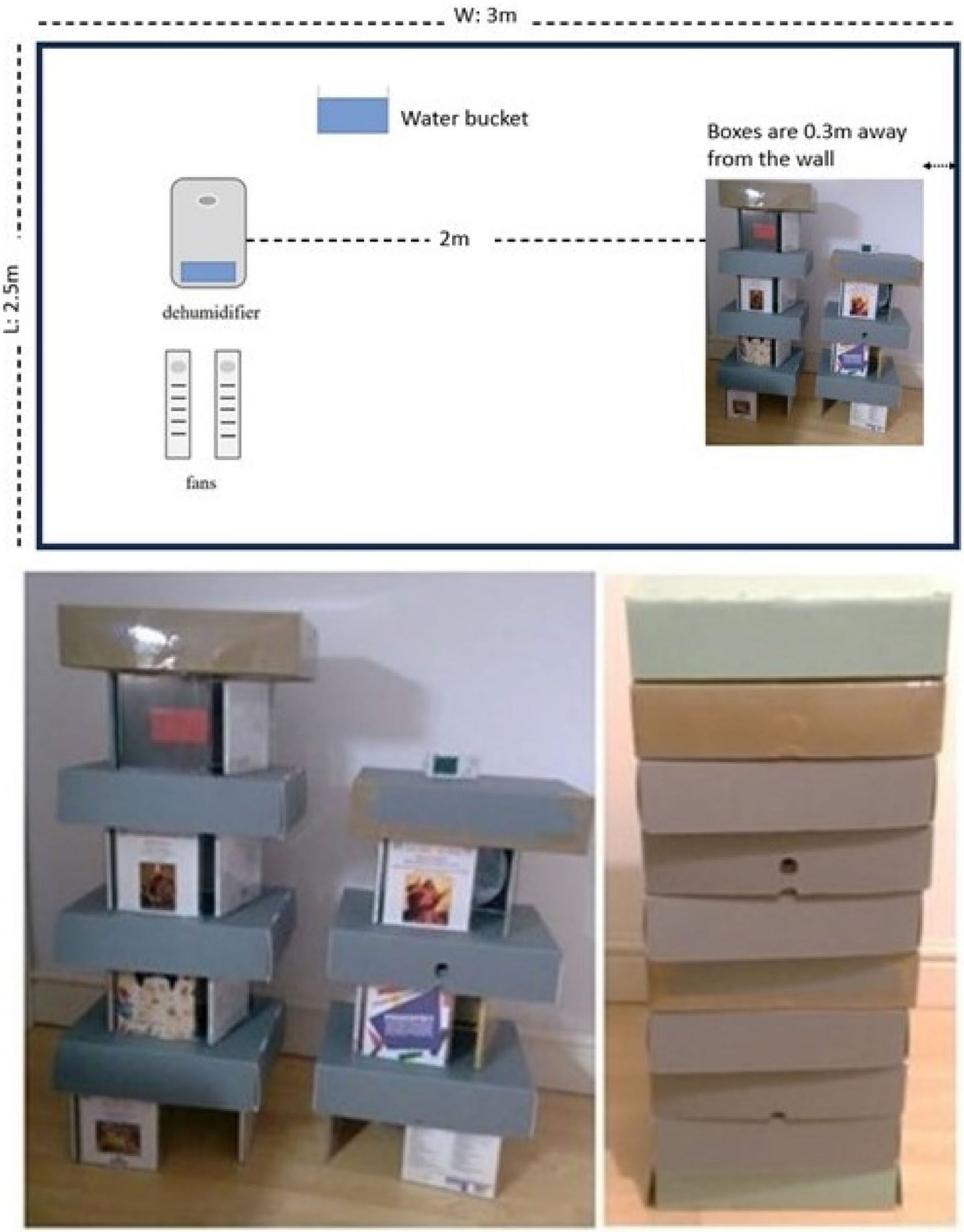

Fig. 1 The experimental setup of the microenvironmental monitoring with a floor plan

to equilibrate with the RH withing the reasonable timeframe. However, the maximal cut-off points were 360 min, after which the system automatically proceeded to the next step, regardless of the mass change. The equilibrium moisture contents (EMC) of the selected paperboards were calculated using the following equation:

$$\mathrm{EMC} = \left(\frac{\mathrm{mRH} - \mathrm{mdry}}{\mathrm{mdry}}\right) * 100\% \quad (1)$$

where m_{RH} is the equilibrium mass of the paperboards at the specific RH and m_{dry} is the mass of the paperboard at 0% RH.

Water vapor transmission rates (WVTR)

The measurements of WVTR for the selected coated and uncoated paperboards (solid, recycled, Kraft, EVA, Paraloid and Moistop) were performed in duplicates. The analysis was done using an ISO 2528:2017 standard for sheet materials [42]. The dried desiccant $CaCl_2$ was placed at the bottom of a metal dish and covered with a board sample with known surface area. The edges of the paperboards cover were sealed to the metal dish with wax so that water vapor could only absorb to $CaCl_2$ if it permeated through the test material. The measurements were done inside an environmental chamber with controlled temperature and relative humidity (30 °C and 50% RH). Due to the difference in relative humidity between the lower part of the dish (~10% RH) and the chamber, water vapor permeates through paperboard from the area of higher RH to the area with lower RH. The samples were taken out of the chamber and weighed every 1.5 h, until the difference in mass change between four consecutive measurements was less than 5%. For each sample, a graph which presents a total increase in mass as a function of exposure time was made. The WVTRs of sample were calculated using the following equation:

$$\mathrm{WVTR} = \frac{\Delta \mathrm{m}}{\Delta \mathrm{t} * \mathrm{S}} \tag{2}$$

where Δm is the mass increase in time Δt (g/hour) and S is the exposed surface area of the sample (m^2), which was 0.0050 m^2.

CXD solid board: α-cellulose (>87%); acid and lignin free; AKD/starch sizing; 3% $CaCO_3$ buffer; reducible sulphur 0.8 ppm

Superior Millboard (recycled board): Recycled paper 100% chemically purified wood-free fibers; AKD/starch sizing; acid and lignin-free

JPP Archival board 0.65 mm: 100% chemical wood-free pulp; chlorine and lignin free; alkyl ketene dimer/$CaCO_3$ sizing, reducible sulphur 0.5 ppm

JPP Archival board 1 mm: 100% chemical wood-free pulp; chlorine and lignin free; alkyl ketene dimer/$CaCO_3$ sizing, reducible sulphur 0.5 ppm

JPP Archival board 1.3 mm: 100% chemical wood-free pulp; chlorine and lignin free; alkyl ketene dimer/$CaCO_3$ sizing, reducible sulphur 0.5 ppm

Results and discussion

Microenvironmental monitoring of archival boxes

In order to present the results of microenvironmental monitoring more clearly, the data were divided to show the influence of individual parameters, such as the presence of paper material or the stacking effect, on the box microenvironment. First, the box parameters such as size, design and type of board were compared. Three different box sizes and two designs (clamshell and 2-part box) were tested. The size of an archival box can affect its buffering properties as larger boxes have larger internal air space, that can help to compensate for RH fluctuations. Also, a larger box can hold more buffering materials, which can help stabilise the humidity in the box. However, a well-designed box is a tight seal to prevent external moisture from entering and internal moisture from escaping. The materials used in the construction, such as adhesives and sealants, can also affect the box's ability to buffer against RH changes. However, all the tested boards, both corrugated and solid, were made from archival grade paper and one was made from recycled archival-grade paper. For all individual measurements inside the boxes of different sizes, designs and board type, the RH levels for these boxes were similar.

The comparison between the monitoring plots for the solid and corrugated boards (see Fig. 2a), shows comparable values two plots, which is within the measurement accuracy of the T/RH logger, namely ~2.5–3% RH. Therefore, the humidity levels between boxes were lower or same as that value, it was not considered as a statistically significant difference. It was concluded that box size, design and different board types do not have major influence on the box buffering properties against humidity ingress. It is expected that in the same external environments these boxes will behave in a similar way and have comparable microenvironments. It can be seen from the monitoring results (see plots in Fig. 2b) that both empty and filled box (with a paper material) show a buffering effect to the changes in the external RH. Nevertheless, this buffering effect is more pronounced for the filled boxes. Throughout the monitoring experiment, the filled boxes showed lower RH levels when compared to the empty ones. A reason for this difference is because filled boxes have additional paper material that absorbs/desorbs moisture from the air and stabilizes internal RH levels [5, 14, 31]. Even though there is a minimal offset in response after the change in humidity levels, generally empty box microenvironments equilibrate with the external environment rapidly (up to 24 h), which is in agreement with the previous studies [33, 43]. It can be also concluded from the monitoring results (Fig. 2c) that putting the boxes in stack, rather

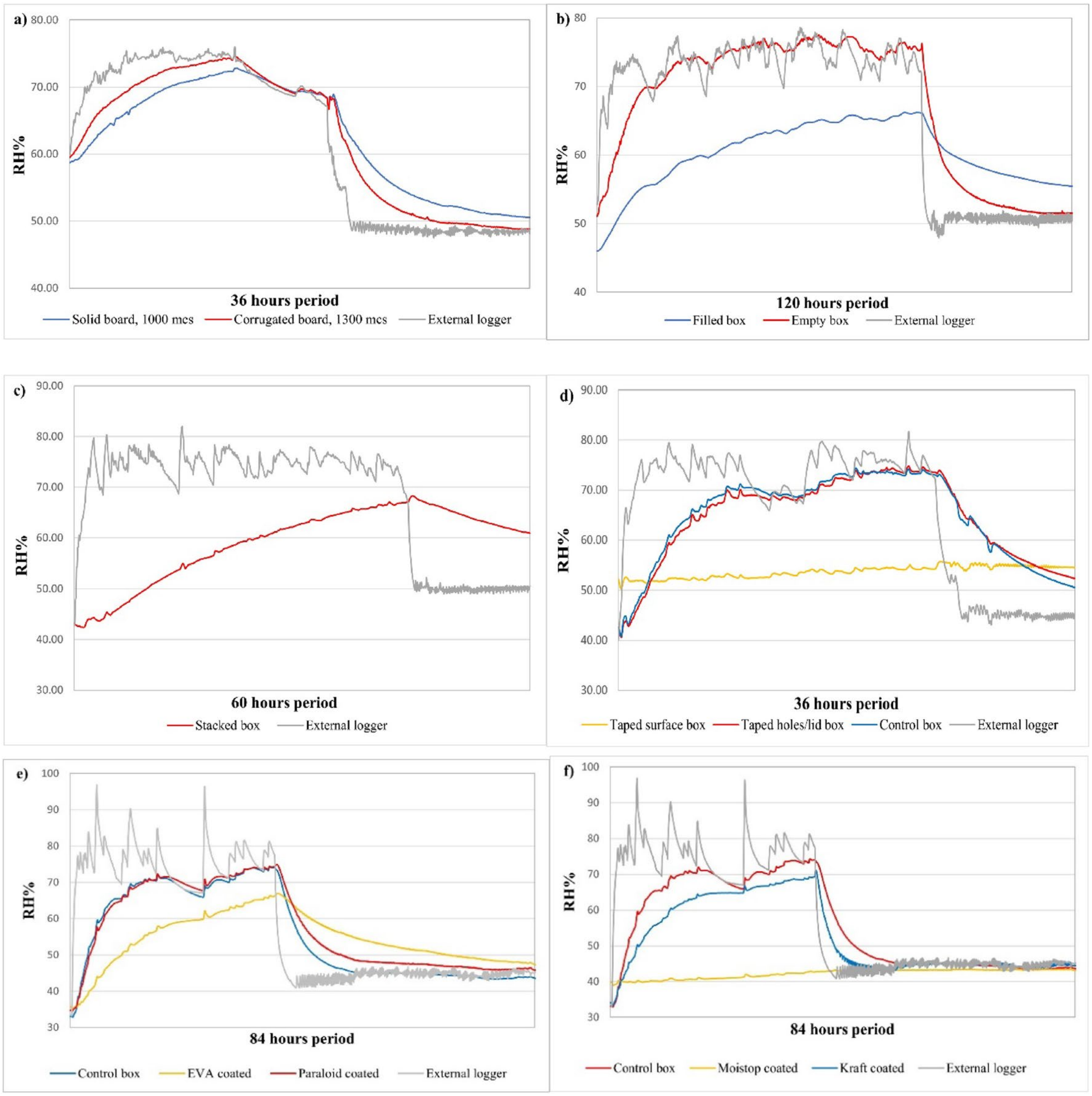

Fig. 2 The RH monitoring data for the selected boxes: **a** board types (solid and corrugated), **b** empty and paper-filled box, **c** stacked box, **d** box with taped openings/holes and surface and control box, **e** chemically coated boxes, **f** wrapped boxes. The grey plots present the external RH values

than having all their sides exposed to the surrounding air, creates a "box-in-box" stabilizing effect. If the upper and lower sides of a box are covered with any material, the box is not interacting with the air moisture through its whole surface, which could result in a longer stabilization of the environments inside this box. Moreover, from the comparison of the microenvironments between the control box and the box with taped openings and slits and the box with the whole surface taped (see Fig. 2d), the most stable RH levels of all the studies boxes were observed for the boxes with modified surface. The surface of the taped box is non-permeable to the moisture, meaning that the box interacts less with the external RH.

Surface-treated boards are expected to enhance the box's ability to buffer against RH fluctuations and also prevent the emission of harmful acidic by products of cardboard that can damage the enclosed material [44]. The effects of surface treatments on the box microenvironments were tested where several boxes were coated with the selected chemical coatings or wrapped (see Fig. 2e, f). The chemical coatings were based on Paraloid and Evacon (EVA), and two boxes were wrapped in Moistop and Kraft paper. For the chemical coating, two commercial adhesive products were used: Evacon (Conservation by Design, Milton Keynes, UK, product code SUEVAR0002), based on ethylene–vinyl acetate

(EVA), and Paraloid (Conservation by Design, Milton Keynes, UK, product code SUPARA7072), based on ethyl methacrylate and methyl acrylate. The Evacon was in the form of water dispersion and Paraloid was in the form of granules. The Moistop foil (Moistop, Conservation by Design, Milton Keynes, UK, product code SUMSPP5100) was used as the wrapping. This foil is made of polyester, polythene, and aluminum, and is used to protect valuable artefacts from moisture. These boxes showed similar results to the taped box, and a long- or short-term stabilization effect on the internal RH was observed for these boxes. The box wrapped in Moistop had the largest stabilizing effect of all the studied boxes. This is expected, as Moistop foil is used to protect objects from the excessive moisture [45]. Wrapping a box with Kraft paper as a very permeable material has a lesser stabilizing effect. The Paraloid coated box showed a lower stabilizing effect than the EVA coated box, which comes from the lower surface coverage by this coating, as only 5% v/v Paraloid solution was used for the coating. Therefore, the coating process could be optimized by applying additional layers or preparing the coating solutions of higher concentrations. Although the EVA (ethylene vinyl acetate) coating has shown promising barrier properties, we do not advise using it in archival storage as it has been shown to emit acetic acid in past studies [46].

AERs

The AER values of the selected archival boxes were measured, to see how air exchange influences environmental performance of archival boxes. For the tested boxes, the air exchange rates were calculated from their CO_2 decay plots. The slope of the linear area of the plot, marked red in Fig. 3, gives a value for the air exchange rates of a box A4 2-P GL JPP1 E.

Figure 4 presents the calculated AER values for the studied boxes. Influence of the individual box parameters, such as holes, board thickness and surface modification, on the air exchange rates is presented. As can be seen, there is a great variation in the AERs between different boxes, with the values starting from 0.2 to more than 10 air exchanges per hour.

For the boxes A4 CLAMss JPP1 E, A4 CLAMss JPP1 H E, A4 2-P GL JPP1 E and A4 2-P GL JPP1 H E, it can be observed that the holes in the box surface do not cause any major increase in the air exchange values, when compared with the identical boxes without holes. As the standard deviations of AER measurements are higher than the observable differences in the AERs between these boxes, the differences are not considered statistically significant.

The plots for A4 CLAMss JPP1 E and A4 CLAMss GL JPP1 E show the effect of box preparation (gluing vs

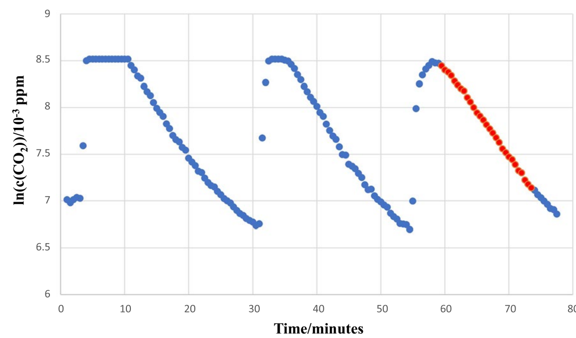

Fig. 3 CO_2 decay curves for a box A4 2-P GL JPP1 E. The red dots present the linear area from which the AER was calculated

non-gluing) on the AERs. The results show that gluing of box edges during construction causes a decrease in the air exchange rates. If box is not glued, there are additional openings on its edges, through which more air can circulate. When the edges of an archival box are glued together, it can create a relatively airtight seal. While this can be beneficial in terms of protecting the archival heritage from external contaminants and moisture, it also impedes the exchange of air important for managing RH levels, preventing the buildup of VOCs, and minimizing the potential for mould growth inside the box. In cases where air exchange is restricted due to sealed edges, VOCs can accumulate, potentially affecting the materials stored within the box. Acetic acid, e.g., is often the most abundant indoor-generated pollutant, its higher concentrations are usually observed in storage enclosures due to the low air-exchange rate [50] (which holds true also for archival boxes of a more airtight construction) and can lead to increased autocatalytic degradation of plastic materials [47–49]. In addition to the glueing, the stacking of the boxes, as seen for boxes A4 CLAMss JPP1 E and A4 2-P GL JPP1 E, also decreases AER values slightly, as part of the box surface is being covered, which reduces the release of CO_2 through paperboard.

The AER values (see Fig. 4) for A4 CLAMls JPP0.65 E, A4 CLAMss JPP1 E, A4 CLAMls JPP1.3 E, A4 CLAMls JPPflut E and A4 CLAMls GL Recy E show how the board thickness affects the air exchange rates. The AERs are higher for the boxes made of thicker boards, the corrugated A4 CLAMls CXDflut E and recycled A4 CLAMls GL Recy E boxes have the highest AER values of all the studied boxes. This is unexpected, since thicker boards generally have denser structure and lower porosity and permeability compared to thinner boards, but it can be explained by the fact that the boxes made of thicker boards are also more rigid and therefore harder to close properly. Lids often get dislocated, and this creates additional openings through

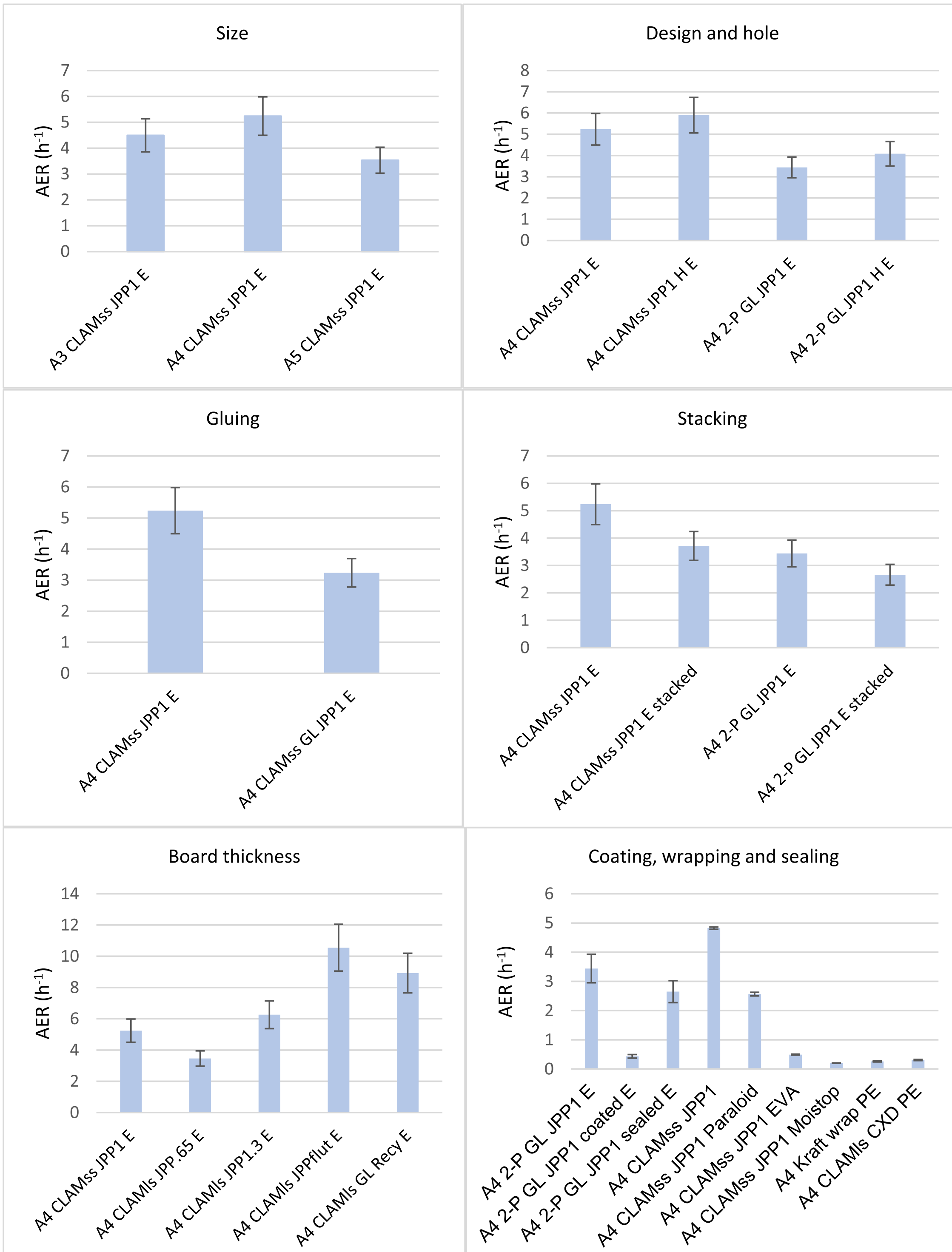

Fig. 4 AER values for the tested archival boxes and the effect of different box parameters on these values. The measurements were made at the air velocity of 0.02 m/s

which air can enter, as in the case of non-glued boxes. Furthermore, A4 CLAMls CXDflut E has a corrugated structure, which could make the air exchange higher compared to more solid boards. A4 CLAMls GL Recy E boxes are made of recycled boards, which could cause a less dense structure of the board, and is made without using the glue, which can also influence the higher air exchange.

The AER values of A4 2-P GL JPP1 E, A4 2-P GL JPP1 coated E and A4 2-P GL JPP1 sealed E (see Fig. 4a) present how sealing of box openings/holes and surface with a tape affects AER. Taping the entire surface of the box causes the highest decrease in the AERs, when compared with the untaped control box. On the other hand, taping of the box openings/holes did not cause a large decrease of its AER. This, combined with the previous RH measurements results, indicates that most of interactions between a box and external environments happens through the box surface, and not through its holes and openings. The effect of the surface modification on AER was also tested for the chemically coated and wrapped boxes. When compared to the non-coated control box, a decrease in the AERs for the modified boxes can be observed (see Fig. 4). This is especially noticeable for the EVA and Moistop boxes as well as the Kraft coated polyethylene (PE) and PE boxes (AER reduced by about 5%), while the effect is less pronounced for the Paraloid coated box (reduction by about 50%), whose surface was not entirely covered with the coating. These results are another indication that most interactions with the external environments happens through the box surface, and a modification of box surface results in the more airtight boxes.

The calculated AERs were compared to the AER values of other enclosures used in heritage institutions, such as display cases. It was concluded that the calculated AERs of archival boxes are higher than the published AER values of display cases. According to the studies done with the CO_2 decay method, typical display cases usually show AER values of less than one per day [29, 30, 50]. The higher AERs for archival boxes probably originate from their non-rigid and open structure—cardboard is more permeable to air than plastic, glass, or wood [51–53], but a box also has more openings when compared to display cases and rigid plastic or wooden boxes. These findings could be useful in terms of storage for types of heritage objects, which emit high levels of VOCs. The traditionally used plastic and metal containers trap VOCs inside due to the lower permeability of plastic and metal. In enclosures with high AERs, VOCs such as acetic acid could easily be removed from the enclosure headspace, which would result in the longer lifetimes of stored artefacts.

Board moisture sorption properties:
As the DVS analysis was time-consuming, with one measurement cycle running for five days, these three samples were chosen because they were of different material compositions and thicknesses. Furthermore, their manufacturing processes are also different. Therefore, a comparison of moisture sorption properties between these three samples would allow a closer comparison between other more similar commercial boards, such as solid archival-grade boards from different manufacturers. The moisture isotherms of selected boards are presented in Fig. 5. The results show that different archival boards absorb similar amounts of moisture, which means these boards will have similar amounts of moisture in their structure when stored in the same environments. This is expected, as both solid and recycled board have similar chemical composition and thickness. Compared to the archival boards, the Kraft paper shows a different behavior and absorbs less moisture than the archival boards. However, its different chemical and physical properties and the thinness of this sample result in lower moisture contents. The Kraft paper is thinner, so its moisture contents could equilibrate in shorter times, compared to the thicker board samples, which need more time to reach equilibrium. In addition, it contains more lignin than the archival boards, which makes it more hydrophobic [54]. For the mid-RH region, the differences between the moisture contents of samples are ~ 2%, while for the high RH regions this difference increases to ~ 4%. However, as these differences originate from the intrinsically different samples, these results indicate that the commercial archival boards of similar thickness and chemical composition will absorb similar amounts of moisture.

In addition, temperature-dependent moisture sorption isotherms were tested for the solid and recycled archival board, to see if different storage temperatures influence the moisture contents of the boards differently. The plots for the archival boards are presented in Fig. 6. For the solid board, there is a slight decrease in its moisture

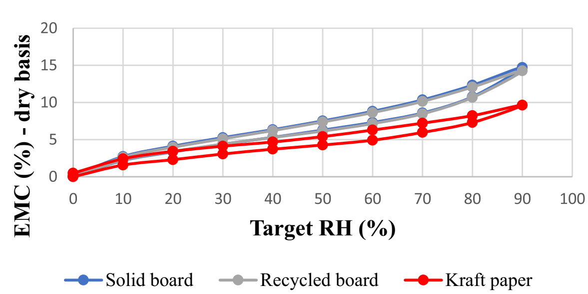

Fig. 5 The moisture sorption isotherms of the selected archival boards and the paper sample. The measurements were done at 20 °C

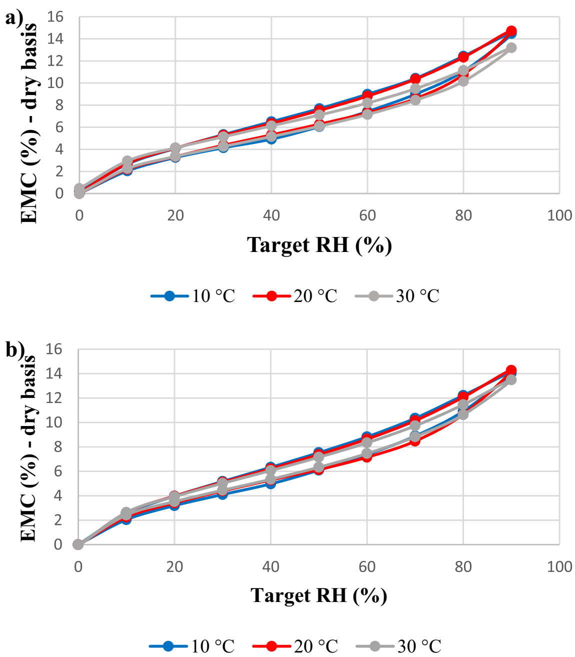

Fig. 6 Temperature-dependent moisture sorption isotherms: **a** solid board and **b** recycled board

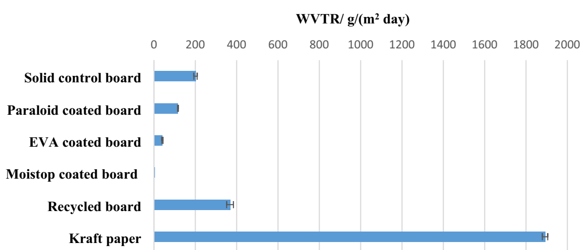

Fig. 7 WVTR for the selected archival boards and papers

content at 30 °C, which starts in the mid-RH region and continues to the high RH regions, with a maximum difference of ~ 1.5%. A decrease in moisture contents at higher temperatures has already been observed by several authors for archival materials [34, 55, 56]. The effect of lower moisture content is less observable for the recycled board. For 10 and 20 °C, the moisture isotherms are almost identical, meaning that the boards will have similar amounts of absorbed moisture in their structure at these temperatures.

WVTR

Finally, an investigation of the moisture transmission rate for the selected archival boards and papers was done (see Fig. 7). The measurements were done in duplicates for each board and paper type. Lower WVTR values indicate a slower transmission of moisture through cardboard, and therefore an improved protection against moisture ingress. The Kraft sample has the largest WVTR value, which is 1892 g/m^2 day. This is due to the sample thinness, which causes a rapid moisture transmission through the material. Similar dependence of WVTR and sample thickness was already observed for the coated paperboards of various thickness, and the samples with thinner coatings had larger WVTR compared to the thicker coatings [57]. For the archival boards, the recycled board had larger WVTR (368 g/m^2 day) compared to the solid board (201 g/m^2 day). As the recycled board has similar chemical properties to the solid board, the variations in WVTRs probably originate from the difference in the manufacture and porosity of these boards. The recycled board is made from solid boards without the use of glues, which causes an increase in the moisture transmission through this board. For the coated board samples, a reduction in WVTRs compared to the uncoated boards is observable, and the Moistop coated board showed the lowest WVTR (< 1 g/m^2 day). The Paraloid coating had a lower effect on the WVTR reduction, which is a consequence of the incomplete surface coverage and a hydrophilic property of this coating [58]. Nevertheless, these results are expected, the coatings reduce the number of interactions between the boards and moisture, due to the reduction in paper porosity and blocking of hydrophilic –OH groups which usually interact with moisture. Consequently, moisture transfer through the coated paperboard is reduced, as stated by other research groups [59–63]. The WVTR results agree with the microenvironmental monitoring experiment, as reduction of moisture ingress through cardboard results in more stable internal environments of the coated boxes, compared to the uncoated ones. This indicates that the moisture transfer through the paperboard influences the rate at which box microenvironments stabilize with the external environments.

In heritage institutions, conservators often have to rely on microenvironmental control of storage environments. An important part of this is the use of archival enclosures. As seen in the microenvironmental monitoring experiment, archival boxes made of cardboard can effectively minimise external RH fluctuations. In addition to this, the moisture buffering of boxes can be improved with several strategies, such as the stacking of boxes and/or the use of coated boxes with improved barrier properties, which reduce the moisture transfer into the box interior. On the shelving, conservators could put boxes on top of each other, and therefore increase the moisture resistance of boxes. When boxes are filled with paper material, paper material will add additional moisture buffering capacity. In addition, boxes can be wrapped with additional material, such as Moistop foil. However, all these materials should be additionally tested before their implementation in the archival collections, as they need to have good mechanical properties, not off-gas chemicals, or contain lignin, acid, sulphur, etc.

The high ventilation present in the storage room should be cautious on the use of boxes with holes, especially in the areas close to the air ventilation system. As it was observed that high air velocity can rapidly increase the air exchange rates of a box, and therefore cause a higher moisture ingress through the box surface. This would decrease the moisture buffering of a box and cause a more rapid equilibration with the external environments, compared to the lower air velocities.

For higher AER values of archival boxes, these results could indicate that there are some advantages of storing high emitting objects, such as cellulose-based plastic, in archival boxes, as they could remove excessive acetic acid more effectively than metal and plastic enclosures. This means that the stored object would be in less contact with acetic acid, and their degradation would occur at lower rates. This could present a potential solution to prevent the degradation of plastics and increase the lifetimes of ageing cellulose-based plastics.

Conclusion

In this study, the performance of several archival boxes in the fluctuating RH environment was evaluated. In addition to the microenvironmental monitoring of RH, the interaction of boards with moisture and the air exchange rates of boxes were studied separately to see how these factors influence the box interior. In the microenvironmental monitoring, the boxes of different configurations (size, design, presence of holes/paper material, board types, surface modification) were included. Most of the boxes showed a short-time buffering effect toward moisture ingress and consequently most of them equilibrated with the external environment in approximately 24 h. Box parameters such as size, design and board type did not show any observable influence on the buffering capabilities. Three exceptions were the stacked boxes, paper-filled boxes and the boxes with modified surface. The stabilization of microenvironments in these cases is caused by the reduction of surface interactions between a box and the external environment. For some non-permeable coatings, such as Moistop wrapping, the internal RH fluctuations were less than 5% RH compared to external fluctuations. The boxes filled with a hygroscopic paper material also showed a considering buffering effect, which is due to the improved moisture adsorption from the additional paper material. It can be concluded from the monitoring results that putting the boxes in stack, rather than having all their sides exposed to the surrounding air, creates a “box-in-box” stabilizing effect.

The tested archival boxes showed a great variation in the AERs values. Most boxes showed high values in their AER, which was on average several air exchanges per hour, between five to 13 air exchange rates per hour. As in the case of monitoring experiment, the boxes with surface coatings showed lower AERs, less than 1 air exchange rate per hour (except for Paraloid), while the sealing of the box openings did not cause any major decrease in the AERs compared to the control boxes. This indicates that most of the interaction between a box and the external environment happens through the box surface and not any cracks or openings.

The interaction of archival boards with humidity was further investigated through their moisture sorption and transmission properties. For the moisture sorption, the results showed that the archival boards of similar chemical composition will have identical amounts of adsorbed moisture in their structure, for the same environmental conditions. In addition, moisture contents will not be influenced by changing external temperature. For the coated boards, a reduction in both moisture contents and moisture transmission was observed, which is due to the limited interactions of these boards with moisture. This causes a stabilizing effect on microenvironments of boxes made of these boards, as was observed in the monitoring experiment. The stabilizing effect of the boxes is only happening for a short time after an environmental change (max 24 h until equilibration with the external environment), which is indeed a very short interval when comparing to the years and decades when boxes stay in archives and storages. However, this stabilization effects could be very helpful for managing less stable environments (such as locations with large daily fluctuations, with poor climate control) or for example when objects are transported between locations. To conclude, both solid and recycled boards show similar moisture contents at different temperatures, meaning that boxes made of these boards will have similar moisture contents at various storage conditions.

While measurements of material properties, such as moisture sorption, AERs, and WVTR, are useful quantitative tools, it’s important to use them alongside other preservation strategies and to consider the specific needs of the archival materials being stored. In addition, the influence of factors like archival box design, construction, and material degradation should not be overlooked when assessing the overall preservation environment—the Packaging box itself might degrade over time due to environmental factors, affecting its properties. This is particularly true for materials that are not chemically stable. As preservation practices and materials evolve, research to select and refine archival boxes will continue contributing to the ongoing understanding of how archival choices impact microenvironments of archival heritage.

Further research will use the direct measurements of RH, outside and inside an enclosure, to develop a simple empirical model to predict the buffering capacity via Humidity Attenuation (HA) index. Furthermore, a multiple linear regression (MLR) model will be built to predict the HA index based on the experimental properties of an enclosure, such as surface area, box mass, moisture sorption isotherm, water vapour transmission rate, and air exchange rate. In addition, the effects of permeability through the wall and the effects of absorption at low ventilation rates will be semi-quantified by including experiments in which boxes were stacked on top of each other or filled with paper.

Abbreviations

RH	Relative humidity
AER	Air exchange rates
WVTR	Water vapour transmission rates
EVA	Ethylene vinyl acetate

Acknowledgements
The authors would like to acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC) through the Centre for Doctoral Training SEAHA, and of Conservation by Design Ltd.

Author contributions
Conceptualisation: MN, JGB, IK, AE; funding acquisition: AE, IK, IK; investigation: MN, JGB, CD, CC, IK, JGB; methodology: MN, IK, AE and JGB; project administration: JGB, IK, AE; resources: MN, CD, CC, IK, IK, and JGB; supervision: MN, IK, AE and JGB; writing—original draft: MN, AE. All authors have read and agreed to the published version of the manuscript.

Funding
Open access funding provided by the research project Slovenian Research Agency (ARIS) project Lignin J4-3085 (Slovenia). The European Union (GREENART project, Horizon Europe research and innovation program under Grant Agreement No. 101060941) is gratefully acknowledged for partial financial support.

Data availability statement
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 16 October 2023 Accepted: 9 January 2024
Published online: 24 January 2024

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