

Characterizing Hydraulic Properties of Drying Poultices Using Soil Physics Measurement Methods

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Abstract

Salt contamination is a major cause of deterioration in masonry and historical buildings. Drying poultices constitute an established, straightforward method for extracting salt from porous substrates. Applied in a wet state, their composition and pore size enable salt removal via evaporation-driven advection, which slows and ceases as the poultice dries.

However, characterizing the poultices, particularly their hydraulic properties and pore size distribution, is challenging due to the material's dynamic behavior during drying. Previous studies have primarily focused on the dry state or indirect measurements, neglecting the critical phase during evaporation when salt removal occurs.

In this work, we have applied measurement techniques traditionally used in soil physics to determine the water retention and the hydraulic conductivity curve across the full drying range of the poultice.

Hyprop, KSAT and WP4C devices reveal poultice hydraulic properties throughout the process of drying. The resulting data are subsequently fitted to established mathematical models. In this study, particular emphasis is placed on the constrained bimodal van Genuchten-PDI (VG-PDI) model.

We show that the hydraulic properties of various mixtures of drying poultices can be measured precisely. Even small changes in the formulation (different materials, various clay content) become clear, particularly in the water retention curve. Nonetheless, we discuss the weakness of the measurement procedure and offer suggestions for improvement.

Insights gained will support poultice optimization and potentially enable substrate-specific poultice tailoring, laying the foundation for more time- and cost-effective salt removal in masonry.

This is a contribution to SWBSS2026 Conference.

Keywords

desalination, drying poultice, hydraulic properties, water retention, hydraulic conductivity

1 Introduction

Salt contamination is a major cause of deterioration in buildings and sculptures worldwide, posing a significant threat to cultural heritage and exposing challenges posed by climate change, resource scarcity, and rising energy costs. Improving the treatment of salt-contaminated materials remains a central focus for both researchers and conservators [1].

The damaging effects of salt contamination were already recognized in ancient Egypt [2], and reducing salt concentrations to non-damaging levels remains essential for sustainable conservation measures [3, 4]. Over time, a variety of desalination methods have been developed [5], including

drying poultices, which are widely used for buildings and larger objects [6]. While alternatives such as immersion in deionized water [7] and electrokinetic desalination [8, 9] have been investigated, drying poultices remain the state-of-the-art technique for these applications [4, 10].

Numerous studies have evaluated poultice formulations, classifying them by material properties [11, 12], testing efficiency [13], and even adapting them to specific substrates [14, 15]. A key factor governing the effectiveness of drying poultices is the pore size distribution of both the substrate and the poultice. An appropriate match

between their pore structure can substantially enhance the efficiency of the desalination [11, 12].

However, accurate assessment of poultice performance requires a detailed understanding of hydraulic properties during drying, an aspect that is frequently overlooked. The majority of studies have characterized the pore size distribution of poultices only in their dry state, neglecting the dynamics of water flow during drying (evaporation) of the material [11, 15]. An exploration of the full drying dynamics from saturation to oven dryness (full range of moisture) of poultices is thus critical to accurately predict their efficiency.

While the hydraulic properties for porous building materials are routinely measured [16], these properties remain poorly characterized for poultices. As a result, although numerical simulations often align well with existing experimental data, they still lack the predictive accuracy necessary for routine application [17]. In practice, efforts to reduce salt *via* drying poultices are still commonly conducted on a trial-and-error basis [18, 19], with up to 100 m² of poultice material applied to buildings with little to no certainty about the potential effectiveness of the poultice material nor treatment.

For decades, soil physicists measure and determine hydraulic properties for different porous soils and soil-like materials [20]. Modern measurement devices from the Meter group, the KSAT, the HYPROP and the WP4C are specially designed for determining full hydraulic properties over the complete drying range. Hyprop and KSAT have recently been recognized for their precision and reliability by leading standards authorities like the ASTM International and the German Institute for Standardization (DIN) [21, 22].

This study addresses this gap by applying hydraulic measurement tools from the field of soil physics and adapting it to various formulations of desalination poultices.

By characterizing poultices throughout the drying cycle, we aim to support more efficient, time- and cost-effective salt removal strategies, away from experimenting [10].

2 Materials

In practice, the basic materials for desalination poultices can be divided into three essential groups:

1. adsorbent materials with organic origin;
2. mineral components with large specific surfaces and ionic exchange- and adsorption properties (mainly clay minerals);
3. inert fillers (quartz – sands) [23].

In this study, as a first step, only mineral components have been used. The formulated mixtures derive from a total of 5 different materials. A light grey, quartz sand consisting of crushed angular material, with a grainsize between 0.5 and 1 mm (Sa051), a brown sand from a commercial sand pit sieved that the grainsize results in a range between 0–1 mm (Sa01) and uniform, transparent glass beads between 0.4 and 0.9 mm (G) are used as inert fillers. Bentonite (B), a highly absorbent clay mineral consisting of montmorillonite and sepiolite (S), a white clay mineral consisting of a complex magnesium silicate were selected for the mixing with the fillers. An overview of the various materials is presented in Table 1. Representative macroscopic photographs of the materials are shown in Fig. 1.

3 Brief background in soil physics

Results in this study are displayed in the manner of soil physical analysis. The hydraulic properties include the dependence of water content (W_c) on the tension (water retention curve) on the one hand and the dependence of hydraulic conductivity on the tension (hydraulic conductivity curve) on the other hand [24].

In this study the so-called pF value is used for describing the tension [25]. It basically describes the force at which water is held in the soil or the tensile strength of water in the soil. It is also called matric head, because of the matric force, that is acting on the soil water. The value derives from the decadic logarithm of the pressure head

Table 1 Overview of the used poultice materials

Product	Comment	Abbreviation	Source of supply
Sieved quartz sand	Light grey, fine, sieved quartz sand between 0.5 and 1 mm	Sa051	Kremer Pigmente Origin: Odenwald, Hesse
Sieved silicate sand	Brown, fine, sieved silicate sand containing quartz and feldspar between 0–1 mm	Sa01	Kieswerk Dormann Origin: Eggolsheim, Bavaria
Uniform glass beads	Glass beads between 0.4–0.9 mm	G	Poolmegastore Evolution
Powdered bentonite	Highly absorbent clay mineral, main component is Montmorillonite	B	Kremer Pigmente
Powdered sepiolite	White clay mineral, main component is a complex magnesium silicate	S	Kremer Pigmente



Fig. 1 Different materials used for poultice formulations. On the top, the inert fillers are displayed, on the bottom are the two clay minerals. As fillers, two different sands with grainsize between 0.5–1 mm and 0–1 mm are used, as well as homogeneous glass beads with a grainsize between 0.4–0.9 mm. Sepiolite and bentonite are used as clay minerals.

in cm. Typically, it is expressed as negative pore water pressure or as the pF value:

$$pF \equiv \log_{10}(|h|), \quad (1)$$

where h is the pressure head in cm.

The hydraulic conductivity also changes over the course of drying and is therefore dependent on the volumetric water content respectively the corresponding pF value. The course basically describes how easily water flows through the material usually in cm/day. The saturated hydraulic conductivity is therefore the value at saturation, so for one specific water content. Because drying poultices are only partially saturated during application, water transport is governed primarily by unsaturated hydraulic conductivity, whereas saturated hydraulic conductivity is of secondary importance. The curve is displayed using saturated and unsaturated hydraulic conductivity, with the unsaturated conductivity clearly decreasing during the drying process.

4 Methods

4.1. Sample preparation

Preparation of the mixtures happened the day prior to the measurements. The volume for each material was determined with cylindrical glass measuring containers.

For the reason of simplification and comparability only mixtures consisting of an inert filler and a clay mineral were formulated. Each inert filler (two sand types and glass beads) was mixed with each of the two clay minerals. Two different ratios were prepared for each combination, resulting in a total of 12 mixtures. A 3/1 ratio where 3 volume parts of inert filler are combined with 1 volume part of clay mineral, and an 8/1 ratio respectively. Since clay containing samples hold the potential of shrinking during drying, for example a 2/1 ratio sand and bentonite has a moderate shrinkage of about 4% [14], the mixture was adapted using a higher sand content with 3 parts sand and 1 part bentonite. The 8/1 ratio is intended to represent the leaner mixture with the minimum content of clay possible. The amount of material used in each mixture is listed in Table 2.

Using the expressions defined earlier, the mixture of glass beads and sepiolite in a ratio of 3/1 has the sample name GS_31. Likewise for a combination of the sand 0–1 mm and bentonite in the ratio of 8/1 is named Sa01B_81 accordingly.

Table 2 Volume ratios of the formulated mixtures

	Mixture ratio 3/1	Mixture ratio 8/1
Vol dry inert filler (mL)	500	500
Vol dry clay (mL)	166.67	62.5

After determining the volumetric proportions of each component – the inert filler and the clay mineral – the two materials were combined in a plastic container and shaken for approximately 30 s to ensure thorough mixing [15]. Water was added to the dry material and stirred by hand with a trowel, till the consistency reached a good workability. The mixture was left in this wet state for about 7 h. After this period, once again, water was added if needed to obtain a 1 mm water film on top of the mixture. The poultice materials were then left soaking overnight in the closed plastic containers until next morning. The properties of the different mixtures are presented in Table 3.

4.2 Measurements

Prior to the measurements, each pre-wetted sample is stirred again by hand for about 1 min and filled into a special soil sampling ring designed for the HYPROP with a total volume of 250 cm³ (Fig. 2).

The weight of each sample ring is determined before the poultice is filled into the container and covered with filter paper and a corresponding lid. To make sure that each sample stays saturated and no evaporation occurs during the procedure, they are stored totally immersed in water.

The measurement procedure is based on the method used by Shokrana and Ghane [26].

4.2.1 KSAT

The measurement of the saturated hydraulic conductivity was performed following the operation manual of the KSAT from the METER group [27]. Measurements are performed using the falling head method, meaning that the water column is gradually decreasing while the water flows through the sample cylinder with the prepared poultice

material. Fig. 3 shows the assembly and the measurement procedure of the KSAT. The assembly of the prepared poultice materials is performed under water about 1 h after filling the sample rings with the prepared poultice mixtures. The change in pressure is continuously measured *via* a pressure sensor. During the measurement, the pressure exponentially decreases with time plotting the course of the darcy equation resulting in the K_s -value. During poultice application on a masonry, the material normally isn't fully saturated, therefore the saturated hydraulic conductivity is the maximum value for a specific mixture. More important is the unsaturated hydraulic conductivity, that is determined by HYPROP.

4.2.2 HYPROP

Determining the hydraulic properties of porous materials is a difficult and time consuming task [26]. The HYPROP (displayed in Fig. 4) is using the simplified evaporation method [28–30]. This device was used as the primary experimental approach because it simultaneously provides the water retention curve and unsaturated hydraulic conductivity over a large part of the measured moisture range [31]. In short, the HYPROP performs tension measurements on porous materials like soils and soil-like materials where two tensiometers with a ceramic tip measure the tension that is implied by water to the soil column during evaporation in different heights (Fig. 5). With the complete setup placed on a balance, the continuous loss of water is measured automatically.

However, limitations of older tensiometers with a cavitation point, indicating the end of the measurement at much lower pressures, are typically between 70 and 90 kPa, meaning data points only until a pF value of 2.7 can be measured [32].

Table 3 Main properties of the selected materials and the prepared dry mixtures. W_c is the ratio of added water to the total dry material in weight.

Sample name	Ratio dry powder (volume – ratio)	Weight sand / glass beads (g)	Bulk density sand / glass beads (g/cm ³)	Weight clay (g)	Bulk density clay (g/cm ³)	W_c (–)
GB_31	3 : 1	763.1	1.53	139.3	0.84	0.27
GB_81	8 : 1	764.0	1.53	54.1	0.87	0.2
GS_31	3 : 1	764.7	1.53	21.1	0.13	0.36
GS_81	8 : 1	764.2	1.53	9.5	0.15	0.26
Sa01B_31	3 : 1	733.5	1.47	150.2	0.9	0.35
Sa01B_81	8 : 1	742.1	1.48	54.6	0.87	0.29
Sa01S_31	3 : 1	733.4	1.47	20.9	0.13	0.4
Sa01S_81	8 : 1	740.0	1.48	8.6	0.14	0.33
Sa051B_31	3 : 1	673.4	1.35	148.4	0.89	0.39
Sa051B_81	8 : 1	674.4	1.35	56.1	0.9	0.32
Sa051S_31	3 : 1	672.0	1.34	20.9	0.13	0.45
Sa051S_81	8 : 1	675.7	1.35	8.9	0.14	0.38

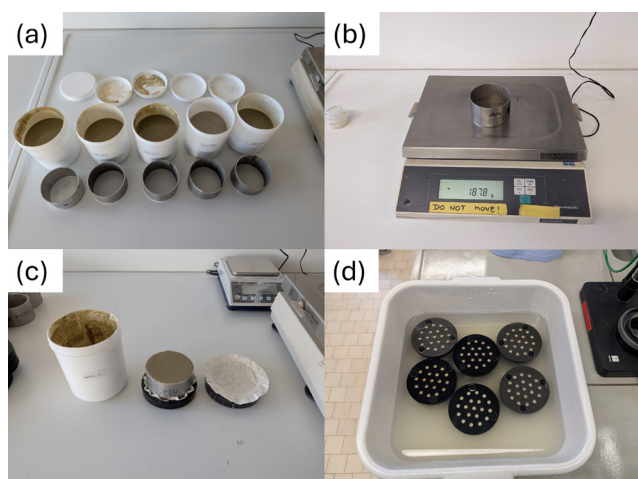


Fig. 2 Steps prior to the first measurement: (a) Each sample is assigned to a soil sample cylinder from the HYPROP device; (b) The weight of the sample cylinder is determined; (c) The prepared poultice material is filled into the cylinder and covered with filter paper and a black lid; (d) Storage of the sample cylinders under water for the next steps

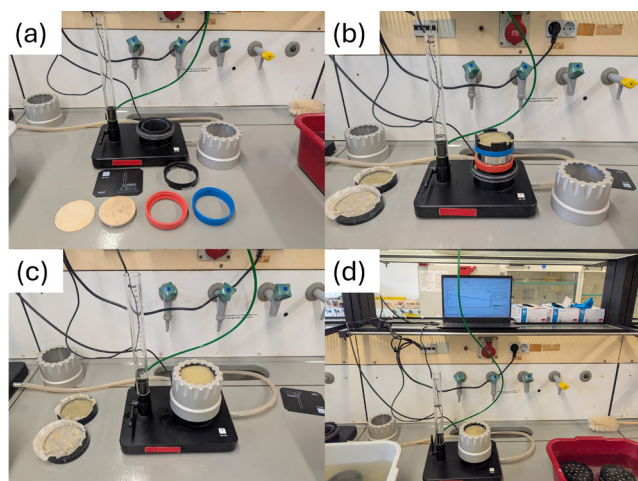


Fig. 3 KSAT assembly and measurement procedure: (a) Parts necessary for the KSAT measurement; (b) Assembled sample ring in the device; (c) KSAT device ready for measurement; (d) Measurement of the saturated hydraulic conductivity

With new tensiometers, that have an improved ceramic tip delaying the boiling of water, values as high as 435 kPa or a pF value of 3.65 before cavitation are reached [26, 33]. An extra data point around pF 3.95 can be generated with the air-entry point of the tensiometer ceramic [34].

This leads to an overall improvement of resolution and data points into the dry range. For the samples characterized in this study the measurement duration is between 8 and 12 days.

4.2.3 WP4C

To cover the very dry range of the water retention curve, the tension was measured by means of a WP4C (Fig. 6).



Fig. 4 Complete HYPROP setup assembled on a balance at the end of a measurement



Fig. 5 HYPROP device after measurement. Here the two suction candles can be seen. The white ceramic tips are placed at different heights inside of the probe volume.

It is an easy to handle, quick and accurate measurement method. In essence, it is a potentiometer using a chilled mirror. The inserted sample is sealed in a chamber which is equipped with sensors, a chilled mirror and a ventilator. The temperature of the mirror is precisely measured by means of a laser beam and a photo detector registers the first time condensation occurs on the mirror.



Fig. 6 WP4C dewpoint potentiometer with a prepared sample placed in the tray

At equilibrium the air in the chamber is equal to the potential of the water in the sample. Soil suction is calculated using the following equation [35]:

$$\psi = \frac{RT}{M} * \ln \frac{p}{p_0}, \quad (2)$$

where ψ is the water potential in MPa, R is the gas constant (8.31 J/mol K), T is temperature in K, M is molecular mass of water (18.01528 g/mol), p is the saturation vapor pressure of the air at dew point temperature, and p_0 is the saturation vapor pressure at the temperature of the sample.

At the end of both measurements (HYPROP and WP4C) the dry weight (378.15 K over 24 h) of the complete HYPROP sample and the WP4C samples are combined estimating the initial water content prior to the start of the HYPROP experiment.

4.3 Fitting

4.3.1 Water retention function

For the fitting of the generated data, the constrained bimodal van Genuchten-PDI model is used [36, 37]. This model was selected, because it can represent heterogeneous pore systems with two capillary pore domains while avoiding the classical residual water asymptote by forcing water content to approach zero at oven dryness. In the unimodal PDI model, the total water retention is expressed as the sum of capillary and adsorptive contributions [36, 38]:

$$\theta(h) = (\theta_s - \theta_r) S^{cap}(h) + \theta_r S^{ad}(h), \quad (3)$$

where h is the pressure head in cm, θ_s (–) is the saturated water content and θ_r (–) denotes to the maximum adsorptive water content. S^{cap} (–) and S^{ad} (–) are the saturation of capillary and adsorptive water retention.

Van Genuchten [39] describes the basic, unscaled saturation function, relating the dimensionless water content to the pressure head as follows:

$$\Gamma(h) = \left[\frac{1}{1 + (\alpha h)^n} \right]^m, \quad (4)$$

where α and n are estimated parameters. For the constrained function of van Genuchten $m = 1 - 1/n$. For more complex samples with a heterogeneous pore system, a multimodal retention function is used [40]:

$$\Gamma(h) = \sum_{i=1}^k w_i \left[\frac{1}{1 + (\alpha_i h)^{n_i}} \right]^{m_i}, \quad (5)$$

where k is the number of modes that form the pore size distribution. $k = 2$ for the bimodal variant and w_i are weighting factors for the sub curves, subject to $0 < w_i < 1$ and $\sum w_i = 1$.

To ensure that the water content is 0 at $h = h_0$ the saturation function is scaled as:

$$S^{cap}(h) = \frac{\Gamma(h) - \Gamma_0}{1 - \Gamma_0}, \quad \Gamma_0 = \Gamma(h_0), \quad (6)$$

with $h_0 = 10^{6.8}$ cm representing the pressure head at oven dryness [41].

The adsorptive saturation was described by the smoothed PDI function [36]:

$$S^{ad}(x) = 1 + \frac{1}{x_a - x_0} \left(x - x_a + b \ln \left(1 + \exp \left(\frac{x_a - x}{b} \right) \right) \right), \quad (7)$$

where $x = pF \equiv \log_{10}(h \text{ in cm})$, $x_a = \log_{10}(h_a)$ and $x_0 = \log_{10}(h_0)$ with h_a being the suction at air entry for the adsorptive retention and h_0 the suction at a water content of 0. The parameter h_a is given as $1/\alpha_i$. For the bimodal variant, h_a is derived from the coarsest subfunction, i.e., the subfunction with the highest α_i and therefore the lowest $h_a = 1/\alpha_i$ [42].

The smoothing parameter b depends on the capillary saturation function [36].

Substituting Eqs. (5) to (7) into (3) gives the constrained bimodal van Genuchten-PDI function used in this study.

4.3.2 Conductivity function

After Peters [38] the liquid hydraulic conductivity is the sum of capillary conductivity and film conductivity:

$$K = K_s \left[(1 - \omega) K_{rel}^{cap} (S^{cap}) + \omega K_{rel}^{film} (S^{ad}) \right], \quad (8)$$

where K_s (cm/d) is the saturated liquid conductivity, $K_{rel}^{cap}(-)$ and $K_{rel}^{film}(-)$ are relative conductivities for capillary and film flow and ω for an estimated fitting parameter.

Peters [37] defined the capillary conductivity from Mualem [43] with Eq. (9):

$$K_{rel}^{cap}(S^{cap}) = \left(\sum_{i=1}^k w_i S_i^{cap} \right)^{\tau} \left[1 - \frac{\sum_{i=1}^k w_i a_i \left(1 - (\Gamma_i)^{\frac{1}{m_i}} \right)^{m_i}}{\sum_{i=1}^k w_i a_i \left(1 - (\Gamma_{0,i})^{\frac{1}{m_i}} \right)^{m_i}} \right]^2, \quad (9)$$

with $S_i^{cap} = \Gamma_i - \Gamma_{0,i} / 1 - \Gamma_0$, $\Gamma_i(h) = [1 + (a_i h)^{n_i}]^{-m_i}$ and $\Gamma_{0,i} = \Gamma_i(h_0)$.

As for the film conductivity, Peters [38] proposed the piecewise function:

$$K_{rel}^{film}(h) = \begin{cases} \left(\frac{h}{h_a} \right)^a & \text{for } h > h_a \\ 1 & \text{for } h \leq h_a \end{cases}. \quad (10)$$

Following Tokunaga [44], film conductivity is proportional to $h^{-1.5}$ for constant viscosity, low ionic strength, high surface electrostatic potentials and at high suctions meaning that a can be set to -1.5 .

Since the capillary conductivity is usually expressed as a function of capillary saturation, Peters [38] suggested Eq. (11):

$$K_{rel}^{film}(S^{ad}) = \left(\frac{h_0}{h_a} \right)^{a(1-S^{ad})}. \quad (11)$$

Combining the capillary and film-flow terms into Eq. (8) gives the liquid hydraulic conductivity function fitted to the data.

4.3.3 Fitting in LabrosSoilView

The HYPROP-FIT software (LABROS SoilView Analysis) [45] was used to analyze the generated data. More detailed information about the model used in this study and the software are given by the HYPROP user manual [46] and the HYPROP-FIT/SHYPPFIT user manual [42].

To quantify the mean deviation between measured and fitted retention and conductivity values, HYPROP-FIT [45] calculates the root mean square error (RMSE).

The RMSE is given by:

$$RMSE = \sqrt{\sum_{i=1}^b \frac{1}{b} (y_i^c - y_i)^2}, \quad (12)$$

with b is the number of measured data and y_i^c and y_i are the measured and calculated values.

5 Results

5.1 Measured data

The results for the water retention curves are shown in Fig. 7, with each data point generated from the HYPROP and the WP4C. Mixture GB_31 was excluded from the dataset because of measurement failure.

Due to the limitations of the tensiometers, the HYPROP can only measure values below a pF of 3 therefore representing saturated to dry range of the water retention curve. An extension gives the extra air entry point between a pF value of 3 and 4. The HYPROP measurements provided high-resolution data, particularly below pF 3, thereby supporting robust numerical fitting.

The WP4C is used for the very dry range above a pF value of 4.

The corresponding saturated volumetric water content, determined after complete drying of the sample, serves as the reference value for proper scaling of the data points.

The data already show a clear difference in the water retention between mixtures with high clay content (31) and with low clay content (81). This shows in an overall shift of the curves to the right, where at the same pF value, for a material with a low water retention capacity the volumetric water content is lower as for a material with a higher capacity of retaining water. This directly correlates to pore size where a low water retention capacity means more volume of larger pores.

In Fig. 8 the data points for hydraulic conductivity curves are shown. The K_s -value generated from the KSAT for the saturated conductivity is plotted in the far left of the diagram and it was assumed to be equal to a pF value around -2 . The saturated hydraulic conductivity shows different values ranging from 7.7 cm/day (Sa01B_31) to 2590 cm/day (Sa051B_81). Samples with higher clay content show a much lower saturated conductivity (Fig. 9). This can be explained by the fine clay minerals blocking the big pores of the inert filler materials. Less clay minerals means more larger pores and therefore a higher rate of hydraulic conductivity.

The unsaturated conductivity is displayed for a majority of the samples between a pF value of 1 and 3. The values for the unsaturated conductivity show nearly the same value, but values on the left axis are displayed as $\log_{10}$ of the K -value, meaning small changes on the y-axis for example from -1 to -2 resulting in a difference of the factor 10 regarding the conductivity.

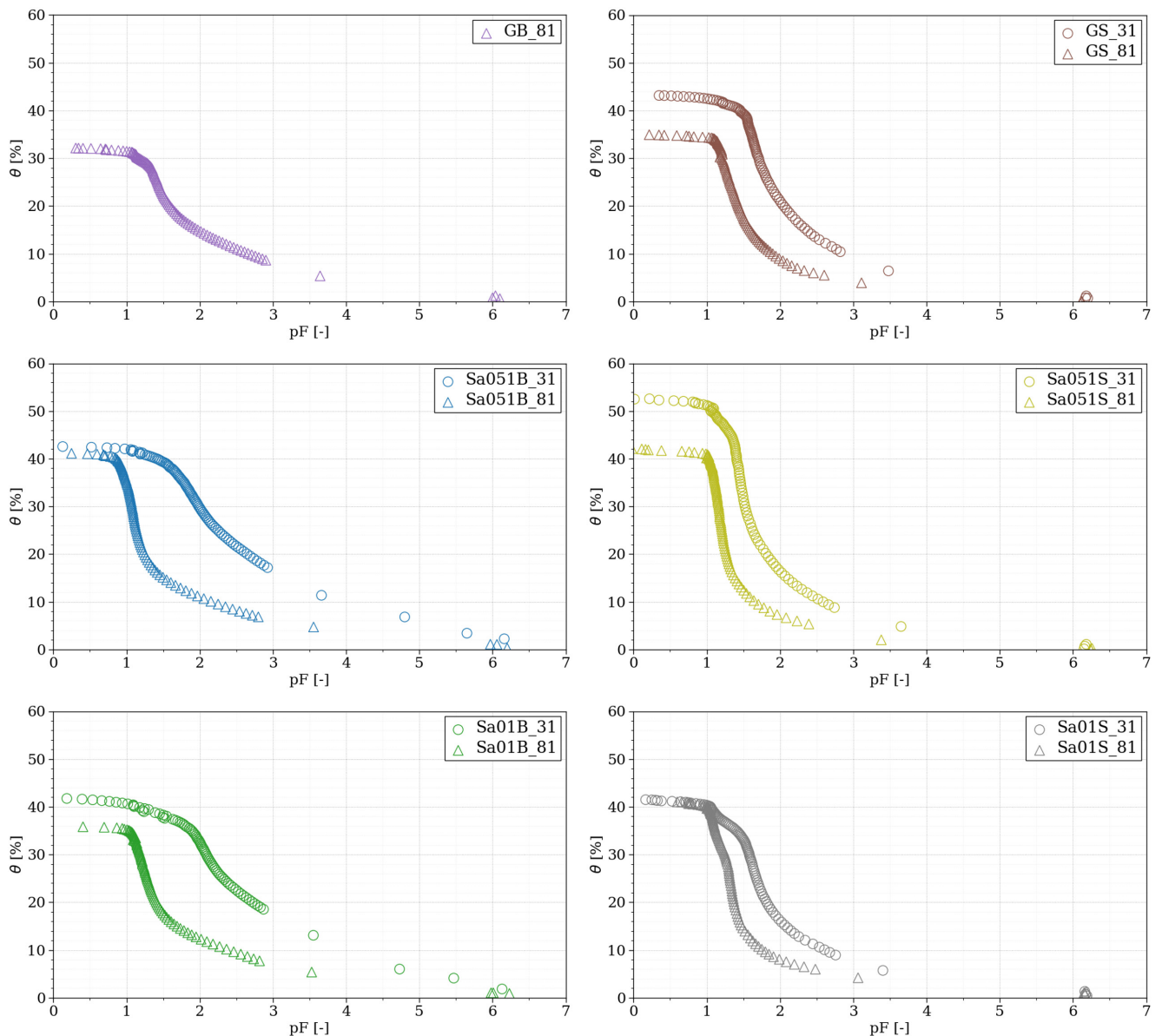


Fig. 7 Combined data from HYPROP and WP4C for all prepared mixtures. On the left side, mixtures with bentonite are displayed. On the right side, mixtures with sepiolite are displayed. The data points between pF 4.5 and 7 derive from the WP4C, representing the dry range of the retention curve. For the wet till dry range (< 4 for the pF value) is measured *via* HYPROP.

As the pF value increases, there is a drastic decrease in conductivity.

5.2 Fitted data

After fitting the data, the different water retention curves are shown in Fig. 10. Here, both the measured data from the measurement of the HYPROP and the WP4C together with the fitted curve are displayed. As a reference, the retention curve of pure glass beads is introduced into the diagrams in Fig. 10. The shape of this curve is clear and typical of a material with a unimodal and homogeneous pore radius distribution. An obvious difference can be seen

between mixtures prepared with sepiolite on the one hand and bentonite on the other. At the same volumetric water content, the samples mixed with bentonite have a higher matric potential than those prepared with sepiolite. Even the slightest difference in the sieve line between the sand 0–1 mm and 0.5–1 mm can be seen in small shifts to higher matric suction in the measurements. See here for example sample Sa051B and Sa01B for both mixtures 3/1 and 8/1.

With lower clay content, the trend of the water retention curves tends towards the properties of pure glass beads, confirming the effectiveness of the measurement and the fitting process.

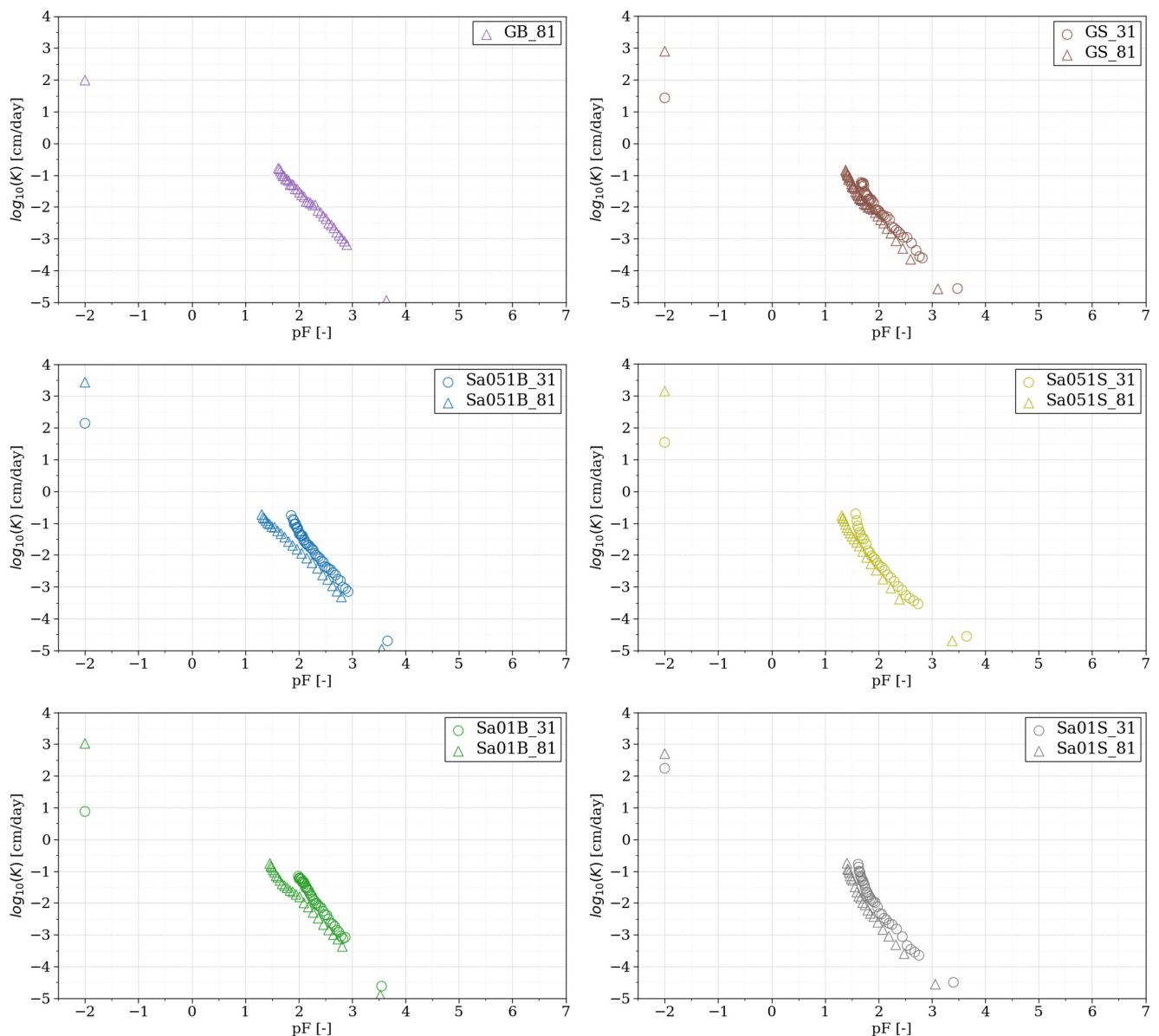


Fig. 8 Measured data for hydraulic conductivity. On the left side, mixtures with bentonite are displayed. On the right side, mixtures with sepiolite are displayed. Only the data points at a pF value of -2 were measured using the KSAT and represent the saturated hydraulic conductivity. The remaining data points derive from HYPROP and represent the unsaturated hydraulic conductivity.

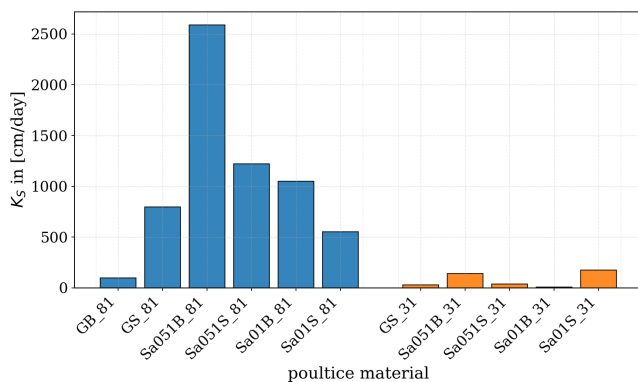


Fig. 9 Comparison of the measured saturated hydraulic conductivity for mixtures with a sand – clay ratio of 8/1 (blue bars) and 3/1 (orange bars)

All fitting parameters used to generate the curves using the constrained bimodal van Genuchten-PDI function are presented in Table 4.

In Fig. 11 KSAT and HYPROP data together with the fitted data curve are shown. Table 5 gives an overview of the fitting parameters used in the liquid hydraulic conductivity function described in Section 4.3.2.

Although the saturated hydraulic conductivity varies throughout the mixtures, the unsaturated conductivities are comparable to a small extent.

The relationship between pF value and conductivity can clearly be seen. Especially for the leaner mixtures,

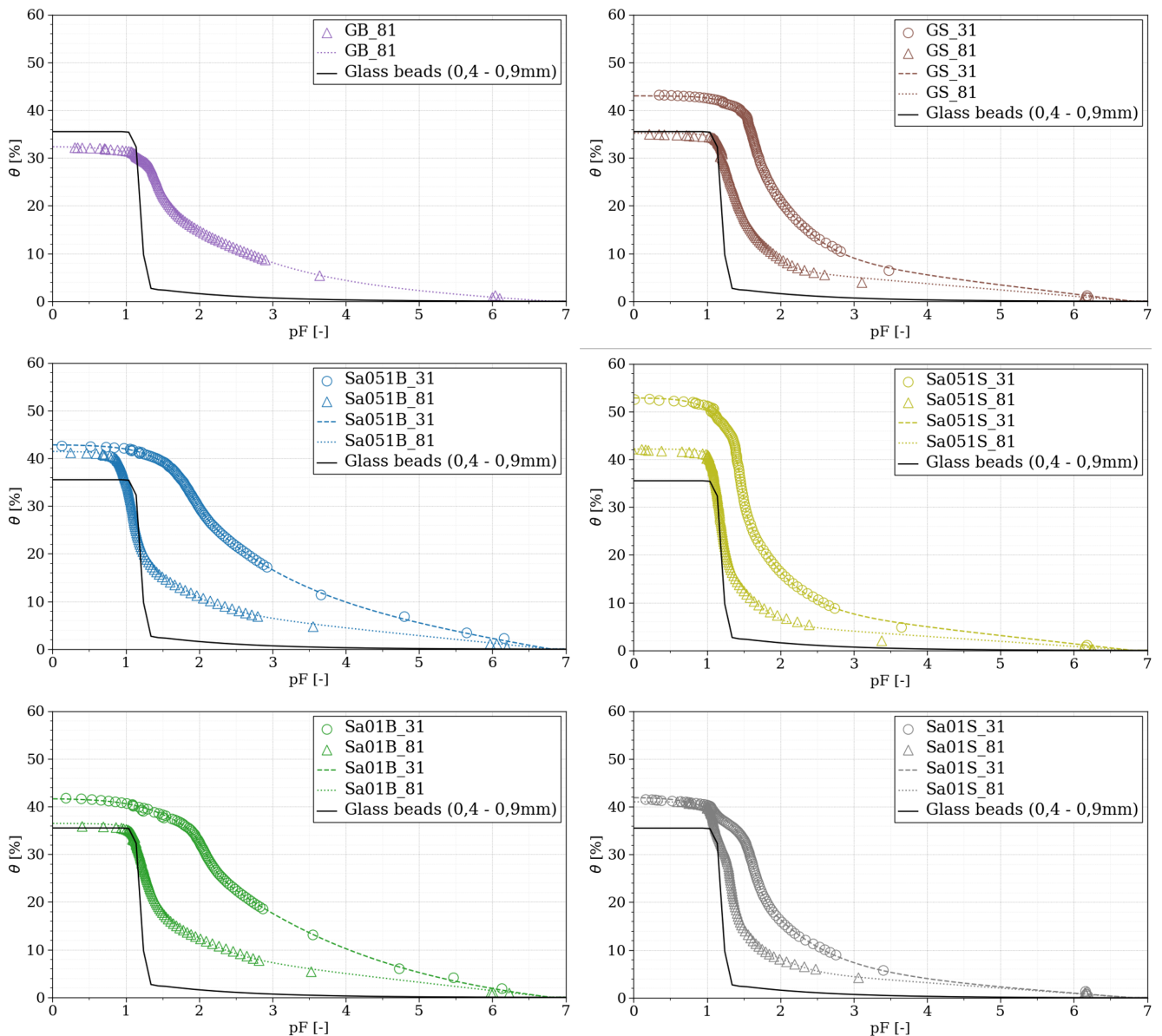


Fig. 10 Fitted water retention curve (dashed lines) of the measured poultice mixtures. Fitted curve and measured data show a good resemblance. As a comparison, the retention curve for pure glass beads was added.

Table 4 Fitting parameter for the constrained bimodal van Genuchten-PDI bimodal model

	GB_81	GS_31	GS_81	Sa051B_31	Sa051B_81	Sa051S_31	Sa051S_81	Sa01B_31	Sa01B_81	Sa01S_31	Sa01S_81
α_1 (1/cm)	0.038	0.018	0.054	0.014	0.086	0.036	0.069	0.008	0.028	0.023	0.010
n_1 (-)	1.3	1.9	7.9	4.1	7.9	10.7	10.4	5.2	1.8	7.1	2.4
θ_r (-)	0.041	0.097	0.073	0.127	0.09	0.093	0.059	0	0.098	0.063	0.062
θ_s (-)	0.324	0.430	0.352	0.428	0.415	0.529	0.421	0.417	0.365	0.419	0.41
α_1 (1/cm)	0.038	0.023	0.031	0.025	0.050	0.041	0.038	0.026	0.059	0.044	0.055
n_1 (-)	5.6	7.9	2.8	1.4	1.8	1.9	2.6	1.2	6.0	1.6	4.4
w_2 (-)	0.34	0.29	0.58	0.8	0.38	0.68	0.37	0.86	0.62	0.74	0.88

small changes in the pF value between 1 and 1.5 leads to a massive decrease in conductivity.

Changes in the workability of mineral poultices happen rapidly with the amount of water added [47]. Adding

too much water leads to a leakage of excess water. In terms of application to a substrate by means of desalination, poultices are never fully saturated, diminishing the effect of the saturated conductivity due to its strong decreasing of the

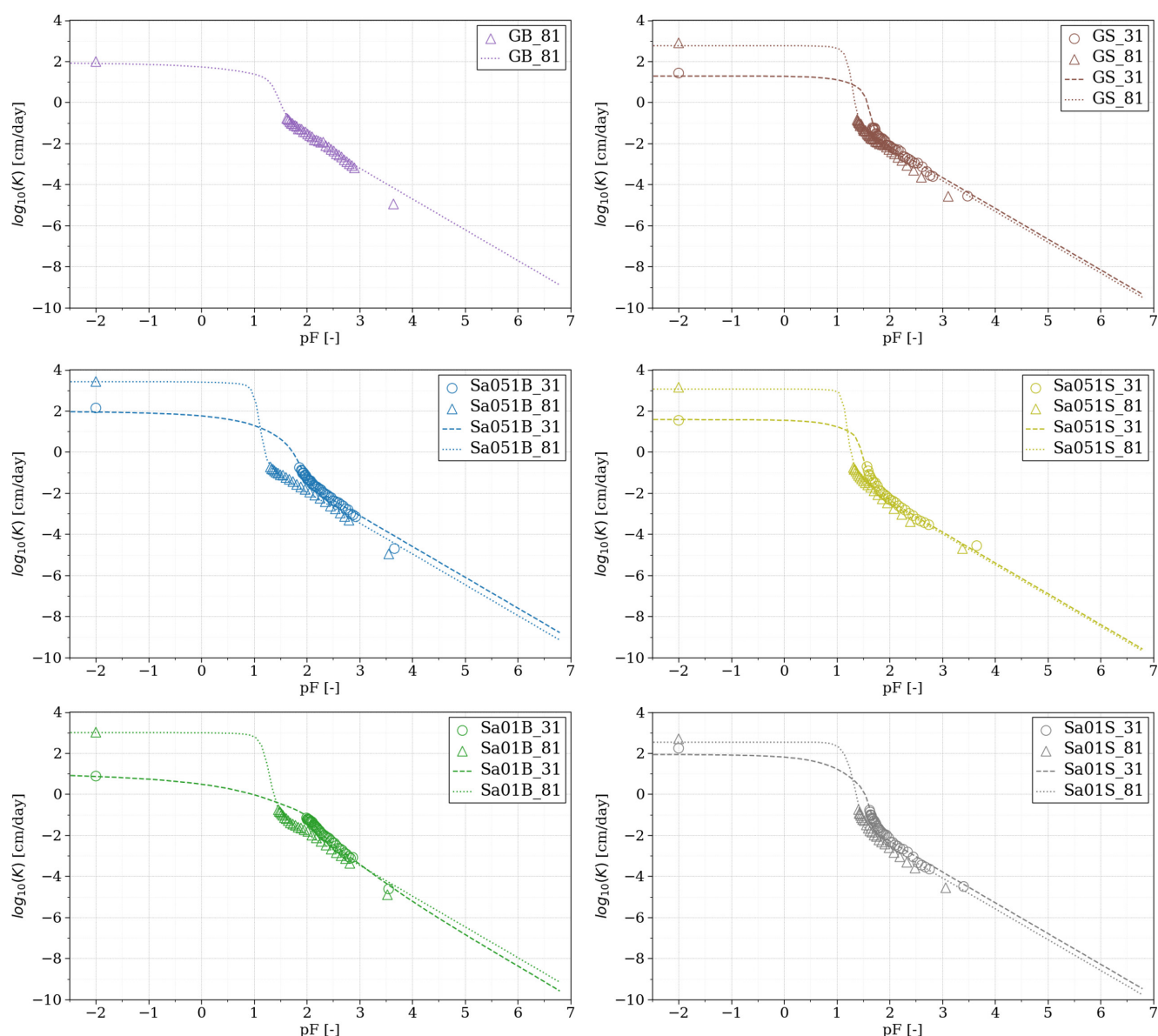


Fig. 11 Fitted hydraulic conductivity of the measured poultrice mixtures shown as dashed lines

Table 5 Fitting parameters for the hydraulic conductivity. Considering, the parameter a is set to -1.5 [44]. K_{sm} is the measured value of the saturated hydraulic conductivity and K_{sf} the fitted value.

	GB_81	GS_31	GS_81	Sa051B_31	Sa051B_81	Sa051S_31	Sa051S_81	Sa01B_31	Sa01B_81	Sa01S_31	Sa01S_81
K_{sm} (cm/day)	98	27	797	138	2590	35	1400	7.7	1050	176	550
K_{sf} (cm/day)	86.4	19.3	577	96.3	2648.1	37.7	1152.3	12.1	998.4	86.5	342.2
τ (–)	2.517	7.512	7.838	5.781	4.186	1.816	3.877	–1	3.967	5.105	3.354
ω (–)	1.69E-3	1.26E-3	1.08E-4	1.03E-3	1.05E-4	8.88E-4	5.14E-5	1.42E-3	1.58E-4	5.58E-4	9.83E-5

conductivity curve at the beginning of drying. Since evaporation is the driving force of drying poultrices, they are not re-moistened, leading to a further decrease in conductivity.

The statistical results for the chosen VG-PDI bimodal model are listed in Table 6.

6 Discussion

In earlier studies only the dry state of poultrices has been characterized respectively only indirect calculations of the water retention have been performed [48]. However, the drying of poultrices is a dynamic process, where water

Table 6 Statistical results of the VG-PDI bimodal model

Sample	Statistical criterion	
	$RMSE_{\theta} (-)$	$RMSE_{\log_{10} K}$ [$\log_{10}(\text{cm/day})$]
GB_81	0.002	0.1547
GS_31	0.002	0.122
GS_81	0.004	0.170
Sa051B_31	0.001	0.1316
Sa051B_81	0.002	0.1547
Sa051S_31	0.003	0.0786
Sa051S_81	0.004	0.1457
Sa01B_31	0.002	0.0643
Sa01B_81	0.003	0.1513
Sa01S_31	0.003	0.1537
Sa01S_81	0.007	0.1952

evaporates from the surface that can lead to a rearrangement of components and a change in the structure. This process cannot be derived reliably from measurements of the dry state alone, requiring measurement devices from the field of soil physics.

The main contribution of this study is the application of soil-physics measurement methods to determine hydraulic properties of poultice materials from saturation to oven dryness.

For realistic simulations, water retention and hydraulic conductivity must be determined under relevant moisture conditions. Especially for clay containing materials, measuring these properties in a dry state is not possible.

Unmeasured parts of the drying curve can be fitted using mathematical models such as the constrained bimodal van Genuchten-PDI model.

The results show that the mixture composition has a clear influence on hydraulic behavior. Formulations with a higher clay content exhibit greater water retention capacities, whereas leaner mixtures with lower clay mineral content approach the course of pure glass beads. The simple two component sample design makes these differences easy to interpret and allows for a comparison between material ratio and sieve-line variation.

It is important to notice that the results highlight several methodological sensitivities. Sample preparation, especially the amount of water added during mixing, strongly affects volumetric water content. A higher mixing water content increases the volumetric water content and reduces the density.

For the mixtures Sa051B and Sa01S, the volumetric water content for the leaner mixture resembles that of the more clay rich material. The problem lies in the continuous measurement of the water retention after the saturated

hydraulic conductivity and the storage in water, leading to leaching of clay and sand and rearranging the structure during KSAT measurement and drainage of water during transition into the HYPROP unit.

This shifts the overall volumetric water content to a lesser amount. Nevertheless, the data generated from the HYPROP in the wet range of the drying process are comparable with other mixtures of the same ratio even so, the water content has an offset.

It also must be noted that especially for the bentonite-containing mixtures, a bypass flow of water between the sample ring and the actual material can occur during KSAT measurements, leading to an overestimated saturated hydraulic conductivity.

Overall, the saturated hydraulic conductivity should not be seen as a primary transport parameter for the drying poultice since they immediately lose water when applied to a substrate [49], shifting the focus to the unsaturated hydraulic conductivity which is measured by the HYPROP.

7 Conclusions

The measurements and fitted curves show that it is possible to generate robust and complete curves of the full hydraulic properties of drying poultices. A clear distinction between different clay minerals is feasible, even small changes in the composition of the grain size of the sand aggregate can be seen. Changes in the mixture show a clear trend where formulations with less clay minerals approach the graph of pure glass beads.

Despite getting valid retention and hydraulic conductivity data, the leaching of materials (Fig. 12), immersion in water and drainage of water during transition between devices leads to uncertainties in the volumetric

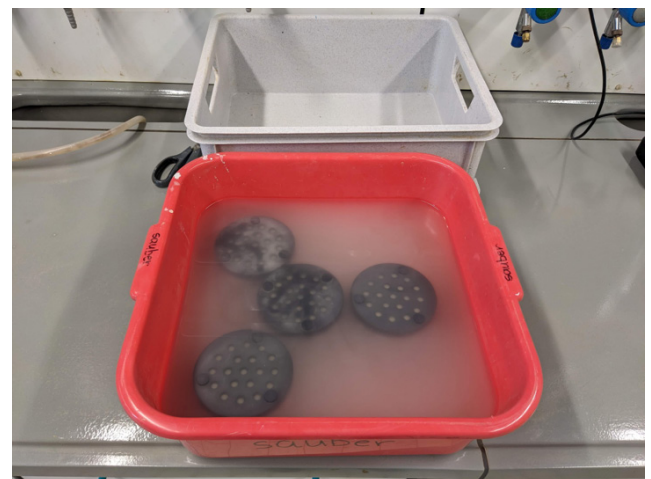


Fig. 12 Samples immersed in water after KSAT measurement. The cloudiness of the water suggests leaching and loss of clay minerals.

water content that needs to be addressed in future measurements. A better approach is measuring the saturated hydraulic conductivity *via* KSAT independently of the HYPROP measurement. Instead of a linear measurement procedure – first KSAT and then HYPROP – a parallel procedure should be implemented.

This study shows that this new approach characterizing the hydraulic properties of drying poultices with soil physical measurement methods can be transferred to the field of stone conservation and can help to better understand and optimize the processes happening in drying poultices during a salt reduction treatment. The generated fitted curves can directly be implemented in specialized hygric simulation programs to predict water movement and salt reduction efficiency.

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The next step is adapting the procedure of measurements to the materials, eliminating uncertainties in the volumetric water content.

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