*ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 13, No. 1. 2007*

# Mathematical Correlations between Properties of Brick / at Various Equilibrium Humidity Content (Part 2)

**Mikuláš ŠVEDA**[*]

*Faculty of Civil Engineering, Slovak University of Technology, Radlinského 11, SK-813 68 Bratislava, Slovak Republic*

*Received 02 February 2006; accepted 07 March 2006*

In the second part of word the author verifies the availability of correlation functions between the pairs of physical properties (total porosity, pore volume, median pore radius, water capillarity, bulk density, compressive strength and thermal conductivity) of the brick body at the various contents of its equilibrium humidity.

*Keywords:* brick, physical properties, pore structure, mathematical functions, equilibrium humidity.

## INTRODUCTION

The porous materials stored free in air absorb a water vapor by the affect of sorption and by the effect of desorption they get her back. An amount adsorbed and desorbed water vapor depends above all on the form of pore structure material itself, temperature and relative humidity of the air [1 – 7].

Unfortunately, previously most of the well-known works were focused only on the relationship between the moisture of material and the selected physical property. From literature the linear dependence between the moisture content and the thermal conductivity material [1] is certainly well known.

Among the pioneer works, which deal with the effect of pore structure brick on its equilibrium humidity, we can include the work of Dondi and coll. [2]. Authors in this work follow the influence of the pore specific surface on the amount of moisture absorbed at equilibrium conditions, in correspondence of different relative humidity rates. A statistical model was set up in order to predict the equilibrium moisture content values.

It is assumption that modification humidity (at our case the equilibrium humidity) in porous inorganic material can affect some physical properties more and some less. Previously listed mathematical relations between the pairs of physical properties of the brick body were derived only for the brick body at dried case, see part 1 [8]. Author considers therefore necessary to prove the availability these mathematical relations also for the brick body at the various content its equilibrium humidity.

## RESEARCH METHOD

Within the scope of the considered intent the test set of specimens was used, which was burned out by the slow heating rate. Thus they were used the same test specimens as in part 1, in which mathematical relations for the pairs of physical properties were determined, where the brick body was at dried case. The dried test specimens were stored into air-conditioned chamber with the regulated humidity in the air at preservation of the constant temperature of 18 ±2 °C. The test specimens were stored in air-conditioned chamber until to constant weight in the all chosen amount of relative humidity of the air in order we could determine the most accurate effect of sorption (desorption) on the change of equilibrium humidity content and thermal conductivity of the brick body. The relative humidity of the air was consecutively increased to values of 20, 40, 60, 80 and 100 %. On the contrary the relative humidity of the air was consecutively decreased for monitoring the influence of desorption.

The experimental measurement values of the bulk volume and median pore radius were modified in second part of article according to assumption that they are probably loaded by systematic measurement errors. These values and the other values, which availability by correlation functions at the various contents of equilibrium humidity will be verified, are listed in Table 1.

## EFFECT OF RELATIVE ATMOSFHERIC HUMIDITY ON THE EQUILIBRIUM HUMIDITY CONTENT AND THERMAL CONDUCTIVITY

The equilibrium humidity values and the thermal conductivity coefficient $\lambda$ at the various relative humidity of the air are given in Table 2 and Table 3. The development hysteresis curves at different contents of the organic combustible admixture are shown in Fig. 1.

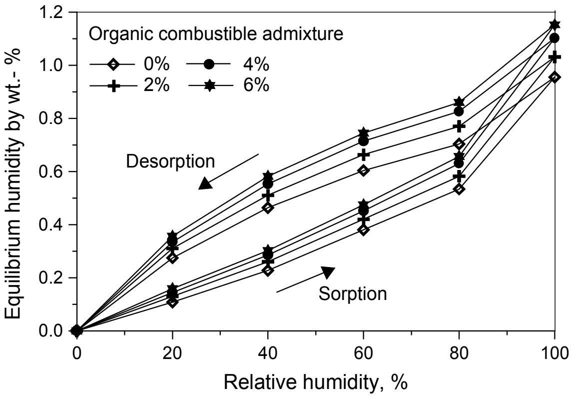

**Fig. 1.** Hysteresis curves for relationship between relative humidity of the air and equilibrium humidity content at different dosages of organic combustible admixture

---

[*] Corresponding author. Tel.: +421-2-59274691; fax: +421-2-52494357. E-mail address: *mikulas.sveda@stuba.sk* (M. Šveda)

**Table 1.** Selected physical properties of the test specimens with different dose of organic combustible admixture

| Property | Dose of the organic combustible admixture [wt.-%] | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| Total porosity **A** [%] | 27.67 | 30.46 | 32.45 | 34.57 | 36.41 | 37.93 | 39.45 |
| Pore volume **B** after modification [$mm^3/g$] | 191.7 | 208 | 221 | 235.8 | 248.5 | 260.3 | 272.2 |
| Median pore radius **C** after modification [nm] | 36.1 | 39.7 | 42.4 | 45.2 | 47.5 | 49.4 | 51.5 |
| Water capillarity **D** [mm/h] | 17.5 | 22.5 | 25.0 | 29.0 | 32.5 | 35.0 | 37.5 |
| Bulk density **E** [$kg/m^3$] | 1890 | 1826 | 1780 | 1730 | 1687 | 1651 | 1615 |
| Compressive strength **F** [MPa] | 76.5 | 63.3 | 54.7 | 46.2 | 40.0 | 35.1 | 31.8 |
| Thermal conduction coefficient at 0% humidity **G** [W/m.K] | 0.693 | 0.638 | 0.603 | 0.564 | 0.534 | 0.511 | 0.489 |

**Table 2.** Relationship between relative humidity of the air and equilibrium humidity content at different dosages of organic combustible admixture

| Relative humidity of the air [%] | Equilibrium humidity content [wt.-%] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Dose of the organic combustible admixture [wt.-%] | | | | | | |
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0.108 | 0.119 | 0.130 | 0.140 | 0.144 | 0.150 | 0.159 |
| 40 | 0.228 | 0.250 | 0.260 | 0.273 | 0.285 | 0.293 | 0.302 |
| 60 | 0.381 | 0.406 | 0.402 | 0.439 | 0.451 | 0.461 | 0.475 |
| 80 | 0.534 | 0.565 | 0.582 | 0.610 | 0.630 | 0.641 | 0.656 |
| 100 | 0.955 | 1.000 | 1.031 | 1.072 | 1.102 | 1.123 | 1.152 |
| 80 | 0.703 | 0.742 | 0.770 | 0.803 | 0.826 | 0.841 | 0.860 |
| 60 | 0.604 | 0.641 | 0.663 | 0.692 | 0.714 | 0.730 | 0.744 |
| 40 | 0.464 | 0.491 | 0.510 | 0.533 | 0.553 | 0.569 | 0.582 |
| 20 | 0.275 | 0.293 | 0.310 | 0.326 | 0.335 | 0.344 | 0.356 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 3.** Relationship between relative humidity of the air and thermal conductivity coefficient $\lambda$ at different dosages of organic combustible admixture

| Relative humidity of the air [%] | Thermal conductivity coefficient $\lambda$ [W/m.K] | | | | | | |
|---|---|---|---|---|---|---|---|
| | Dose of the organic combustible admixture [wt.-%] | | | | | | |
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| 0 | 0.693 | 0.638 | 0.603 | 0.564 | 0.534 | 0.511 | 0.489 |
| 20 | 0.708 | 0.649 | 0.615 | 0.575 | 0.543 | 0.520 | 0.494 |
| 40 | 0.732 | 0.674 | 0.636 | 0.597 | 0.563 | 0.538 | 0.512 |
| 60 | 0.750 | 0.694 | 0.658 | 0.613 | 0.579 | 0.551 | 0.525 |
| 80 | 0.780 | 0.718 | 0.679 | 0.631 | 0.594 | 0.567 | 0.542 |
| 100 | 0.829 | 0.773 | 0.729 | 0.678 | 0.635 | 0.605 | 0.575 |
| 80 | 0.801 | 0.739 | 0.699 | 0.650 | 0.612 | 0.583 | 0.554 |
| 60 | 0.780 | 0.721 | 0.682 | 0.635 | 0.597 | 0.569 | 0.539 |
| 40 | 0.760 | 0.702 | 0.661 | 0.618 | 0.581 | 0.555 | 0.525 |
| 20 | 0.735 | 0.674 | 0.636 | 0.595 | 0.562 | 0.537 | 0.509 |
| 0 | 0.693 | 0.638 | 0.603 | 0.564 | 0.534 | 0.511 | 0.489 |

Based on achieved results we can state that with the increase of the relative humidity and dosage of organic combustible admixture, the equilibrium humidity content increases, see Fig. 1.

The equilibrium humidity content achieves for example in the test specimen without the organic combustible admixture the maximal value of 0.955 %, however in dose organic combustible admixture 6 wt.-% it is increased by 1.152 %.

It is generally known that the humid porous material influences on its thermal conductivity negatively, this relation is even linear, see Fig. 2. Then it is obvious that if the equilibrium humidity content grows with the increasing relative air humidity, then its thermal conductivity grows too, see Fig. 3. As we can see on this Figure, single hysteresis curves are moved in the vertical direction gradually below with an increase of the dose of organic combustible admixture. Their slope to horizontally axis is practically constant. The slenderness ratio of hysteresis curves varies and a difference between the minimal and maximal amount of thermal conductivity coefficient (see Δa and Δb). Then with the increase dose of organic combustible admixture, the hysteresis curve is narrower and it decreases also the difference between the values of thermal conduction coefficient at zero and maximal relative air humidity. It is the considerable knowledge mainly for practical purposes.

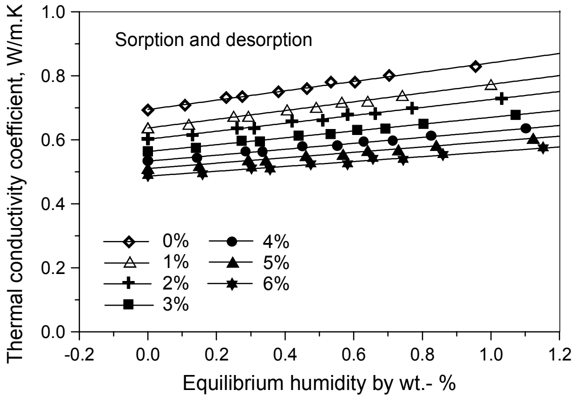

**Fig. 2.** Linear relationship between the equilibrium humidity content and thermal conductivity at different dosages of organic combustible admixture

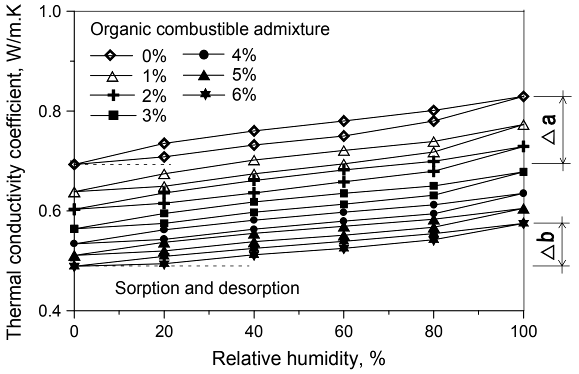

**Fig. 3.** Hysteresis curves for relationship between the relative humidity of the air and thermal conductivity at different dosages of organic combustible admixture

As is mentioned above, the maximum equilibrium humidity content achieves an amount about 1 %. We can suppose then that this amount will not affect the further following properties as total porosity **A**, pore volume **B**, median pore radius **C**, water capillarity **D**, bulk density **E** and compressive strength **F**. On this account, the values of these properties given in Table 1 can be constant.

We will assume also that the equilibrium humidity content of 1 wt.-% can affect more expressively only the thermal conductivity **G**. On this account our attention will concentrated only on those pairs of physical properties, in which the thermal conductivity **G** occurs.

## METHODIC

The same methodical proceeding as is listed in part 1 (chapter 4) was chosen for the determination of mathematical relations between the pairs of physical properties with the various equilibrium humidities content. It was created again the control scheme for the single pairs of physical properties, where the optimal correlation functions were searched by the exploiting computer software and least-square method. Our attention was then focused only on those relations already, in which thermal conductivity **G** occurs.

## RESULTS OF CALCULATIONS

The mathematical relations between the pairs of physical properties at the various relative humidities are demonstrated in Figs 4 – 9. The all correlation functions between the pairs of physical properties after the modification of experimental measured values (at 100 percent relative air humidity) are on the contrary given in Table 4.

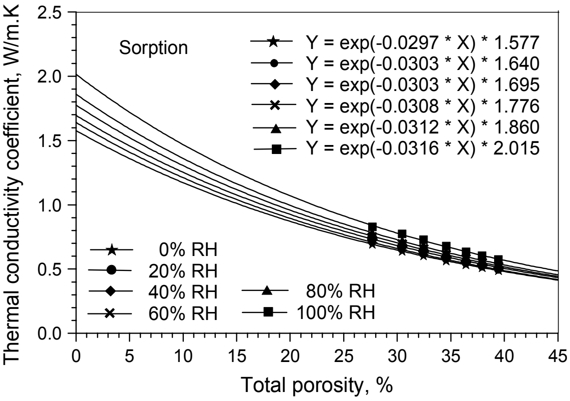

**Fig. 4.** Relationship between the total porosity and thermal conductivity at various relative humidity of the air and at different dosages of the organic combustible admixture

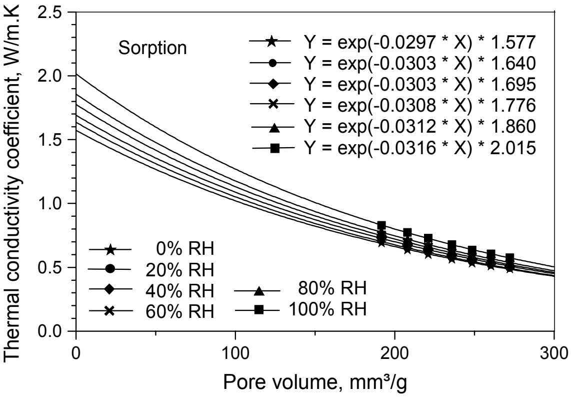

**Fig. 5.** Relationship between the pore volume and thermal conductivity at various relative humidity of the air and at different dosages of the organic combustible admixture

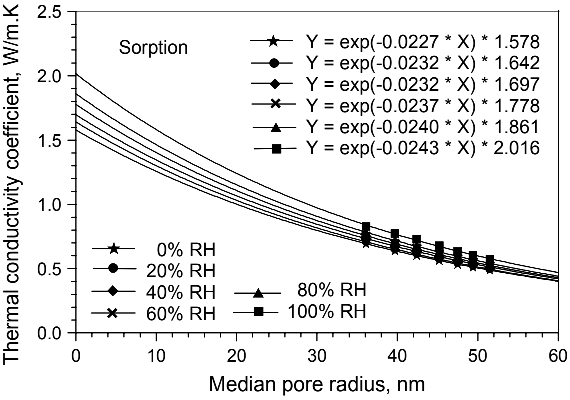

**Fig. 6.** Relationship between the median pore radius and thermal conductivity at various relative humidity of the air and at different dosages of the organic combustible admixture

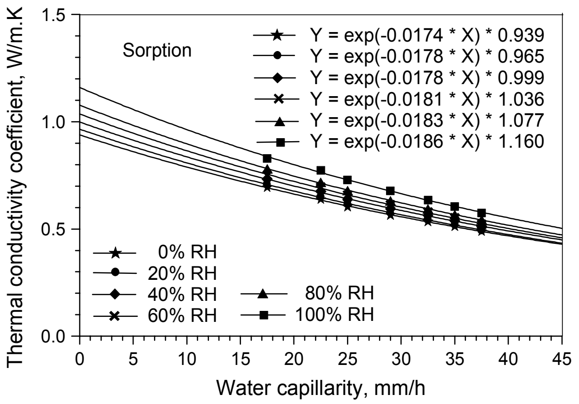

**Fig. 7.** Relationship between the water capilallarity and thermal conductivity at various relative humidity of the air and at different dosages of the organic combustible admixture

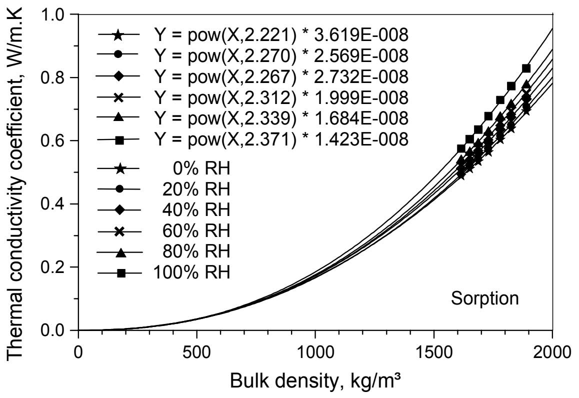

**Fig. 8.** Relationship between the bulk density and thermal conductivity at various relative humidity of the air and at different dosages of the organic combustible admixture

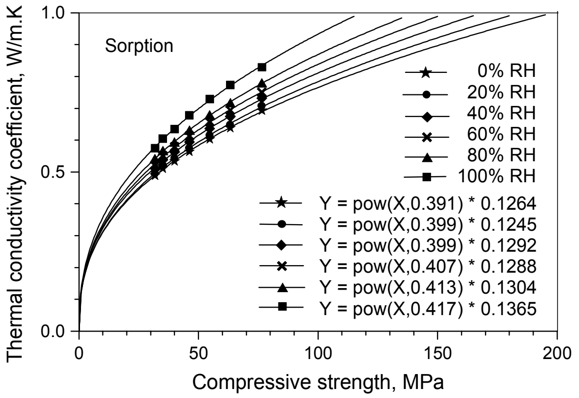

**Fig. 9.** Relationship between the compressive strength and thermal conductivity at various relative humidity of the air and at different dosages of the organic combustible admixture

At the sight of Figs 4 – 9 we can state that in all cases the single mathematical functions have a similar course although the relative air humidity varies. These correlation functions remain always of the equal type for each pair of physical properties, only their coefficients are changed.

**Table 4.** Correlation functions between the pairs of physical properties after modification of the experimentally determined values at 100 percent relative air humidity

| Designation correlation | Correlation function |
|---|---|
| **AB** | Y = 6.85339 · X |
| **AC** | Y = 1.30387 · X |
| **AD** | Y = 1.70391 · X – 29.7331 |
| **AE** | Y = exp(–0.0133629 · X) · 2741.69 |
| **AF** | Y = exp(–0.0759055 · X) · 633.917 |
| **AG** | Y = exp(–0.0316623 · X) · 2.01538 |
| **BC** | Y = 0.189745 · X |
| **BD** | Y = 0.248149 · X – 29.6205 |
| **BE** | Y = exp(–0.0019477 · X) · 2740.3 |
| **BF** | Y = exp(–0.0110601 · X) · 631.569 |
| **BG** | Y = exp(–0.00462002 · X) · 2.01535 |
| **CD** | Y = 1.30623 · X – 29.7548 |
| **CE** | Y = exp(–0.0102463 · X) · 2742.43 |
| **CF** | Y = exp(–0.0581955 · X) · 634.686 |
| **CG** | Y = exp(–0.0242749 · X) · 2.01639 |
| **DE** | Y = exp(–0.00783306 · X) · 2170.87 |
| **DF** | Y = exp(–0.0445009 · X) · 168.348 |
| **DG** | Y = exp(–0.0185727 · X) · 1.15955 |
| **EF** | Y = pow(X,5.6792) · 1.89059E – 017 |
| **EG** | Y = pow(X,2.37094) · 1.42337E – 008 |
| **FG** | Y = pow(X,0.417335) · 0.136522 |

## TESTING OF MATHEMATICAL RELATIONSHIPS

The correctness of mathematical functions (illustrated graphic in Figs 4 – 9 was verified by equal method as is listed in part 1 (chapter 5). Mathematical functions given in Table 4 were selected for the control of mathematical relationships. As an initial point was chosen an arbitrary value of the total porosity (**A** = 20 %) in area, in which don't occur the experimentally measured values. The control was obtained by sequential substitution of calculate values according to scheme in Fig. 5 (part 1), see Fig. 10. By comparing the values calculated for the single physical properties we can state that correlation functions given in Table 4 are correct.

The control of relationships also in the boundary conditions was carried out in the last step. Consequently there were selected these boundary conditions: total porosity **A** = 0 %, pore volume **B** = 0 $mm^3$/g and median pore radius **C** = 0 nm and thermal conductivity **G** at 100 percent relative air humidity. The results of these controls are given in Table 5, where only the pairs of correlation relations **AG, BG and CG** occur already. On the basis of the achieved results we can state that the values of thermal conductivity **G** obtained in a "different way" are totally identical. These results extend then mentioned above knowledge already that they have availability not only in the case zero, but also in the case the maximal equilibrium humidity content in the brick body.

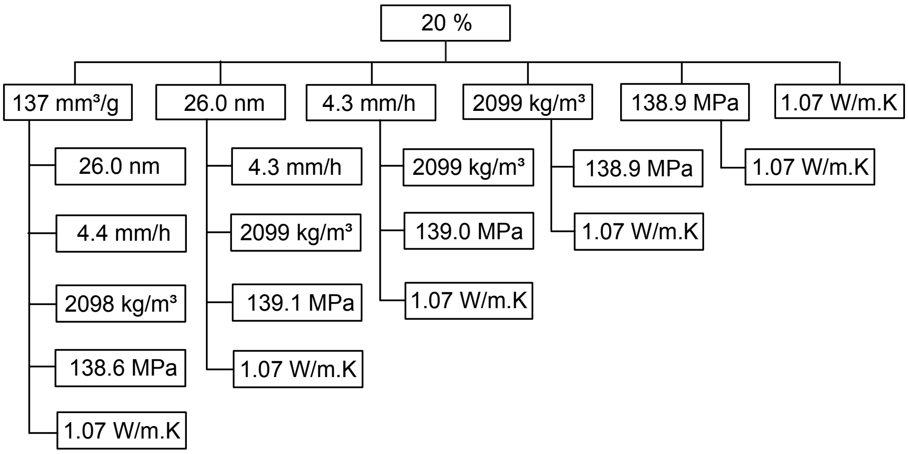

**Fig. 10.** Checking scheme for correlation functions between physical properties at total porosity **A** = 20 % and 100 percent relative air humidity

**Table 5.**Thermal conductivity **G** determined at **A** = 0 %, **B** = 0 mm$^3$/g, **C** = 0 nm, 100 percent relative air humidity

| Property | Designation correlation | Total porosity **A** = 0 % | Pore volume **B** = 0 mm$^3$/g | Median pore radius **C** = 0 nm |
|---|---|---|---|---|
| Thermal conduction coefficient **G** [W/m.K] | **AG, BG, CG** | 2.02 | 2.02 | 2.02 |

At the sight of exponential functions in Figs 4 – 6, which display the correlation relations between the pairs of physical properties **AG**, **BG** and **CG** at various relative humidity, an interesting knowledge was found. The exponential functions: Y = exp(aX) · b at the same relative air humidity have also equal coefficient b. Based on this knowledge we can deduce that in boundary conditions (where **A** = 0 %, **B** = 0 mm$^3$/g or **C** = 0 nm) the values of thermal conductivity **G** will be always equal to the amount of coefficient b at the certain relative air humidity.

Within the scope of third part of article the availability of mathematical relations was verified for the selected pairs of physical properties of the brick body also changing in equilibrium humidity content. On the basis achieved results we can state that the types of mathematical functions according to Table 4 remain, there is a change only of their coefficients. These mathematical functions are available also in boundary conditions (**A** = 0 %, **B** = 0 mm$^3$/g or **C** = 0 nm), though the equilibrium humidity content of the brick body is changed.

## CONCLUSIONS

In the first and second part of article it is mentioned the existence of correlation relations expressed by mathematical functions (linear, exponential and power) between the pairs of physical properties of the brick body. For each pair it is defined only one of type mathematical function. The availability these functions was demonstrated also in boundary conditions (total porosity = 0 %, pore volume = 0 mm$^3$/g and median pore radius = 0 nm) not only at zero, but also at various equilibrium humidity content of the brick body.

## REFERENCES

1. **Mrlík, F.** *Vlhkostné problémy stavebných materiálov a konštrukcií* (Humidity Problem of Building Materials and Constructions). Bratislava, Alfa 1985: 269 p. (in Slovakian).
2. **Dondi, M., Principi, P., Raimondo, M., Zaranini, G.** Water Vapour Permeability of Clay Bricks *Construction and Building Materials* 17 (4) 2003: pp. 253 – 258.
3. **Šveda, M.** Influence of Equilibrium Humidity on the Thermal Conductivity of Brick Products *Brick and Tile Industry International* 51 (12) 1998: pp. 810 – 817.
4. **Raimondo, M., Dondi, M., Mazzanti, P. Stefanizzi, P.** Equilibrium Moisture Content of Clay Bricks *Key Engineering Materials* 264 – 268 (II): pp. 1483 – 1486
5. **Yakovlev, G. I., Gailyus, A.** Salt Corrosion of Ceramic Brick *Glass and Ceramics* 62 (9 – 10) 2005: pp. 321 – 323
6. **Hoffman, D., Niesel, K., Wagner, A.** Capillary Rise and the Subsequent Evaporation Process Measured on Columns of Porous Material *American Ceramic Society Bulletin* 69 (3) 1990: pp. 392 – 96.
7. **Mangel, A.** Investigating a Range of Solid Samples by Automatic Water Sorption *Journal of Thermal Analysis and Calorimetry* 55 (2) 1999: pp. 581 – 599.
8. **Šveda, M.** Mathematical Correlations between Properties of Brick / in a Dried State (Part 1) *Materials Science* (*Medžiagotyra*) 12 (3) 2006: pp. 230 – 236.