

The environmental impacts of foamed concrete production and exploitation

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Abstract. This paper presents a study focusing on the environmental impacts of foamed concrete production and exploitation. CO₂ emissions are very important factor for describing durability and sustainability of any building material and its life cycle. The building sector is one of the largest energy-consuming sectors in the world. In this study CO₂ emissions are evaluated with regard to three types of energy resources (gas, coal and eco-friendly fuel). The related savings on raw materials are up to 120 t of water per 1000 t of traditionally mixed foamed concrete and up to 350 t of sand per 1000 t of foamed concrete produced with intensive mixing technology. In addition, total reduction of CO₂ emissions (up to 60 t per 1000 m³ of material) and total energy saving from introduction of foamed concrete production (depending on the type of fuel) were calculated. In order to analyze the conditions of exploitation, both thermal conductivity and thickness of wall was determined. All obtained and calculated results were compared to those of the commercially produced autoclaved aerated concrete.

1. Introduction

Buildings constitute a significant part of the energy consumption in the world [1]. In accordance with data from the U.S. Green Building Council [2], building sector accounts for 40% in average from all worlds' use of energy in average. Environmental impact of the factories involves CO₂ emissions, air and water pollution, because carbon and hydrogen are widely used in fossil fuels [3].

The European Union has a number of official documents and guidelines aimed at reducing CO₂ emissions up to 20% by 2020 [4], up to 40% by 2030 [5] and the energy performance of Buildings Directive requires all new buildings to be nearly zero-energy by the end of 2020 [4].

In many cases, production process of the building materials is non-sustainable. Life cycle energy analysis of buildings begins from the production phase of building materials and ends with the demolition of structure. In this phase the embodied energy refers to the raw material mining/quarrying, building material production and transportation to the building site. This type of energy divides into two parts: initial and recurred [6]. The embodied energy is connected with construction process of the whole building – starting from all materials used and ending with its renovation and technical installations. The operating energy in its turn is related to the maintenance of the building, namely, its heating, ventilation, and other processes in order to ensure comfortable indoor climate [7]. The aim of this study is to examine the environmental impact of traditionally mixed foamed concrete and the



foamed concrete produced with intensive mixing technology. The obtained results are compared to those of the commercially produced autoclaved aerated concrete.

2. General information about porous concrete

Foamed concrete is a traditional building material; cement, sand and foam (obtained by foaming additive) are the basic components used in the production process of foamed concrete. Technological methods of foamed concrete date back to the ancient times, when eggs were added to the masonry mortar (aimed at improving its properties). They acted as a protein additive and served like a surface active agent – air bubbles are involved in a mixture, improving its workability and frost resistance. Preparation of foamed concrete took place in the first half of the 20th century, when in 1911 a Danish engineer Bayer first offered to generate foamed concrete by mixing the foam with mineral components [8]. Industrial production of foamed concrete was launched in Germany and Denmark in 1930s.

Cellular or porous concrete belongs to a group of lightweight concrete with a density less than 2000 kg/m³ [9]. There are several kinds of porous concrete, depending on binders, silicate components, manufacturing technology used, etc.: foamed concrete, autoclaved aerated concrete, foamed silicate, etc. [10]. Simplified classification of mineral-bound foams is shown in figure 1.

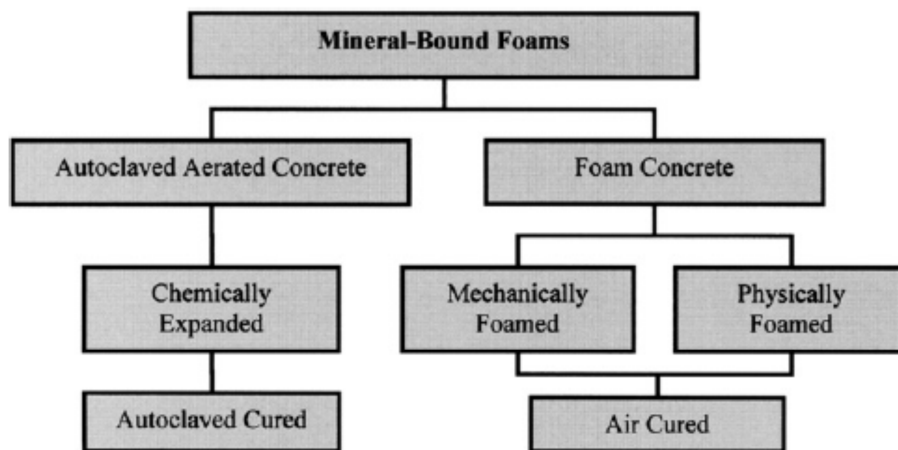


Figure 1. Classification of mineral-bound foams according to the manufacturing method. [11]

Autoclaved aerated concrete is a cellular concrete, where finely ground sand, calcium oxide, cement, water, gas-foaming additives and high-pressure vapor are used during its manufacturing process. The porous structure of aerated concrete is obtained with the chemical reaction between aluminum powder and the calcium hydroxide (See figure 1 for the chemical method of porous concrete manufacturing) (pores make about 85 % of the volume of aerated concrete) [12].

The cellular structure of foamed concrete is obtained with both mechanical and physical means. With regard to the first, foaming agent is added to a mortar. Already in 1925, two methods in the manufacturing process of foamed concrete were used: mixing of the pre-prepared foam with cement dough and adding of foaming agent in cement dough during the mixing. Nowadays these methods are known as 'pre-foaming' and 'mixed foaming' technologies [13]. The second method demands use of intensive mixing with turbulent mixers, providing simultaneous mixing and porisation.

2.1. The role of curing conditions

The ultimate strength of cellular concrete is largely influenced by curing condition of the concrete. By maximizing use of the silicate binder and using a special heat treatment (temperature > 170°C and pressure about 12 atm), it is possible to obtain autoclaved aerated concrete with greater values of compressive strength compared to those of the foamed concrete. However, the heat treatment is an

energy-intensive system and it requires use of massive equipment. Another advantage of autoclaved aerated concrete is lower shrinkage rate, but it is important to remember that the producing technology of autoclaved aerated concrete is complex and cannot be realized in situ (as it is possible with foamed concrete).

Nowadays the autoclave technology is widely used in the manufacturing of silicate aerated concrete blocks (for example, companies 'Aeroc', 'Ytong', etc.). Local materials, such as sand and lime, are used during the producing process. In 1930s there was a factory 'Siporex' in Latvia producing aerated concrete blocks with the Swedish technology. The first houses using aerated concrete blocks were built in 1939, and they are still well-preserved [12].

2.2. The role of mixing technologies

To obtain foamed concrete with high values of strength and good exploitation properties, several mixing technologies are used today:

- 1) Classical method of two stages – previously prepared foam is mixed with cement slurry. The method is called 'pre-foaming' technology.
- 2) Mineralization method of dry foam – previously prepared foam is mixed with dry components.
- 3) Barotechnology – cement, silicate component, water and foaming agent are mixed using hermetic mixer under pressure. The additional volume of air is involved in the mixture during this mixing procedure. When the level of pressure is lower, the volume of the mixture increases.
- 4) Aeration method – mixing of cement sand mortar with a foaming agent using an intensive mixer. The mixing, porisation and activation proceed simultaneously. The method is called 'mixed foaming' technology.
- 5) The method of turbulence and cavitation – the intensive high-speed mixers are used, as a result – homogeneity of the fresh mixture is improved, as well as the physical and mechanical properties of hardened material.

Modern technologies of foamed concrete production involve the use of intensive mixing methods with the opportunity of obtaining stable mixtures and effective use of binder components. As a result, higher values of strength or minimization of density can be achieved (providing lower thermal conductivity). The intensive mixers include the effect of shear, greater capacity and high mixing speed – 2 m/s using traditional mixers and more than 5 m/s using mixers with the effect of turbulence [14].

3. Materials and methods

Traditionally such components as sand mortar and foaming agent are used in the production of foamed concrete cement.

The sand used is usually natural, dried and finely ground. Sand in the foamed concrete has two functions – it is useful as a filler and as a component generating foam.

One of the most important tasks in the production process of foamed concrete is to obtain stable and flexible foam. Surface active agent (foaming agent) determines the foaming ability and is a key component of foamed concrete, as the properties of foamed concrete depend on the quality of obtainable foam. Foaming agents are classified according to their origin – synthetic foam and protein or organic foam. The foam with organic origin is produced using animal proteins (bones, horns, blood, etc.) and the size of foam diameter is 0,2...0,8 mm. The foam with synthetic origin usually is more stable and persistent, the foam size ranges 0,1...0,4 mm [8, 15].

To ensure the acquisition of high performance foamed concrete, the basic components are mixed by a variety of fillers and additives, such as microsilica, metakaolin, polymer fibers, nano additives, etc. The use of additive components ensures forming of dense cement stone microstructure, reducing the fragility and shrinkage of foamed concrete, increasing tensile strength, etc.

For example, the use of pozzolanic additives (microsilica or silica fume and metakaolin) improves properties of foamed concrete: microsilica together with cement hydrates it, making dense structure of concrete; adding of mineral component (metakaolin) improves the values of concrete strength and

workability of mixture; decrease of permeability ensures increased resistance to aggressive environment [11].

Foamed concrete was obtained using micro/nano additives and the technology of intensive mixing, including two types of mixers – traditional conventional low-speed mixer and high-speed mixer with the effect of turbulence and cavitation. All materials used were dosed by weight. Two different mixes of foamed concrete were obtained – traditional foamed concrete (FC - T) and intensive mixing foamed concrete (FC - I). All obtained results were compared to autoclaved aerated concrete (AAC) properties. The data about the concrete mixes are presented in table 1.

Table 1. Mixes of porous concrete.

	AAC	FC - T	FC - I
Portland Cement CEM I 42.5R	90	340	320
Lime	90	–	–
Sand, fraction 0/1 mm	–	220	160
Sand, fraction <0.7 mm	350	–	–
Gypsum	15	–	–
Calcium chloride	2	–	–
Microsilica (silica fume)	–	–	5
Metakaolin	–	–	10
Polypropylene fibers	–	0.6	0.6
Foaming agent	–	1.2	1
Plasticizer	–	–	–
Aluminum powder	0.5	–	–
Water	280	210	250
Together	827.5	771.8	746.6

The group of density for both foamed concrete and autoclaved aerated concrete was D600 (density 600 kg/m³). The properties of density, compressive strength, water absorption, frost resistance and forecasted lifetime of these types of aerated concrete are shown in table 2.

Table 2. The comparison of the properties of aerated concrete.

	AAC	FC - T	FC - I
Density, kg/m ³	600	600	600
Compressive strength, MPa	3.0	1.8	3.0
Water absorption (after 1 h), g/dm ²	140	80	40
Frost resistance, cycles	10	20	100
Forecasted lifetime, years	70	100	120

According to Simmons [3], there are three methods how to determine estimated CO₂ emissions – reference approach (RA), sectorial approach (SA) and detailed technology-based method ('bottom-up'). RA is characterised by simple calculations for CO₂ emissions in those countries, where sufficient data for the Sectorial approach or 'bottom-up' is not available. If it is necessary to determine many combustion operations, RA can be used as probation of the total emission. SA is more accurate method than RA, because it uses consumption of each source of fuel. This method also defines carbon content that helps to value CO₂ emissions. 'Bottom-up' method evaluates emission data from manufactures in more detailed form. These obtained quantities distinguish different types of combustion sources.

The impact on environment from producing two types of foamed concrete: traditional foamed concrete (FC – T) and intensive mixing foamed concrete (FC - I) compared to commercially produced autoclaved aerated concrete (AAC) were evaluated by analyzing their CO₂ emissions, saving of raw materials (sand and water), total reduction of CO₂ depending on fuel type and total saving of fuel depending on fuel type.

Analysis of the environment impacts begins with calculation of emission factor of CO₂, oxidation factor and actual emission factor. Actual emission factor can be determined by emission factor of CO₂ (E'_{CO_2}) and oxidation factor (p). Emission factor of CO₂ (formula 1.1.) [16] is calculated by using a local expert study of certain physical and chemical parameters of fuel:

$$E'_{CO_2} = \frac{C^d \cdot M_{CO_2} \cdot 1000}{Q_z^d \cdot M_C \cdot 100} \quad (1.1.)$$

E'_{CO_2} – emission factor of CO₂ (t CO₂/TJ)

C^d – content of carbon in fuel operating weight (%)

M_{CO_2} – molecular weight of CO₂ (44.0098 g/mol)

M_C – molecular weight of carbon (12.011 g/mol)

Q_z^d – net calorific value of fuel operating weight (GJ/t)

1000 – transition from GJ to TJ

100 – definition in percent

Net calorific value (NCV) is defined in [17]. Total CO₂ emissions can be calculated by actual factor of emission, factor of oxidation, net calorific value and fuel consumption (formula 1.2.) [16] :

$$CO_2 = E_{CO_2} \cdot B_q = (E'_{CO_2} \cdot p) \cdot (B_n \cdot Q_z^d) \quad (1.2.)$$

E_{CO_2} – actual emission factor (t/TJ)

B_q – fuel-injected amount of heat period (TJ)

E'_{CO_2} – emission factor of CO₂ (t/TJ)

p – oxidation factor

B_n – fuel consumption during the period (1000 t or 1000000 m³)

Q_z^d – net calorific value of fuel operating weight (TJ/1000 t or TJ/1000000 m³)

Oxidation factor is the fraction, which is oxidized and can be counted by formula 1.3. [16] :

$$p = \frac{100 - q_4}{100} \quad (1.3.)$$

q_4 – mechanically incomplete combustion losses

p – oxidation factor

Oxidation factors are different, depending on the fuel type and fuel equipment. These two main reasons influence on completeness of oxidation and explain mechanically incomplete combustion losses. For coal $p=0.98$, but for gas oxidation factor is the lowest value – 0.995 [3].

4. Results and discussion

Results of CO₂ emissions are presented in figure 2. This article analyzes the environment impact from three types of fuel – gas, coal and eco-friendly fuel. According to formula (1.2.), emissions were calculated for two types of foamed concrete – prepared with traditional mixing technology (FC – T) and intensive mixing technology (FC – I). The results were compared to autoclaved aerated concrete (AAC), using data from producer for emission calculation.

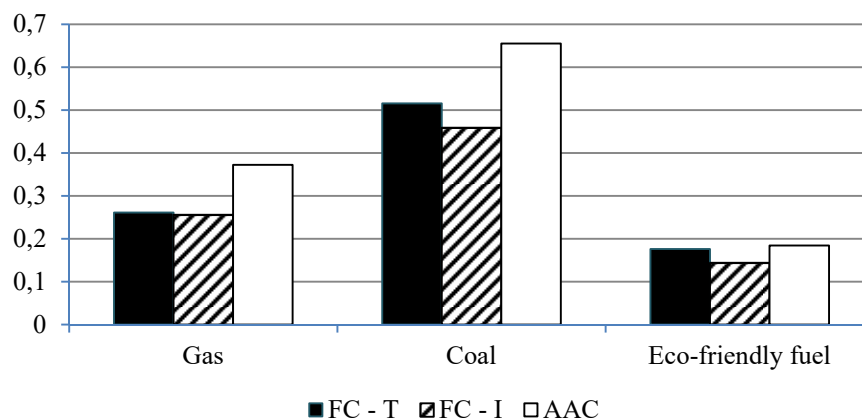


Figure 2. Emission of carbon dioxide (t).

By summarizing theoretical and calculated data, it may be concluded that higher CO₂ emissions are from coal, but lower emissions from eco-friendly fuel. Calculation of two foamed concrete types has lower emissions than AAC. In case of producing foamed concrete as building materials using gas, reduction of CO₂ emissions is 45%, but using coal – 42%. It may be explained with roasting temperature of AAC.

Producing foamed concrete with intensive mixing, CO₂ emissions are lower than producing it with the traditional method – 0.06 tones by using coal and 0.03 tones by using eco-friendly fuel. This difference may be explained by type of producing technology.

Quantities of raw materials used in producing building materials also play an important role in analysis of on the environmental impact. Figure 3 presents water savings from the foamed concrete production.

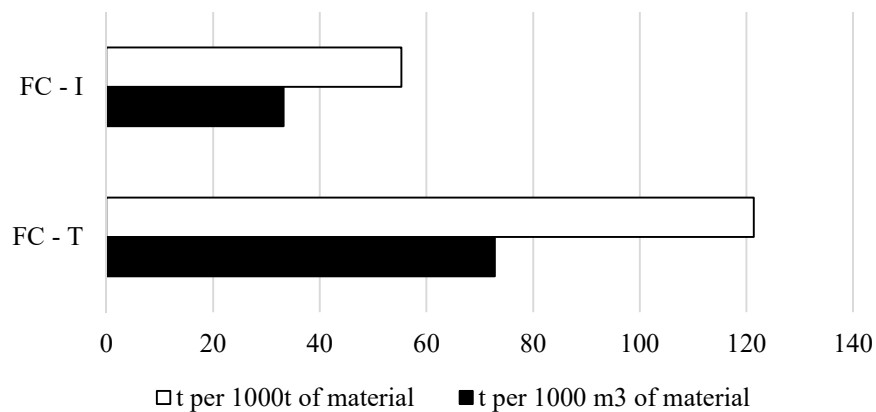


Figure 3. Saving of water (t).

Comparing amount of water necessary for producing FC and AAC, larger saving of water is for traditionally produced foamed concrete – 121.4 t per 1000 t and 72.8 t per 1000 m³. Two times lower saving is for the intensive mixed foamed concrete – 72.8 t per 1000 m³ and 55.3 t per 1000 t. The difference is 39.6 t per 1000 m³ of material and 66.1 t per 1000 t of material respectively. This phenomenon may be explained by higher amount of cement in producing of foamed concrete, comparing to AAC.

Results of saving of sand are shown in figure 4. Comparing to manufacturing FC with AAC, larger amount of sand saving is for intensive mixed foamed concrete – 349.9 t per 1000 t and 210 t per 1000 m³.

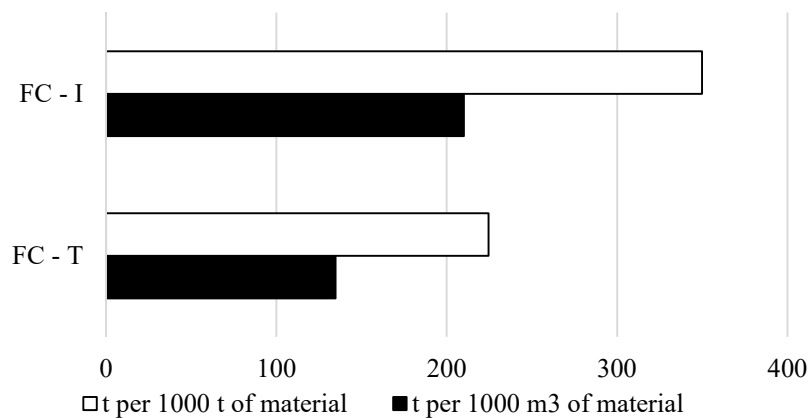


Figure 4. Saving of sand (t).

Lower saving of sand is for traditionally produced foamed concrete – 224.5 t per 1000 t and 134.7 t per 1000 m³. The difference is 125.4 t per 1000 t of material and 75.5 t per 1000 m³ of material. It may be explained by higher amount of cement used for producing foamed concrete, comparing to AAC.

Total reduction of CO₂ emissions is shown in figure 5. By comparing two methods of manufacturing foamed concrete with producing of AAC, it can be observed that intensive mixing leads to higher total saving of CO₂ – up to 60 t per 1000 m³.

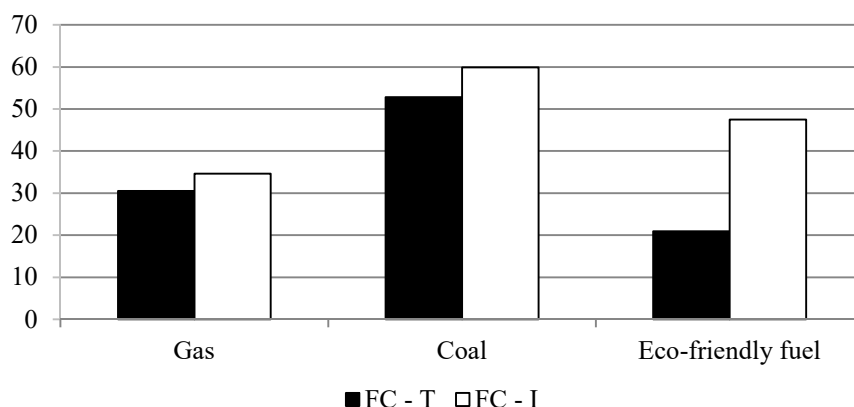


Figure 5. Total reduction of CO₂ emissions depending on fuel type.

It may be concluded that higher total reduction is for coal – 59.8 t per 1000 m³ of foamed concrete by using intensive mixing and 52.8 t per 1000 m³ of traditionally produced foamed concrete. Almost two time lower reduction of CO₂ emissions is for eco-friendly fuel in combination with traditionally produced foamed concrete – 20.9 t per 1000 m³. All these results are related to the CO₂ emissions (see figure 2). Higher value of emissions is from coal and lower value – from eco-friendly fuel. In calculation it was assumed that amount of material saving is equal for each type of fuel, but different for each type of foamed concrete. Therefore higher reduction of CO₂ is related to higher emission.

Results of total saving of fuel are shown in figure 6. Comparing two methods of foamed concrete producing with AAC producing, it can be observed that intensive mixing show higher total saving of fuel – up to 30 t per 1000 m³.

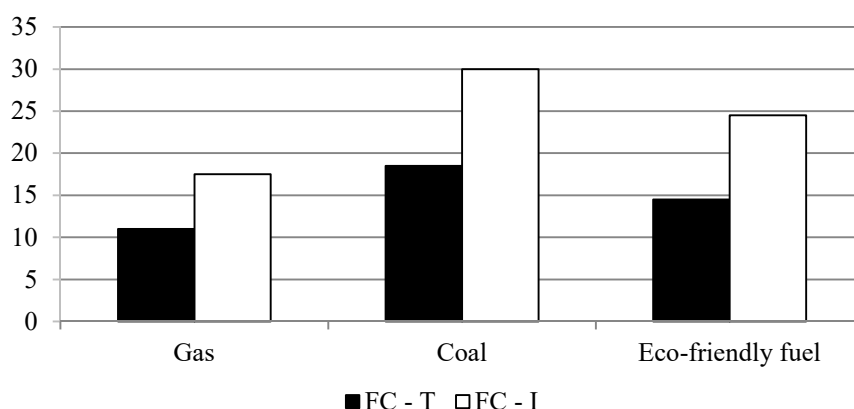


Figure 6. Total saving of fuel depending on type of fuel.

Higher value of saved fuel is for coal – 30 t per 1000 m³ for intensive mixing and 18.5 t per 1000 m³ for traditionally produced foamed concrete. Almost two times lower value is for gas – 17.5 t per 1000 m³ for intensive mixing and 11 t per 1000 m³ for traditionally produced foamed concrete. The results of total reduction of CO₂ are related to the levels CO₂ emissions (see figure 2). Higher value of emissions is for coal and lower value – for eco-friendly fuel. In calculation it is assumed that amount of material saving is equal for each type of fuel, but different for each type of foamed concrete. Therefore higher value of total saving of CO₂ is connected to higher emissions.

Comparing with AAC, foamed concrete construction materials have lower values of thermal conductivity. This allows achieving equal thermal transmittance of wall construction by lower consumption of material (see table 3).

Table 3. The comparison of the thermal properties of foamed concrete.

	AAC	FC - T	FC - I
Thermal conductivity, W/mK	0.15	0.145	0.135
Thickness of wall by $U=0.18 \text{ W/m}^2\text{K}$ (mm)	825	797.5	742.5

For example, in Latvia (Riga) in order to reach heat transfer coefficient $U=0.18 \text{ W/m}^2\text{K}$ (for residential house) by the density class of D600, thickness of the wall should be 742.5 mm for intensive mixing and 797.5 mm for traditionally mixed foamed concrete. Value of thermal conductivity will decrease up to 0.135 W/mK for intensive mixing and up to 0.145 W/mK for traditionally mixed foamed concrete. By calculating the saved material, 3.6% economy is obtained for traditionally mixed foamed concrete and almost up to three times - 10.5% for intensive mixing foamed concrete.

5. Conclusions

- Introducing production of foamed concrete by using gas will help to reduce total CO₂ emissions by up to 34.62 t per 1000 m³ with regard to foamed concrete produced with intensive mixing technology and up to 30.5 t per 1000 m³ with regard to traditionally mixed foamed concrete.
- By replacing production of autoclaved aerated concrete with production of foamed concrete, the following savings in materials can be reached: water – up to 120 t per 1000 t for traditionally mixed foamed concrete, up to 55.3 t per 1000 t for foamed concrete produced with intensive mixing technology, sand – up to 349 t per 1000 t for foamed concrete produced with intensive mixing technology, up to 224 t per 1000 t for traditionally mixed foamed concrete.
- Lower value of thermal conductivity was reached for foamed concrete produced with intensive mixing technology with density class of D600 and with heat transfer coefficient $U=0.18 \text{ W/m}^2\text{K}$.
- Comparing to autoclaved aerated concrete, use of foamed concrete will save the wall construction material up to 10.5% by $U=0.18 \text{ W/m}^2\text{K}$.

Acknowledgement

The financial support of European Regional Development Fund project Nr.1.1.1.1/16/A/007 "A New Concept for Sustainable and Nearly Zero-Energy Buildings" is acknowledged.

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