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# Water Retention Transfer Functions of Old Ceramic Bricks

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ABSTRACT: The building stock of Dresden consist of a large number of brick buildings, constructed during the 20th century. Different brick types were sampled and their moisture storage function was measured using pressure plate apparatus and desiccators with different saturated salt solutions. A multi-variate cluster analysis procedure was carried out to detect natural groupings within the data. Multi modal water retention functions were applied to smooth and interpolate between the scattered data of the discovered clusters to provide a complete, unbroken and consistent functional description. In total, four representative retention transfer functions could be found for the collection of the bricks of the Dresden building stock.

## 1 INTRODUCTION

The Dresden building stock consists of a large number of buildings, constructed of brick masonry. Different type of bricks and brickworks were used, depending on the period of construction. During the second world war, many houses in Dresden were destroyed. In most cases, the old bricks were reused in reconstruction of the former buildings, after the mortar had been removed. In this process, different brick types were mixed, which has led to heterogeneous masonry of the old traditional loam and clay brick types. In addition, during the last 20 years, new types of bricks have been used for modernisation and renovation of old buildings.

Modern demands require an improvement of the thermal insulation for buildings with facades worth preserving, which raises a number of problems. It is not possible to apply external insulation to most old buildings without ruining the ornamental facades, while internal insulation is linked to the risk of interstitial condensation (Häupl et al. 1999). Since 1. February 2001, the renovation of buildings is controlled by the German EnEv 2001 regulations and the national standard DIN 4108-2, in which heat insulation is given greater importance than moisture protection in building modernisation. This often leads to serious damp problems, resulting from e.g. moisture condensation and mould growth, revealing errors during the design and construction phase of the modernisation.

Prerequisite for a service life evaluation of building envelopes is the analysis of the coupled heat and moisture transport of the brick masonry. The constructive evaluation gives the opportunity to assess optimal solutions for different retrofitting problems. This is usually done by the application of simulation tools, e.g. Delphin or WUFI, and requires knowledge of the moisture storage and transport properties of the materials (Häupl et al. 1997). Since the brick masonry of the Dresden building stock is very heterogeneous, this is a difficult task. In view of the variability of the hydro physical properties of a single brick material, it is necessary to search for common natural groupings within the bricks.

The purpose of this paper is to find suitable and representative transfer functions, able to describe the water storage properties of the ceramic bricks used in the Dresden building stock.

## 2 MATERIALS AND METHODS

The examination of the hydro physical properties requires the application of a number of different experimental methods (Plagge et al. 1999). Since the analysis of moisture storage is the main topic of this paper, the investigations of hydraulic conductivity and water vapor transmission are not used for the statistical calculations and are excluded from this analysis.

### 2.1 Sampling

For the present investigation, a set of 17 different ceramic bricks of the Dresden building stock have been collected and analysed. They display a representative selection of the bricks used during the last 130 years. Their coloration extends from bright yellow brown to dark carmine red. Their bulk density varies between 1610 and 2010 kg/m$^3$, while their dimensions vary from 280*120*80 to 230*110*65 mm. For sampling, all planes of about 1 cm margin are cut off and the inner material of the bricks is used for the preparation of specimens. Regarding the water retention characteristics, sample sizes of 50*30*10 mm dimension are used.

### 2.2 Measuring methods

The moisture storage is measured in the hygroscopic and overhygroscopic range by means of saturated salt-in-water solutions in desiccator chambers (DIN EN ISO 12571) and pressure plate extractors (ISO 11274). Since hysteresis may affect the water retention, only the desorption characteristic of the overhygroscopic and hygroscopic range is used in this investigation. The brick specimens are placed on a ceramic saturation table for capillary saturation. The samples are frequently weighed to verify that the daily changes in mass of the specimens are less than 0.1% of the balance reading. The procedure takes about 7 to 12 days.

Subsequently the samples are placed on a ceramic plate, where a filter paper for the low range and silt/kaolin mixture for the high range provide an optimal contact with the ceramic systems. For measurement of the wet range at 0.03 bar, the specimens are placed on suction controlled ceramic plates, where a suction is applied to drain the sample specimen. The corresponding water content is measured by gravimetric method. For measurement of the moist and intermediate range, the specimens are placed in pressure plate extractors, where a defined gas pressure is applied. This leads to a drainage of the material. A quasi equilibrium between the applied capillary pressure and the moisture content of the specimen is attained, when the water level in the outflow capillary stays constant. Afterwards the pressure chamber is opened and the water content of the bricks is measured by weighing the specimen.

Figure 1 : Pressure plate apparatus was used for measurement of water retention in the overhygroscopic range.

Sequential quasi equilibration at different pressures is carried out by removing and weighing the samples and replacing and resetting the pressure. In total 9 capillary pressure steps of 0.3, 0.6, 1.5, 2, 3, 4, 8 and 15 bar are applied.

To determine the desorption isotherm, the samples of the 15 bar pressure step are used. To control the relative humidity of the environment, the samples are placed in desiccators which contain different salt-in-water solutions. The selected salt-in-water solutions and the corresponding relative humidities are: 96.9% by K2SO4, 96.0% by KH2PO4, 84.3% by KCl, 75.3% by NaCl, 43.2% by NaBr, 32.8% by MgCl, 22.5% by CH3COOK and 11.3% by LiCl. Analogous to the previous procedure, the specimens are placed in desiccators and are brought to a quasi equilibration at the respective humidity. Equilibrium between moisture content and relative humidity is achieved by repeated weighings, at intervals, indicating a difference in mass of <0.1%. Beginning at 96.9% relative humidity, the hygroscopic function is determined by weighing and replacing the samples in desiccators, decreasing the relative humidity in stages.

After measurement, the brick specimens are dried at 105°C. A sample is considered oven dry when the weight loss is less than 0.1% between two successive measurements within 24 hours, which is achieved after approximately 3 days of drying. All water retention measurements in the overhygroscopic and hygroscopic range took nine and a half months.

### 2.3 *Data transformation*

The water retention and the hygric sorption data are measured as a function of capillary pressure as well as relative humidity. To combine both in a complete and consistent manner, the data have to be converted. The connection between capillary pressure and relative humidity via pore size is given by the equations 1 and 3:

$$\psi = c/r \tag{1}$$

where $\psi$ is the capillary pressure [Pa], c is equivalent to the capillary rise of water [cm] and r stands for the respective pore size of equivalent pore diameter [cm] times the constant of ~ $9.81*10^{-3}$. c is defined by:

$$c = \frac{2\sigma \cos \omega}{g p_w} \tag{2}$$

The parameters $\sigma$ and $\omega$ correspond to the surface tension [Pa/m] and the contact angle between water and solid phase. g and $p_w$ are the gravity [$ms^{-2}$] and the density of water [kg $m^{-3}$]. The relative humidity, $\varphi$, [-] is given by Kelvins law using equation 3:

$$\varphi = e^{-\frac{2\sigma}{r p_w R_V T}} \tag{3}$$

where $R_V$ equals the general constant of gases [W s $kg^{-1}K^{-1}$] and T the temperature [K]. Equation 1, 2 and 3 allow the conversion between capillary pressure, relative humidity and equivalent pore radius. This makes possible the use of physically based pore-size-distribution models capable of predicting the water transport function as well as fitting conductivity data in a concise description.

## 3 EXPERIMENTAL RESULTS AND DATA PROCESSING

For the collection of the 17 different types of ceramic bricks of the Dresden building stock, this results in a total of 306 measures of mean water retention data. All moisture storage measurements are plotted as functions of log capillary pressure in figure 2. The water retention data show a wide variation between all type of ceramic bricks. The variability of water content at specific capillary pressures exceeds 0.2 $m^3/m^3$ in the moist range, while in the dry part of the hygroscopic range the variation is less than 0.05 $m^3/m^3$.

### 3.1 *Functional description of the retention data*

To describe the capillary pressure data in the overhygroscopic and hygroscopic range, the multimodal function proposed by Durner (1991) is used. The approach is derived from the Van Genuchten (1980) closed form equation, which bases on the statistical pore models of Burdine

(1953) and Mualem (1976), and is capable of predicting the water transport function. The closed form equation and the multi-modal function for building materials has been applied earlier by Hoffman et al. (1996), Carmeliet & Roels (2000) and Plagge et al. (2002). The general multi-modal equation is:

$$\theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^{k} w_i \left[ \frac{1}{\left(1 + |\alpha\psi|^{n_i}\right)} \right]^{m_i} \tag{4}$$

where $\theta_s$ and $\theta_r$ are the saturated and residual water content [$m^3m^{-3}$], $\alpha$ corresponds to the air-entry value [1/m] and is a functional fitting parameter in addition to n and m. K and w correspond to the respective modality of the pore size distribution and its respective volume fraction. The parameter combination is solved in an iterative way by searching for the minimum of the objective function and the starting values as well as initial estimates. The least-squares objective function to be minimized can be written as:

$$O = \sum_{j=1}^{a} \left(\theta - \theta_j\right)^2 \tag{5}$$

where $\theta$ and $\theta_j$ are the observed and the estimated water contents, O is the value of the objective function with j as the number of points measured. Dependent on the amount of pore modals, 5, 10 or 14 parameters have to be optimized. Thus, e.g. a 3-modal function has to optimize 14 parameters, which requires at least 15 data points for fitting. Since 18 measured mean points are available for each type of brick, the proposed approach can only be used to construct 3-modals.

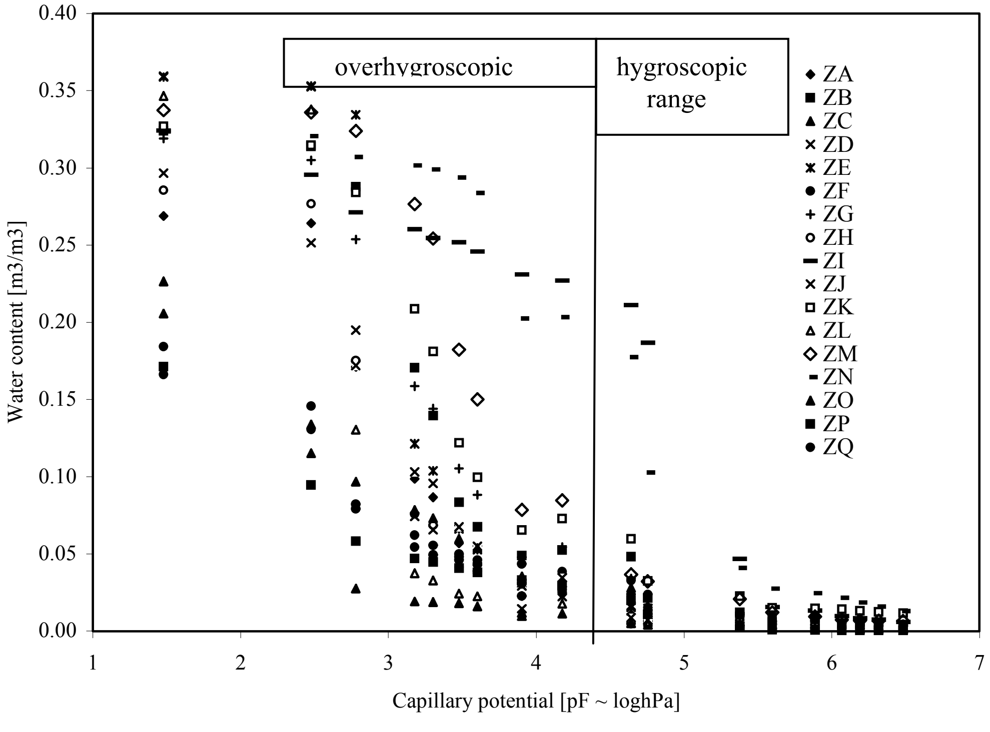


Figure 2 : Measured water retention data (n = 306) of the collected ceramic bricks.

$\theta s$ and $\theta r$ are given by the measured data for the respective material. To minimize the amount of functional parameters, m was generally set to mi = (1-1/ni). Since the parameters n and m are not independent and show a correlation, Plagge et al. (1996) and Plagge et al. (2002) among others found this simplification acceptable, reducing the amount of fitting parameters to 6 or 9 for the bi- and 3-modal approach. But for three bricks, the parameter identification procedure still fails, because a global minimum of the sum of squares could not be found. In those cases we fix the considerable parameters and start the fitting procedure by new initial estimates or fix the parameters manually step by step and adjust by visual control. In this manner we have optimized uni-, bi- and 3-modal functions of the van Genuchten type equation to each data set of the 17 brick types.

### *3.2 Performance criteria*

The performance of the modal functions can be measured by the coefficient of determination or the value of the objective function, indicating how much of the variation is explained by the model. The model with the smallest value of the objective function performs best. Because more parameters always lead to better performance, the effectiveness of the respective modal function has to be analysed too. This can be done by accounting for the number of parameters used in the parameter optimization by equation 6:

$$MSE = \frac{O}{a - p} \tag{6}$$

Where MSE is the mean squared error, O is the objective function and p is the number of parameters of the model used. To compare the different models, a parameter S is defined, characterizing the overall performance of the respective modal function.

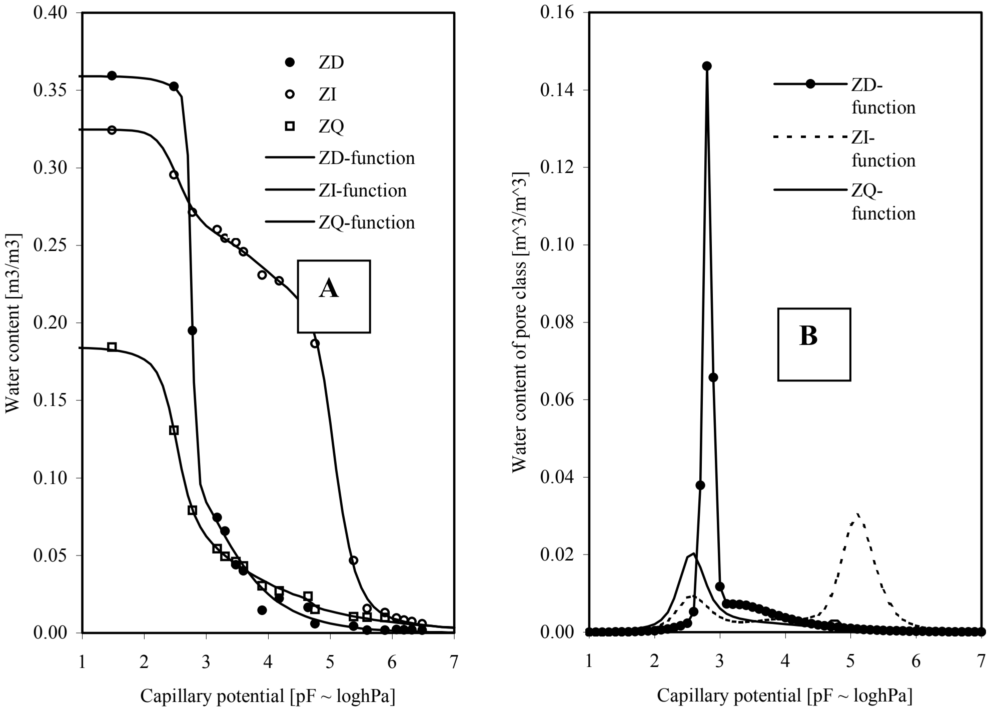


Figure 3 : (A) Example of measured and fitted water retention data of three ceramic bricks of the Dresden building stock. (B) Corresponding pore size distribution functions of the selected examples.

$$S = \sum_{j=1}^{b} MSE / b \tag{7}$$

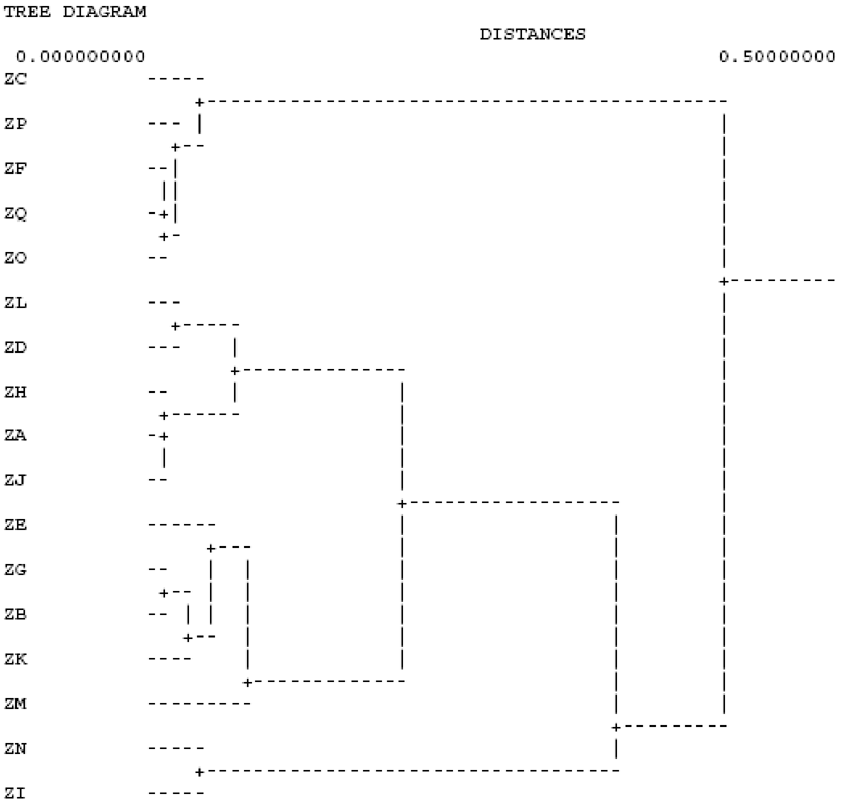
where b is the number of observations. For 12 types of bricks, the 3 modal water retention approach operates best according to the performance criteria. In 5 cases only, brick types ZG, ZH, ZJ, ZL and ZM, the bi-modal approach is effective enough to fit the measured data. The unimodal function does not deliver the best description in any case. From the overall performance evaluation, given by equation 7, the 3-modal approach performs best.

To show the performance of the multi-modal approach used, 3 materials are selected as examples for visualization in figure 3A. The 3-modal function is able to interpolate between the scattered data and to provide a smooth and complete characterization of the whole moisture retention function. The function combines both the overhygroscopic and the hygroscopic ranges.

The approach works for stiff curves (brick ZD) for shallow curves (brick ZQ) and for a system of curves as well (brick ZI). The simplification of reducing the amount of parameters by fixing the parameters of m to $m_i = (1\text{-}1/n_i)$ delivers acceptable results. The interpretation of the water retention characteristic leads to an equivalent pore size distribution function, but based on thermodynamic forces. The corresponding pore size distribution functions of the examples for the multi modal equation are presented in figure 3B. It can be seen that brick ZD has a large pore domain at ~ pF 2.7, while the other bricks show a wider distribution of the present pore classes. Furthermore the brick ZI has a dominant pore domain in the hygroscopic range at ~ pF 5.1 and a smaller pore domain at ~ pF 2.7.

## 4 IDENTIFICATION OF BRICK CLUSTERS

To detect natural groupings within the data, a multivariate cluster analysis is applied. It resembles the discriminant analysis to classify the objects into groups although neither the number nor members of the subgroups are known (Hartigan 1975).



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TREE DIAGRAM
                                        DISTANCES
 0.000000000                                                0.50000000
ZC          -----
                +--------------------------------------------
ZP          --- |                                           |
              +--                                           |
ZF          --|                                             |
             ||                                             |
ZQ          -+|                                             |
             +-                                             |
ZO          --                                              |
                                                            +---------
ZL          ---                                             |
              +-----                                        |
ZD          ---    |                                        |
                   +--------------                          |
ZH          --     |             |                          |
             +------             |                          |
ZA          -+                   |                          |
             |                   |                          |
ZJ          --                   |                          |
                                 +------------------        |
ZE          ------               |                 |        |
                 +---            |                 |        |
ZG          --   |  |            |                 |        |
             +-- |  |            |                 |        |
ZB          -- | |  |            |                 |        |
               +--  |            |                 |        |
ZK          ----    |            |                 |        |
                    +-------------                 |        |
ZM          ---------                              |        |
                                                   +---------
ZN          -----                                  |
                +-----------------------------------
ZI          -----
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Figure 4 : Tree diagram of the hierarchical cluster of the ceramic bricks of the Dresden building stock, distance metric is euclidean distance using the minimum variance linkage method of Ward (1963).

To produce clusters, we must be able to compute some measure of dissimilarity between the different types of bricks. Similar bricks should appear in the same cluster and dissimilar bricks in different clusters. To cluster the performance attributes, we have to give each variable comparable influence. The correlation measures can be significantly affected by differences in scale. Since the performance attributes, water content at different log capillary pressures, are measured on a common scale, euclidean distance metrics can be used for the correlation analysis (Hartigan, & Wong 1979). The ceramic brick type ZQ has some missing data in the hygric sorption isotherm between 43.2 and 11.3% relative humidity. Normalizing by the sample size allows comparison of clustering across different size samples with missing data. Therefore we used normalized euclidean distances, which are root mean squared distances for the statistical calculations.

According to Hartigan (1975), various methods can be used to compute the distance of an object or a cluster of objects from another and to determine whether the two should be merged in a given step. We tested the different hierarchical cluster procedures on the water retention data of the ceramic bricks. The calculations were executed using the computer code SYSTAT version 5.2 (1992). In figure 4 a part of the results are presented as examples for the Ward linkage methods. The linkage of each brick or group of bricks is shown as a joining of branches in a tree. The root of the tree is the linkage of all clusters into one set (right hand side), and the ends of the branches lead to each separate brick (left hand side). The distances between the bricks and joining branches of the clusters are given as numbers on the right hand side of the tree diagrams. The numbers represent the dissimilarity based on the minimum variance, figure 4. The respective distances used for separation into groups are shown in boxes. Each branch is lined up in a unique order when the tree is printed, so that the most similar objects are closest to each other.

Depending on the chosen linkage method and distance, the bricks can be clustered into a number of groups. With decreasing distance metric, the number of clusters increases. The figure 4 identify a large dissimilarity down to the distance 0.166 for Ward´s method, dividing the collection of bricks into 4 clusters. Independent of the linkage methods, 4 clusters can be separated. In this amalgamation, each cluster consists of the same type of bricks. Regarding all above-mentioned linkage methods, the separation into 4 clusters leads to identical groups of bricks.

## 5 REPRESENTATIVE WATER RETENTION TRANSFER FUNCTIONS

To derive representative transfer functions of the identified brick clusters, the tested multimodal water retention function of equation 4 is used to smooth and interpolate between scattered data and to provide a complete and unbroken description. The whole set of transfer functions are plotted in figure 5 and 6, while the functional parameters are given in table 1.

Cluster A represents the hard brick type which is used for clinker constructions. This brick has a lower porosity and a low hydraulic conductivity and works as outside covering to protect against driving rain. Cluster B stands for the new type of bricks and is a technologically designed product. One typical representative is the so called standard brick NZ of the „Wienerberger“ brick industries in Germany. The classical loamy- and clay bricks manufactured from natural deposit resources belong to cluster C. Dependent on the composition, e.g. the amount of silt and clay, the water retention curve is shifted. Increasing clay content leads to more finer pores, while the silt content has a strong influence on the medium pore size fraction. Cluster D is dominated by the loamy- and clay content and characterized by the addition of sand to keep the brick dimensions within bounds during the manufacturing process.

The classification of the different bricks into the clusters requires a visual control. Bricks of cluster 1 can be often detected by their size and shape. One lateral margin looks good„ while the other margins look more ordinary. Moreover, hitting a clinker brick sounds like hitting glass. Since the bulk density is significant higher than for the other brick types, a simple laboratory determination of weight and volume can prove the prediction. Bricks of cluster 2 are new type of bricks, which have been in use for the last 15-20 years. The intermixture of the different textures and the extruded production leads to circular cracks within the bricks. Traditional bricks of the cluster type 3 and 4 have more ore less one dimensional cracks due to their production process. Often the old classical brick types vary in their dimensions, which can be measured by a foot rule. Their dimensions differ considerably from the new type of bricks. Very often the name of the manufacture and the year of production is given at one margin. To detect differences between bricks of cluster 3 and 4 a hammer for striking the material is required. Ceramic bricks of cluster 4 show hemisphere grains of coarse sand or other grains in the hidden fragments.

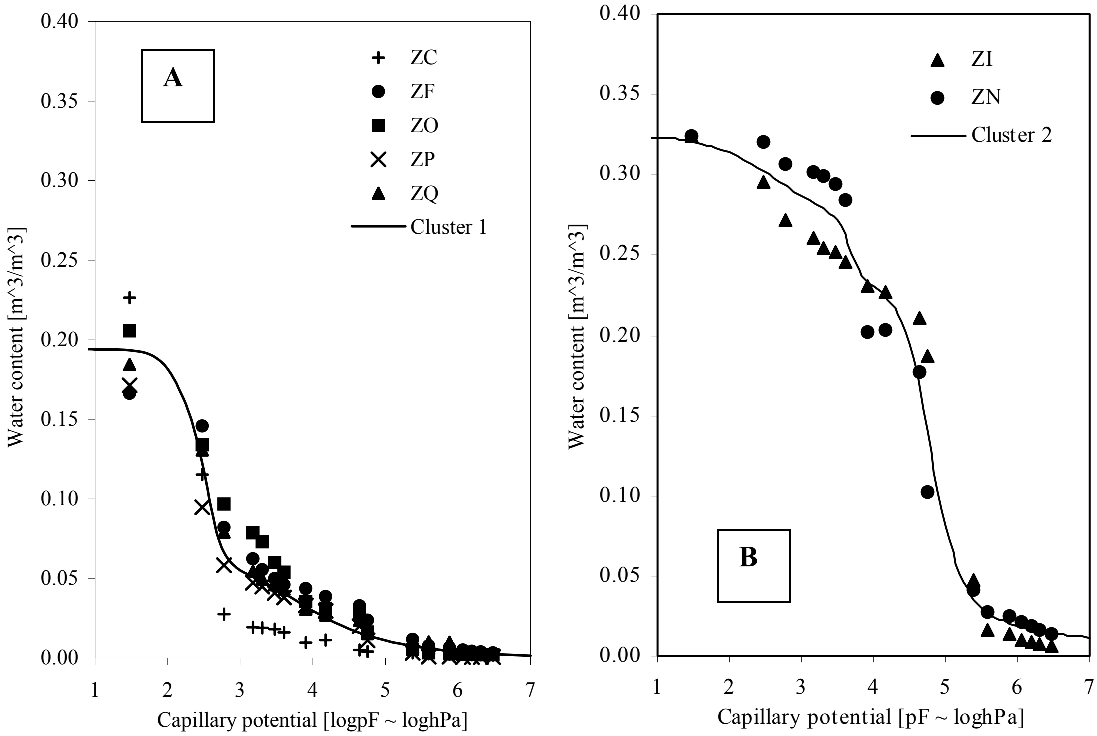

Figure 5 : Natural groupings detected within the water retention data of the ceramic bricks collected from the Dresden building stock. (A) cluster 1: ZC, ZP, ZF, ZQ, ZO. (B) cluster 2: ZI. ZN. The lines correspond to the multi-modal function of equation 4 which is applied for smoothing and interpolation of the data.

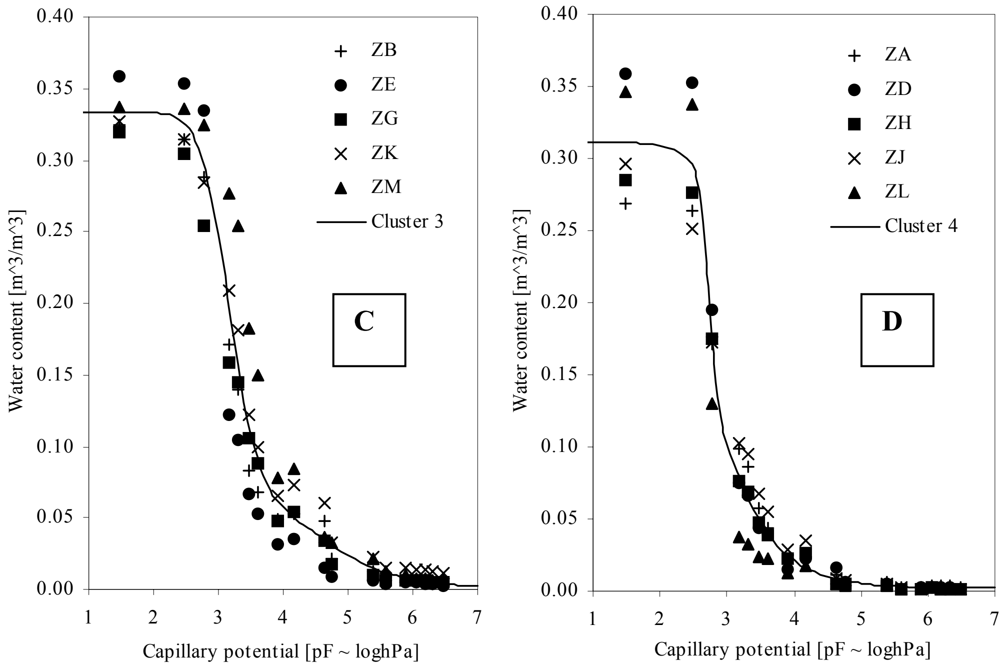

Figure 6: Natural groupings detected within the water retention data of the ceramic bricks collected from the Dresden building stock. (C) cluster 3: ZE, ZG, ZB, ZK, ZM. (D) cluster 4: ZL, ZD, ZH, ZA, ZJ. The lines correspond to the multi-modal function of equation 4.

Table 1 : Estimated parameter combination of the water retention data of the ceramic bricks collected from the Dresden building stock. The residual water content is set to zero for all brick clusters.

| Cluster | θs | weight$_1$ | $\alpha_1$ | $n_1$ | weight$_2$ | $\alpha_2$ | $n_2$ | weight$_3$ | $\alpha_3$ | $n_3$ |
|---|---|---|---|---|---|---|---|---|---|---|
| type | m$^3$/m$^3$ | - | 1/cm | - | - | 1/cm | - | - | 1/cm | - |
| cluster A | 0.194 | 0.39 | 0.00653 | 2.659 | 0.33 | 0.02890 | 5.213 | 0.28 | 0.00350 | 1.448 |
| cluster B | 0.324 | 0.32 | 0.00938 | 1.193 | 0.10 | 0.00022 | 5.800 | 0.58 | 0.00002 | 2.680 |
| cluster C | 0.333 | 0.43 | 0.00122 | 2.477 | 0.42 | 0.00066 | 2.593 | 0.15 | 0.00004 | 1.549 |
| cluster D | 0.311 | 0.53 | 0.00152 | 1.792 | 0.47 | 0.00190 | 8.328 | - | - | - |

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