# Capillary Active Insulations Based on Waste Calcium Silicates

**Aleš Břenek, Vojtěch Václavík, Tomáš Dvorský, Jaromír Daxner,
Vojtech Dirner, Miroslava Bendová, Marta Harničárová
and Jan Valíček**

**Abstract** The issue of capillary active calcium silicate insulation used in the systems of energy redevelopment of historic buildings is a very up-to-date topic. This article describes the properties of the developed material structures built on cement composites with a defined inner surface using industrial waste materials containing aluminosilicates. The article presents the structures containing fly ashes from heating plants improving the rheological properties of the mixture and the latent hydraulic properties allowing a reduction of the necessary amount of the binding matrix, represented by cement in this case, which has a direct impact on

---

A. Břenek · V. Václavík (✉) · T. Dvorský · V. Dirner
Faculty of Mining and Geology, Institute of Environmental Engineering, VŠB-Technical
University of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava-Poruba, Czech Republic
e-mail: vojtech.vaclavik@vsb.cz

A. Břenek
e-mail: ales.brenek.st@vsb.cz

T. Dvorský
e-mail: tomas.dvorsky@vsb.cz

V. Dirner
e-mail: vojtech.dirner@vsb.cz

A. Břenek · V. Václavík · M. Bendová
Faculty of Mining and Geology, Institute of Clean Technologies for Mining and Utilization
of Raw Materials for Energy Use, VSB-Technical University of Ostrava, 17. listopadu
15/2172, 708 33 Ostrava-Poruba, Czech Republic
e-mail: miroslava.bendova@vsb.cz

J. Daxner
K Pikovine 847, 739 34 Senov, Czech Republic
e-mail: daxner@email.cz

M. Harničárová · J. Valíček
Faculty of Mining and Geology, Institute of Physics, VSB-Technical University of Ostrava,
17. listopadu 15/2172, 708 33 Ostrava, Czech Republic
e-mail: marta.harnicarova@vsb.cz

J. Valíček
e-mail: jan.valicek@vsb.cz

A. Öchsner and H. Altenbach (eds.), *Mechanical and Materials Engineering of Modern Structure and Component Design*, Advanced Structured Materials 70,
DOI 10.1007/978-3-319-19443-1_14

the economy of the final material. The aim of the developed material is to extend the segment of capillary thermal insulation board materials used for the purpose of energy redevelopment of historic buildings. The article will present the parameters evaluating the capillary activity of the material, the coefficient of diffusion resistance, the thermal conductivity coefficient and the physical and mechanical properties. The acquired values are then implemented into the simulation software Delphin, taking into account the moisture transport in porous materials under non-stationary conditions. The output of the software is a simulation describing the developed material in time, after the incorporation into a moisture-defined building structure showing a disruption of the waterproofing layers of the lower structure.

**Keywords** Calcium silicates · Numerical expression Delphin · Building insulation · Energy redevelopment

## 1 Introduction

This article responds to a current trend in the building industry, which is the reconstruction of historic buildings combining the extension of the service life of these buildings, while reducing the thermal resistance of the building envelope. The conventional procedure meeting these expectations is the application of exterior thermal insulation based on expanded polystyrene materials used for the thermal insulation of new buildings. Practical experience with the utilization of objects reconstructed in this way has shown that the use of these materials on historic buildings with non-functional waterproofing leads to the emergence of new previously unknown problems in the form of moisture spots and moulds in the interior of the building. This is caused by a significant increase in the diffusion resistance of the building envelope supporting vertical capillary elevation of moisture from the footing of the foundation structure. The solution for similarly reconstructed objects is the use of diffusion-open, insulation supporting systems drying moisture from the affected foundation structure. This paper presents the outcome of the development of diffusion-open and capillary active materials [1] intended for the energy redevelopment of historic buildings [2–5] and focused on the utilization of waste materials based on aluminosilicates arising during the production of cellular concrete. The aim of the research was to reduce the technological intensity of the

---

M. Harničárová
Nanotechnology Centre, VŠB-Technical University of Ostrava, 17. listopadu 15/2172,
708 33 Ostrava, Czech Republic

J. Valíček
Faculty of Metallurgy and Materials Engineering, RMTVC, VŠB-Technical University
of Ostrava, 17. listopadu 15/2172, 708 33 Ostrava, Czech Republic

production of capillary active insulations, thus facilitating an increase of the thermal resistance of buildings with damaged waterproofing or a high degree of moistening. The aim of the development of a suitable recipe was to produce a material with strength in the range of 0.3–0.6 MPa, without the use of an autoclave, with the thermal conductivity coefficient within the range of 0.06–0.08 W/m·K. The monitored properties of these materials include the thermal conductivity coefficient, the diffusion resistance coefficient and the capillary absorption coefficient. The function of the developed recipes for the production of non-autoclaved diffusion-open board insulations is presented on calculation simulations performed in the Delphin software [6], which allows you to take into account the real moisture processes taking place in the construction. Another view of the preparation of lightweight cement composites using hemp shive is presented in works [7–9]. The best results in these works are achieved by lightweight cement composites using binders based on MgO cements, which we also want to deal with in the next stages of development in similar fashion, i.e. replacing the primary binding matrix with fly ash from power plants.

## 2 Methodology

### 2.1 Theory of Moisture Transport in Materials

According to the way in which moisture can get into the building structure, we distinguish [1]:

- building moisture (initial—built-in during the production): disappears from the structures after a certain period of operation of the building;
- subsoil moisture (action of capillary forces of the surrounding soil): is considered only in the case of missing or non-functioning waterproofing;
- rain moisture (the effect of atmospheric precipitation);
- operating moisture (from the internal environment): depends on the method of operation of the building;
- sorption moisture (from the internal and from the external environment, as a result of the hygroscopic properties of the material): at steady temperature and humidity, there is a balance between the material moisture and the moisture of air that surrounds it—the so-called equilibrium moisture (sorption and operating moisture can be the same under certain conditions);
- condensed moisture (water vapour condensation on the surface of or inside the structure).

If the moisture in the structure after some time of operation of the building (2–4 years) is affected only by rain, sorption and condensed moisture (initial building moisture has already vaporized and the waterproofing is fully functional), this moisture is referred to as stable or practical.

In conventional building materials (porous), moisture spreads in two ways [2]:

- diffusion of water vapours (moisture movement in the vapour phase): it takes place when there is a gradient of the partial pressures of water vapour between the external and internal environment, which separates the building structures—the condition is that the pores and capillaries in the material of the structure must have a larger diameter than the diameter of a water molecule (generally >$10^{-7}$ m);
- moisture conductivity (also: capillary conductivity—the ability of a material to convey moisture in the liquid phase towards its surface, where it evaporates or diffuses): it takes place when there is a temperature gradient (the temperature affects the viscidity of water and its surface tension), and when there is a moisture gradient in the material (the conveyance of a water "film" on the surface of the pores depends on the difference of relative humidity on the opposite sides of the pores)—the condition is a continuous network of pores and capillaries.

## *2.2 Description of the Simulation Tool Delphin*

The calculation performed in the Delphin simulation software tries to achieve the most accurate result of hygrothermal processes in structures approaching reality. The calculation uses the actual climatic conditions in the region of Ostrava.

The dynamic processes taken into account in the simulation are:

- conduction of heat—thermal conductivity depending on moisture (not taking into account latent heat);
- accumulation of heat—accumulation of heat depending on moisture;
- diffusion of water vapour—diffusion of water vapour depending on the changing moisture content of the material;
- transformations of phases—balancing of the evaporation and condensation processes with regard to the evaporating cooling;
- capillary transfer of liquid water—transfer of liquid water depending on the moisture;
- accumulation of moisture—from the difference of moisture flows to and from the space (diffusion of water vapour + capillary transfer); hygroscopic charge according to the measured function of the accumulation of moisture;
- air flow—calculation of the air pressure profile, convective air flow due to pressure gradients.

The possible phenomena that have been excluded from the calculation can include:

- thermo-diffusion, diffusion thermics (Dufour and Soret phenomenon) and the production of internal energy due to compression and friction;
- the transport properties are isotropic, with no directional dependence.
- the effects of electric fields (gravity acts as a single volume force);

- turbulent flow;
- the hysteresis of the function of moisture accumulation is not taken into account,
- the material properties are homogeneous in each discretized volume element,
- time changes of the baric field during the pre-definable time step (in the order of 1–10 min).

**Numerical simulation of the critical detail of the construction in the Delphin software** The presented critical detail of construction, see Fig. 1, is numerically evaluated from the point of view of the course of the weight of moisture in the foundation structure after gluing thermal insulation calcium silicate boards.

The examined detail was evaluated in unsteady weather conditions, with constant added moisture representing damaged waterproofing, and increased initial weight of moisture representing an object unused for a long time. These boundary conditions were used to model a structure in seven versions of redevelopment treatments and a reference state with lime-cement plaster only. The measured thermal and technical parameters of the developed recipes (materials) were incorporated into the Delphin software, which was used to prepare a 2D moisture model of the peripheral structure of the house at the point of connection to the foundation structure of the house. The moisture simulation takes into account both the formation of condensates in the place of application of calcium silicate boards and the moisture added due to the penetration of moisture through the damaged waterproofing. The area in question was evaluated using six options, see Fig. 3, by applying the materials developed with a thickness of 50 mm. The simulations also included the currently used autoclaved board materials. The best boundary value, which the technical measure is attempting to get close to, is the simulation of 30 mm lime-cement plaster on the exterior of the building representing the original operating condition. The boundary conditions of the calculation are presented in Table 1.

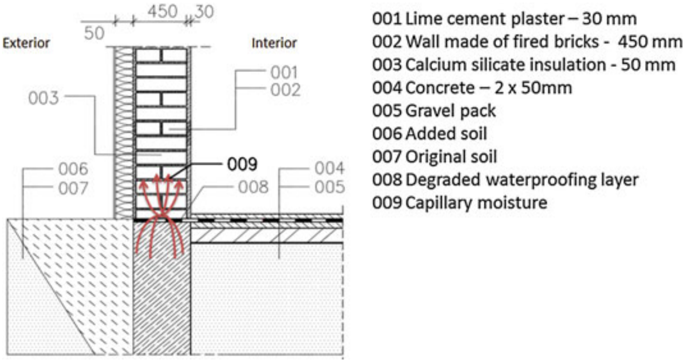

**Fig. 1** Detail of the most common method of the construction of a peripheral building foundation with damaged waterproofing evaluated by the Delphin simulation software

**Table 1** The initial boundary conditions of the calculation if the moisture behaviour of the building in the Delphin software

| [a]The boundary conditions calculation | | |
|---|---|---|
| Thermal resistance to heat transfer in the interior | Calculation of condensation on the surface | [b]Rsi:<br>0.25 $m^2$ ·K/W |
| Thermal resistance to heat transfer in the exterior | Calculation of condensation on the surface | [b]Rse:<br>0.04 $m^2$ ·K/W |
| The design outdoor temperature | Long-term average temperature measured by [c]CHMI | |
| The design temperature of indoor air | [e]Sinusoidal variable temperature in the range of 19.5–20.5 °C | |
| The design relative humidity of outside air | Long-term average moisture content measured by [c]CHMI | |
| The design relative humidity of indoor air | [d]Sinusoidal variable moisture content in the range of 44–55 % | |
| Direct sun radiation (short wave component) | [c]Reflection coefficient of the surrounding ground: 0.4 [−] | |
| Diffuse sun radiation (short wave component) | [c]Absorption coefficient of the building surface: 0.6 [−] | |
| Atmospheric counter radiation | [c]Emission coefficient of the building surface 0.9 [−] | |

[a] All the used input data is based on hourly measurements of an average year

[b] CSN EN ISO 13788 [10] determines a standard value of the heat resistance during the transfer on the inner side of the structure with the value of Rsi = 0.25 $m^2$·K/W and on the outer side with the value of Rse = 0.04 $m^2$·K/W, for the calculations of water vapour condensation

[c] The calculation uses long-term average hourly values for the area of Ostrava CZ, taken from the Czech Hydro-meteorological Institute (CHMI)

[d] The design temperatures of indoor air are based on the recommendations of CSN EN 12831 [11], which have been adjusted by taking into account the hysteresis of the thermostat of indoor environment ±0.5 °C

[e] The dispersion of the design relative humidity of indoor air is based on long-term measurements of relative humidity of indoor air in the reference building in order to more accurately describe the hygroscopic load of the structure

## *2.3 Input Material*

The production of calcium silicate thermal insulation boards takes advantage of the following materials:

- Aggregate—Aluminosilicate pulp with the fraction of 0.063/0.125 mm;
- Water—water from the water supply network;
- Binder—cement CEM I 42, 5R (from Cement Hranice, a.s. company);
- Binder—fly ash K12 (from Dalkia Česká republika, a.s.—Třebovice company);
- lime Cl90 (6–9) min (from Carmeuse Czech Republic s.r.o. company);
- foaming agent—aluminium powder with the specific surface of 9500 $cm^2/g$.

A scheme of the treatment of waste autoclaved cellular concrete used as filler in calcium silicate insulation is presented in Fig. 2.

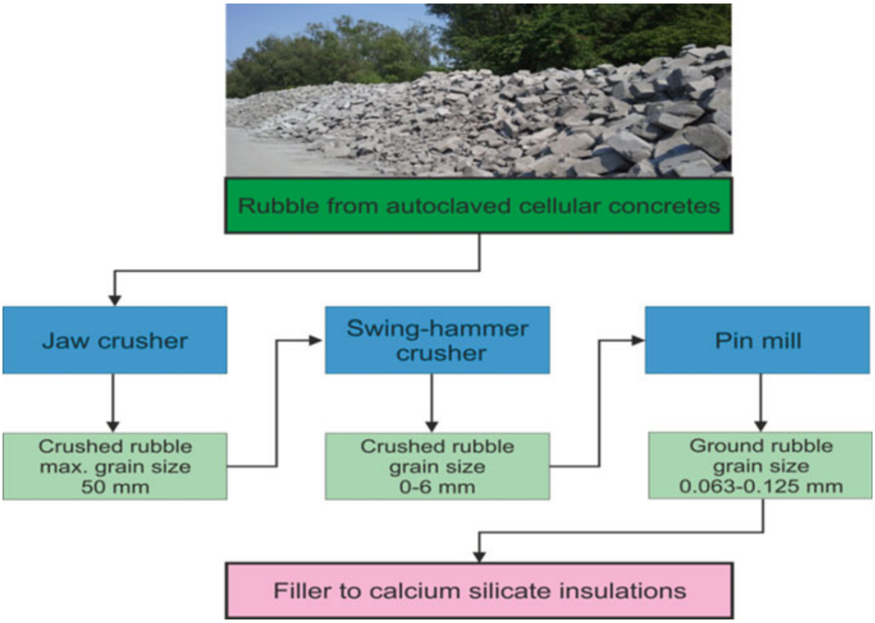

**Fig. 2** The treatment process of waste autoclaved cellular concrete to be used as filler in calcium silicate insulations

## 2.4 Tested Properties

The newly developed material of thermal insulation calcium silicate boards based on waste autoclaved cellular concrete with a maximum grain size of 0.125 mm prepared according to the scheduled recipes has been tested to: density according to CSN EN 1015-10 [12], compressive strength according to CSN EN 12390-3 [13], capillary absorption coefficient according to CSN EN 1015-18 [14], diffusion resistance coefficient, thermal conductivity coefficient λ and porosity.

The determination of the diffusion resistance coefficient was carried out using the wet bowl method. The test specimen was placed between two environments of the same temperature and of different relative humidities. A bowl of water was placed in the environment with a higher relative humidity of 95 % and it was weighed at the beginning of the test. There is a diffusion of water vapour through the material from the environment with the higher relative humidity into the environment of relative humidity below 50 %. The bowl with water was weighed again, including the increase of weight in the measured body, and Eq. (1) was used to calculate the equivalent diffusion thickness.

$$s_{dw} = \frac{\delta_o \cdot A \cdot \Delta t \cdot \Delta p}{\Delta m} \quad (1)$$

where

$\delta_0$ water vapor permeability of air (kg· Pa$^{-1}$· s$^{-1}$ ·m$^{-1}$);
$A$ specimen area (m$^2$);
$\Delta t$ time difference (s);
$\Delta p$ difference of partial pressures of water vapours (Pa);
$\Delta m$ change of weight (kg);

The thermal conductivity coefficient was determined using a measuring device ISOMET 2114 from the Applied Precision company. It is an instrument designed for direct measurements of the thermal conductivity coefficient of solid, loose or liquid materials. The measuring method is non-stationary and it is based on the analysis of the course of time dependence of the thermal response to a pulse of heat flux of the tested material. The heat flux is generated by a sensor of the device by means of scattered electrical resistor power in the material. The condition of achieving correct results is a conductive connection of the probe with the measured material. The measured value of the thermal conductivity coefficient can be read directly from the instrument in (W·m$^{-1}$·K$^{-1}$). The determination of the thermal conductivity coefficient was performed using cubes with the dimensions of 100 mm. After 28 days of aging, the sample was kept in a drying oven, where it was dried at 105 ± 1 °C for 48 h. The dried sample was then placed in an exicator and, after cooling, it was inserted into a propylene bag. The measurements were performed using a surface probe with the range of 0.04–2.00 W·m$^{-1}$·K$^{-1}$ placed in the middle of the test specimen area. The determination of the porosity was conducted on a dried test specimen with the dimensions of 100 × 100 × 100 mm, which was crushed and ground to a grain size of 0.06 mm. The resulting pulp of the sample was poured into a measuring cylinder and the value of the volume was subsequently read from the measuring cylinder scale. The difference between the above presented volumes provides an approximate total porosity in the material.

## 3 Results and Discussion

### 3.1 Proposed Experimental Recipes

5 experimental recipes have been prepared in order to verify the incorporation of finely ground waste autoclaved cellular concrete with the fraction of 0.063/0.125 mm as a source filler of calcium silicate cement composite, and their compositions are shown in Table 2.

Only Portland cement CEM I 42.5R was used as the binding agent in recipe 1. In order to save cement, this binding agent was replaced with fly ash K12 from Trebovic with amounts of 10 % of the weight (recipe 2), 20 % of the weight

**Table 2** Composition of experimental recipes of capillary active insulation

| Mixture components | Measuring unit | Recipe 1 | Recipe 2 | Recipe 3 | Recipe 4 | Recipe 5 |
|---|---|---|---|---|---|---|
| Aluminosilicate pulp (crushed 0.063–0.125 mm) | g | 261.5 | 261.5 | 261.5 | 261.5 | 261.5 |
| Water | g | 351 | 351 | 351 | 351 | 351 |
| Cement CEM I 42.5R | g | 60.0 | 54.0 | 48.0 | 42.0 | 36.0 |
| Lime Cl90 (6–9) min | g | 16.2 | 16.2 | 16.2 | 16.2 | 16.2 |
| Al powder 9500 $cm^2/g$ | g | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| Fly ash K12 Třebovice | g | – | 6.0 | 12.0 | 18.0 | 24.0 |

(recipe 3), 30 % of the weight (recipe 4) and 40 % of the weight (recipe 5). The mixtures for the production of lightweight concrete boards were prepared in laboratory conditions at the Faculty of Mining and Geology, VŠB—Technical University of Ostrava. The dosing of the individual components was performed according to weight. The mixing time of a mixture was 5 min. to obtain a compact (homogeneous) mixture, which was further applied in moulds with the volume of 8 $dm^3$.

## 3.2 Properties of Experimental Recipes

The results of the tested properties of experimental recipes are presented in Table 3.

Table 3 clearly shows that the compressive strength of the experimental recipes ranged from 0.38 to 0.82 $N \cdot mm^{-2}$, the density of hardened lightweight concrete in the dry state ranged from 347 to 369 $kg \cdot m^{-3}$, the capillary absorption coefficient was within the interval of 0.095–0.149 $kg \cdot m^{-2} \cdot s^{-0.5}$, the thermal conductivity coefficient $\lambda$ was within the range from 0.070 to 0.081 $W \cdot m^{-1} \cdot K^{-1}$ and the porosity was within the range from 78.27 to 81.01 %.

**Table 3** Results of the tests of physical and mechanical properties of experimental recipes

| Marking | Compressive strength ($N \cdot mm^2$) | Density ($kg \cdot m^{-3}$) | Coefficient of capillary absorption Aw ($kg \cdot m^{-2}. \cdot s^{-0.5}$) | Thermal conductiv. coefficient λ ($W \cdot m^{-1}. \cdot K^{-1}$) | Total porosity (%) |
|---|---|---|---|---|---|
| Recipe 1 | 0.82 | 347 | 0.095 | 0.070 | 81.01 |
| Recipe 2 | 0.75 | 357 | 0.128 | 0.073 | 78.31 |
| Recipe 3 | 0.64 | 357 | 0.121 | 0.073 | 78.27 |
| Recipe 4 | 0.52 | 357 | 0.149 | 0.081 | 78.39 |
| Recipe 5 | 0.38 | 369 | 0.145 | 0.079 | 75.23 |

### 3.3 The Course of Moisture Contained in the Evaluated Structure After the Installation of Calcium Silicate Boards During the Following 5 Years

Figure 3 presents curves characterizing the course of moisture in the substructure made from solid bricks that was redeveloped using the developed insulator with an indication of the specific recipes according to Table 2.

The curve in the lowest part of the graph describes the course of moisture in the original structure protected only by lime-cement plaster. The best results have been obtained by applying the board insulation with the thickness of 5 cm manufactured according to the experimental recipe no. 5, where the weight of moisture in the substructure increases from the initial upper limit value of 4.31 % to the value of 4.65 %. According to [15], the structure with the weight of moisture in the range of 3–5 % is included in the moisture category of “low”, which is why we rate the effect of this technical measure with very low impact on the increase of the built-in weight of moisture as functional. The difference in the weights of moisture corresponds to approximately 2 kg of water in 1 $m^3$ of construction. The purpose of this technical measure is to improve the transmission heat loss coefficient U = 1.38 $W/m^2 \cdot K$ to U = 0.74 $W/m^2 \cdot K$, i.e., by 46 %. On the other hand, if the same structure is insulated using an insulator based on expanded polystyrene with the thickness of 2.5 cm, thus obtaining the same heat resistance as in the case of recipe no. 5 with the thickness of 5 cm, 10 % of the weight of moisture in the structure is exceeded as early as during the third year. The amount of moisture is classified as very high and leads to moisture effects in the interior of the building. The lower part of the graph makes it possible to compare the course of moisture in the developed recipes with

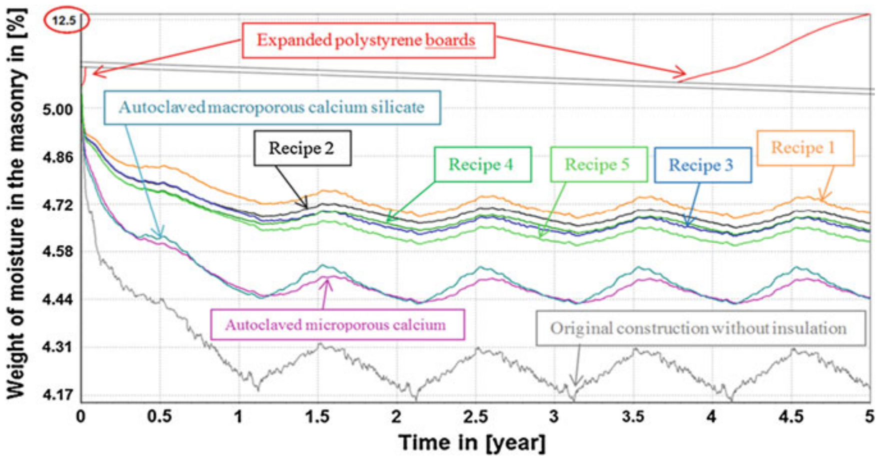

**Fig. 3** Output of a numerical simulation of the course of the weight of moisture in masonry substrates after application the insulating material

autoclaved materials, which are available on the market. These materials differ from each other in their pore structure, where one material is of macro-porous and other one of micro-porous character.

## 4 Conclusion

The presented results have demonstrated that modified rubble from autoclaved cellular concrete with the fraction of 0.063–0.125 mm is suitable as a new type of filler for the production of thermal insulation calcium silicate boards for the segment of energy redevelopment. It is also possible to say that all the developed recipes appear to be suitable for use in the area of energy redevelopment of buildings with damaged waterproofing. The new feature of the research lies in the determination of the recipes for the production of thermal insulation boards based on waste cellular concrete pulp, omitting the autoclave process. The resulting board retains the good properties approaching autoclaved materials, i.e., it can naturally remove moisture from the structure and increase the thermal resistance of the building envelope, while improving the quality of the waste materials.

**Acknowledgments** Article has been done in connection with projects:

SGS reg. no. SP2014/9 Utilization of industrial waste containing aluminosilicate for material structures with defined surface.

Institute of clean technologies for mining and utilization of raw materials for energy use—Sustainability program, reg. no. LO1406 supported by Research and Development for Innovations Operational Programme financed by Structural Founds of Europe Union and from the means of state budget of the Czech Republic.

IT4Innovations Centre of Excellence project, reg. no. CZ.1.05/1.1.00/02.0070 supported by Operational Programme Research and Development for Innovations funded by Structural Funds of the European Union and state budget of the Czech Republic.

RMTVC No. LO1203.

## References

1. Grunewald J, Ruisinger U, Häupl P (2006) The Rijksmuseum Amsterdam—hygrothermal analysis and dimensioning of thermal insulation. In: 3rd international building physics conference—research in building physics and building engineering, Canada
2. Ruochong Y, Jipeng Z, Zhishen W, Zhiren W, Min L, Changhai P (2011) Thermal insulation and strength of autoclaved light concrete. J Wuh Uni Tech Mater Sci Edn. doi:10.1007/s11595-011-0184-6
3. Ruisinger U, Grunewald J (2009) Title of preprint. http://tu-dresden.de/die_tu_dresden/fakultaeten/fakultaet_architektur/ibk/research/researchprojects/2006_Feuchteatlas/Feuchteatlas.pdf. Accessed 22 April 2009
4. Václavik V, Dvorský T, Dirner V, Daxner J, Šťastný M (2012) Polyurethane foam as aggregate for thermal insulating mortars and lightweight concrete. Tehnicki Vjesnik 19 (3):665–672

5. Václavik V, Valíček J, Dvorský T, Hryniewicz T, Rokosz K, Harničárová M, Kušnerová M, Daxner J (2012) A method of utilization of polyurethane after the end of its life cycle. Rocz Ochrona Srodowiska 14:96–106
6. Scheffler G, Grunewald J (2003) Material development and optimisation supported by numerical simulation for a capillary-active inside insulation materiál. In: 2nd international conference on building physics, Antwerp
7. Stevulova N, Kidalova L, Cigasova J, Junak J, Sicakova A, Terpakova E (2013) Lightweight composites containing hemp hurds. In: 6th international conference on concrete and concrete structures 2013, Zilina
8. Cigasova J, Stevuvola N, Sicakova A, Junak J (2013) Some aspects of lightweight composites durability. Chem Eng Trans 32:1615–1620. doi:10.3303/CET1332270
9. Junak J, Stevulova N (2011) Potential of selected industrial wastes in civil engineering applications. In: 1st international multidisciplinary scientific geoconference and EXPO, Varna, 20–25 June 2011
10. CSN EN ISO 13788 (2013) Hygrothermal performance of building components and building elements—internal surface temperature to avoid critical surface humidity and interstitial condensation—calculation methods, (Czech normalization institute, Prague, 2013)
11. CSN EN 12831 (2005) Heating systems in buildings—method for calculation of the design heat load, (Czech normalization institute, Prague, 2005)
12. CSN EN 1015-10 (2000) Methods of test for mortar for masonry—part 10: determination of dry bulk density of hardened mortar, (Czech normalization institute, Prague, 2000)
13. CSN EN 12390-3 (2009) Testing hardened concrete—part 3: compressive strength of test specimens, (Czech normalization institute, Prague, 2009)
14. CSN EN 1015-18 (2003) Methods of test for mortar for masonry—part 18: determination of water absorption coefficient due to capillarity action of hardened mortar, (Czech normalization institute, Prague, 2003)
15. CSN P 73 0610 (2000) Waterproofing of buildings—the rehabilitation of damp masonry and additional protection of buildings against ground moisture and against atmospheric water—basic provision, (Czech normalization institute, Prague, 2000)