Investigation of water retention functions of artificial soil-like substrates for a range of mixing ratios of two components

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Abstract

Purpose Urban greening is politically fostered as an adaptation strategy to climate change. Therefore, the demand for fertile planting substrates increases. Such substrates are usually mixed from mined geogenic resources but should rather be produced from recycled materials. Furthermore, their hydraulic properties should be designed according to their application, e.g., by optimizing the mixing ratio of their components. Therefore, this study introduces an approach to investigate the water retention curves (WRC) of soil-like substrates as a function of the mixing ratio of two recycled components: exemplarily for green waste compost (GWC) and ground bricks (GB) in the fraction of sand.

Materials and methods Seven mixing ratios for GWC and GB, 0/100, 18/82, 28/72, 37/63, 47/53, 68/32, and 100/0 have been packed to mixture-specific densities using a newly constructed packing device. The packing density resulted from applying six strokes with a constant momentum of $5.62 \times 10^{-3} \text{ N s m}^{-2}$ that was chosen according to the German green roof guideline. Thus, a standardized compaction was assured. The WRCs were measured using the simplified evaporation method in five replicates for each of the seven mixtures. A set of water retention models was parameterized and analyzed in regard to their suitability to represent the full range of binary mixtures.

Results and discussion The newly constructed packing device enables to pack cylinders reproducibly. The densities in the cylinders for the mixtures varied from 0.64 g cm^{-3} (GWC/GB = 100/0) to 1.35 g cm^{-3} (GWC/GB = 0/100) with a coefficient of variation less than 1.3%. The simplified evaporation method delivered homogeneous results for all five replicates of the investigated mixtures. The WRC of the seven mixtures is the result of a complex combination of the pore systems of GWC and GB. The multi-modal water retention models of Peters, Durner, and Iden are principally suitable to describe soil-like substrates that are rich in organic matter. The models PDI (van Genuchten) and PDI (Fredlund–Xing) best described the WRCs for the full range of mixing ratios according to the quality criterion RMSE.

Conclusions The study delivers a template how to prepare and analyze soil-like substrates regarding their WRCs using the simplified evaporation method. Complemented by total porosity and measurements at $pF > 4$, it is a suitable method to gain high-resolution WRCs of soil-like substrates. Available water retention models are capable to describe the hydraulic behavior of binary mixtures over the full mixing ratio. Therefore, it would be possible to model the WRC of binary mixtures as a function of their mixing ratio.

Keywords Soil-like substrates · Water retention function · Binary mixtures · Simplified evaporation method

1 Introduction

Fertile soil-like substrates, especially their water storage and supply function, play a key role for the establishment of urban

greening which is considered a path towards adaptation of cities to challenges arising from climate change (Kabisch et al. 2016). Increasing incidents of urban heat island effects, susceptibility to floods due to heavy rain fall events, and the ever-increasing numbers of inhabitants in cities require greener cities. As ecosystem functions like soil fertility and water retention function of soils are extensively lost due to sealing by built infrastructure, such as housing and streets, secondary greening on top of sealed surfaces (green roofs, facade green, etc.) will be of increasing importance in the shift towards climate resilient cities. Planting substrates in green

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infrastructure are often made of mined parent materials, such as natural soil material, peat, lava, and pumice, thus destroying rural ecosystems and landscapes (Fig. 1) (Flores-Ramirez et al. 2018).

A promising alternative is the use of soil-like substrates that are upcycled from suitable waste material (Caron et al. 2015a), generated in the cities (Nehls et al. 2015). This idea follows the concept of circular cities (Pearlmutter et al. 2019). The variety of potential ingredients as well as the possibility of combining them to mixtures lead to the assumption that it is possible to design soil-like substrates by the means of combining the constituents in certain ratios (Rokia et al. 2014).

Therefore, there is a need to systematically explore and predict in what way mixing ratios influence resulting properties of soil-like substrates regarding their ecosystem functions. Rokia et al. (2014) introduced a dose–response curve model approach to study and predict six agronomic relevant characteristics in binary and tertiary waste mixtures of 11 waste materials. In order to judge their fertility as constructed soils, they studied chemical properties such as C_{tot} P (Olsen), CEC, and pH. The study provides an overview concluding a typology (organic or mineral) of input materials and deriving thresholds for ingredients. Next to the chemical properties, one main aspect of soil fertility are soil physical properties. As a starting point, Rokia et al. (2014) evaluated 75 mixtures regarding their bulk densities and water contents at a tension of 100 hPa (pF 2). For profound understanding of how the mixing ratio influences the hydraulic performance of a

planting substrate under different conditions, it is crucial to determine full water retention curves (WRCs) for a range of mixtures.

On laboratory scale for mineral soils, there are several methods available for determining the water retention curve of soil samples (Dane and Hopmans 2002). Next to the multi-step outflow method (Hopmans et al. 2002), the simplified evaporation method (Schindler et al. 2010) delivers high-resolution measurements of water contents for a range of pressure heads. Soil-like substrates are combinations of unusual materials with unknown water retention characteristics. It is therefore especially helpful to obtain highly resolved experimental data in order to characterize them.

As soil-like substrates can generally be seen as mixtures of organic and mineral components (Rokia et al. 2014), a systematic analysis of the WRCs of a full mixing range requires the adaptation of such high-resolution measurements to substrates that have high contents of organic material. Generally, soil physical properties of growing media are studied in the context of agricultural production (Fields et al. 2018; Caron et al. 2015a; Bohne and Wrede 2005). However, the demand for growing media is extending to other fields of application, such as urban greening, building greening, or more general: “nature based solutions.” Also the focus of studies is changing accordingly, including testing and investigations of unconventional input materials, their combinations (Ramirez-Flores 2017; Rokia et al. 2014), and the general hydraulic performance (Brunetti et al. 2016). In horticultural science, the

Fig. 1 Two photos representing the impact of mining in the protected landscape area Vulkaneifel, a volcanic region in Germany. While in the upper photo from 1926 the volcano cone is only damaged, it is completely erased in 2007 (Fikentscher and Neumann 2012, orig. source upper photograph: Busch 1952)

adaptation of soil physical methods to purely organic growing media has already been fostered with the aim to improve the way growing media is manufactured (Caron et al. 2010, 2015a, b). Furthermore, the simplified evaporation method has been proven to be suitable for determination of the water retention curve of organic soils (Weber et al. 2017) and also growing substrates (Fields et al. 2016; Schindler et al. 2015).

However, the challenge is to systematically determine the water retention curves for all mixing ratios in a comparable way. Therefore, the mixing process and the sample packing as well as a choice for a suitable parametrization of the obtained data, accounting for a full mixing range, has to be developed accordingly.

Many studies on planting substrates, soil-like substrates, or Technosols that are considering different mixing ratios of their constituents are based on volumetric mixing ratios. Often studies do not explicitly describe how they formulate recipes for mixtures but only state which volumetric ratios were investigated (Deeb et al. 2016; Young et al. 2014; Al Naddaf et al. 2011; Molineux et al. 2009). However, especially organic and more irregularly shaped materials such as composted green waste or bark are known for a high variability in particle shapes and therefore need to be characterized with special attention for reproducibility and homogeneity regarding their bulk densities in similar volumes. The coefficient of variation in inter-laboratory ring tests of standardized bulk densities determination according to the method described in DIN EN 13040 (2007) is 8.86% for composted straw with sewage sludge, 19.77% for bark humus, and 13.62% for a mixture of peat and perlite. A more reproducible way of mixture formulation is based on weighted compositions as Yilmaz et al. (2018) use for constructing Technosols of different ratios of structural material and growing material or Vidal-Beaudet et al. (2018) use for substrates for plant biomass production. Another promising approach is presented by Naseri et al. (2019) who prepare mixtures of homogeneous ratios of soil and stones by matching up the weighted composition to a desired volumetric mixing ratio.

The technical mixing process, having the aim of achieving homogeneous mixtures, depends on sample sizes needed for each experimental method. In the before-mentioned studies, materials were sieved to a determined particle size (Deeb et al. 2016; Vidal-Beaudet et al. 2018; Rokia et al. 2014) and wetted either before the mixing process 80% of the water content they show at 100 hPa or slightly moistened during the mixing process (Naseri et al. 2019). The sample sizes prepared range from 0.25 to 20 L. Accordingly, the technical mixing process was realized by different means: manually, using a rotating shaker (Vidal-Beaudet et al. 2018; Rokia et al. 2014), and using a cement mixer (Deeb et al. 2016). Other studies do not mention the method used. The duration of each mixing procedure varies between 5 and 10 min.

Generally, when packing samples for water retention curve measurements, a bulk density at which the measurements are being done is determined beforehand. The corresponding weight of soil material is prepared into the steel cylinder in layers, manually compacting the sample by stamping, if necessary using a hammer (DIN 18127:2012-09). The number of layers, the moisture state of the sample, and pressure applied are different in each study and usually adjusted in order to reach the desired bulk density. A more standardized way of packing samples was implemented by Naseri et al. (2019), who use a constant weight, falling from a defined height in order to apply compaction strokes (seven strokes per layer, three layers). However, hydraulic comparability of soil-like substrate with differing organic contents is not given at a fixed bulk density, as compressibility decreases with increasing share of organic content (Paradelo and Barral 2013). Therefore, a comparable bulk density has to be either chosen relative to some material characteristic density of the substrate (e.g., particle density or proctor density (Flores-Ramirez et al. 2018)) or as a result of a standardized packing procedure. Standardization attempts towards packing samples for inter-comparative measurements aim at leveling out differing basic water contents (Schindler et al. 2015, Verdonck and Gabriels 1992) or at establishing a bulk density, as is found in application cases in planting containers (Fields et al. 2016). In both studies, the material is pre-wetted and left to equilibrate for 1 or 2 days before being filled into the cylinders. While Schindler et al. (2015) compact the samples by stamping it 10 times during the filling process, Fields et al. (2016) use a packing column, constructed from the to be filled cylinder together with axillary cylinders, and reach a compaction by tapping the column five times from a height of 10 cm onto a level surface. Whereas some studies do not explain how they place their sample into the cylinders (Al Naddaf et al. 2011), others prepare a use case scenario, filling planting pots without additional compaction and take samples there (Deeb et al. 2016). Even though standardization of the packing procedure is considered in several studies, compaction is usually realized manually by different means. As the applied force or pressure is not quantified, such packing methods are not reproducible. However, there is a guideline on characterization of green roof planting substrates (FLL 2018) including methods for determination of bulk densities that result from natural settling of the substrate simulated by a quantified compaction process also realized through a defined falling weight. This guideline is legally binding in Germany and has been adapted in other countries as well.

Last but not the least, a comparison of the WRCs of binary soil-like substrates with different mixing ratios requires a parametrization of a water retention functions that applies to all representatives of the mixing range in an adequately way. Sakaki and Smits (2015) investigated a range of mixtures of coarse and fine particles (sands) regarding the effect of mixing

on soil water retention characteristics (among other properties). They come to the conclusion that more flexible parametrization models like the model proposed by Durner (1994) should be chosen in order to account for resulting dual porosity in binary mixtures. Soil-like substrates are mixtures of less uniform particles than sand–sand mixtures and contain organic compartments, and they are therefore expected to show more complex water retention curves. For organic soils from peat lands, Weber et al. (2017) found most suitable parametrizations using the comprehensive approach of the Peters–Durner–Iden model (Peters 2013, 2014; Iden and Durner 2014). In order to evaluate the suitability of one parametrization for all water retention curves of a mixing range, the description of model performance has to comprise a quality of fit criterion of each representative of the mixing range.

With the aim to study the water retention curves of binary soil-like substrates as functions of their mixing ratio, this study introduces a method that allows to measure the water retention curves of a soil-like substrate formulated as a binary mixture from ground bricks (GB) and green waste compost (GWC) for broad range of mixing ratios in a comparably and reproducible way. The following research questions are addressed:

- 1 How can soil-like substrates in the form of a full range of binary mixtures be formulated and produced in a reproducible way?
- 2 How can WRCs of such substrates be measured in a standardized and comparable way?
- 3 Can one parametric WRC model account for all representatives of a mixing range in an adequate way?

2 Materials and methods

2.1 Properties of materials processed to soil-like substrates

For the study, soil-like substrates in seven mixing ratios were formulated as binary mixtures of ground bricks (GB) as the mineral and green waste compost (GWC) as the organic component. The materials were determined suitable to formulate a fertile planting substrate by Rokia et al. (2014) and Nehls et al. (2013). Both materials were derived from a local producer of compost and horticultural soils that additionally features recycling of horticultural waste (Galafa GmbH Erdenwerk, Falkensee). The ground bricks (sieved to pass to < 2 mm) was characterized using dry and wet sieving and the pipette method and was classified to be a loamy sand (Su2) with a particle size distribution of 84.2/14.1/1.8 (sand/silt/clay in w/w%). The compost was certified according to the guideline RAL GZ-251 by the German Gütevereinigung Kompost and

classified as substrate compost, containing particles with sizes ranging from 0 to 2 mm (RAL 2018).

2.2 Process of mixing soil-like substrates

Seven binary volumetric mixtures covering the full range from 0 to 100% GWC were produced. We assumed that the number of seven mixtures represents the full range sufficiently: on the one hand excluding mixtures that are not distinguishable from each other and on the other hand avoiding excessive amounts of samples to process. Due to the higher relevance for practice, more mixtures with lower shares of GWC were produced. With the aim to produce homogenized and reproducible mixtures, the recipe for each mixture was calculated by weights. A mixing reference density was determined using the packing device developed for this study (compare Section 2.4). The resulting bulk densities were $\rho_{GB} = 1.35 \text{ g cm}^{-3}$ for GB and $\rho_{GWC} = 0.64 \text{ g cm}^{-3}$ for GWC which were used to calculate the weights of components in each mixtures recipe for a desired total volume of 2000 cm³ substrate. GB was sieved to four fractions: coarse sand (cs), medium sand (ms), fine sand (fs), and silt/clay (sc) and resembled for each mixture according to the results of the original particle size distribution: (cs, 0.328 g g⁻¹; ms, 0.325 g g⁻¹; fs, 0.189 g g⁻¹; sc, 0.159 g g⁻¹). The sample names for each mixture were chosen according to the magnitude of volumetric GWC contents in % (v/v) and given in parts per ten to shorten the sample identifiers. Table 1 displays an overview of all mixtures produced together with the corresponding volumetric and gravimetric GWC contents, as well as LOI and particle densities.

All ingredients were added to a bucket and thoroughly mixed together with water for 5 min using an Einhell metal stirrer for mortar and paint (diameter 10 cm) attached to a drilling machine. The mixtures were allowed to equilibrate for at least 48 h before samples were prepared for further measurements.

2.3 Determination of loss on ignition and particle density

The LOI was determined for three samples of all mixtures using the muffle furnace according to the German norm DIN 19684-3 (2005). The particle density was measured using the multi-pycnometer QuantaChrome with helium gas exchange according to the German norm DIN 66137-2 (2019).

2.4 Determination of water retention curves of a full mixing range

Packing the samples into 250 cm³ stainless steel cylinders was realized in a standardized way that was developed in concordance with the method for determination of the bulk density described in the German FLL guideline for green roofs (FLL

Table 1 Overview of fractions of green waste compost (GWC) and ground bricks (GB) in all produced binary mixtures, as well as their loss on ignition (LOI, $n = 3$), their bulk (ρ_{BD}) and particle density (ρ_{PD} , $n = 5$), and their porosity (φ)

Sample	GWC ($\text{m}^3 \text{ m}^{-3}$)	GB ($\text{m}^3 \text{ m}^{-3}$)	GWC (g g^{-1})	LOI (g g^{-1})	ρ_{BD} (g cm^{-3})	ρ_{PD} (g cm^{-3})	φ (–)
C10B0	1.00	0.00	1.000	0.268 ± 0.0052	0.64 ± 0.0045	2.06	0.689^a
C7B3	0.67	0.33	0.494	0.151 ± 0.0008	0.83 ± 0.0104	2.32	0.642^b
C5B5	0.47	0.53	0.295	0.100 ± 0.0029	1.00 ± 0.0053	2.41	0.585^c
C4B6	0.37	0.63	0.218	0.079 ± 0.0008	1.08 ± 0.0074	2.46	0.561^d
C3B7	0.27	0.73	0.152	0.061 ± 0.0033	1.16 ± 0.0080	2.50	0.536^e
C2B8	0.18	0.82	0.095	0.043 ± 0.0008	1.24 ± 0.0067	2.56	0.516^f
C0B10	0.00	1.00	0.000	0.024 ± 0.0008	1.35 ± 0.0069	2.63	0.487^g

Results are means $\pm$ SD. Different letters a–g indicate significant differences between the mixtures, $p < 0.05$, Tukey test

2018). Following their approach, samples are wetted to a fresh soil moisture state (0.10 to $0.15 \text{ m}^3 \text{ m}^{-3}$) and compacted applying six strokes with a falling weight from a defined height. The water content at compaction must be determined and indicated. The proctor hammer according to DIN 18127 and cylinders with a diameter of 15 cm are used for the method described in the guideline.

Translating the FLL approach to the process of packing cylinders for HYPROP measurements, a packing apparatus, shown in Fig. 2, was constructed according to the dimensions of the 250 cm^3 stainless steel cylinders. The falling weight from a constant height of 45 cm has a mass of 1280 g, applying strokes onto a plate, compacting the sample with a momentum of $5.62 \times 10^{-3} \text{ N s m}^{-2}$.

The samples were packed with water contents ranging between 0.119 and $0.303 \text{ m}^3 \text{ m}^{-3}$. For mixtures rich in organic material, water contents exceed the suggestion made in the FLL guideline, which is usually applied for mineral-rich substrates or mineral bulk substrates. The compaction was realized in three layers applying two strokes on each layer. The total porosity φ of each mixture was calculated from the resulting mean bulk densities ρ_{BD} and the assessed particle

densities ρ_{PD} accordingly $\varphi = 1 - \frac{\rho_{BD}}{\rho_{PD}}$. In order to evaluate whether the seven produced mixtures can be considered different, an ANOVA and a post hoc Tukey test was performed for the calculated porosity of all seven mixtures.

2.5 Measurement setup simplified evaporation method

The evaporation experiments were conducted in a laboratory with controlled temperatures ranging between 19 and 23°C . After the samples were saturated with water, the HYPROP sensor units were installed, inserting the tensiometers in 1.25 and 3.75 cm depth. The regular HYPROP setup for parallel measurements of several samples in single balance mode was extended to a combined multi-balance and multi-probe mode to guarantee measurements in equally high temporal resolution of matric potential and water contents. Up to seven substrate samples could be measured simultaneously by separately logging tensiometer data using the classic HYPROP View software and parallel weight data logging. The measurements were started when the samples were uncovered and allowed to evaporate. Data was logged with a 10-min resolution. The measurements were stopped when air entered the upper tensiometer shaft (cavitation phase reached). After the measurements, the samples were oven-dried at 105°C for 24 h in order to determine their dry mass. Weight and tension measurement data were synchronized into one dataset using spline interpolation (Peters and Durner 2008) to tensiometer logging times.

2.6 Evaluation of variability of WRC measurements

In order to determine how strongly the measured water retention curve data differs between the five replicates (compare Fig. 4), they were compared to their mean curve using routines written in R (R Core Team (2018)). For calculating the mean curves, the dataset was trimmed to injective representations. By linear interpolation for each dataset, water contents are calculated for similar output pressure heads. The overall

Fig. 2 Packing apparatus for standardized sample preparation and its dimensions

deviation of five replicates from the mean curve is quantified by the grand mean absolute error (grand MAE). The grand MAE for each mixture is calculated as follows for an example of the mixture C0B10:

$$\text{grand MAE}_{\text{C0B10}} = \frac{1}{5} \sum_{n=1}^5 \left[\sum_{j=i}^N |y_{n,j} - m_j| \right]_n \quad (1)$$

where $y_{n,j}$ stands for the interpolated water content in replicate n at observation j and m_j stands for the mean water content of mixture C0B10 at observation j , N stands for the total number of observations.

2.7 Determination of water contents at higher tension

In addition to measurements using the evaporation method, the dew point method, commercially realized in the dew point hygrometer WP4C apparatus (Decagon Devices), was used to determine water contents of each sample at $pF > 4$. Therefore, the oven dried samples were carefully rewetted, homogenized and filled into stainless steel dishes for measurements in precise mode. After each measurement water content was determined gravimetrically. Schelle et al. (2013) report that combining these two methods is a reliable way to extend the range of the water retention curve, delivering results after a comparably reasonable duration.

2.8 Parametrization of water retention models

The retention data determined as described above, were combined to one dataset and further evaluated using the HYPROP-FIT software. Three different models were fitted to the observed data of every replicate of each mixture. Following the suggestion of Sakaki and Smits (2015) and in concordance with the findings of Weber et al. (2017) regarding organic soils, the bimodal form of different water retention models in the Peters–Durner–Iden variant (PDI) (Peters 2013, 2014; Iden and Durner 2014) was fitted to represent the measured water retention data. The PDI retention model (compare Eq. 2) accounts for capillary and also adsorptive water retention and includes a water content of zero at oven dryness for 105 °C. Here, oven dryness corresponds to $pF > 6.8$.

$$\theta(h) = (\theta_s - \theta_r) \cdot S^{\text{cap}} + \theta_r S^{\text{ad}} \quad (2)$$

In this equation, $\theta(h)$ stands for volumetric water content ($\text{cm}^3 \text{ cm}^{-3}$), θ_s ($\text{cm}^3 \text{ cm}^{-3}$) stands for water content at saturation, θ_r ($\text{cm}^3 \text{ cm}^{-3}$) stands for maximum water content for adsorption, S^{cap} stands for the saturation of capillary, and S^{ad} stands for the saturation of adsorptive water retention. While the saturation function for adsorptive water retention is

elaborated as described by Iden and Durner (2014), the capillary saturation function $S^{\text{cap}}(h)$ contains a basic saturation function $\Gamma(h)$ that can be replaced by a suitable retention function model:

$$S^{\text{cap}}(h) = \frac{\Gamma(h) - \Gamma_0}{1 - \Gamma_0} \quad (3)$$

As basic capillary saturation functions $S^{\text{cap}}(h)$, the bimodal forms (Durner 1994) (see Eq. 7) of the model functions described by Fredlund and Xing (1994) (Eq. 4), Kosugi (1996) (Eq. 5), and van Genuchten (1980) (unconstrained) (Eq. 6) were chosen.

$$\Gamma(h) = \{\ln[e + (\alpha h)^n]\}^{-m} \quad (4)$$

$$\Gamma(h) = \frac{1}{2} \operatorname{erfc} \left[\frac{\ln \left(\frac{h}{h_m} \right)}{\sqrt{2\sigma}} \right] \quad (5)$$

$$\Gamma(h) = \left[\frac{1}{1 + (\alpha h)^n} \right]^m \quad (6)$$

A bimodal approach provides the flexibility that was expected to facilitate satisfying fitting quality over the full range of the binary mixture, and for the capillary saturation function, the bimodality is expressed as weighted sum of two basic functions:

$$\Gamma(h) = \sum_{i=1}^2 w_i \cdot \Gamma_i \quad (7)$$

The three before-described model variants were fitted to the observed data of every replicate of all mixtures. The performance of each fitted model was evaluated by the means of the RMSE that describes the mean deviation between the observed and modeled data. The sum over RMSE_{mix} of all replicates of one mixture ($n = 5$) is used as a means to quantify and compare the suitability of each model between the mixtures. The sum of all $\text{RMSE}_{\text{total}}$ over all replicates of all mixtures ($n = 34$) of the full mixing range is used as a means to compare the model performances for the full mixing range and to select the model that delivers the soundest representations.

3 Results

The reproducibility of the mixture formulation as well as the mixing procedure was evaluated by determining the homogeneity of the produced mixtures, concerning their LOI ($n = 3$) and bulk densities ($n = 5$), representing equal contents and distribution of compost or organic content respectively. Secondly, the resulting bulk densities are considered a measure for reproducibility of the new packing method introduced

in Section 2.4. Furthermore, the grand MAE is interpreted as a means to quantify homogeneity resulting from the mixing or packing process that could impact the measurement results.

3.1 Producing binary mixtures of soil-like substrates in a reproducible way

Table 1 summarizes the results of LOI assessment as well as bulk densities (ρ_{BD}), particle densities (ρ_{PD}), and porosities (φ) resulting from the packing process for all seven mixtures. All mixtures produced have a significantly different porosity indicating that the choice of seven mixtures is not an overestimate for representing the full mixing range. However, it could be considered to produce mixtures with less equidistant mixing ratios and with higher resolution in that range, where observable differences in the water retention curves are biggest (compare Fig. 3). For instance, for mixtures containing more than 50%, GWC additional mixtures could be interesting; however, in practice soil-like substrates with smaller GWC ratios are preferred. According to the (FLL 2018) organic matter content is restricted to <40 up to <90 g L⁻¹ which corresponds to the mixtures C0B10 to C5B5.

With increasing share of GWC, the assed LOI increases linearly. The LOI ranges from 0.024 g g⁻¹ for C0B10 mixtures to 0.268 g g⁻¹ for C10B0 mixtures. The order of magnitude of variation is generally smaller than 3.5% with one exception. The samples of C7B3 mixtures result in having the smallest CV with 0.51%, whereas C3B7 mixtures show the highest variation of 5.48% (compare Table 1). The variations do not increase with increasing share of compost. They imply a homogeneous spread of GWC within the mixtures. Surprisingly, the pure brick sand does already show a LOI of 0.024 g g⁻¹ with a comparably high variability of 3.2% respectively. That is most probably due to water of crystallization from brick clay or plaster residues and from organic impurities.

Packing the soil-like substrates with the method developed, using the packing apparatus depicted in Fig. 2, results in

substrate or mixture-specific bulk densities with the pure compost mixture C10B0 having the lowest density of 0.64 g cm⁻³ and the pure brick sand mixture C0B10 the highest with 1.35 g cm⁻³. The standard deviation of bulk densities measured in the packed cylinders is generally smaller than 0.01 g cm⁻³. The highest variations are measured for the C7B3 mixture with a relative standard deviation of 1.26%. These small variations prove the repeatability of the newly introduced packing method. Methods from other studies for packing organic substrates into sampling cylinders using the means of stamping from a defined height for compaction yield bulk densities with relative deviations of 5.4 and 15.7% for bark substrate and peat substrate respectively (Fields et al. 2016) ($n = 3$). In other studies (Schindler et al. 2015), no replicates are considered in order to verify the packing method or the variations in bulk densities in sampled replicates are not quantified (Deeb et al. 2016). Furthermore, Naseri et al. (2019) report “excellent agreement” (not quantified) of measurement results for three replicates packed into steel cylinders with a comparable packing method as used in this study.

3.2 Standardized WRC measurements of binary mixtures representing a full mixing range

Figure 3, displaying all mean water retention curves within one plot, gives a first impression of how the water retention curves of a full mixing range of binary mixtures change depending on the mixing ratio. The differences between the mixtures are biggest in the wet range for pressure heads smaller than 31 hPa and decrease for higher pressure heads. Whereas in the wet range the water contents are higher in mixtures containing more GWC, this does not account for higher pressure heads anymore. The mean water retention curve of the pure GWC, mixture C10B0, reveals a dual pore structure. The differences between the mixtures C2B8, C3B7, and C4B6 are the smallest, whereas mixtures containing more than 50% GWC show the biggest differences of water

Fig. 3 **a** Mean water retention curves of all binary mixtures investigated, representing the full mixing range. **b** Pore size distribution of GWC, GB, and the 50/50 mixture, containing 47% GWC and 53% GB respectively

contents in the wet range. Here, it would be interesting to have more representatives of mixing ratios in the range where the biggest changes occur, whereas less representatives could account for the behavior of mixtures with GWC contents smaller than 50%. According to the results found by Sakaki and Smits (2015), there can be crucial mixing ratios in binary mixtures that indicate where properties are dominated by one or the other component of the mixture. Figure 3 shows that the influence of GB on the resulting WRC dominates for mixtures with GWC contents smaller than 40%.

From these results, we conclude that finding significantly different porous mixtures can be based on easily available properties of the components of these mixtures. As particle density as well as organic matter (quantified by LOI) of the mixtures behave according to linear mixing of their components, only the bulk density needs to be determined following the above-suggested method for three to five replicates in order to calculate the total porosity for the mixtures. From the statistical analysis (LSD) describing the selectivity based on the reproducibility of the packing, the least relevant mixture step can be determined for any mixture in any mixing

range—according to the application. For instance, a green roof substrate would be mixed in the range between 0 and 50% GWC and producers might be interested in optimizing hydraulic properties of their product in that special mixing range. Particularly pleasing, that little effort in the beginning of the characterization procedure reduces time and cost-intensive measurements of redundant mixtures.

Figure 4 shows the retention curves of all replicates ($n = 5$) of each mixture measured with the simplified evaporation method and the corresponding calculated mean curve. Due to technical problems during the measurement for mixture C3B7, only four replicates could be measured. The duration of the measurements increased with increasing content of GWC and differed between 4.5 days for C0B10 mixtures and 12 days for C10B0 mixtures.

The mean deviation of the measured replicates from the corresponding mean retention curve is generally smaller than 2%. For the majority of curves, bigger differences occur in the wet range, while in the dry range, above pressure heads of 100 hPa, the curves appear more similar. The mixture C5B5 shows the highest deviation with a grand MAE of 1.79% with

Fig. 4 Measured water retention curves for all replicates ($n = 5$) of all soil-like substrate mixtures investigated (red dots). Data was measured using the simplified evaporation method, trimmed and spline interpolated for calculating mean retention curves (compare Section 2.6) representing each mixture (black line). The grand MAE quantifies the mean deviation of all replicate curves from the mean curve

comparably bigger deviation throughout the full curve. This could be due to the comparably biggest variations in particle and pore sizes as illustrated in Figs. 3 and 4. Fields et al. (2016) determine higher variations between replicates of evaporation experiment measurements in such substrates that contain larger irregularly shaped particles and particles with bigger variation in size. This can lead to contact issues between the substrates and the tensiometers. In this study, the GWC introduces irregular particles with bigger variation in particle size, e.g., in the form of small pieces of wood. In a mixture with GB, the variation in particle size is even pronounced, as GB introduce particles in the clay section representing the other end of the spectrum of particle sizes.

However, the results obtained over the full mixing range of soil-like substrates show that the simplified evaporation method on samples, prepared in a standardized way as described above, delivers high-resolution data with generally small deviation between the replicates. Compared the other methods for determining water retention curves, like the classical pressure plate method, only few replicates can be measured investing a reasonable amount of time and money. Variations between replicates due to irregularly shaped particles and higher variability between the particle sizes, are reported to be smaller when measured with the pressure plate method (Fields et al. 2016). However, the range of pressure heads that can be determined using the classical method is smaller because of contact loss between organic substrates and the pressure plates occur for smaller pressure heads than for the simplified evaporation method. Other challenges are the unknown time until equilibration is reached, hysteresis effects, and the low

resolution of data points for fitting WRCs, especially for unknown substrates (Schelle et al. 2013). It can make further sense to use the equi-pF apparatus that enables to measure pF-WC pairs in high resolution in the low pF range. At the other end of the pF range, salt solutions or different concentrations of sulfuric acid in desiccators or mercury intrusion porosimetry enable measurements of WCs at certain suctions with a higher number of replicates (Nehls et al. 2006). However, measuring water adsorption is highly temperature dependent and time-consuming.

3.3 Suitability of one parametric WRC model to represent all mixtures of a full mixing range

Table 2 sums up the model diagnostics resulting from fitting three different parametrizations to the water retention curve data measured for each replicate of all mixtures of the mixing range. According to the grand mean of all RMSEs of the full mixing range, the bimodal PDI model in the variant of the unconstrained van Genuchten model shows the best performance with a grand mean of 0.00294. The difference to the next better option, bimodal PDI model in the variant of the Fredlund–Xing model is small with a grand mean of 0.00318 and not significantly different ($n = 7$, $p < 0.05$). Figure 5 illustrates mean RMSE for the three different water retention model fits to all five replicates of each mixture and quantifies the variations of the model performance between the replicates. The van Genuchten variant shows the best performance representing the mixtures C7B3 and the worst representing the mixture C0B10 containing only ground bricks, whereas the Fredlund–Xing variant performs best representing C3B7 and also worst for the mixture C0B10. For the van Genuchten model, the RMSE of the best fit realized for one mixture replicate compared to the overall average representing the full mixing range is in the order of magnitude of 39% smaller and the RMSE of the worst fit exceeds the overall average by 47%. Figure 6 illustrates the fitting of the three tested models for two examples: mixture C2B8 and C7B3. Weber et al. (2017) conclude from their study on peat moss samples that only multi-modal models are able to account for the behavior shaped by a secondary pore structure that is typical for organic soils. However, as the LOI of the pure GWC used in this study was only 26.8%, thus having much lower LOI than the peat moss investigated by Weber et al. (2017), we question that the GWC can be classified as organic. GWC and GB show bimodal pore structure as shown by Fig. 3, and accordingly the bimodal parametrization models tested in this study show satisfying representations.

Although the capillary bundle model might not be the right mechanistic approach to describe pores of constructed soil-like substrates, the developed models describe the hydraulic behavior of the substrates in a quite satisfying way.

Table 2 Overview of model diagnostics for full mixing range, means of RMSE over all replicates of each mixture ($n = 5$), and grand mean of RMSE over all mixtures

Mixture	Mean RMSE		
	FX	Kos	vGn_un
C0B10	0.00424	0.00556	0.00456
C2B8	0.00282	0.0055	0.00310
C3B7	0.00235	0.00395	0.00262
C4B6	0.00258	0.00522	0.00262
C5B5	0.00386	0.00472	0.00274
C7B3	0.00326	0.00626	0.00204
C10B0	0.00314	0.00468	0.00288
grand mean	0.00318 ^a	0.00513 ^b	0.00294 ^a

Values followed by the same superscripted letter are not significantly different, $n = 7$, $p < 0.05$

FX: PDI bimodal Fredlund–Xing, Kos: PDI bimodal Kosugi model, vGn_un: PDI bimodal van Genuchten (unconstrained) model

Fig. 5 Boxplot comparing the means and variations between all replicates ($n = 5$) of RMSE assessing the model performance of three water retention model parametrizations for seven binary mixtures. The models are FX (PDI bimodal Fredlund–Xing model), Kos (PDI bimodal Kosugi model), and vGn_un (PDI bimodal van Genuchten (unconstrained))

4 Conclusions

The standardized procedure for packing of cylinders as it was developed in this study enables to find a mixture-specific density, operationally and in a highly reproducible way. Furthermore, the packing apparatus introduced here enables the preparation of a non-compacted upper surface of the

Fig. 6 Measured water retention curves of mixtures C2B8_1 and C7B3_1 with 18% and 67% GWC content respectively. Measured data (red dots) was determined using the simplified evaporation method and dew point method. Three parametric models were fitted and their performance compared. FX, PDI bimodal Fredlund–Xing model (solid line); Kos, PDI bimodal Kosugi model (dotted line); vGn_un, PDI bimodal van Genuchten (unconstrained) (dashed line)

cylinder, which is crucial for the employment of the simplified evaporation method. This method, expanded by the dew point method, is shown to be suitable for determining water retention curves of unknown soil-like substrates formulated as binary mixtures from organic and mineral components.

Thus, the study delivers a template how to prepare and analyze soil-like substrates regarding their WRCs. Studying full water retention curves instead of only few points on the curve allows predictions for many tension states and is a prerequisite for deriving models that can also predict the behavior of unmeasured mixtures. This study also discussed the question, how many significant different mixtures need to be prepared and can be prepared in order to derive useful datasets for the aforementioned modeling. Mixing substrates and packing them in cylinders and then analyzing variability of LOI and bulk densities is fast and delivers the needed information to calculate the highest number of different mixtures.

Available water retention models are capable to describe the hydraulic behavior of binary mixtures over the full mixing ratio. Therefore, it would be possible to model the hydraulic behavior of substrate mixtures as a function of their mixing ratio based on these functions, a prerequisite for purpose-designed soil-like substrates (Hill et al. 2019).

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Authors' contributions Both authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Moreen Willaredt. Discussion was performed by both authors. The first draft of the manuscript was written by Moreen Willaredt. Both authors commented on previous versions of the manuscript and finalized the manuscript together—both authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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