Thermal-Humidity Parameters of 3D Printed Wall

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Abstract. The purpose of the external walls is to secure the internal microclimate of the building. External walls not only must have proper strength and durability but also prevent heat escape, overheating during summer, protect from noise and increase of humidity. The main parameter that describes the thermal properties of external walls is the heat transmission coefficient $U$ [W/(m²·K)] determined in accordance with EN ISO 6946:2008. One of most recent technology of constructing walls is the additive manufacturing. The aim of the study is to determine the thermal properties of wall printed with use of High Performance Concrete and insulated with mineral wool. The study determines the temperature and vapour pressure inside the wall and presents calculations of thermal factor. The study compares the characteristics of traditional walls with 3D printed elements. The tests have shown that insulating printed structures does not pose any difficulty. Corrugated structure of printed walls increases the adhesion of adhesive mortar. Proposed tests are the starting point for further studies on the thermal-humidity of 3D printed structures. The main goal is to propose a solution for cheap, efficient insulation technology for 3D printed structures.

1. Introduction
Rapid development of the large-size 3D printing for civil engineering allowed to implement the technology in real life [1–7]. Currently many research teams have taken interest in the rheological properties of the fresh mix for 3D printing. These scholars test various mix characteristics such as the workability, extrudability, open time and buildability [1,7,8]. Issues concerning the design of printers including the precision, control, shape of the nozzle and printing path are also studied [1,7,9]. However, except of mechanical and rheological parameters printed wall have to meet the requirements of the building code. The code requires that the wall must limit the heat escape in winter, prevent overheating in summer, protect from excessive noise and moisture. In case of High-Performance Concretes (with compressive strength of more than 50 MPa) used for 3D printing [10–16] the thermal aspects are a key issue. The basic parameter for describing the thermal properties of external wall is the heat transfer coefficient $U$ [W/(m²·K)] defined in EN ISO 6946:2008.

The heat-transfer issue in 3D printed walls have been studied by several research teams [9,12,17]. The scientists [17] noticed that the concrete mix for 3D printing can be modified by adding Graded Polystyrene Aggregate (GPA). They have prepared the optimization model for heat transfer in analyzed structures. Other study [12] conducted by the same research team introduced an analysis of the influence of shape of the printed structure on the heat transfer. They have proved the correlation between the shape...
of printed structures and thermal properties. The researchers additionally point to the issue of free spaces within the structure, which can be utilized as additional insulation. The mix introduced in [12] is composed of Ordinary Portland Cement CEM I 52.5N (30-40%w), crystalline silica (40-50%w), silica fume (10%w) and limestone filler (10%w). The mix had water/(cement+sand) ratio of 0.1 and did not involve the GPA as in [17]. The compressive strength obtained for the mix was 120 MPa. Other research team [9] focused on the thermal characteristics of the printed walls, by preparing special holes for thermal insulation. Additionally, the scientists notices that the sinusoidal 3D shape of the shell structure allowed to reduce the heat loss. However, in all of the aforementioned studies on the thermal characteristics, the thermal conductivity (λ) is not determined for particular printed elements.

The main aim of the study was to prove that it is possible to design and produce an external concrete wall using additive printing that meets the thermal-humidity requirements as for standard type of walls (insulated brick walls, insulated concrete walls or insulated stud walls). The paper presents the designs and analyses of two traditional walls and one 3D printed wall and the comparison of thermal-humidity characteristics. The 3D printed wall was designed to have thermal-humidity parameters similar to the standard walls. The thermal conductivity (λ) was determined with stationary method for each individual component of the designed wall. The temperature distribution and water vapor distribution in designed walls was prepared using the computer models. The analysis involved climatic conditions for different locations in Europe. The real model of the wall was prepared.

2. Materials and methods
For the study purposes two standard walls were prepared. Fig. 1a) presents a traditional 18 cm concrete wall, while Fig. 1b) a ceramic block wall. Both walls were insulated with mineral wool.

Before the thermal-humidity tests for assumed wall design, the authors determined the thermal characteristics of individual wall components. Three different construction materials were tested: mineral wool for outer insulation layer, polyurethane foam (that can be used as an insulation of spaces between 3D printed wall layers) and concrete. The concrete used in the study was designed based on the research from Loughborough University [8,18]. The concrete mix meets the requirements for 3D printing. The concrete mixes for 3D printing have to exhibit proper rheological properties, low shrinkage [19–21], and high rate of strength development in the early stages [22,23].

The mix was composed of 830 kg/m³ of binder, including 70% of cement, 10% of silica fume and 20% of fly ash. The water/binder ratio was set to w/b=0.23. The rheological properties were obtained by adding 1% (of binder mass) of superplasticizer. The density of the fresh mix was determined as 2168
kg/m³ (CoV=0.24%, n=3). Preliminary tests determined the 28-day compressive strength of 113.7 MPa (CoV=1.13%, n=4) on 100x100x100 mm samples.

The thermal characteristics of used construction materials were tested with stationary method using plate apparatus. The research was conducted on dry mass samples with thickness of at least 4 cm. The surface of the concrete sample was evaluated in terms of flatness and parallelism to ensure proper application of the probe. Materials were then placed in the apparatus and tested for thermal characteristics as seen in Figure 2. Tables 1-3 present the measurements for three basic construction materials.

![Figure 2](Image) The stationary method apparatus: a) measurement of mineral wool, b) measurement of concrete

| Measurement | d [m] | Heating plate [°C] | Cooling plate [°C] | Q [W] | R [m²K/W] | λ [W/(m·K)] |
|-------------|-------|--------------------|--------------------|-------|-----------|-------------|
| 1           | 0.0482| 25.01              | 5.82               | 0.2733| 1.580     | 0.0305      |
| 2           | 0.0482| 25.00              | 5.81               | 0.2745| 1.573     | 0.0306      |
| 3           | 0.0482| 25.00              | 5.81               | 0.2764| 1.562     | 0.0308      |
| 4           | 0.0482| 30.00              | 10.67              | 0.2913| 1.493     | 0.0323      |
| 5           | 0.0482| 30.00              | 10.67              | 0.2895| 1.502     | 0.0321      |
| 6           | 0.0482| 30.00              | 10.66              | 0.2909| 1.496     | 0.0322      |
| 7           | 0.0482| 35.00              | 15.58              | 0.3022| 1.446     | 0.0333      |
| 8           | 0.0482| 35.00              | 15.57              | 0.3025| 1.445     | 0.0333      |

Average: 0.2893 1.5043 0.0321

| Measurement | d [m] | Heating plate [°C] | Cooling plate [°C] | Q [W] | R [m²K/W] | λ [W/(m·K)] |
|-------------|-------|--------------------|--------------------|-------|-----------|-------------|
| 1           | 0.0552| 25.03              | 5.78               | 0.2835| 1.528     | 0.0361      |
| 2           | 0.0552| 25.01              | 5.78               | 0.2778| 1.558     | 0.0355      |
| 3           | 0.0552| 25.03              | 5.78               | 0.2799| 1.547     | 0.0357      |
| 4           | 0.0552| 30.02              | 10.68              | 0.3088| 1.409     | 0.0392      |
| 5           | 0.0552| 30.00              | 10.68              | 0.3044| 1.428     | 0.0387      |
| 6           | 0.0552| 30.01              | 10.68              | 0.3026| 1.437     | 0.0384      |
| 7           | 0.0552| 35.03              | 15.57              | 0.3271| 1.339     | 0.0413      |
| 8           | 0.0552| 35.02              | 15.58              | 0.3124| 1.400     | 0.0394      |

Average: 0.3026 1.442 0.0384
Table 3. The thermal tests results for high-performance concrete obtained with stationary method

| Measurement | d [m] | Heating plate [°C] | Cooling plate [°C] | Q [W] | R [m²K/W] | λ [W/(m·K)] |
|-------------|-------|--------------------|--------------------|-------|-----------|-------------|
| 1           | 0.0428| 24.90              | 7.57               | 10.4326| 0.037     | 1.4599      |
| 2           | 0.0428| 24.99              | 7.59               | 10.5107| 0.037     | 1.4499      |
| 3           | 0.0428| 25.00              | 7.59               | 10.5280| 0.037     | 1.5111      |
| 4           | 0.0428| 30.02              | 12.41              | 10.6602| 0.037     | 1.523       |
| 5           | 0.0428| 30.00              | 12.41              | 10.6445| 0.037     | 1.5199      |
| 6           | 0.0428| 30.00              | 12.41              | 10.6408| 0.037     | 1.515       |
| 7           | 0.0428| 35.03              | 17.28              | 10.7662| 0.037     | 1.546       |
| 8           | 0.0428| 35.00              | 17.27              | 10.7739| 0.037     | 1.567       |

Average: 10.6362 0.037 1.1522

3. Results and Simulation
The results of heat transfer calculations for standard walls are presented in Table 4. Based on acquired information and conducted thermal-humidity simulations, the geometry of 3D printed wall was proposed. The wall consisted of two layers of HPC with thickness of 3 cm and 14 cm of space between. The inner space was filled with a polyurethane foam. The outer layer was insulated with 5 cm of mineral wool. The whole segment was then covered with gypsum plaster from the inner side and mineral plaster from the outer side. The cross section of the layers is visible in Figure 3. The heat transfer coefficient $U$ of produced wall was 0.18 W/(m²K). As seen in Table 4, the heat transfer coefficient of designed wall is approximate to the traditional walls.

![Figure 3. Section of printed wall](image)

For designed wall the analysis of temperature distribution and water vapour were performed. For calculations, the internal temperature was assumed as 20°C, while the external temperature was assumed as in the 1st climatic zone in Poland: -16°C. Thermal resistances on the external and internal surfaces was assumed as 0.04 m²K/W and 0.13 m²K/W respectively. To calculate the thermal factor the resistance $R_{si}$ was set to 0.25 m²K/W. To calculate the water vapour distribution the authors assumed high level of humidity: 60% inside and 90% outside. Figure 4 presents the temperature distribution for three contemplated walls. Figure 5 shows water vapour distribution in proposed walls.
Table 4. The heat transfer coefficients for chosen wall types

|                     | Concrete wall d = 0.34 m | Brick wall d = 0.40 m | 3D printed wall d = 0.26 m |
|---------------------|--------------------------|-----------------------|---------------------------|
| Rsi [m]             | -                        | -                     | -                         |
| \( \lambda \) [W/(m\cdot K)] | 0.008 0.008 0.18 0.150 | 0.008 0.008 0.03 0.050 | 0.008 0.008 0.03 0.050 |
| R [m\cdot K/W]     | 0.400 0.400 1.152 1.152 | 0.400 0.400 1.152 1.152 | 0.400 0.400 1.152 1.152 |
| U [W/(m²\cdot K)]  | 0.02 0.02 0.16 0.16 | 0.02 0.02 0.16 0.16 | 0.02 0.02 0.16 0.16 |

*Coefficient units: \( \lambda \) [W/(m\cdot K)]; R [m\cdot K/W]

Figure 4. The temperature distribution for proposed walls:

a) concrete wall; b) brick wall; c) 3D printed wall

Figures 4a) and 4b) present the temperature distribution in traditional walls. The 0°C isotherm is located in the insulation of the external wall which is desired. Figure 4c) presents the temperature distribution in the 3D printed wall. Thanks to additional insulation of mineral wool it was possible to transfer the 0°C isotherm more to the external surface. Almost whole internal layer of insulation is secured from freezing.
Figure 5. Distribution of water vapor pressure in the proposed walls: a) concrete wall; b) brick wall; c) 3D printed wall.

Figures 5a)-5c) present the water vapor distribution for conditions of the 1st climatic zone of Poland. For the concrete wall (Fig. 5a) and masonry wall (Fig. 5b) the graphs of the real water vapor pressure and equilibrium water vapor pressure cross in a close proximity to external surface, which denies the occurrence of the condensation of water vapor inside the wall. For 3D printed concrete wall there was a significant improvement, the graphs do not cross. Even with adverse thermal-humidity conditions assumed for the simulation it is impossible for water vapor to condense inside the tested wall.

A summary of the results of the thermal factor is visible in table 5. The values $f_{Rsi,min}$ were calculated for data from meteorological stations from five different places in Europe. Proposed wall meets the requirements of the EN ISO-10211 for all of those places and every months, resulting in impossibility of water vapor condensation in the internal corner of the wall.

Table 5. The climate data and the results for temperature factor

| Mont | Warszawa | Madrid | Edinburgh | Oslo |
|------|----------|--------|-----------|------|
| h    | $\theta_e$ | $\phi_e$ | $f_{Rsi,min}$ | $f_{Rsi}$ | $\theta_e$ | $\phi_e$ | $f_{Rsi,min}$ | $f_{Rsi}$ | $\theta_e$ | $\phi_e$ | $f_{Rsi,min}$ | $f_{Rsi}$ |
| I    | -3.3     | 0.8   | 0.746    |        | 6.1    | 0.71  | 0.576    |        | 3.6    | 0.8   | 0.722    |        | -4.3   | 0.90  | 0.751    |
| II   | -2.1     | 0.8   | 0.755    |        | 7.9    | 0.65  | 0.456    |        | 3.9    | 0.8   | 0.712    |        | -3.1   | 0.85  | 0.747    |
| III  | 1.9      | 0.7   | 0.690    |        | 10.7   | 0.62  | 0.266    |        | 5.5    | 0.8   | 0.680    |        | 0.7    | 0.80  | 0.747    |
| IV   | 7.7      | 0.7   | 0.527    |        | 12.3   | 0.65  | 0.211    |        | 7.3    | 0.7   | 0.578    |        | 6.3    | 0.84  | 0.674    |
| V    | 13.5     | 0.7   | 0.298    |        | 16.1   | 0.62  | -        |        | 10.1   | 0.7   | 0.541    |        | 10.8   | 0.75  | 0.477    |
| VI   | 16.7     | 0.6   | -        | 0.91    | 21.0   | 0.51  | -        |        | 13.8   | 0.7   | 0.663    | 0.91    | 15.2   | 0.67  | -        |
| VII  | 18.0     | 0.6   | -        |        | 24.8   | 0.41  | -        |        | 15.0   | 0.8   | 0.506    | 16.4    | 0.70  | -        |
| VIII | 17.3     | 0.7   | -        |        | 24.4   | 0.37  | -        |        | 14.8   | 0.8   | 0.540    | 15.2    | 0.72  | 0.171    |
| IX   | 13.1     | 0.8   | 0.532    |        | 20.5   | 0.35  | -        |        | 12.5   | 0.8   | 0.541    | 10.8    | 0.79  | 0.540    |
| X    | 8.2      | 0.8   | 0.637    |        | 14.6   | 0.45  | -        |        | 9.4    | 0.8   | 0.643    | 4.5     | 0.70  | 0.614    |
| XI   | 3.2      | 0.8   | 0.723    |        | 9.7    | 0.78  | 0.551    |        | 5.9    | 0.8   | 0.716    | -0.2    | 0.82  | 0.764    |
| XII  | -0.9     | 0.8   | 0.756    |        | 7.2    | 0.82  | 0.647    |        | 4.2    | 0.8   | 0.730    | -3.8    | 0.92  | 0.759    |

The temperature factor $f_{Rsi}$ is calculated in accordance with EN ISO 10211 for wall corner and data from [25]. The calculation model was prepared in accordance with EN ISO 10211, The distance between the corner and adiabatic sections was equal to 1.5 m. The thermal resistances on the surface of the wall were set to 0.25 (m²K)/W [24]. The temperature distribution in the tested wall is presented in figure 6. Based on the minimal temperature in the corner $\theta_{di}$ the temperature factor was calculated with the formula (1):

$$f_{Rsi} = \frac{\eta_{di} - \theta_e}{\theta_{di} - \theta_e}$$  \hspace{1cm} (1)

This method for the calculation of the $f_{Rsi}$ more precisely represent the actual conditions the wall is exposed to.

Performed analysis, simulations and design allowed to produce a wall using additive manufacturing technology. The first stage involved printing multi-layer closed structure (figure 7a)) using Cartesian
robot with pumping module. Mix preparation and printing were made in a laboratory at temperature of 20°C (± 2°) and relative humidity of RH=55% (± 5%). After the concrete hardened the internal space of the structure was filled with polyurethane foam. The wall was then insulated from one side and plastered. The cross section of the prepared wall is visible in figure 7b).

![Figure 6. The temperature distribution for the tested wall corner](image)

**Figure 6.** The temperature distribution for the tested wall corner

![Figure 7. a) Printing process b) Examples of printed walls](image)

**Figure 7.** a) Printing process b) Examples of printed walls

### 4. Conclusion

Thanks to determination of the thermal conductivity coefficient $\lambda$, we acquired the data necessary to perform the analyses, simulation and designing of the 3D printed wall.

Compared to traditional walls the 3D printed wall has lower thickness while meeting the same requirements. The 3D printed wall is by 8 cm and by 14 cm less thick than traditional concrete and masonry wall respectively. Figure 4 shows that the 3D printed wall has the 0°C isotherm in a desired place, distant to the external environment, even with lower thickness. The analysis presented in the figure 5 showed that the condensation of the water vapor will not occur. For the 3D printed wall the real
and equilibrium vapor pressure graph do not cross, thus the wall provide better safety from condensation of the vapor in comparison to traditional walls. The water vapor pressure distribution for the 3D printed wall is more beneficial than in traditional walls (figure 5 a, figure 5 b).

Analysing the thermal conductivity coefficient determined for the concrete, it should be noted that the value can differ for various types of concretes. Researchers [12] assumed the value of $\lambda$ as $1 \text{ W/(m } \cdot \text{ K)}$ which is not always correct. Concretes with various additives can have lower conductivity. For example, lightweight concretes or aerated concrete can have the $\lambda$ of $0.5 \text{ W/(m } \cdot \text{ K)}$ [26,27].

Figure 6 presents the evaluation of linear thermal bridge occurring in the corner of two outer walls. The analyzed temperature distribution in the section suggests that this sample connection is correctly done. The linear thermal bridge does not occur – the temperature in the corner decreases. In case of elevated relative humidity above 60% the occurrence of linear thermal bridge would result in the condensation on the surface, resulting in the development of fungus and mould.

Obtained results proved the hypothesis and showed that it is possible to design and produce external wall using additive manufacturing. The 3D printed wall meets all the same thermal-humidity requirements as traditional walls. Based on the calculations it can be said that the wall has good thermal-humidity characteristics, while being less thick than traditional walls. Those types of walls can be used under atmospheric conditions assumed in the study.

The following stage of the research will include experimental determination of thermal-humidity characteristics of the 3D printed wall. The study will allow to determine the economical and efficient method of insulating the 3D printed walls.

References

[1] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, "Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing," Virtual and Physical Prototyping, vol. 11 (3), pp. 209–25, 2016.
[2] B. Khoshnevis, D. Hwang, K.-T. Yao, Zhenghao Y., "Mega-scale fabrication by contour crafting," Int. J. Industrial and Systems Engineering, vol. 1 (3, 2006).
[3] T. Wangler, E. Lloret, L. Reiter, N. Hack, F. Gramazio, M. Kohler et al., "Digital Concrete: Opportunities and Challenges," RILEM Letters, vol. 1), pp. 67–75, 2016.
[4] D. Delgado Camacho, P. Clayton, W. J. O'Brien, C. Seepersad, M. Juenger, R. Ferron et al., "Applications of additive manufacturing in the construction industry – A forward-looking review," Automation in Construction, vol. 89), pp. 110–9, 2018.
[5] E. Lloret, A. R. Shahab, M. Linus, R. J. Flatt, F. Gramazio, M. Kohler et al., "Complex concrete structures," Computer-Aided Design, vol. 60), pp. 40–9, 2015.
[6] B. Nematollahi, M. Xia, J. Sanjayan, "Current Progress of 3D Concrete Printing Technologies, 2017.
[7] R. Duballet, O. Baverel, J. Dirrenberger, "Classification of building systems for concrete 3D printing," Automation in Construction, vol. 83), pp. 247–58, 2017.
[8] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, R. Law, A.G.F. Gibb et al., "Hardened properties of high-performance printing concrete," Cement and Concrete Research, vol. 42 (3), pp. 558–66, 2012.
[9] S. Lim, R. A. Buswell, T. Le T, S. A. Austin, A. G. F. Gibb, T. Thorpe, "Developments in construction-scale additive manufacturing processes," Automation in Construction, vol. 21), pp. 262–8, 2012.
[10] A. Kazemian, X. Yuan, E. Cochran, B. Khoshnevis, "Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture," Construction and Building Materials, vol. 145), pp. 639–47, 2017.
[11] A. Perrot, D. Rangeard, A. Pierre, "Structural built-up of cement-based materials used for 3D-printing extrusion techniques," Mater Struct, vol. 49 (4), pp. 1213–20, 2016.
[12] C. Gosselin, R. Duballet, P. Roux, N. Gaudillièrre, J. Dirrenberger, P. Morel, "Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders," Materials & Design, vol. 100), pp. 102–9, 2016.

[13] J. Nylund, A. Järf, K. Kekäle, J. Rönnskog, F. Al-Neshawy, P. Kiviluoma et al., "Implementation of contour crafting system to a 3-dimensional concrete printer," In: 10th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING", 2015.

[14] Z. Malaeb, H. Hachem, A. Tourbah, T. Maalouf, El Zarwi N., Hamzeh F., "3d concrete printing: Machine and mix design," International Journal of Civil Engineering and Technology (IJCIET), vol. 6 (6), pp. 14–22, 2015.

[15] V. N. Nerella, M. Krause, M. Näther, V. Mechtcherine, "Studying printability of fresh concrete for formwork free Concrete on-site 3D Printing technology (CONPrint3D)," In: 25th Conference on Rheology of Building Materials, 2016.

[16] G. Ma, Z. Li, L. Wang, "Printable properties of cementitious material containing copper tailings for extrusion based 3D printing," Construction and Building Materials, vol. 162), pp. 613–27, 2018.

[17] R. Duballet, C. Gosselin, P. Roux, "Additive Manufacturing and Multi-Objective Optimization of Graded Polystyrene Aggregate Concrete Structures," In: Thomsen MR, Tamke M, Gengnagel C, Faircloth B, Scheurer F, editors. Modelling Behaviour: Design Modelling Symposium 2015. Cham: Springer International Publishing, p. 225–235, 2015.

[18] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, T. Thorpe, "Mix design and fresh properties for high-performance," Materials and Structures, vol. 45), pp. 1221–32, 2012.

[19] M. Kaszynska, A. Zielinski, "Effect of Lightweight Aggregate on Minimizing Autogenous Shrinkage in Self-Consolidating Concrete," Procedia Engineering, vol. 108), pp. 608–15, 2015.

[20] M. Kaszynska, A. Zielinski, "Influence of mixture composition on shrinkage cracking of lightweight self-consolidating concrete," In: Brandt A.M., Olek J, Glinicki MA, Leung CKY, editors. BRITTLE MATRIX COMPOSITES 10: 10th International Symposium on Brittle Matrix Composites (BMC). Warsaw, Poland, 2012.

[21] M. Kaszynska, S. Skibicki, "Solution to hydration heat problem in bridge abutments and piers," In: Bittencourt TN, Frangopol DM, Beck AT, editors. 8th International Conference on Bridge Maintenance, Safety and Management (IABMAS): MAINTENANCE, MONITORING, SAFETY, RISK AND RESILIENCE OF BRIDGES AND BRIDGE NETWORKS, 2016.

[22] M. Kaszynska, S. Skibicki, "Influence of Eco-Friendly Mineral Additives on Early Age Compressive Strength and Temperature Development of High-Performance Concrete," IOP Conference Series: Earth and Environmental Science, vol. 95 (4), pp. 42060, 2017.

[23] S. Skibicki, "Optimization of Cost of Building with Concrete Slabs Based on the Maturity Method," IOP Conf. Ser.: Mater. Sci. Eng., vol. 245 (2), pp. 22061, 2017.

[24] PN-EN ISO 10211:2007. Thermal bridges in building construction. Heat flows and surface temperatures. Detailed calculations.

[25] A. Stolarska, J. Strzałkowski, "Modelling of Edge Insulation Depending on Boundary Conditions for the Ground Level," IOP Conf. Ser.: Mater. Sci. Eng., vol. 245), pp. 42003, 2017.

[26] J. Strzałkowski, H. Garbalińska, "Thermal and strength properties of lightweight concretes with the addition of aerogel particles," Advances in Cement Research, vol. 28 (9), pp. 567–75, 2016.

[27] J. Strzałkowski, H. Garbalińska, "Porosimetric, Thermal and Strength Tests of Aerated and Nonaerated Concretes," IOP Conf. Ser.: Mater. Sci. Eng., vol. 245), pp. 32017, 2017.