Development of Water Retention Transfer Functions of Ceramic Bricks of Dresden Building Stock

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ABSTRACT

The building stock of Dresden consists of a large number of brick buildings constructed during the 20th century. Different type of bricks were sampled and their moisture storage function was measured using pressure plate apparatus and desiccators with different saturated salt solutions. A multivariate 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.

INTRODUCTION

The Dresden building stock consists of a large number of buildings constructed of brick masonry. Depending on the period of construction, different type of bricks and brickworks were used. During the Second World War, many houses were destroyed in Dresden. Usually the mortar of the former bricks was removed and the cleaned bricks were subsequently reused for the reconstruction of the buildings. The way of assembling the bricks has caused a mix of different brick types, leading to heterogeneous masonry of the old traditional loam and clay brick types. Additionally, during the past 20 years, a new type of bricks was used for modernization and renovation of the old buildings.

Today´s demands for comfort require a thermal reconstruction of the buildings. The necessary improvement of the thermal insulation for buildings with façades worth preserving raises a number of problems. For most old buildings, for example, those having ornaments, it is not possible to apply outside insulation since the façade would be destroyed, while inside insulation is linked to the risk of interstitial condensation (Häupl et al. 1999). Since February 1, 2001, the renovation of buildings has been controlled by the German EnEv 2001 regulations and the national standard DIN 4108-2, and the heat insulation has higher importance in building modernization than moisture protection. This often leads to serious moisture problems coming from, e.g., moisture condensation and mold growth, from errors during the design and construction phase of the modernization.

A prerequisite for a service life evaluation of building envelopes is analysis of the coupled heat and moisture transport of the brick masonry. This evaluation gives the opportunity to assess optimal solutions for different retrofit problems. This is usually done by the application of simulation tools, such as Delphin or WUFI, and requires knowledge of the moisture storage and transport properties of the materials (Häupl et al. 1999). Since the brick masonry of the Dresden building stock is very heterogeneous, this is a difficult task. Facing 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 of the ceramic bricks used in the Dresden building stock.

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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, investigations on hydraulic conductivity and water vapor transmission are not used for the statistical calculations and are excluded from this analysis.

Sampling

For the present investigation, a set of 17 different ceramic bricks of the Dresden building stock were collected and analyzed. They are a representative selection of the bricks used during the last 130 years. Their coloration exceeds from bright yellow brown to dark carmine red. Their bulk density varies between 1610 and 2010 kg/m^3, while their dimensions range among 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 specimen. Regarding the water retention characteristics, sample sizes of 50·30· and 10 mm are used.

Measuring Methods

The moisture storage is measured in the hygroscopic and overhygroscopic range by means of saturated salt-in-water solutions in desiccator chambers (ISO 12571) and pressure plate extractors (ISO 11274). Since hysteresis may affect the water retention, the desorption characteristic of the overhygroscopic and hygroscopic range is used in this investigation only.

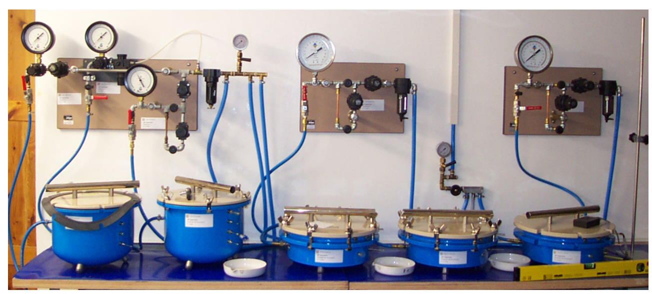
To capillary saturate the brick specimen, they are placed on a ceramic saturation table. The samples are frequently weighed to verify that the daily changes in mass of the specimen are less than 0.1% of the balance reading. For the bricks this procedure takes about 7 to 12 days.

Subsequently, the samples are placed on a ceramic plate, where a filter paper for the low range and a silt/kaolin mixture for the high range provide 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 suction is applied to drain the sample specimen. The corresponding water content is measured by the 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. The pressure step leads to 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. Afterward the pressure chamber is opened and the water content of the bricks is measured by weighing the specimen.

A procedure of sequential quasi-equilibration at different pressures is carried out by removing and weighing the samples and replacing and resetting the pressure (Figure 1). In total nine 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 released specimens of the 15 bar pressure step are used. To control the relative humidity of the environment, the samples are placed in desiccators that contain different salt-in-water solutions. The selected salt-in-water solutions and the corresponding relative humidities are 96.9% by K_2SO_4, 96.0% by KH_2PO_4, 84.3% by KCl, 75.3% by NaCl, 43.2% by NaBr, 32.8% by MgCl, 22.5% by CH_3COOK, and 11.3% by LiCl. Analogously to the previous procedure, the specimens are placed into desiccators and are brought to a quasi-equilibration at the respective humidity. Equilibrium between moisture content and relative humidity is achieved by repeated weightings, at intervals of one week, indicating a difference in mass of <0.1%. Beginning at 96.9% relative humidity, the hygroscopic desorption characteristics are determined by weighing and replacing the samples in desiccators and by stepwise decreasing the relative humidity.

After the measurement, the brick specimens are dried at 105°C. A sample is assumed to be oven dried when the weight loss exceeds less than 0.1% between two successive measurements within 24 hours and is achieved after approximately three days of drying. For material data completion, some mean characteristic data, e.g., porosity, saturated hydraulic conductivity, and water vapor resistance, of the investigated bricks are given in Table 1.



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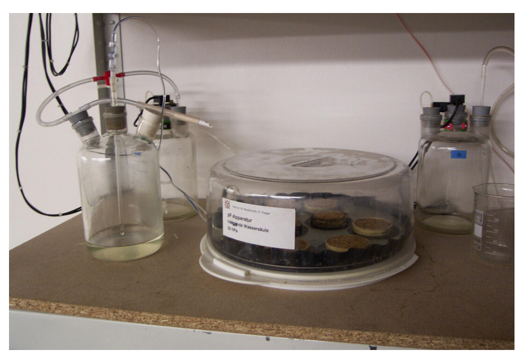


(b)

Figure 1 *Pressure plate apparatus and suction controlled ceramic plates were used for measurement of water retention in the moist and in the wet range.*

Table 1. Characteristic Material Property Data of the Ceramic Bricks Collected from the Dresden Building Stock

Brick Type	Porosity	Saturated Hydraulic Conductivity	Water Vapor Resistance
	m/m	m/s	µ
ZA	0.3318	2.85E-10	9.03
ZB	0.3491	1.68E-08	8.56
ZC	0.3069	1.80E-09	9.34
ZD	0.3873	2.06E-08	7.5
ZE	0.3736	8.62E-06	7.75
ZF	0.2933	5.79E-10	10.1
ZG	0.3635	1.43E-08	8.11
ZH	0.3317	3.06E-08	9.04
ZI	0.3583	3.00E-08	8.25
ZJ	0.3523	6.36E-08	8.54
ZK	0.3534	2.42E-08	8.31
ZL	0.369	1.96E-07	7.86
ZM	0.3601	5.14E-08	8.15
ZN	0.3585	2.31E-09	8.24
ZO	0.3222	5.86E-10	59
ZP	0.2925	5.81E-10	72.4
ZQ	0.2969	6.05E-10	71.1

The time required for all water retention measurements in the overhygroscopic and hygroscopic range took nine and a half months.

Data Transformation

The water retention and the hygric sorption data are measured as a function of capillary pressure and 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 Equations 1 and 3.

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

where ψ 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

$$c = \frac{2\sigma\cos\omega}{gp_w} . \tag{2}$$

The parameters σ and ω correspond to the surface tension (Pa/m) and the contact angle between water and solid phase;

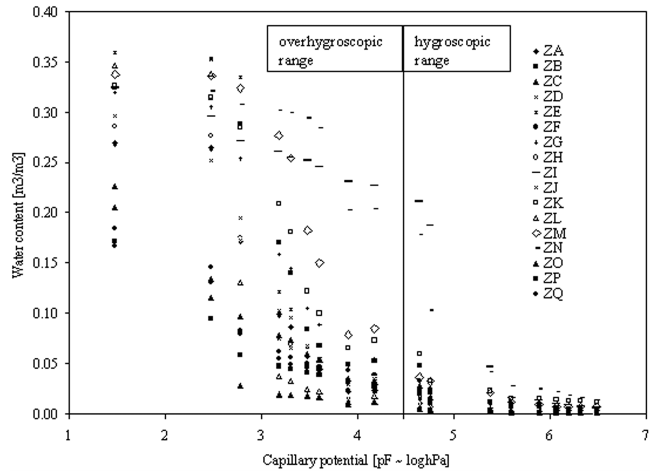


Figure 2 *Measured water retention data (*n *= 306) of the collected ceramic bricks of the Dresden building stock.*

g and p_w are the gravity (ms^{-2}) and the density (kg m^{-3}) of water. The relative humidity φ, (-) is given by Kelvin's law using Equation 3.

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

where R_V equals the general constant of gases (W s kg^{-1}K^{-1}) and T the temperature (K). Equations 1, 2, and 3, allow the conversion between capillary pressure, relative humidity, and equivalent pore radius. This opens the possibility of using physically based pore-size distribution models capable of predicting the water transport function or fit conductivity data in a concise description as well.

EXPERIMENTAL RESULTS AND DATA PROCESSING

For the collection of the 17 different types of ceramic bricks of the Dresden building stock, this resulted in 306 measures of mean water retention data. All moisture storage measurements are plotted as function of log capillary pressure in Figure 2.

The measured water retention data show a large 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 overhygroscopic range, while in the dry part of the hygroscopic range the variation is less than 0.05 m^3/m^3.

Functional Description of the Retention Data

To describe the capillary pressure data in the overhygroscopic and hygroscopic range, the multi-modal function proposed by Durner (1991) is used. This approach is derived from the Van Genuchten (1980) closed-form equation, which was based on the statistical pore models of Burdine (1953) and

Mualem (1976) and can predict the water transport function. The closed-form equation and the multi-modal function for building materials has been applied by Hoffman et al. (1996), Carmeliet et al. (2000), and Plagge et al. (2002). The general multi-modal equation is

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

where θ_s and θ_r are the saturated and residual water content (m^3/m^3), α corresponds to the air-entry value (1/m) and is, beside n and m, a functional fitting parameter. 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 the minimum of the objective function and the starting values as initial estimates as well. The least-squares objective function to be minimized can be written as

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

where θ and θ_j are the observed and the estimated water content, O is the value of the objective function, with j as the number of measured points. Depending on the amount of pore modals, 5, 10, or 14 parameters have to be optimized. Thus, e.g., a three-modal function has 14 parameters to be optimized, 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 be used to construct a maximum three modals only.

θ_s and θ_r are given by the measured data for the respective material. To minimize the amount of functional parameters, m was generally set to $m_i = (1\text{-}1/n_i)$. 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 six or nine for the bimodal and three-modal approach. But still, for three bricks, the parameter identification procedure 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 a uni-, bi-, and three-modal function of the van Genuchten type equation to each data set of the 17 brick types.

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 are always leading to better performance, the effectiveness of the respective modal functions has to be analyzed, 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 square 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.

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

where b is the number of observations. The results of the optimized parameter combinations, found for all analyzed bricks, are given in Table 2.

For 12 types of bricks, the three-modal water retention approach operates best according to the performance criteria. In five cases only, brick types ZG, ZH, ZJ, ZL, and ZM, the bimodal approach is effective enough to fit the measured data. The uni-modal function delivers in no case the best description. From the overall performance evaluation, given by Equation 7, the three-modal approach performs best.

To show the performance of the multi-modal approach used, three materials are selected as examples for the visualization in Figure 3a. The three-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 the overhygroscopic and the hygroscopic range as well. 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 multimodal function is still flexible enough to follow the data.

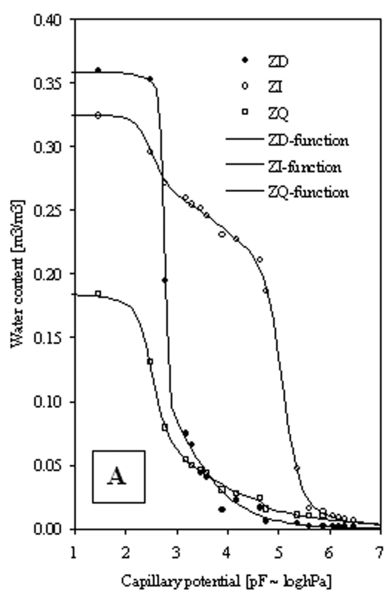
The interpretation of the water retention characteristic leads to an equivalent pore size distribution function, based on thermodynamic forces. The corresponding pore size distribution functions of the examples for the multi- modal equation are presented in Figure 3b. It can be seen that brick ZD has 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.

IDENTIFICATION OF BRICK CLUSTERS

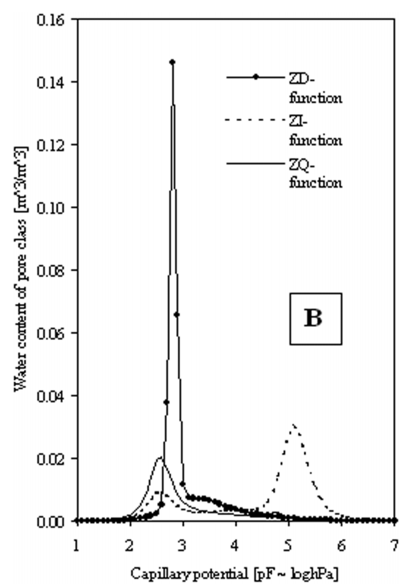
To detect natural groupings within the data, a multivariate cluster analysis is applied. It resembles the discriminant analysis to classify the objects into groups, although neither the number nor members of the subgroups are known (Hartigan 1975). To produce clusters, we must be able to compute some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

Table 2. Estimated Parameter Combination of the Water Retention Data of the Ceramic Bricks and the Mean Square Error (*MSE*) of the Respective Optimization Procedure. The Residual Water Content Is Set at Zero

Brick	θs	$weigth_1$	α_1	n_1	$weigth_2$	α_2	n_2	$weigth_3$	α_3	n_3	w_s	MSE
type	m^3/m^3	-	1/cm	-	-	1/cm	-	-	1/cm	-	m^3/m^3	
ZA	0.269	0.63	0.00268	2.343	0.34	0.00061	2.152	0.03	0.00002	1.374	0.205	7.70E-03
ZB	0.324	0.25	0.00042	4.803	0.60	0.00122	3.098	0.15	0.00004	1.640	0.324	4.17E-03
ZC	0.369	0.45	0.13381	2.325	0.46	0.00322	8.112	0.09	0.00213	1.381	0.166	1.58E-03
ZD	0.359	0.45	0.00170	12.810	0.23	0.00183	12.168	0.32	0.00117	1.616	0.317	8.45E-03
ZE	0.355	0.54	0.00086	2.243	0.42	0.00119	25.232	0.04	0.00005	1.334	0.319	4.03E-03
ZF	0.159	0.47	0.00256	1.860	0.29	0.00275	8.986	0.24	0.00002	1.641	0.104	2.04E-03
ZG	0.316	0.54	0.00046	2.018	0.46	0.00172	3.181	-	-	-	0.269	7.24E-03
ZH	0.286	0.42	0.00085	1.904	0.58	0.00184	6.480	-	-	-	0.220	1.27E-03
ZI	0.325	0.20	0.00348	2.863	0.22	0.00029	1.386	0.58	0.00001	3.057	0.297	1.13E-02
ZJ	0.292	0.44	0.00054	2.017	0.56	0.00246	3.714	-	-	-	0.286	3.85E-03
ZK	0.327	0.39	0.00160	2.851	0.38	0.00043	4.325	0.23	0.00005	1.462	0.285	3.49E-02
ZL	0.347	0.20	0.00182	1.588	0.80	0.00174	25.442	-	-	-	0.287	3.59E-03
ZM	0.337	0.39	0.00082	1.377	0.61	0.00042	2.970	-	-	-	0.329	1.57E-02
ZN	0.324	0.50	0.00014	4.331	0.24	0.00322	1.186	0.26	0.00001	2.627	0.305	3.38E-03
ZO	0.206	0.45	0.00381	8.121	0.50	0.00123	1.516	0.05	0.00002	15.069	0.165	5.03E-03
ZP	0.171	0.44	0.00370	6.990	0.43	0.00578	1.500	0.13	0.00002	6.334	0.128	1.27E-03
ZQ	0.184	0.42	0.00460	1.502	0.42	0.00308	4.663	0.16	0.00080	1.186	0.153	2.58E-03



(a)



(b)

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.*

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 and 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. For the analysis of the retention data of the ceramic bricks, we tested six different kind of linkage methods to detect the brick clusters. The "single linkage method" takes the distance between two bricks or brick clusters as the distance between the two closest members of those clusters, and it tends to produce long, stringy clusters. The "complete linkage method" of Johnson (1967) uses the most distant pairs of objects in clusters to compute the distances. This method produces compact, globular clusters. The "centroid linkage method" uses the average value of all objects in a cluster as the reference point for distances to the other bricks or brick clusters. A variant of the centroid linkage is the Ward "minimum variance linkage method" (Ward 1963), resembling the centroid linkage by adjusting for covariances within the data.

"Average linkage" and "median linkage" methods average all distances between pairs of bricks in different clusters to decide how far apart they are.

We tested the different hierarchical cluster procedures with the water retention data of the ceramic bricks of the Dresden building stock. The calculations were done using the computer code SYSTAT version 5.2 (1992). In Figures 4, 5, and 6, a part of the results are presented for the complete and 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, 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 most far neighbor (Figure 5) or the minimum variance (Figures 4 and 6). The respective distances used for separation into groups are shown in boxes. The tree is printed with a unique ordering in which every branch is lined up so that the most similar objects are closest to each other.

The first cluster is derived at a variance of 0.919 and the data are split into two groups: group 1 = step 1 to step 3, group 2 = step 4 to step 18. Thus, the first three values close saturation shows the largest disimilarity from the other data. The next cluster is developed at a distance of 0.514, dividing the previous two groups into two new groups. The next three distinctions appear at variances of 0.211, 0.13, and 0.089. At the variance of 0.089, six different clusters can be divided. The statistical treatment groups the hygric sorption isotherm into two different clusters. The values for pF 4.64 and 4.76, corresponding to 95% and 96.7% relative humidity, statistically belong more to the water retention data than to the hygric sorption isotherm.

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. Figures 5 and 6 identify a large dissimilarity down to the distance of 0.082 for the complete linkage and 0.166 for Ward's method, dividing the collection of bricks into four clusters. Tables 3 and 4 indicate at which given step the respective type of brick merges into smaller clusters. Independent of the mentioned linkage methods, four clusters can be separated. At this amalgamation each cluster consists of the same type of bricks. Regarding all above-mentioned linkage methods, the separation into four clusters leads to identical groups of bricks as shown in Tables 3 and 4.

REPRESENTATIVE WATER RETENTION TRANSFER FUNCTIONS

To derive representative transfer functions of the identified brick clusters, the tested multi-modal 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 is plotted in Figures 7 and 8.

Cluster A represents the hard brick type that 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 brick and is a technological designed product. One typical representative is the so-called standard brick NZ of the brick industry in Germany. The classical loamy and clay bricks manufactured from natural deposit resources belong to cluster C. Depending on the composition of the texture, 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 strong influence on the medium pore size fraction. The cluster D is dominated by loamy and clay content and characterized by the surcharge of sand to keep the brick dimensions within bounds during the manufacturing process.

The classification of the different bricks into clusters requires visual control. Bricks of cluster 1 can be often detected by their size and shape. One lateral margin is nice looking, while the other margins have an ordinary outlook. Moreover, a hit on a clinker brick sounds like a hit on a glass body. Since the bulk density is significantly 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 past 15-20 years. The intermixture of the different textures and the

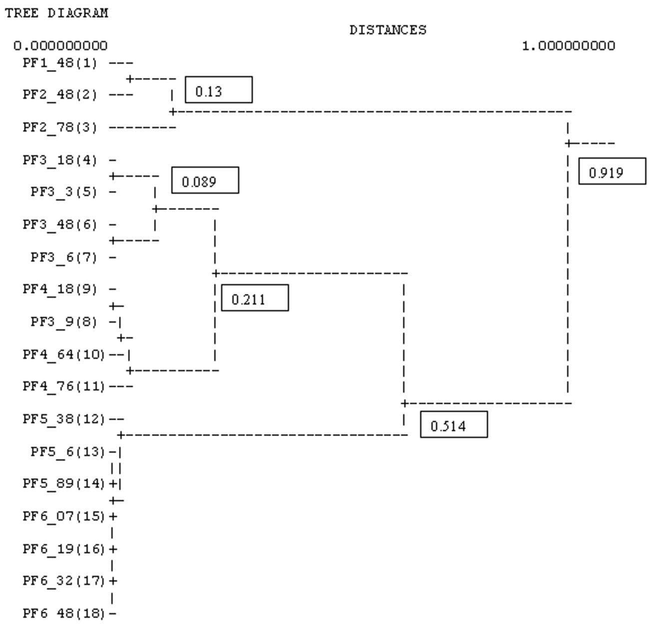


Figure 4 *Tree diagram of the hierarchical cluster of water retention pressure steps is given in log capillary pressure = pF and corresponds to a pressure step (in brackets no. 1, 2, …18); distance metric is Euclidean distance using the minimum variance linkage method of Ward (1963).*

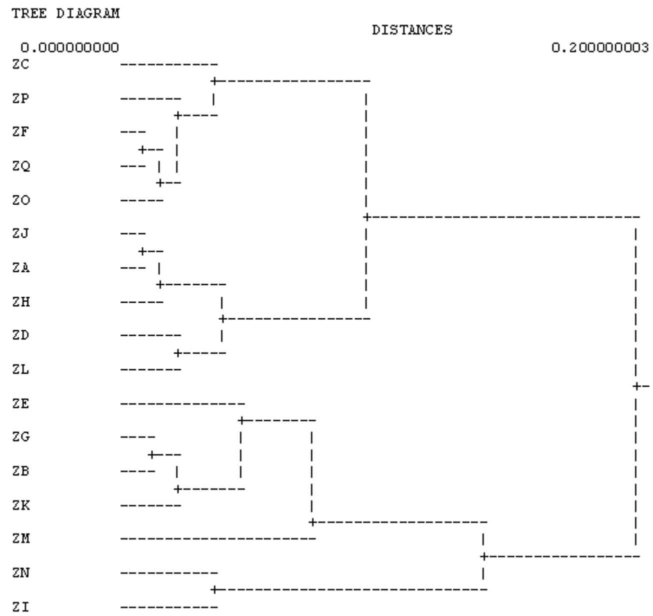


Figure 5 *Tree diagram of the hierarchical cluster of the ceramic bricks of the Dresden building stock. Distance metric is Euclidean distance using the complete linkage method of Johnson (1967).*

extruded production leads to circular cracks within the bricks. Traditional bricks of cluster types 3 and 4 have more or 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 dimension differs remarkably from the new type of bricks. Very often the name of the manufacture and the year of production are given at one margin. To detect differences between bricks of clusters 3 and 4, a hammer for striking the material is required. Ceramic bricks of cluster 4 show hemispheric grains of coarse sand or grains at the hidden fragments.

SUMMARY AND CONCLUSIONS

In this paper, a transfer function approach is proposed to obtain the water retention characteristics of a representative collection of 17 different brick types of the Dresden building stock. Several operations to obtain the transfer functions have been carried out:

- Measurement of 18 points of the storage characteristics in the hygroscopic and the overhygroscopic range for each set of bricks.
- Data transformation and analysis of a multi-modal function for description of the water retention characteristics and definition of performance criteria for the selection of suitable functions.

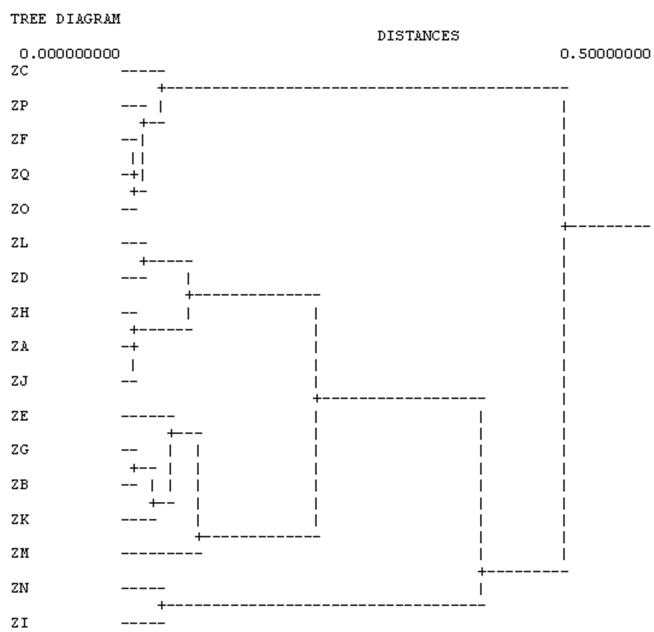


Figure 6 *Tree diagram of the hierarchical cluster of the ceramic bricks of the Dresden building stock. Distance metric is Euclidean distance using the minimum variance linkage method of Ward (1963).*

Table 3. Distances and Corresponding Clusters Using Complete Linkage Method for the Water Retention Data of the Dresden Building Stock

Distance	Cluster 1	Cluster 2	Cluster 3	Cluster 4
0.175	ZC, ZP, ZF, ZQ, ZO, ZJ, ZA, ZH, ZD, ZL,	ZE, ZG, ZB, ZK, ZM, ZN, ZI,		
0.123	ZC, ZP, ZF, ZQ, ZO, ZJ, ZA, ZH, ZD, ZL,	ZN, ZI,	ZE, ZG, ZB, ZK, ZM,	
0.082	ZC, ZP, ZF, ZQ, ZO,	ZN, ZI,	ZE, ZG, ZB, ZK, ZM,	ZJ, ZA, ZH, ZD, ZL,

Table 4. Distances and Corresponding Clusters Using Complete Linkage Method for the Water Retention Data of the Dresden Building Stock

Distance	Cluster 1	Cluster 2	Cluster 3	Cluster 4
0.346	ZC, ZP, ZF, ZQ, ZO,	ZL, ZD, ZH, ZA, ZN, ZJ, ZE, ZG, ZB, ZI, ZK, ZM,		
0.301	ZC, ZP, ZF, ZQ, ZO,	ZN, ZI,	ZL, ZD, ZH, ZA, ZM, ZJ, ZE, ZG, ZB, ZK,	
0.166	ZC, ZP, ZF, ZQ, ZO,	ZN, ZI,	ZE, ZG, ZB, ZK, ZM,	ZL, ZD, ZH, ZA, ZJ,

- Detection of natural groupings within the data by means of several cluster analyses on the normalized performance attribute water content; distance metric is in Euclidean distances by using several linkage methods.
- Application of the physically based multi-modal function to smooth and to interpolate between the scattered data of the brick clusters to receive water retention transfer functions.
- Empirical assignment of different brick types to the discovered representative clusters.

The proposed procedure can divide the set of 17 different bricks into four different types of clusters. All linked brick clusters are representative of the natural groupings for the following classifications:

- Hard clinker bricks
- New, texturally designed bricks
- Traditional loamy and clay bricks
- Traditional loamy and clay bricks with surcharge of sand and grains.

The application of the multi-modal approach to the clusters deliver four water retention transfer functions representative of the Dresden building stock. The fitted functional parameters can be easily used as input parameters for simulation models.

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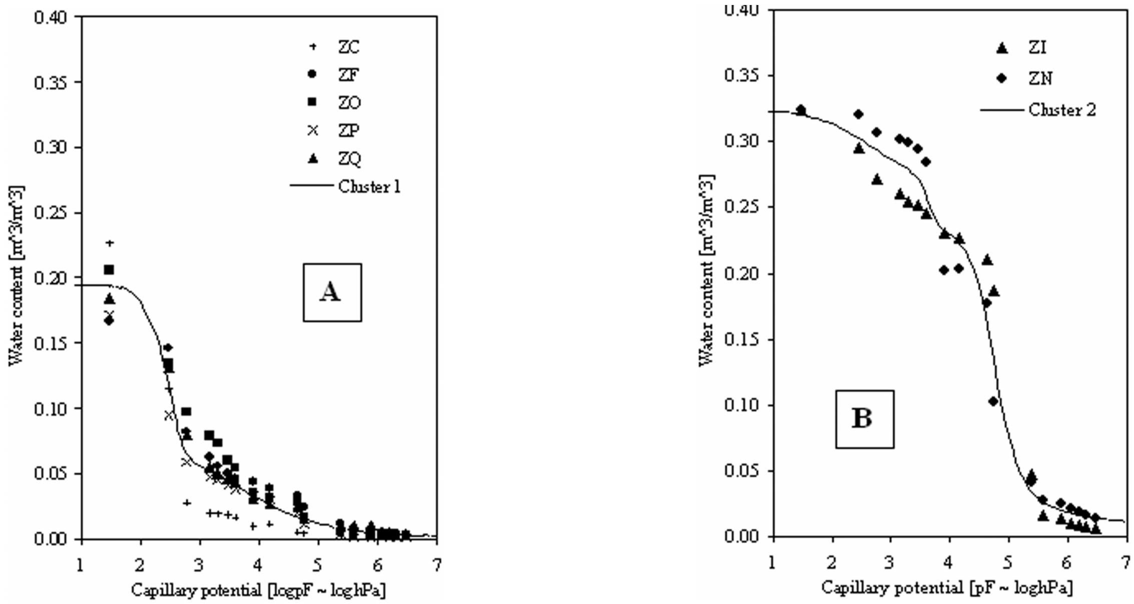

Figure 7 *Detected natural groupings within the water retention data of the ceramic bricks collected from the Dresden building stock. (A) Cluster 1: ZC, ZP, ZF, ZQ, ZO. (B) Cluster 2: ZI. ZN. The lines correspond to the multi-modal function of Equation 4, which is applied for smoothing and interpolation of the cluster data.*

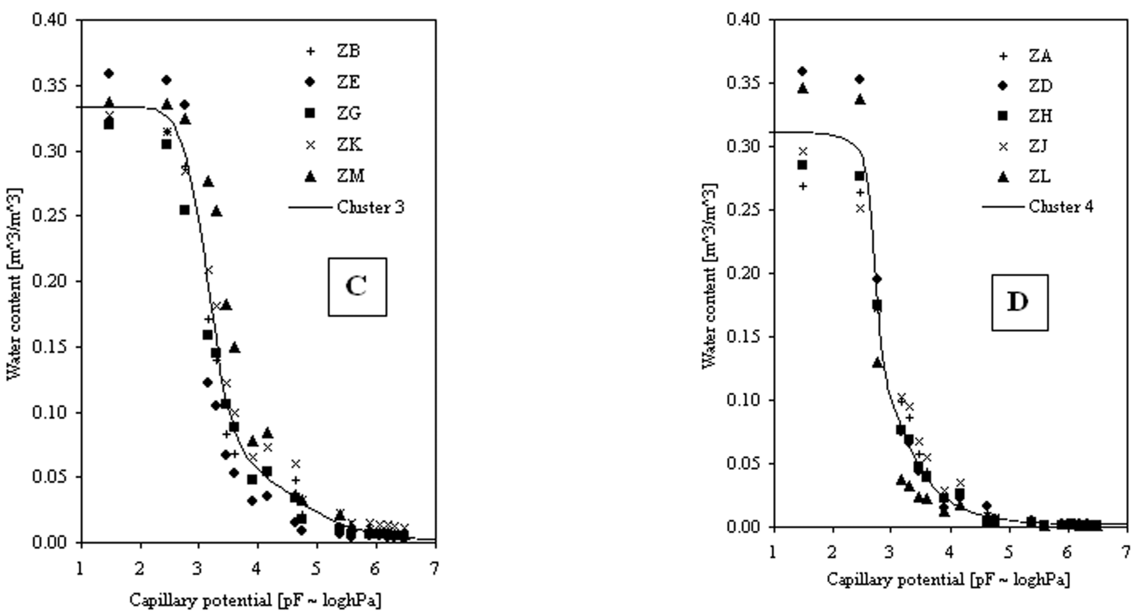

Figure 8 *Natural groupings detected within the water retention data of the ceramic bricks collected from the Dresden building stock. (C) Cluster 3: ZE, ZG, ZB, ZK, ZM. (D) Cluster 4: ZL, ZD, ZH, ZA, ZJ. The lines correspond to the multi-modal function of Equation 4, which is applied for smoothing and interpolation of the cluster data.*

Table 5. Estimated Parameter Combination of the Water Retention Data of the Ceramic Bricks; Residual Water Content Is Set To Be Zero for All Brick Clusters

Cluster type	θs m^3/m^3	$weigth_1$ -	α_1 1/cm	n_1 -	$weigth_2$ -	α_2 1/cm	n_2 -	$weigth_3$ -	α_3 1/cm	n_3 -
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	0.1	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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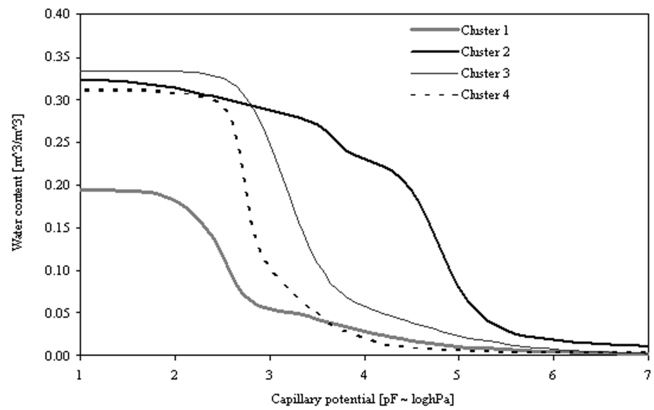

Figure 9 *Common plot of the ceramic brick transfer functions of the water retention characteristics found for the collection of bricks of the Dresden building stock.*

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