Stabilisation of waterlogged archaeological wood: the application of structured-light 3D scanning and micro computed tomography for analysing dimensional changes

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Abstract

Cultural heritage objects made of wood can be preserved under waterlogged conditions for many years, where decay is slowed down and the wood structure is more or less completely filled with water. Depending on the degree of degradation, finds may collapse and shrink when they are allowed to dry in an uncontrolled manner after excavation, leading to total loss of the object and its information. Conservation measures are taken to prevent damage of objects and dimensional stability is an important criterion. In this study, structured-light 3D scanning and micro-computed tomography were used to analyse the dimensional stability of wood after conservation, as well as its long-term stability. 83 samples from a reference collection established between 2008 and 2011 allowed this comparative study of the most common conservation methods at that time. The effects of conservation methods using alcohol-ether resin, melamine-formaldehyde (Kauramin 800®), lactitol/trehalose, saccharose, and silicone oil on dimensional stability were investigated. In addition, different polyethylene glycol (PEG) treatments with subsequent freeze-drying were also investigated: one-stage with PEG 2000, two-stage with PEG 400 and PEG 4000 and three-stage with PEG 400, PEG 1500 and PEG 4000. The data received from analyses of both volume and surface gave detailed information about the success of each conservation method. Attempts were made to quantify the damage patterns, specifically shrinkage, collapse, and cracks. While PEG and freeze-drying, alcohol-ether-resin, as well as the Kauramin 800® method gave the best results, analysis also highlighted the failures of each method.

Keywords: Conservation, Waterlogged archaeological wood, Volume, Shrinkage, Computed tomography, Structured-light 3D scanning

Introduction

Wood can be preserved in waterlogged anoxic environments for thousands of years. There, only a few microorganisms such as bacteria and fungi that use wood as a nutrient are viable in an environment with a low oxygen level [1–7]. During burial, microorganisms have had time to degrade the wood by actually consuming the material from it so that physical weakening of the structure has occurred. Water swells the wooden structure and fills the pore spaces—the capillaries and the microcapillaries. As the cell wall suffers from material loss more water will fill up the internal voids. Though, the moisture content of decayed wood is raised. The maximum moisture content is related to the state of preservation of wood and is a universally used indicator [8–10].

Depending on its condition, waterlogged archaeological wood will change its dimensions in two stages upon
drying, due to collapse and shrinkage [11]. Above the fibre saturation point, cell cavities or lumina will collapse meaning irregular distortion unforeseeable in extent and distribution. The cause of collapse is capillary tension exerting compressive forces on the cell wall. As a result, the considerably weakened cell walls inevitably collapse [8, 12, 13]. Because of its heterogeneous state of preservation, there will be stresses developed in the object. In particular, the decayed shelf will dry first while the core is still wet [14].

Below the fibre saturation point, the cell walls will shrink [8, 15, 16]. The wood will then contract to a minimum of the original dimensions. Shrinkage in the tangential direction is generally more severe than radial and longitudinal shrinkage. But volumetric shrinkage is directly proportional to the water content of archaeological wood [10, 14].

There are several criteria to assess the effectiveness of conservation methods [14, 16–18]. One of the main criteria is to prevent the wood from shrinking and to stabilise the volume of the object. The stabilisation involves the preservation of the shape of the object, which contains information such as the manufacturing technique and the function of the object [19]. The dimensions of the actual but swollen waterlogged state should be preserved and intervention should be kept to a minimum [20].

To avoid shrinkage and collapse of waterlogged wood upon drying is the main challenge for the conservation of archaeological wet finds [21, 22]. The damaging effect of air-drying and the question of how to solve this problem has already been noted in the nineteenth century as being not an easy task [23, 24]. Since then, a variety of methods and conservation agents have been tested in conservation [16, 25–33]. The heterogeneous material, the different types of wood and especially the widely varying states of preservation make it difficult to assess the success of a conservation method, and studies to compare different conservation methods have been made since the beginning of wood conservation [8, 18].

To check the dimensional stabilisation of a method, the condition after the conservation is compared with the condition before conservation. In conservation science, several measurement methods have been applied to assess methods by comparing the dimensions before and after conservation: The extent of dimensional changes was evaluated on thin sections under the microscope [13] or on wooden samples with exact dimensions [16, 18, 19, 34–42]. The surfaces were also compared by drawing the outline of objects [43]. To assess the anisotropic character of archaeological wooden objects during drying, samples were cut in accordance with the specific alignments [17, 44] or stainless pins were introduced into the wood [15, 16, 34, 45–51]. In recent times, also optical 3D measurement methods are used in laboratory studies [45–47, 49, 50, 52] and on shipwrecks [53].

The aim of this study is to assess the dimensional stabilisation of a number of established and most commonly used conservation methods on larger sample series consisting of different wood species. The research in this study focuses on the volume changes after conservation using structured-light 3D scanning. In addition, the sample material studied allowed to investigate the volume stability of the conservation methods after 10 years.

Normally, the evaluation of the dimensional stability of conservation methods is limited to the outer surface of the wood. Micro-computed tomography (µCT) offers a non-destructive technology for the visualisation of the structures inside. Until now there are only a few cases that have also considered changes inside wood after conservation using tomographic methods [52, 54–62]. These investigations have shown that shrinkage of the wood can also result in cavities inside. In addition to cavities, cracks in the structure can also be detected [62]. However, it is the overall structure that provides information on whether an object has been stabilised. For this reason, the samples in this study were also examined by µCT after their conservation, which allowed internal defects such as cell collapse and cracks to be taken into account when evaluating the conservation result.

Materials and methods

Samples

The material under investigation is a reference collection held at the Römisch-Germanisches Zentralmuseum (RGZM), Leibniz Research Institute for Archaeology. In a research project that was performed from 2008 to 2011 the most established conservation methods were investigated where approximately 800 samples were conserved at different Institutions with their standard methods (Table 1, Fig. 1). A detailed overview of the conservation methods and the samples is given on the project homepage [45]. The methods employed were alcohol-ether-resin [18], melamine-formaldehyde (Kauramin 800®) [63], lactitol/trehalose [64], saccharose [26], silicone oil [65] and polyethylene glycol (PEG) with subsequent freeze-drying. PEG treatment followed either a one-stage process with PEG 2000 [66], two-stages with PEG 400 and PEG 4000 [67] or three-stages with PEG 400, PEG 1500 and PEG 4000 [45].

The samples were taken from archaeological objects that were collected from different sites. The objects were made of different types of wood and have different degrees of degradation, which were divided into the samples. The degree of degradation was determined by the maximum water content ($U_{\text{max}}$). The mass of the waterlogged wood was determined without vacuum impregnation with water before measuring. $U_{\text{max}}$ is defined as the water present in the sample compared to the absolute dry wood substance [2, 10]:
| Conservation method                  | Institutions and short descriptions of the methods                                                                                                                                                                                                 |
|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alcohol-ether-resin (AlEt)           | Institution: Schweizerisches Nationalmuseum, Zürich, Switzerland  
Treatment: Exchange of water with ethanol. Exchange of ethanol with diethyl ether. Soaking of wood with diethyl ether in resin-diethyl solution. Drying by evaporation of the diethyl ether in the vacuum vessel. Application of surface protection 3% Paraloid B72 solution in acetone  
Impregnation solution: 70.7% diethyl ether, 16.1% dammar resin, 6.4% rosin, 3.2% dionol D102, 3.2% rhizinus oil, 0.4% PEG 400  
Application of surface protection 3% Paraloid B72 solution in acetone  |
| Kauramin 800® (K800)                | Institution: Römisch-Germanisches Zentralmuseum, Mainz, Germany  
Treatment: Bath impregnation at room temperature. Replacement of the solution when early polymerisation occurs. Curing of the impregnated wood in the heating cabinet at 60 °C. Afterwards slow, controlled air-drying. Dip in linseed oil varnish  
Impregnation solution: 25% Kauramin 800® solution (72 L resin + 210 L deionised water, 3.6 L urea, 7.2 L triethylene glycol) |
| Lactitol/trehalose (LaTr)           | Institution: Brandenburgisches Landesamt für Denkmalpflege, Zossen, Germany  
Treatment: Starting with 30% concentration. Increasing monthly in 10% steps up to 70%. Bath temperature 55 °C. After removal from the bath, the surfaces were dusted with crystalline lactitol monohydrate and dried in a heating oven over a period of 1 week. After drying, the surface was cleaned by dabbing with damp cloths  
Impregnation solution: lactitol/trehalose solution (9:1) 30–70%. Addition of biocide if necessary (0.1% Bioban 404) |
| Polyethylene glycol (PEG 2000) one-step and freeze-drying (PEG1) | Institution: Nationalmuseet, Copenhagen, Denmark  
Treatment: Starting with 10% PEG 2000 solution. Increasing the concentration up to 40% at room temperature. Freeze-drying in cooled chamber (approx. — 30 °C). Removal of excess PEG from the surface with a soft brush and ethanol. Subsequent surface stabilisation with 25% PEG 2000 solution in ethanol  
Impregnation solution: PEG 2000, 10–40% solution with tap water |
| Polyethylene glycol (PEG 400 and 4000) two-step and freeze-drying (PEG2) | Institution: Brandenburgisches Landesamt für Denkmalpflege, Zossen, Germany  
Treatment: Soaking in demineralised water. Starting with 5% PEG 400 solution.  
Raising the concentration in 5% steps. At its calculated final concentration, it was kept constant. Then the increase of PEG 4000 solution was continued in 5% steps up to its final concentration. Precooling of the wood to 5 °C then deep-freezing to — 25 to — 35 °C, freeze-drying in cooled chamber (approx. — 30 °C).  
Impregnation solution: PEG-solution in demineralised water (PEG 400 and PEG 4000) was adapted according to the condition of the wood (PEGcon) |
| Polyethylene glycol (PEG 400, 1500 and 4000) three-step and freeze-drying (PEG3) | Institution: Archäologische Staatssammlung, Munich, Germany  
Treatment: Soaking in demineralised water. Starting with 11% increasing to 15% PEG 400 solution at room temperature.  
16% increasing to 20.5% PEG 1500 solution at 40 °C.  
20.5% increasing to 27.5% PEG 4000 solution at 40 °C.  
Washing of the wood and wrapping in cellulose tissues. Intermediate storage in freezer (− 25 to − 35 °C) until freeze-drying. Subsequent freeze-drying in a cooled chamber (approx. − 30 °C).  
Excess of PEG was removed with a brush and ethanol  
Impregnation solution: PEG-solution in demineralised water: 15% PEG 400, 6.5% PEG 1500, 7% PEG 4000 |
| Saccharose (Sac)                    | Institution: Sächsische Landesamt für Archäologie, Dresden, Germany  
Treatment: Concentrated the solution in 10% steps, from 10% up to 60% sugar solution at room temperature. Slow, controlled air-drying in microperforated bags. Removal of crystallised sugar residues from the surface with damp sponge  
Impregnation solution: Aqueous saccharose solution 10–60%. If necessary biocide addition composed of 0.6%, sodium benzoate (E211), 0.5% Parmetol K40, 0.5% Quarasept Plus and 0.02% Tallofin OT |
| Silicone oil (Sil)                  | Institution: Texas University, Texas, USA  
Treatment: Exchange of water with ethanol. Exchange of ethanol with acetone. Placing the still dripping wet acetone-impregnated samples in impregnation solution under normal atmospheric conditions. Triggering the polymerisation of the impregnation solution by gaseous catalyst: DBTDA (dibutyl diacetate)  
Impregnation solution: 80% silicone oil (SFD1 (66%) + SFD5 (34%) — silanol functional polydimethylsiloxanes “PDMS”) and 20% crosslinker MTMS (methyltri-methoxysilane) |
Values of $U_{\text{max}}$ have been classified by de Jong [51]. The numbers correspond to the water content ranges of the samples: (1) $U_{\text{max}} > 400\%$, (2) $U_{\text{max}} 185–400\%$, and (3) $U_{\text{max}} < 185\%$. The maximum water content was determined destructively for the control samples to be air-dried, and non-destructively for the samples to be conserved [45, 67]. The density of the cell wall substance is usually assumed to be $1.5\, \text{g/cm}^3$ [10, 68]. The water content is proportional to the void volume in the wood and inversely proportional to the basic or conventional density (BD, standard ISO 13061) of the wood in question (amount of wood substance per volume, g/cm³) [2, 69, 70]:

$$BD = \frac{100}{(66.7 + U_{\text{max}})}\, \left[\frac{\text{g}}{\text{cm}^3}\right]$$

(2)

To get an impression of how much wood has been decayed, the residual basic density (RBD) was calculated, in percent, as the ratio between the measured density of the archaeological material and the average basic density for non-degraded wood of the same species [10, 69], as derived from the literature [14, 71]:

$$RBD = \frac{BD}{BD(\text{fresh wood})} \cdot 100(\%)$$

(3)

The non-destructive determination of the condition of the wood does not always lead to reliable results, due to both mineral inclusions and inclusions of air in intact fibres with non-degraded pits and cell-walls. Therefore, the average value from all samples was taken (Appendix A).

This systematic collection of samples provides a unique chance to compare the structural differences of the conserved wood [43, 46]. Each test series of the collection includes samples derived from the same object (same wood species and finding place, similar state of preservation) that were conserved with the different treatments. Due to the different sizes of the objects, the number of samples varied. Therefore, not all test series contain all conservation methods. For the volume analyses in this study, the ten largest test series of the collection were selected in order to cover a high variety of methods and wood genera. Sample series of different wood species were investigated: three from oak (Oa1, Oa2 and Oa3), two from fir (Fi1 and Fi2) and one from alder (Al1), ash (As1), beech (Be1), pine (Pi1) and spruce (Sp1). 83 samples were analysed (Appendix A). Figure 2 gives an overview of the sampling and measurement methods of this research.

Structured-light 3D scanning

From 2008 onwards, the wet samples were captured before conservation and in dry condition after conservation using a structured-light 3D scanner. The capturing device was an ATOS III Rev. 01 scanner from GOM (a ZEISS company) with a field of view of 500 mm × 500 mm × 500 mm and a point distance of 0.25 mm. After data capture, all scans were processed in the ATOS Professional 2016 Software using same parameters by employing Python scripts to control the workflow and obtain a reduced 3D mesh with a closed surface. To analyse volume changes after 10 years the conserved samples were captured again in 2020. Since the same sensor was no longer available, a successor model was used. The ATOS III Rev.02 Triple Scan from GOM (a ZEISS company) with a field of view of 320 mm × 240 mm × 240 mm and a point distance of 0.10 mm was used. The processing of scans results in 3D meshes of the samples.

Micro-computed tomography

Analysis of the condition of the wood structure inside the samples about 10 years after their original conservation was carried out at Lucerne University of Applied Sciences and Arts with a μCT-system. The tomographic analysis was performed on the in-house laboratory XCT system (Diondo d₂, Germany). An optimised setup and acquisition protocol for the μCT measurements was developed for conserved wood. The measurements were conducted by setting the X-ray source (XWT-225 TCHE+ from X-ray works, Garbsen, Germany) in high power mode and choosing an operation voltage of 120 kV and a filament current of 167 μA with a 1 mm aluminum filter. The wood samples were mounted in a sample holder and placed in the sample chamber. The sample was rotated 360° in continuous mode during the acquisition. The radiographical
projections were recorded with a 4343 DX-I X-ray detector (Varex, Salt Lake City, USA), with a pixel size of 139 μm. The distance between the X-ray source and the sample was between 160 and 250 mm and the distance between the X-ray source and the detector was 860 mm, giving a magnification between 3.4 and 5.4 and a nominal voxel size between 27 and 44 μm. A total of 3000 projection images were acquired during the sample rotation of 360°. The resulting projections were converted into a 3D image stack of approx. 3000 × 3000 × 3000 voxels using the CERA reconstruction software based on the filtered back projection Feldkamp algorithm [72] from Siemens. The achieved resolution of the µCT measurements depends on the size of the samples [73]. Appendix A gives an overview of the samples, their size and the achieved resolution of the µCT measurements. Image cross-sections and 3D renderings of the wood were visualised in VGStudioMax3.4© software.

Surface and volume determination and calculation of the dimensional changes

To get information about the surface and the volume of the samples measured with µCT the data was analyzed with VGStudioMax3.4. To obtain values of the wood volume concerning inner cracks and collapse, surface determination of the very heterogeneous material was done manually for each sample with the different segmentation tools of the software. Afterwards the surface and volume values of the segmented µCT data and that of the structured-light 3D scanning were calculated with the same software.

The evaluation of the conservation methods was done by determining the dimensional stability on the basis of the volume data that was derived from the surface of the whole sample. The values of the individual wood anatomical directions (tangential, radial and longitudinal) can be taken from the database [45].

To evaluate the volume changes in the measurement, data from structured-light 3D scanning was used to calculate the shrinkage (S) from the volume of the samples before (V_{wet}) and after (V_{dry}) conservation [74–77]:

$$S = \frac{V_{wet} - V_{dry}}{V_{wet}} \times 100 [\%]$$

Fig. 2 Graphical overview of the experimental procedure: sampling, conservation, measurements with structured-light 3D scanning and µCT

The anti-shrink efficiency (ASE) was determined from the shrinkage of a non-conserved control sample (S₀) and the shrinkage of the conserved sample (S_{con}) [15, 16, 78]:

$$ASE = \frac{S₀ - S_{con}}{S₀} \times 100 [\%]$$

100% ASE means a very good conservation has been achieved, whereas an ASE of 0% indicates a result equal to that accomplished by air-drying. An ASE of 75% seems to be acceptable [15, 16]. By using ASE, a statistical evaluation and comparison of conservation results is possible.
To probe the volume stability of conserved archaeological wood over time and the dimensional stability of the wood volume with respect to the inner structure, the values of the whole samples from structured-light 3D scanning and µCT were used. Analogous to the shrinkage after conservation analysis (Eq. 4), the volume change of the samples after 10 years was calculated from the volume after conservation and the volume 10 years after conservation. Similarly, the volume change concerning the inner structures of the wood was calculated from the volume of the structured-light 3D scanning 10 years after conservation and the volume of the µCT-data after 10 years. Surface changes ($A_O$) were calculated additionally from the values of structured-light 3D scanning and µCT after 10 years:

$$A_O \text{change} = \frac{A_O \mu CT - A_O \text{scan}}{A_O \text{scan}} \times 100[\%] \quad (6)$$

To get an impression of the size and shape of the cavities inside the samples the volumes and surface areas were determined by the difference between structured-light 3D scanning and µCT data. From these values the sphericity $\psi$ was calculated:

$$\psi = \frac{\sqrt{36\pi V^2}}{A_O} \quad (7)$$

The sphericity $\psi$ relates the shape of a body based on its volume ($V$) and its surface ($A_O$) to the smallest possible surface of a sphere of the same volume [79]. The value of the sphericity $\psi$ for a sphere is 1. The lower a value of sphericity $\psi$ is for a shape, the larger the surface area is compared to a sphere.

**Results and discussion**

**Volume changes**

Appendix B shows the values for the volumes of the structured-light 3D scans before and after conservation. The measurements show extensive shrinkage of the unconserved wood samples. In Fig. 3 the loss of volume after air-drying of the untreated wood shows a relationship with the condition of the wood which is calculated as the residual basic density in per cent (Eq. 3). There is a clear trend showing that the better the wood is preserved, the less volume change occurs during air-drying. Figure 3 also demonstrates less shrinkage of all conserved samples in comparison to the air-dried samples. There is a difference between the conservation methods concerning the samples with a higher degradation and a lower residual basic density. It is evident that the stabilisation of these samples treated with saccharose, lactitol/trehalose or silicone oil is not as sufficient as compared to the other treatments.

This tendency is also confirmed by the calculation of the ASE (Eq. 5). Figure 4 shows the ASE of all sample series in relation to the preservation status. For a better overview, the average value ($\bar{x}$) of the residual basic density is given here for each sample series. In Fig. 4 it becomes even clearer that strongly degraded sample series are less stabilised by the conservation agents saccharose, lactitol/trehalose and silicone oil than by the other conservation agents. In addition, it also becomes obvious that the overall volume stabilisation decreases with a better state of preservation. The threshold here is a residual basic density of about 60%. This limit indicates that the preservation state 2 after de Jong [51, 80, 81] is particularly difficult to conserve due to two different states of preservation in one object [17]. The µCT data confirms that in these test series (Pi1, Fi1, Oa1 and Oa2) samples have highly degraded and low degraded areas. In contrast, the more degraded sample series show a consistent picture in the µCT data. The cross-sections of the samples As1-K800 and Pi1-AlEt show the difference between one homogeneous state of preservation (Fig. 5) and two states of preservation in one object (Fig. 6).

Apart from the state of preservation, there are also considerable variances in the conservation methods in the individual test series with different wood species. All conservation methods improve stabilisation to some degree. Taking all the results into account and looking at the average of the volume changes for the different conservation methods, a general trend can be seen (Fig. 7). The best results are mostly achieved using PEG, the alcohol-ether method or Kauramin, although there are exceptions. The individual conservation methods with their deviations and special features will be discussed later in detail.

Appendix C shows the values of the volume changes after 10 years. Here, it is particularly noticeable that almost all unconserved wood samples are not stable. With a few exceptions, the changes in the conserved samples are very slight and no clear trends can be identified for the individual conservation methods. All conservation methods thus seem to permanently stabilise the samples, as can be seen from the average values for volume change after 10 years (Fig. 7). In Appendix C, the internal structures are considered and the extent to which this changes the volume. Since no µCT data of the previous state is available, the values of the µCT data are compared with the values of the surface scans of the current state 10 years after conservation. Since the original condition of the interior of the samples is unknown, this is primarily a comparison of methods. It should be noted here that the µCT not only considers internal cavities, but also, in contrast to the surface scan, considers and more accurately depicts crevices and depressions (Fig. 8). Nevertheless, differences in the conservation methods become apparent when looking at the average value of the volume change inside all samples. The conservation methods with Kauramin 800®,
Fig. 3 Loss of volume after air-drying untreated samples and conserved ones in relation to the condition of the wood (residual basic density in %)

Fig. 4 Volume stability (ASE) dependent on the average residual basic density $\bar{x}$. The conservation method is given on the data point.
saccharose, lactitol/trehalose and silicone oil seem to lead to a greater change in volume inside the samples than the other conservation methods (Fig. 7).

**Volume changes in relation to the surface**

Another indicator for the stabilisation of a sample that can be obtained from surface scans and µCT are changes in surface values. Obviously, if only the outer surface is considered, it will also decrease with volume shrinkage. By comparing the surface data with the µCT data, a value for the surface inside the sample is obtained, which can provide information about cell collapse and cracks in the sample (Appendix D, Eq. 6).

If the surface area increases in the µCT data, we are dealing with cavities inside the sample. Again, it must be considered that due to the lack of the previous condition, it cannot be clearly proven whether the cavity was already inside the wood before the conservation. In some cases, there is also some uncertainty due to deeper cracks in the surface that were not detected by the structured-light 3D scanner (Fig. 8). When looking at the µCT data, however, cell collapse is definitely evident (Fig. 9). In addition, clear cracking can be seen in the samples conserved with PEG that were freeze-dried (Fig. 14) [46, 52].

The values for the enlargement of the surface and the shrinkage in percent, resulting from the comparison of surface scan and µCT, are listed in Appendix D. From the values, it is possible to see, to some extent, if collapse and cracks appear inside the wood samples. If neither the volume nor the surface have changed much, this means that the sample is also stable inside. In contrast, it can be assumed that a large surface increase combined with a large volume loss can only be explained by a significant collapse inside the sample. An example of this is the alder sample (Al1-LaTr, Fig. 10). A surface increase of 305% and a shrinkage of 16%. If only the volume has changed considerably and the surface does not change so significantly, it can be assumed that isolated, large cracks or fissures have occurred within the wood. This is the case with the oak sample (Oa2-K800), which is also shown in the cross-section of the sample (Fig. 13). In relation to the volume loss with 15%, the surface with 144% has changed far less compared to the alder sample (Al1-LaTr, Fig. 10). If, on the contrary, the surface has increased considerably with a smaller change in volume, this is a sign of many fine cracks within the wood, as has already been mentioned for the wood conserved with PEG and freeze-dried. An example of this is the ash sample (As1-PEG1), which has a relatively stable volume with a shrinkage of 1% but a large surface enlargement with a value of 218%. The fine cracks, leading to these values, can be seen in Fig. 14. Such obvious changes in the wood structure and the measured volume and surface values are discussed below individually for each conservation method studied.

Another way to approximate the shape of these cavities inside the wood is to calculate the sphericity $\psi$, which relates the shape of a body based on its volume and its surface to the smallest possible surface of a sphere of the same volume (Eq. 7) [79]. The lower this value for a shape, the larger the surface in relation to a sphere. The values determined in this way show a wide variation and are probably dependent on the conservation agent, the type of wood and the state of preservation. However, tendencies for the different conservation methods can be derived from the averaged values (Fig. 11). In contrast to the other methods, the values obtained from samples treated with PEG scatter far less. This could be an indication that a more uniform and reliable conservation result can be achieved here. Furthermore, the average values obtained from samples treated with PEG are noticeably low. The
Fig. 7  Average shrinkage of all selected samples after conservation, after 10 years and including the inner structures derived from µCT.

Fig. 8  µCT cross sections of two examples (Oa3-K800 left and Oa3-Sac right) for the comparison of the surface detection with structured-light 3D scanner and µCT.
sphericity \( \psi \) confirms the picture that fine cracks tend to form in these cases.

**Dimensional stabilisation provided by the conservation methods**

**Alcohol-ether-resin**

The samples conserved with the alcohol-ether-resin show very good volume stabilisation overall. With two exceptions, the values determined for the ASE of the scans before and directly after conservation are above 90% (Appendix B). The oak sample (Oa2-AlEt) also has a very good ASE value of 88%, while the pine sample (Pi1-AlEt) having the lowest value, with an ASE of 76%. This could be due to the preservation state 2 according to de Jong [51, 80, 81] with two different levels of degradation (Fig. 6). The scans after 10 years show consistently good values for volume stability. Considering the internal structures resulting from the \( \mu \)CT data, the method also shows good volume stabilisation (Appendix C, Fig. 7). Only the alder sample (Al1-AlEt) shows a poor value with more than 5% additional volume loss. If the surface change of the samples preserved with alcohol-ether-resin is added, the predominantly positive overall picture is reinforced (Appendix D). The low surface increase when considering the internal structures on the basis of the \( \mu \)CT, together with the simultaneous low volume loss, indicates that there was little collapse or crack formation in the interior of the specimens, which is also confirmed by the cross sections of the samples in \( \mu \)CT data. An exception is again the alder sample (Al1-AlEt), which shows a comparatively high value of 137% surface increase, which in connection with the volume loss indicates an increased cell collapse inside the sample. This is supported by the observation of the \( \mu \)CT data (Fig. 9). It should be noted here that in this series, poorer values are observed overall in comparison with all conservation methods, which may be explained by the fact that cavities were already present in the wood before conservation. This positive assessment is also confirmed in previous studies [18] especially for broadleaved woods [82].

**Kauramin 800\(^{\circledast}\)**

The samples conserved with Kauramin 800\(^{\circledast}\) also show mainly very good results. With two exceptions, the ASE directly after conservation shows values above 90% (Appendix B). Five of the ten samples even show an ASE of 99% to 101%. The samples with lower values are the pine sample (Pi1-K800) with an ASE of 87% and the oak sample (Oa1-K800) with an ASE of 88%. The pine sample (Pi1-K800) comes from the same sample series as the previously mentioned pine sample (Pi1-AlEt), which, with two different areas of degradation (de Jong: 2), also has the worst value of the alcohol-ether-resin. Volume stability is guaranteed for Kauramin 800\(^{\circledast}\) even after 10 years. A somewhat different picture of the method emerges when looking at the \( \mu \)CT data. While the positive results for most samples are confirmed by a small additional volume loss, a different picture emerges for the oak samples (Oa1-K800 and Oa2-K800) with two different states of preservation (de Jong: 2, Appendix C). The additional volume loss of 10% and 15%, respectively, is also significantly reflected in the overall results of the method (Fig. 7). It is striking that this volume loss is caused, in both cases, by large gaps that run along the two different maintenance states in the wood (Figs. 12 and 13). The low values of surface area increase in relation to volume loss confirm here that large fissures are involved (Appendix D). Overall, the samples preserved with Kauramin 800\(^{\circledast}\) show greater surface area increase than the samples preserved with alcohol-ether-resin, suggesting that cell collapse and cracking have increased in these. This may be due to
the fact that it is too stiff and is not easy to deform. This has been criticised in the literature regarding previous methods using melamine resins [18]. It has also been described that Kauramin 800® stabilises highly degraded wood very well, while well-preserved wood is stabilised more poorly. This could be due to poorer penetration of the amino resin prepolymer, resulting in collapse and shrinkage of the well-preserved wood [17]. This becomes obvious in samples with two different states of preservation.

Lactitol/trehalose

The samples conserved with lactitol/trehalose were inferior to the previously mentioned methods. The ASE of the samples directly after conservation is between 76% and 92%, whereby only the beech sample (Be1-LaTr) with an ASE of 92% has a value above 90% (Appendix B). A change in volume after ten years is also not observed in the woods conserved with lactitol/trehalose. Looking at the internal structures based on the µCT of the samples preserved with lactitol/trehalose, this also confirms poor volume stabilisation (Appendix C, Fig. 7). In particular, the alder sample (Al1-LaTr) and the oak sample (Oa3-LaTr) have poor values with 16% and 14% additional volume loss, respectively. If one adds to the volume loss the strong surface change in these samples (Appendix D), this indicates that considerable collapse has occurred inside these samples. Figure 10 shows a cross-sectional image of the µCT, which illustrate the collapse of the wood structure.
**Polyethylene glycol (PEG 2000) one-step and freeze-drying**

The samples conserved with PEG 2000 and then freeze-dried show predominantly very good volume stabilisation (Appendix B). Except for two samples, the ASE values are above 90%. In six of the ten samples, the ASE is between 99% and 105%. The samples with the lowest values are the oak sample (Oa1-PEG1) with a value of 83% and the oak sample (Oa2-PEG1) with a value of 89%. The scans after 10 years also show consistently high values of volume stability for the samples conserved with PEG 2000. Similarly, the µCT data confirm good volume stabilisation inside the samples (Fig. 7). With just over 2% additional shrinkage inside the samples, the alder sample (Al1-PEG1) and one of the two fir samples (Fi2-PEG1) have the highest values (Appendix C). If the surface change is also considered, it is noticeable that these two samples also exhibit a large surface enlargement with values above 200%. With the exception of the first fir sample (Fi1-PEG1), such a surface increase is observed in all samples preserved with PEG 2000 and freeze-drying (Appendix D), which can be explained by the formation of cracks. Figure 14 shows these cracks, for example, in the ash sample (As1-PEG1). With the exception of the fir sample (Fi1-PEG1), these cracks occur in all samples conserved with PEG 2000.

The first step in the freeze-drying process is the freezing of the impregnated wood. Freezing the aqueous solution in the wood leads to the expansion of its volume [83] leading to cracks. Specimens preserved with PEG exhibit low strength [18]. This fragility is further increased by the cracks that have formed as a result of the conservation.

**Polyethylene glycol (PEG 400 and 4000) two-step and freeze-drying**

The samples conserved in stages with PEG 400 and PEG 4000 and afterwards freeze-dried also show a predominantly favourable volume stabilisation (Appendix B). With the exception of the values of three samples, the calculated ASE is above 90%. The samples with the poorest values are the oak sample (Oa2-PEG2) with a value of 89%, the pine sample (Pi1-PEG2) with a value of 87%, and the second oak sample (Oa1-PEG2), which dropped sharply to 74%. The scans after 10 years show satisfactory volume stability, in line with the other conservation methods. Considering the results of the µCT, a similar picture appears as for the conservation with PEG 2000. The volume stabilisation inside the samples is good and with a value above 3%, the oak sample (Oa3-PEG2) has the highest additional shrinkage (Appendix C). An increase of the surface area with a good volume stabilisation inside the samples can also be observed, which in turn suggests the formation of cracks inside the samples (Appendix D). The cracks occur less strongly than with the other PEG methods. However, they are clearly visible in seven sample series. The fir samples (Fi1-PEG2, Fi2-PEG2) and the spruce sample (Sp1-PEG2) have no obvious cracks. In one case, in addition to cracks in the outer area, it can also be observed that the wood structure in the centre has collapsed (Fig. 15).

**Polyethylene glycol (PEG 400, 1500 and 4000) three-step and freeze-drying**

The samples conserved in three stages with PEG 400, PEG 1500 and PEG 4000 and then freeze-dried are among the best results of the methods with PEG (Appendix B). With the exception of two samples, the ASE values are above 90%. The samples with poorer values are the oak sample (Oa1-PEG3) with a value of 85% and the pine sample (Pi1-PEG3) with a value of 80%. The scans after 10 years show satisfactory volume stability (Appendix C). As with the other conservation methods using PEG, the µCT data show good volume stabilisation with a simultaneous increase in surface area inside the samples, again indicating the formation of fine cracks (Appendix D). The µCT cross-sections (Fig. 16) confirm that these cracks occur in all samples conserved with the three-step PEG method except the fir sample (Fi1-PEG3). In particular, the alder sample (Al1-PEG3) stands out with a shrinkage of almost 7% and a surface area increase of over 600%. This sample is an exception among the samples conserved with PEG because, in addition to the cracks, there is also considerable collapse in the conserved wood structure (Fig. 17).

**Saccharose**

The samples conserved with saccharose show a poorer conservation overall and the results vary greatly. Thus, the ASE of the ten samples directly after conservation ranges between 64% and 94%, with only the fir sample (Fi1-Sac) with 94% and the pine sample (Pi1-Sac) with 90% showing a value above 90% (Appendix B). The ASE of the pine sample (Pi1-Sac) is

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**Fig. 14 µCT cross section of the ash sample treated with PEG 2000 and freeze-dried (As1-PEG1) with cracks in the wood structure**
particularly remarkable in this context, as the other conservation methods consistently perform rather poorly in this series of samples. A change in volume after ten years is also not observed in the wood samples conserved with saccharose (Fig. 7). The µCT data also show very different results, with very poor values of volume stabilisation inside the samples in some cases (Al1-Sac, As1-Sac, Oa3-Sac, Appendix C). Together with the high values of surface change (Appendix D), this indicates a significant collapse of the wood structure, as confirmed by the images of the ash sample (As1-Sac, Fig. 18). However, low stabilisation is not solely related to low concentration of consolidant. Highly concentrated solutions can also be problematic. Their susceptibility to degradation by osmotolerant microorganisms can lead to the development of slime and gases, which can prevent consolidants from penetrating the wood. Even an excess of biocides, due to the low penetration of the same, could not prevent these fermentation processes. The decomposition of saccharose takes place by chemical or microbiological processes, whereby the sugar is converted into the monosaccharides of fructose and glucose. This prevents volume stabilisation and, as the degradation products are more hygroscopic, leads to a damp surface and poorer drying [84–86].

Silicone oil
The samples conserved with silicone oil tend to show poorer volume stabilisation overall and the ASE of the samples is between 71% and 89% (Appendix B). No change in volume can be observed in the wood conserved with silicone oil after ten years (Fig. 7). As with the saccharose-conserved samples, the µCT data show very different results (Appendix C). Thus, there are also striking samples (Al1-Sil, As1-Sil, Sp1-Sil) with poor volume stabilisation and an interior surface enlargement, which again indicates the collapse of the wood structure (Appendix D). This is also confirmed, for example, by the images of sample As1-Sil (Fig. 19).

Conclusion
On the basis of the surface data from structured-light 3D scanning of ten test series with a total of 83 wood samples, it was possible to comparatively investigate the preservation results of different conservation methods with regard to their volume stabilisation. Wood is a very heterogeneous material and the successful conservation and volume stabilisation depends on different factors. This study showed that first of all the state of preservation is of great importance. The dimensional changes upon air-drying are dependent on the water content. This was also confirmed by other studies [2, 5, 13, 80].
There are also enormous differences between the conservation methods studied. It should be noted that all methods investigated in the study stabilised the wood to some extent, in contrast to air-drying. The investigation of the volume stability after 10 years further showed that all conserved samples remained stable in contrast to the air-dried samples. However, it should also be noted that only the methods using PEG, alcohol-ether-resin and Kauramin 800® guarantee reliable volume stabilisation. The other methods were subject to considerable fluctuations and in some cases showed a large volume loss due to cell collapse.

For the first time, the internal structures of a large sample series were considered by the application of μCT. In contrast to the structured-light 3D scans performed here, the μCT measurements show the considerable damage such objects can take during conservation due to cracks and cell collapse. Such disadvantages could also be observed in samples that were treated with the methods using PEG, alcohol-ether-resin and Kauramin 800®. For example, in a condition with two differently degraded areas in the wood, large gaps can form during conservation with Kauramin 800®. This is possibly due to the fact that the conservation agent has the ability to stabilise heavily degraded wood better than well preserved wood, which may be explained by poorer penetration into well preserved wood [17, 87]. In the samples conserved with PEG and subsequently freeze-dried, a large number of fine cracks in the wood were very often visible in the μCT data. This can be explained by the fact that the aqueous PEG solution expands during freezing, resulting in damage to the wood structure. The two-step method using aqueous solutions of PEG 400 and PEG 4000 showed slightly better results with fewer cracks. This may be attributed to the fact that low molecular weight PEG lowers the critical freeze-drying temperature and a proportion of the solution does not freeze. Though less volume expansion may occur [46]. In addition, it was observed in one sample that there is considerable collapse in the centre. That may be explained by the fact that the aqueous solution of PEG thawed during the freeze-drying process. Afterwards, the wood structure collapsed when drying from the liquid phase. It is likely the conservation agent was transported to the outside areas by capillary forces, thus, appearing as though there is no conservation agent present in this area in the μCT data. This has already been described in the literature as being a crucial parameter in the conservation treatment with PEG [17, 18, 54, 58].

These observations show the importance of tomographic methods and the need to take into account the internal structures when assessing the conservation result. However, these observations also show that further research and validation of the results is required. In order to be able to assess the changes in the wood caused by the conservation with certainty, it is necessary in further test series to also record the preliminary condition of the samples using tomographic methods. However, in the case of the waterlogged condition of wood, it should be noted that the presence of water in the wood reduces the quality of the μCT data and complicates the measurement procedure. Therefore, for waterlogged wood, magnetic resonance imaging, for example, would be a suitable method to better capture the preliminary wet condition [55, 88, 89]. It should be mentioned that in this study only volume stabilisation of conservation methods was considered for evaluation. Other factors such as reversibility, effort, toxicity of the ingredients and long-term stability are also of great importance in the choice of the procedure.
### Appendix A: Genus, conservation method, condition, dimensions and resolution µCT of the samples

| Sample | KUR-No | Genus | Conservation method | Umax (% | Condition (de Jong) | Basic density (g/cm³) | Residual basic density (%) | Dimensions (cm) L, Ø/L, W, H | Resolution µCT (µm) |
|--------|--------|-------|---------------------|---------|---------------------|-----------------------|---------------------------|-----------------------------|-----------------|
| A11‑Air V24‑23 | Alder | Air dried | 743 | 1 | 0.124 | 28 | 20, 3–5 | 27 |
| A11‑AlEt V24‑45 | Alder | Alcohol-Ether | 706 | 1 | 0.129 | 29 | 12, 3–5 | 27 |
| A11‑K800 V24‑60 | Alder | Kauramin 800® | 958 | 1 | 0.098 | 22 | 16, 3–5 | 30 |
| A11‑LaTr V24‑19 | Alder | Lactitol/trehalose | 891 | 1 | 0.104 | 24 | 14, 3–5 | 30 |
| A11‑PEG1 V24‑13 | Alder | PEG (1) | 853 | 1 | 0.109 | 25 | 17, 3–5 | 35 |
| A11‑PEG2 V24‑63 | Alder | PEG (2) | 671 | 1 | 0.136 | 31 | 18, 3–5 | 27 |
| A11‑PEG3 V24‑21 | Alder | PEG (3) | 1048 | 1 | 0.090 | 20 | 19, 3–5 | 30 |
| A11‑Sac V24‑34 | Alder | Saccharose | 820 | 1 | 0.113 | 26 | 13, 3–5 | 27 |
| A11‑Sil V24‑56 | Alder | Silicone oil | 807 | 1 | 0.114 | 26 | 15, 3–5 | 30 |
| A12‑Air V24‑23 | Alder | Air dried | 738 | 1 | 0.124 | 22 | 11, 12 | 43 |
| A12‑AlEt V24‑45 | Alder | Alcohol-Ether | 994 | 1 | 0.094 | 17 | 11, 12 | 44 |
| A12‑K800 V24‑60 | Alder | Kauramin 800® | 961 | 1 | 0.097 | 17 | 11, 12 | 35 |
| A12‑LaTr V24‑19 | Alder | Lactitol/trehalose | 1291 | 1 | 0.074 | 13 | 11, 12 | 35 |
| A12‑PEG1 V24‑80 | Alder | PEG (1) | 1195 | 1 | 0.079 | 14 | 11, 12 | 35 |
| A12‑PEG2 V24‑36 | Alder | PEG (2) | 929 | 1 | 0.100 | 18 | 11, 12 | 44 |
| A12‑PEG3 V24‑21 | Alder | PEG (3) | 1376 | 1 | 0.069 | 12 | 11, 12 | 35 |
| A12‑Sac V24‑34 | Alder | Saccharose | 983 | 1 | 0.095 | 17 | 11, 12 | 35 |
| A12‑Sil V24‑56 | Alder | Silicone oil | 664 | 1 | 0.127 | 24 | 20, 8, 8 | 35 |
| A12‑AlEt V24‑60 | Alder | Kauramin 800® | 720 | 1 | 0.127 | 23 | 19, 8, 2,5 | 32 |
| A12‑LaTr V24‑19 | Alder | Lactitol/trehalose | 566 | 1 | 0.158 | 28 | 17, 8, 2,5 | 32 |
| A12‑PEG1 V24‑13 | Alder | PEG (1) | 772 | 1 | 0.119 | 21 | 13, 8, 2,5 | 35 |
| A12‑PEG2 V24‑63 | Alder | PEG (2) | 654 | 1 | 0.139 | 25 | 14, 8, 2,5 | 35 |
| A12‑PEG3 V24‑21 | Alder | PEG (3) | 747 | 1 | 0.123 | 22 | 15, 8, 2,5 | 35 |
| A12‑Sac V24‑34 | Alder | Saccharose | 748 | 1 | 0.123 | 22 | 16, 8, 2,5 | 35 |
| A12‑Sil V24‑56 | Alder | Silicone oil | 808 | 1 | 0.114 | 20 | 18, 8, 2,5 | 35 |
| A12‑Air V24‑23 | Alder | Air dried | 381 | 2 | 0.223 | 59 | 30, 8, 2,5 | 32 |
| A12‑AlEt V24‑45 | Alder | Alcohol-Ether | 398 | 2 | 0.215 | 57 | 22, 8, 2,5 | 32 |
| A12‑K800 V24‑60 | Alder | Kauramin 800® | 487 | 1 | 0.181 | 48 | 26, 8, 2,5 | 32 |
| A12‑LaTr V24‑19 | Alder | Lactitol/trehalose | 352 | 2 | 0.239 | 63 | 24, 8, 2,5 | 32 |
| A12‑PEG1 V24‑13 | Alder | PEG (1) | 432 | 1 | 0.201 | 53 | 27, 8, 2,5 | 32 |
| A12‑PEG2 V24‑63 | Alder | PEG (2) | 371 | 2 | 0.228 | 60 | 28, 8, 2,5 | 32 |
| A12‑PEG3 V24‑21 | Alder | PEG (3) | 241 | 2 | 0.325 | 86 | 29, 8, 2,5 | 32 |
| A12‑Sac V24‑34 | Alder | Saccharose | 285 | 2 | 0.284 | 75 | 23, 8, 2,5 | 32 |
| A12‑Sil V24‑56 | Alder | Silicone oil | 333 | 2 | 0.250 | 66 | 25, 8, 2,5 | 32 |
| A12‑Air V24‑23 | Alder | Air dried | 465 | 1 | 0.188 | 49 | 11, 6–7 | 40 |
| A12‑AlEt V24‑45 | Alder | Alcohol-Ether | 695 | 1 | 0.131 | 35 | 11, 6–7 | 40 |
| A12‑K800 V24‑60 | Alder | Kauramin 800® | 601 | 1 | 0.150 | 39 | 11, 6–7 | 40 |
| A12‑PEG1 V24‑13 | Alder | PEG (1) | 542 | 1 | 0.164 | 43 | 11, 6–7 | 40 |
| A12‑PEG2 V24‑63 | Alder | PEG (2) | 632 | 1 | 0.143 | 38 | 11, 6–7 | 40 |
| A12‑PEG3 V24‑21 | Alder | PEG (3) | 554 | 1 | 0.161 | 42 | 11, 6–7 | 40 |
| A12‑Sac V24‑34 | Alder | Saccharose | 599 | 1 | 0.150 | 40 | 11, 6–7 | 40 |
| A12‑Sil V24‑56 | Alder | Silicone oil | 548 | 1 | 0.163 | 43 | 11, 6–7 | 40 |
| Sample  | KUR-No | Genus | Conservation method | Umax (%) | Condition (de Jong) | Basic density (g/cm³) | Residual basic density (%) | Dimensions (cm) L, Ø/L, W, H | Resolution µCT (µm) |
|---------|--------|-------|---------------------|----------|---------------------|----------------------|---------------------------|----------------------------|------------------|
| Oa1-Air | V10-02 | Oak   | Air dried           | 201      | 2                   | 0.374                | 67                        | 17, 7                     | 32               |
| Oa1-K800| V10-06 | Oak   | Kauramin 800®       | 198      | 2                   | 0.378                | 67                        | 16, 7                     | 32               |
| Oa1-LaTr| V10-33 | Oak   | Lactitol/trehalose  | 160      | 3                   | 0.441                | 79                        | 15, 7                     | 32               |
| Oa1-PEG1| V10-29 | Oak   | PEG (1)             | 179      | 3                   | 0.407                | 73                        | 11, 7                     | 32               |
| Oa1-PEG2| V10-31 | Oak   | PEG (2)             | 176      | 3                   | 0.412                | 74                        | 12, 7                     | 32               |
| Oa1-PEG3| V10-39 | Oak   | PEG (3)             | 181      | 3                   | 0.404                | 72                        | 13, 7                     | 32               |
| Oa1-Sac | V10-03 | Oak   | Saccharose          | 163      | 3                   | 0.435                | 78                        | 14, 7                     | 32               |
| Oa2-Air | V16-15 | Oak   | Air dried           | 362      | 2                   | 0.233                | 42                        | 12, 15, 4,5               | 33               |
| Oa2-AlEt| V16-09 | Oak   | Alcohol-ether       | 175      | 3                   | 0.414                | 74                        | 12, 15, 4,5               | 32               |
| Oa2-K800| V16-25 | Oak   | Kauramin 800®       | 228      | 2                   | 0.339                | 61                        | 12, 15, 4,5               | 44               |
| Oa2-PEG1| V16-18 | Oak   | PEG (1)             | 189      | 2                   | 0.391                | 70                        | 12, 15, 4,5               | 35               |
| Oa2-PEG2| V16-32 | Oak   | PEG (2)             | 237      | 2                   | 0.329                | 59                        | 12, 15, 4,5               | 44               |
| Oa2-PEG3| V16-36 | Oak   | PEG (3)             | 188      | 2                   | 0.393                | 70                        | 12, 15, 4,5               | 35               |
| Oa2-Sac | V16-17 | Oak   | Saccharose          | 184      | 3                   | 0.399                | 71                        | 12, 15, 4,5               | 35               |
| Oa2-Sil | V16-13 | Oak   | Silicone oil        | 187      | 2                   | 0.394                | 70                        | 12, 15, 4,5               | 32               |
| Oa3-Air | V27-17 | Oak   | Air dried           | 577      | 1                   | 0.155                | 28                        | 12–14, 5–6                | 19               |
| Oa3-AlEt| V27-40 | Oak   | Alcohol-ether       | 527      | 1                   | 0.168                | 30                        | 12–14, 5–6                | 32               |
| Oa3-K800| V27-07 | Oak   | Kauramin 800®       | 646      | 1                   | 0.140                | 25                        | 12–14, 5–6                | 26               |
| Oa3-LaTr| V27-30 | Oak   | Lactitol/trehalose  | 566      | 1                   | 0.158                | 28                        | 12–14, 5–6                | 26               |
| Oa3-PEG1| V27-12 | Oak   | PEG (1)             | 691      | 1                   | 0.132                | 24                        | 12–14, 5–6                | 32               |
| Oa3-PEG2| V27-02 | Oak   | PEG (2)             | 578      | 1                   | 0.155                | 28                        | 12–14, 5–6                | 32               |
| Oa3-PEG3| V27-01 | Oak   | PEG (3)             | 557      | 1                   | 0.160                | 29                        | 12–14, 5–6                | 39               |
| Oa3-Sac | V27-21 | Oak   | Saccharose          | 434      | 1                   | 0.200                | 36                        | 12–14, 5–6                | 26               |
| Oa3-Sil | V27-10 | Oak   | Silicone oil        | 520      | 1                   | 0.170                | 30                        | 12–14, 5–6                | 26               |
| Pi1-Air | V03-01 | Pine  | Air dried           | 390      | 2                   | 0.219                | 52                        | 20, 7–9–12                | 39               |
| Pi1-AlEt| V03-17 | Pine  | Alcohol-Ether       | 332¹     | 2                   | 0.251¹               | 60¹                       | 12, 7–9–12                | 40               |
| Pi1-K800| V03-41 | Pine  | Kauramin 800®       | 332¹     | 2                   | 0.251¹               | 60¹                       | 19, 7–9–12                | 40               |
| Pi1-LaTr| V03-28 | Pine  | Lactitol/trehalose  | 332¹     | 2                   | 0.251¹               | 60¹                       | 17, 7–9–12                | 40               |
| Pi1-PEG1| V03-35 | Pine  | PEG (1)             | 332¹     | 2                   | 0.251¹               | 60¹                       | 13, 7–9–12                | 40               |
| Pi1-PEG2| V03-32 | Pine  | PEG (2)             | 332¹     | 2                   | 0.251¹               | 60¹                       | 14, 7–9–12                | 40               |
| Pi1-PEG3| V03-20 | Pine  | PEG (3)             | 332¹     | 2                   | 0.251¹               | 60¹                       | 15, 7–9–12                | 40               |
| Pi1-Sac | V03-45 | Pine  | Saccharose          | 332¹     | 2                   | 0.251¹               | 60¹                       | 16, 7–9–12                | 40               |
| Pi1-Sil | V03-42 | Pine  | Silicone oil        | 332¹     | 2                   | 0.251¹               | 60¹                       | 18, 7–9–12                | 40               |
| Sp1-Air | V23-20 | Spruce | Air dried           | 503      | 1                   | 0.176                | 46                        | 21, 10, 6                 | 40               |
| Sp1-K800| V23-08 | Spruce | Kauramin 800®       | 482      | 1                   | 0.182                | 48                        | 20, 10, 6                 | 40               |
| Sp1-LaTr| V23-02 | Spruce | Lactitol/trehalose  | 454      | 1                   | 0.192                | 51                        | 19, 10, 6                 | 40               |
| Sp1-PEG1| V23-25 | Spruce | PEG (1)             | 427      | 1                   | 0.203                | 53                        | 15, 10, 6                 | 40               |
| Sp1-PEG2| V23-30 | Spruce | PEG (2)             | 280      | 2                   | 0.288                | 76                        | 16, 10, 6                 | 40               |
| Sp1-PEG3| V23-28 | Spruce | PEG (3)             | 282      | 2                   | 0.287                | 75                        | 17, 10, 6                 | 40               |
| Sp1-Sac | V23-29 | Spruce | Saccharose          | 374      | 2                   | 0.227                | 60                        | 18, 10, 6                 | 40               |

¹ = Mean value of the sample series
## Appendix B: Volumes of the samples before and after conservation with calculated shrinkage and ASE

| Sample     | KUR-No | Volume Scan1 (mm$^3$) before conservation | Volume Scan2 (mm$^3$) after conservation | Shrinkage (%) | ASE (%) |
|------------|--------|------------------------------------------|-----------------------------------------|---------------|---------|
| Al1-Air    | V24-23 | 146,308                                   | 31,179                                   | 78.69         | 0       |
| Al1-AlEt   | V24-45 | 102,902                                   | 99,115                                   | 3.68          | 95      |
| Al1-K800   | V24-60 | 160,907                                   | 162,261                                   | -0.84         | 101     |
| Al1-LaTr   | V24-19 | 128,825                                   | 104,028                                   | 19.25         | 76      |
| Al1-PEG1   | V24-13 | 224,601                                   | 223,555                                   | 0.47          | 99      |
| Al1-PEG2   | V24-63 | 105,005                                   | 104,819                                   | 0.18          | 95      |
| Al1-PEG3   | V24-21 | 159,932                                   | 156,425                                   | 2.19          | 97      |
| Al1-Sac    | V24-34 | 113,119                                   | 81,711                                    | 27.77         | 65      |
| Al1-Sil    | V24-56 | 154,675                                   | 140,245                                   | 9.33          | 88      |
| As1-Air    | V28-27 | 1,333,063                                  | 235,173                                   | 82.36         | 0       |
| As1-AlEt   | V28-23 | 1,243,400                                  | 1,205,707                                  | 3.03          | 96      |
| As1-K800   | V28-30 | 571,461                                   | 573,401                                   | -0.34         | 100     |
| As1-PEG1   | V28-08 | 731,204                                   | 755,998                                   | -3.39         | 104     |
| As1-PEG2   | V28-10 | 416,108                                   | 421,655                                   | -1.33         | 102     |
| As1-PEG3   | V28-36 | 1,121,247                                  | 1,145,266                                  | -2.14         | 103     |
| As1-Sac    | V28-07 | 757,823                                   | 604,063                                   | 20.29         | 75      |
| As1-Sil    | V28-24 | 1,220,413                                  | 1,099,338                                  | 9.92          | 88      |
| Be1-Air    | V07-23 | 772,702                                   | 151,476                                   | 80.40         | 0       |
| Be1-AlEt   | V07-18 | 597,620                                   | 565,700                                   | 5.34          | 93      |
| Be1-K800   | V07-14 | 689,166                                   | 688,499                                   | 0.10          | 100     |
| Be1-LaTr   | V07-Exp3 | 671,849                                | 630,914                                   | 6.09          | 92      |
| Be1-PEG1   | V07-09 | 674,679                                   | 671,609                                   | 0.46          | 99      |
| Be1-PEG2   | V07-27 | 690,016                                   | 697,988                                   | 0.15          | 100     |
| Be1-PEG3   | V07-08 | 585,750                                   | 569,672                                   | 2.74          | 97      |
| Be1-Sac    | V07-01 | 609,858                                   | 434,048                                   | 28.83         | 64      |
| Be1-Sil    | V07-37 | 507,941                                   | 389,231                                   | 23.37         | 71      |
| Fi1-Air    | V22-28 | 453,549                                   | 222,550                                   | 50.93         | 0       |
| Fi1-AlEt   | V22-09 | 460,970                                   | 440,617                                   | 4.42          | 91      |
| Fi1-K800   | V22-33 | 384,611                                   | 371,581                                   | 3.39          | 93      |
| Fi1-LaTr   | V22-26 | 360,264                                   | 328,850                                   | 8.72          | 83      |
| Fi1-PEG1   | V22-22 | 494,810                                   | 478,138                                   | 3.37          | 93      |
| Fi1-PEG2   | V22-31 | 445,544                                   | 434,733                                   | 2.43          | 95      |
| Fi1-PEG3   | V22-35 | 500,516                                   | 483,497                                   | 3.40          | 93      |
| Fi1-Sac    | V22-11 | 480,933                                   | 465,727                                   | 3.16          | 94      |
| Fi1-Sil    | V22-05 | 434,348                                   | 392,397                                   | 9.66          | 81      |
| Fi2-Air    | V30-Exp1 | 88,000                               | 49,539                                   | 43.71         | 0       |
| Fi2-AlEt   | V30-33 | 427,312                                   | 414,753                                   | 2.94          | 93      |
| Fi2-K800   | V30-09 | 495,437                                   | 492,590                                   | 0.57          | 99      |
| Fi2-PEG1   | V30-04 | 307,024                                   | 306,696                                   | 0.11          | 100     |
| Fi2-PEG2   | V30-18 | 269,965                                   | 270,071                                   | -0.04         | 100     |
| Fi2-PEG3   | V30-15 | 421,682                                   | 411,711                                   | 2.36          | 95      |
| Fi2-Sac    | V30-17 | 357,884                                   | 338,088                                   | 5.53          | 87      |
| Fi2-Sil    | V30-24 | 404,852                                   | 386,070                                   | 4.64          | 89      |
| Oa1-Air    | V10-02 | 725,355                                   | 399,675                                   | 44.90         | 0       |
| Oa1-K800   | V10-06 | 895,292                                   | 868,531                                   | 2.99          | 93      |
| Sample    | KUR-No | Volume Scan1 (mm$^3$) before conservation | Volume Scan2 (mm$^3$) after conservation | Shrinkage (%) | ASE (%) |
|-----------|--------|------------------------------------------|------------------------------------------|---------------|---------|
| Oa1-LaTr  | V10-33 | 768,421                                   | 705,640                                  | 8.17          | 82      |
| Oa1-PEG1  | V10-29 | 1,008,166                                 | 930,839                                  | 7.67          | 83      |
| Oa1-PEG2  | V10-31 | 997,903                                   | 883,538                                  | 11.46         | 74      |
| Oa1-PEG3  | V10-39 | 969,533                                   | 883,916                                  | 8.83          | 80      |
| Oa1-Sac   | V10-03 | 901,297                                   | 798,944                                  | 11.36         | 75      |
| Oa2-Air   | V16-15 | 512,214                                   | 249,991                                  | 51.19         | 0       |
| Oa2-AlEt  | V16-09 | 806,657                                   | 758,211                                  | 6.01          | 88      |
| Oa2-K800  | V16-25 | 1,214,955                                 | 1,160,158                                | 4.51          | 91      |
| Oa2-PEG1  | V16-18 | 1,002,133                                 | 944,715                                  | 5.73          | 89      |
| Oa2-PEG2  | V16-32 | 1,258,876                                 | 1,188,430                                | 5.60          | 89      |
| Oa2-PEG3  | V16-36 | 1,208,876                                 | 1,157,459                                | 4.25          | 92      |
| Oa2-Sac   | V16-17 | 1,056,104                                 | 961,673                                  | 8.94          | 83      |
| Oa2-Sil   | V16-13 | 844,580                                   | 725,961                                  | 14.04         | 73      |
| Oa3-Air   | V27-17 | 293,261                                   | 47,476                                   | 83.81         | 0       |
| Oa3-AlEt  | V27-40 | 267,820                                   | 250,129                                  | 6.61          | 92      |
| Oa3-K800  | V27-07 | 340,889                                   | 338,726                                  | 0.63          | 99      |
| Oa3-LaTr  | V27-30 | 266,238                                   | 220,194                                  | 17.29         | 79      |
| Oa3-PEG1  | V27-12 | 363,884                                   | 362,077                                  | 0.50          | 99      |
| Oa3-PEG2  | V27-02 | 283,059                                   | 268,144                                  | 5.27          | 94      |
| Oa3-PEG3  | V27-01 | 289,788                                   | 266,534                                  | 8.02          | 90      |
| Oa3-Sac   | V27-21 | 316,392                                   | 249,489                                  | 21.15         | 75      |
| Oa3-Sil   | V27-10 | 379,014                                   | 325,680                                  | 14.07         | 83      |
| Pi1-Air   | V03-01 | 901,145                                   | 693,464                                  | 23.07         | 0       |
| Pi1-AlEt  | V03-17 | 771,098                                   | 727,558                                  | 5.65          | 76      |
| Pi1-K800  | V03-41 | 1,067,031                                 | 1,034,388                                | 3.06          | 87      |
| Pi1-LaTr  | V03-28 | 776,356                                   | 755,903                                  | 2.63          | 89      |
| Pi1-PEG1  | V03-35 | 867,035                                   | 849,403                                  | 2.03          | 91      |
| Pi1-PEG2  | V03-32 | 983,539                                   | 953,583                                  | 3.05          | 87      |
| Pi1-PEG3  | V03-20 | 747,056                                   | 721,864                                  | 3.37          | 85      |
| Pi1-Sac   | V03-45 | 752,562                                   | 734,681                                  | 2.38          | 90      |
| Pi1-Sil   | V03-42 | 783,823                                   | 739,365                                  | 5.67          | 75      |
| Sp1-Air   | V23-20 | 1,062,100                                 | 365,165                                  | 65.62         | 0       |
| Sp1-K800  | V23-08 | 906,595                                   | 850,773                                  | 6.16          | 91      |
| Sp1-LaTr  | V23-02 | 839,765                                   | 768,510                                  | 8.49          | 87      |
| Sp1-PEG1  | V23-25 | 1,031,354                                 | 1,063,448                                | 3.11          | 105     |
| Sp1-PEG2  | V23-30 | 955,998                                   | 944,487                                  | 1.20          | 98      |
| Sp1-PEG3  | V23-28 | 1,053,538                                 | 1,047,572                                | 0.57          | 99      |
| Sp1-Sac   | V23-29 | 885,828                                   | 771,872                                  | 12.86         | 80      |
### Appendix C: Volume changes of the samples 10 years after conservation considering inner structures from µCT

| Sample | VUR-No | Volume Scan2 (mm$^3$) after conservation | Volume Scan3 (mm$^3$) 10 years after conservation | Volume µCT (mm$^3$) 10 years after conservation | Shrinkage (%) Scan 2 and 3 | Shrinkage (%) Scan 3 and µCT |
|--------|--------|------------------------------------------|-------------------------------------------------|-----------------------------------------------|--------------------------|-----------------------------|
| Al1‑Air | V24‑23 | 31,179                                   | 24,760                                           | 17,706                                         | 20.59                     | 28.49                       |
| Al1‑AlEt | V24‑45 | 99,115                                   | 98,384                                           | 93,231                                         | 0.74                      | 5.24                        |
| Al1‑K800 | V24‑60 | 162,261                                  | 161,185                                          | 156,812                                        | 0.66                      | 2.71                        |
| Al1‑LaTr | V24‑19 | 104,028                                  | 102,996                                          | 86,192                                         | 0.99                      | 16.31                       |
| Al1‑PEG1 | V24‑13 | 223,555                                  | 223,018                                          | 217,914                                        | 0.24                      | 2.29                        |
| Al1‑PEG2 | V24‑63 | 104,819                                  | 102,585                                          | 100,481                                        | 2.13                      | 2.05                        |
| Al1‑PEG3 | V24‑21 | 156,425                                  | 154,216                                          | 143,465                                        | 1.41                      | 6.97                        |
| Al1‑Sac | V24‑34 | 81,711                                   | 78,017                                           | 68,037                                         | 4.52                      | 12.79                       |
| Al1‑Sil | V24‑56 | 140,245                                  | 139,209                                          | 132,425                                        | 0.74                      | 4.87                        |
| As1‑Air | V28‑27 | 235,173                                  | 216,694                                          | 193,375                                        | 7.86                      | 10.76                       |
| As1‑AlEt | V28‑23 | 1,205,707                                | 1,197,414                                        | 1,184,689                                      | 0.69                      | 1.06                        |
| As1‑K800 | V28‑30 | 573,401                                  | 569,276                                          | 564,613                                        | 0.72                      | 0.82                        |
| As1‑PEG1 | V28‑08 | 755,998                                  | 754,140                                          | 744,974                                        | 0.25                      | 1.22                        |
| As1‑PEG2 | V28‑10 | 421,655                                  | 419,105                                          | 410,026                                        | 0.60                      | 2.17                        |
| As1‑PEG3 | V28‑36 | 1,145,266                                | 1,147,825                                        | 1,137,275                                      | −0.22                     | 0.92                        |
| As1‑Sac | V28‑07 | 604,063                                  | 597,524                                          | 512,904                                        | 1.08                      | 14.16                       |
| As1‑Sil | V28‑24 | 1,099,338                                | 1,089,794                                        | 939,898                                        | 0.87                      | 13.75                       |
| Be1‑Air | V07‑23 | 151,476                                  | 147,738                                          | 127,144                                        | 2.47                      | 13.94                       |
| Be1‑AlEt | V07‑18 | 565,700                                  | 559,303                                          | 558,498                                        | 1.13                      | 0.14                        |
| Be1‑K800 | V07‑14 | 688,499                                  | 686,595                                          | 677,402                                        | 0.28                      | 1.34                        |
| Be1‑LaTr | V07‑Exp3 | 630,914                                  | 630,508                                          | 593,651                                        | 0.06                      | 5.85                        |
| Be1‑PEG1 | V07‑09 | 671,609                                  | 668,946                                          | 662,300                                        | 0.40                      | 0.99                        |
| Be1‑PEG2 | V07‑27 | 697,988                                  | 693,637                                          | 681,991                                        | 0.62                      | 1.68                        |
| Be1‑PEG3 | V07‑08 | 569,672                                  | 566,796                                          | 559,662                                        | 0.50                      | 1.26                        |
| Be1‑Sac | V07‑01 | 434,048                                  | 433,702                                          | 427,680                                        | 0.08                      | 1.39                        |
| Be1‑Sil | V07‑37 | 389,231                                  | 390,118                                          | 379,094                                        | −0.23                     | 2.83                        |
| Fi1‑Air | V22‑28 | 222,550                                  | 219,359                                          | 215,214                                        | 1.43                      | 1.89                        |
| Fi1‑AlEt | V22‑09 | 440,617                                  | 437,768                                          | 434,591                                        | 0.65                      | 0.73                        |
| Fi1‑K800 | V22‑33 | 371,581                                  | 369,032                                          | 364,899                                        | 0.69                      | 1.12                        |
| Fi1‑LaTr | V22‑26 | 328,850                                  | 326,867                                          | 326,097                                        | 0.60                      | 0.24                        |
| Fi1‑PEG1 | V22‑22 | 478,138                                  | 478,878                                          | 478,834                                        | −0.15                     | 0.01                        |
| Fi1‑PEG2 | V22‑31 | 434,733                                  | 436,025                                          | 433,782                                        | −0.30                     | 0.51                        |
| Fi1‑PEG3 | V22‑35 | 483,497                                  | 483,900                                          | 483,138                                        | −0.08                     | 0.16                        |
| Fi1‑Sac | V22‑11 | 465,727                                  | 464,262                                          | 461,471                                        | 0.31                      | 0.60                        |
| Fi1‑Sil | V22‑05 | 392,397                                  | 393,697                                          | 389,657                                        | −0.33                     | 1.03                        |
| Fi2‑Air | V30‑Exp1 | 49,539                                  | 48,737                                           | 45,156                                         | 1.62                      | 7.35                        |
| Fi2‑AlEt | V30‑33 | 414,753                                  | 413,424                                          | 409,599                                        | 0.32                      | 0.93                        |
| Fi2‑K800 | V30‑09 | 492,590                                  | 491,311                                          | 486,574                                        | 0.26                      | 0.96                        |
| Fi2‑PEG1 | V30‑04 | 306,696                                  | 305,457                                          | 298,768                                        | 0.40                      | 2.19                        |
| Fi2‑PEG2 | V30‑18 | 270,071                                  | 269,760                                          | 265,858                                        | 0.12                      | 1.45                        |
| Fi2‑PEG3 | V30‑15 | 411,711                                  | 412,560                                          | 403,988                                        | −0.21                     | 2.08                        |
| Fi2‑Sac | V30‑17 | 338,088                                  | 336,763                                          | 330,397                                        | 0.39                      | 1.89                        |
| Fi2‑Sil | V30‑24 | 386,070                                  | 385,594                                          | 384,166                                        | 0.12                      | 0.37                        |
| Sample   | KUR-No | Volume Scan2 (mm³) after conservation | Volume Scan3 (mm³) 10 years after conservation | Volume µCT (mm³) 10 years after conservation | Shrinkage (%) Scan 2 and 3 | Shrinkage (%) Scan 3 and µCT |
|----------|--------|--------------------------------------|-----------------------------------------------|---------------------------------------------|-----------------------------|-----------------------------|
| Oa1-Air  | V10-02 | 399,675                              | 375,634                                       | 360,292                                     | 6.02                        | 3.91                        |
| Oa1-K800 | V10-06 | 868,531                              | 852,548                                       | 760,510                                     | 1.84                        | 10.80                       |
| Oa1-LaTr | V10-33 | 705,640                              | 684,208                                       | 679,196                                     | 3.04                        | 0.73                        |
| Oa1-PEG1 | V10-29 | 930,839                              | 925,324                                       | 922,177                                     | 0.59                        | 0.34                        |
| Oa1-PEG2 | V10-31 | 883,538                              | 873,966                                       | 871,588                                     | 1.08                        | 0.27                        |
| Oa1-PEG3 | V10-39 | 883,916                              | 884,323                                       | 863,624                                     | -0.05                       | 2.34                        |
| Oa1-Sac  | V10-03 | 798,944                              | 800,842                                       | 798,595                                     | -0.24                       | 0.28                        |
| Oa2-Air  | V16-15 | 249,991                              | 242,620                                       | 232,541                                     | 2.95                        | 4.15                        |
| Oa2-AlEt | V16-09 | 758,211                              | 746,747                                       | 746,471                                     | 1.51                        | 0.04                        |
| Oa2-K800 | V16-25 | 1,160,158                            | 1,159,215                                     | 980,995                                     | 0.08                        | 15.37                       |
| Oa2-PEG1 | V16-18 | 944,715                              | 944,951                                       | 927,353                                     | -0.02                       | 1.86                        |
| Oa2-PEG2 | V16-32 | 1,188,430                            | 1,175,774                                     | 1,171,048                                   | 1.06                        | 0.40                        |
| Oa2-PEG3 | V16-36 | 1,157,459                            | 1,148,261                                     | 1,131,193                                   | 0.79                        | 1.49                        |
| Oa2-Sac  | V16-17 | 961,673                              | 965,032                                       | 960,526                                     | -0.35                       | 0.47                        |
| Oa2-Sil  | V16-13 | 725,961                              | 723,683                                       | 722,258                                     | 0.31                        | 0.20                        |
| Oa3-Air  | V27-17 | 47,476                               | 44,990                                        | 41,674                                      | 5.24                        | 7.37                        |
| Oa3-AlEt | V27-40 | 250,129                              | 245,888                                       | 243,032                                     | 1.70                        | 1.16                        |
| Oa3-K800 | V27-07 | 338,726                              | 338,272                                       | 325,887                                     | 0.13                        | 3.66                        |
| Oa3-LaTr | V27-30 | 220,194                              | 220,472                                       | 189,715                                     | -0.13                       | 13.95                       |
| Oa3-PEG1 | V27-12 | 362,077                              | 360,424                                       | 356,083                                     | 0.46                        | 1.20                        |
| Oa3-PEG2 | V27-02 | 268,144                              | 266,536                                       | 258,136                                     | 0.60                        | 3.15                        |
| Oa3-PEG3 | V27-01 | 266,534                              | 269,946                                       | 261,177                                     | -1.28                       | 3.25                        |
| Oa3-Sac  | V27-21 | 249,489                              | 246,670                                       | 226,558                                     | 1.13                        | 8.15                        |
| Oa3-Sil  | V27-10 | 325,680                              | 318,458                                       | 311,940                                     | 2.22                        | 2.05                        |
| Pi1-Air  | V03-01 | 693,464                              | 690,464                                       | 669,462                                     | 0.43                        | 3.04                        |
| Pi1-AlEt | V03-17 | 727,558                              | 720,240                                       | 715,479                                     | 1.01                        | 0.66                        |
| Pi1-K800 | V03-41 | 1,034,388                            | 1,029,360                                     | 1,024,444                                   | 0.49                        | 0.48                        |
| Pi1-LaTr | V03-28 | 755,903                              | 747,161                                       | 744,845                                     | 1.16                        | 0.31                        |
| Pi1-PEG1 | V03-35 | 849,403                              | 848,117                                       | 844,877                                     | 0.15                        | 0.38                        |
| Pi1-PEG2 | V03-32 | 953,583                              | 941,285                                       | 937,230                                     | 1.29                        | 0.43                        |
| Pi1-PEG3 | V03-20 | 721,864                              | 723,021                                       | 720,784                                     | -0.16                       | 0.31                        |
| Pi1-Sac  | V03-45 | 734,681                              | 736,946                                       | 733,326                                     | -0.31                       | 0.49                        |
| Pi1-Sil  | V03-42 | 739,365                              | 745,165                                       | 738,476                                     | -0.78                       | 0.90                        |
| Sp1-Air  | V23-20 | 365,165                              | 355,505                                       | 350,248                                     | 2.65                        | 1.48                        |
| Sp1-K800 | V23-08 | 850,773                              | 842,600                                       | 821,603                                     | 0.96                        | 2.49                        |
| Sp1-LaTr | V23-02 | 768,510                              | 759,002                                       | 728,992                                     | 1.24                        | 3.95                        |
| Sp1-PEG1 | V23-25 | 1,063,448                            | 1,059,582                                     | 1,053,036                                   | 0.36                        | 0.62                        |
| Sp1-PEG2 | V23-30 | 944,487                              | 937,396                                       | 933,264                                     | 0.75                        | 0.44                        |
| Sp1-PEG3 | V23-28 | 1,047,572                            | 1,048,511                                     | 1,045,822                                   | -0.09                       | 0.26                        |
| Sp1-Sac  | V23-29 | 771,872                              | 766,530                                       | 745,213                                     | 0.69                        | 2.78                        |
Appendix D: Surface and volume changes of the samples 10 years after conservation considering inner structures from µCT

| Sample | KUR-No | Surface Scan3 (mm²) 10 years after conservation | Surface µCT (mm²) 10 years after conservation | Surface change (%) Scan 3 and µCT | Shrinkage (%) Scan 3 and µCT |
|--------|--------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|-------------------------------|
| Al1-Air| V24-23 | 12,415                                        | 35,734                                        | 188                               | 28.49                         |
| Al1-AlEt| V24-45 | 14,420                                        | 34,211                                        | 137                               | 5.24                          |
| Al1-K800| V24-60 | 20,390                                        | 49,633                                        | 143                               | 2.71                          |
| Al1-LaTr| V24-19 | 21,314                                        | 86,288                                        | 305                               | 16.31                         |
| Al1-PEG1| V24-13 | 23,221                                        | 80,711                                        | 248                               | 2.29                          |
| Al1-PEG2| V24-63 | 14,962                                        | 30,272                                        | 102                               | 2.05                          |
| Al1-PEG3| V24-21 | 18,914                                        | 140,336                                       | 642                               | 6.97                          |
| Al1-Sac| V24-34 | 16,940                                        | 37,182                                        | 119                               | 12.79                         |
| Al1-Sil| V24-56 | 18,652                                        | 38,461                                        | 106                               | 4.87                          |
| As1-Air| V28-27 | 35,082                                        | 119,044                                       | 239                               | 10.76                         |
| As1-AlEt| V28-23 | 63,506                                        | 107,480                                       | 69                                | 1.06                          |
| As1-K800| V28-30 | 44,077                                        | 87,917                                        | 99                                | 0.82                          |
| As1-PEG1| V28-08 | 48,955                                        | 155,842                                       | 218                               | 1.22                          |
| As1-PEG2| V28-10 | 37,882                                        | 96,622                                        | 155                               | 2.17                          |
| As1-PEG3| V28-36 | 65,935                                        | 148,547                                       | 125                               | 0.92                          |
| As1-Sac| V28-07 | 44,404                                        | 208,448                                       | 369                               | 14.16                         |
| As1-Sil| V28-24 | 63,532                                        | 220,025                                       | 246                               | 13.75                         |
| Be1-Air| V07-23 | 26,021                                        | 84,639                                        | 225                               | 13.94                         |
| Be1-AlEt| V07-18 | 44,767                                        | 54,400                                        | 22                                | 0.14                          |
| Be1-K800| V07-14 | 48,788                                        | 67,928                                        | 39                                | 1.34                          |
| Be1-LaTr| V07-Exp3 | 48,653                                        | 168,337                                       | 246                               | 5.85                          |
| Be1-PEG1| V07-09 | 48,109                                        | 119,721                                       | 149                               | 0.99                          |
| Be1-PEG2| V07-27 | 49,745                                        | 132,591                                       | 167                               | 1.68                          |
| Be1-PEG3| V07-08 | 43,384                                        | 73,579                                        | 70                                | 1.26                          |
| Be1-Sac| V07-01 | 39,509                                        | 57,242                                        | 45                                | 1.39                          |
| Be1-Sil| V07-37 | 37,812                                        | 70,962                                        | 88                                | 2.83                          |
| Fi1-Air| V22-28 | 43,576                                        | 60,517                                        | 39                                | 1.89                          |
| Fi1-AlEt| V22-09 | 53,868                                        | 66,645                                        | 24                                | 0.73                          |
| Fi1-K800| V22-33 | 50,126                                        | 86,374                                        | 72                                | 1.12                          |
| Fi1-LaTr| V22-26 | 50,801                                        | 67,624                                        | 33                                | 0.24                          |
| Fi1-PEG1| V22-22 | 55,726                                        | 59,109                                        | 6                                 | 0.01                          |
| Fi1-PEG2| V22-31 | 56,394                                        | 78,984                                        | 40                                | 0.51                          |
| Fi1-PEG3| V22-35 | 57,206                                        | 65,082                                        | 12                                | 0.16                          |
| Fi1-Sac| V22-11 | 53,339                                        | 71,043                                        | 33                                | 0.60                          |
| Fi1-Sil| V22-05 | 53,077                                        | 65,926                                        | 24                                | 1.03                          |
| Fi2-Air| V30-Exp1 | 8635                                         | 19,131                                        | 122                               | 7.35                          |
| Fi2-AlEt| V30-33 | 32,416                                        | 51,646                                        | 59                                | 0.93                          |
| Fi2-K800| V30-09 | 37,876                                        | 86,145                                        | 127                               | 0.96                          |
| Fi2-PEG1| V30-04 | 26,653                                        | 90,152                                        | 238                               | 2.19                          |
| Fi2-PEG2| V30-18 | 26,381                                        | 71,852                                        | 172                               | 1.45                          |
| Fi2-PEG3| V30-15 | 34,819                                        | 100,612                                       | 189                               | 2.08                          |
| Fi2-Sac| V30-17 | 29,908                                        | 71,373                                        | 139                               | 1.89                          |
| Fi2-Sil| V30-24 | 31,114                                        | 38,846                                        | 25                                | 0.37                          |
| Sample   | KUR-No | Surface Scan3 (mm²) 10 years after conservation | Surface µCT (mm²) 10 years after conservation | Surface change (%) Scan 3 and µCT | Shrinkage (%) Scan 3 and µCT |
|----------|--------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|-------------------------------|
| Oa1-Air  | V10-02 | 52,255                                        | 85,432                                        | 63                               | 3.91                          |
| Oa1-K800 | V10-06 | 61,457                                        | 131,774                                       | 114                              | 10.80                         |
| Oa1-LaTr | V10-33 | 57,718                                        | 102,110                                       | 77                               | 0.73                          |
| Oa1-PEG1 | V10-29 | 62,422                                        | 88,035                                        | 41                               | 0.34                          |
| Oa1-PEG2 | V10-31 | 58,833                                        | 81,532                                        | 39                               | 0.27                          |
| Oa1-PEG3 | V10-39 | 61,296                                        | 122,801                                       | 100                              | 2.34                          |
| Oa1-Sac  | V10-03 | 56,280                                        | 68,620                                        | 22                               | 0.28                          |
| Oa2-Air  | V16-15 | 35,080                                        | 59,160                                        | 69                               | 4.15                          |
| Oa2-AlEt | V16-09 | 57,645                                        | 89,005                                        | 54                               | 0.04                          |
| Oa2-K800 | V16-25 | 81,202                                        | 198,276                                       | 144                              | 15.37                         |
| Oa2-PEG1 | V16-18 | 73,083                                        | 151,386                                       | 107                              | 1.86                          |
| Oa2-PEG2 | V16-32 | 80,898                                        | 134,853                                       | 67                               | 0.40                          |
| Oa2-PEG3 | V16-36 | 78,207                                        | 131,352                                       | 68                               | 1.49                          |
| Oa2-Sac  | V16-17 | 73,739                                        | 163,807                                       | 122                              | 0.47                          |
| Oa2-Sil  | V16-13 | 56,663                                        | 76,156                                        | 34                               | 0.20                          |
| Oa3-Air  | V27-17 | 11,681                                        | 23,883                                        | 104                              | 7.37                          |
| Oa3-AlEt | V27-40 | 29,406                                        | 41,819                                        | 42                               | 1.16                          |
| Oa3-K800 | V27-07 | 31,023                                        | 62,587                                        | 102                              | 3.66                          |
| Oa3-LaTr | V27-30 | 31,972                                        | 146,691                                       | 359                              | 13.95                         |
| Oa3-PEG1 | V27-12 | 31,420                                        | 49,818                                        | 59                               | 1.20                          |
| Oa3-PEG2 | V27-02 | 34,300                                        | 81,133                                        | 137                              | 3.15                          |
| Oa3-PEG3 | V27-01 | 32,071                                        | 62,450                                        | 95                               | 3.25                          |
| Oa3-Sac  | V27-21 | 37,746                                        | 101,695                                       | 169                              | 8.15                          |
| Oa3-Sil  | V27-10 | 36,179                                        | 47,156                                        | 30                               | 2.05                          |
| Pi1-Air  | V03-01 | 56,362                                        | 70,166                                        | 24                               | 3.04                          |
| Pi1-AlEt | V03-17 | 52,635                                        | 71,872                                        | 37                               | 0.66                          |
| Pi1-K800 | V03-41 | 69,860                                        | 98,177                                        | 41                               | 0.48                          |
| Pi1-LaTr | V03-28 | 58,601                                        | 63,425                                        | 8                                 | 0.31                          |
| Pi1-PEG1 | V03-35 | 59,624                                        | 93,104                                        | 56                               | 0.38                          |
| Pi1-PEG2 | V03-32 | 65,219                                        | 94,048                                        | 44                               | 0.43                          |
| Pi1-PEG3 | V03-20 | 52,700                                        | 68,616                                        | 30                               | 0.31                          |
| Pi1-Sac  | V03-45 | 54,560                                        | 61,158                                        | 12                               | 0.49                          |
| Pi1-Sil  | V03-42 | 54,128                                        | 72,204                                        | 33                               | 0.90                          |
| Sp1-Air  | V23-20 | 45,100                                        | 98,004                                        | 117                              | 1.48                          |
| Sp1-K800 | V23-08 | 60,128                                        | 177,153                                       | 195                              | 2.49                          |
| Sp1-LaTr | V23-02 | 57,273                                        | 206,642                                       | 261                              | 3.95                          |
| Sp1-PEG1 | V23-25 | 68,803                                        | 144,463                                       | 110                              | 0.62                          |
| Sp1-PEG2 | V23-30 | 68,719                                        | 95,985                                        | 28                               | 0.44                          |
| Sp1-PEG3 | V23-28 | 70,485                                        | 107,966                                       | 35                               | 0.26                          |
| Sp1-Sac  | V23-29 | 56,646                                        | 226,761                                       | 300                              | 2.78                          |
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Author contributions

JS designed, analysed and interpreted the data regarding the surface/shrinkage analyses of archaeological wood and was the major contributor in writing the manuscript. IS designed, analysed and interpreted the data and wrote the manuscript. DG performed the CT measurements. AC, GH were responsible for the structured-light 3D scanning. MW, WM, ME were responsible for the preparation of the KUR sample collection. DG, JM, MV, WM, AC, GH, ME, PS supported the analysis of the data as well as contributed to the manuscript writing. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and/or analysed during the current study are available in the repository of the RGZM, [www.rgzm.de/kur]. Further datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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