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Cement based foam concrete with aluminosilicate microspheres for monolithic construction

Цементный пенобетон с алюмосиликатной микросферой для монолитного домостроения

A.B. Steshenko*,
A.I. Kudyakov,
Tomsk State University of Architecture and Building, Tomsk, Russia

Канд. техн. наук, доцент А.Б. Стешенко*,
д-р техн. наук, профессор А.И. Кудяков,
Томский государственный архитектурно-строительный университет, г. Томск, Россия

Key words: foam concrete mixture; microsphere; plastic shrinkage; average density; porosity; strength; softening coefficient; thermal conductivity; monolithic construction

Ключевые слова: пенобетонная смесь; микросфера; пластическая усадка; средняя плотность; пористость; прочность; коэффициент размягчения; теплопроводность; монолитное домостроение

Abstract. The present paper investigates cement foam concrete of natural hardening with aluminosilicate microsphere made from bottom ash waste from Seversk Heat and Power Station in Tomsk Region. The relevance of the given study is conditioned by the necessity to provide the required process parameters of mixture for transportation and laying the formwork, as well as providing strength and thermal and physical characteristics of wall structures for economy-class housing construction. Porous microsphere from bottom ash wastes applied within the technology of cement foam concrete of natural hardening contributes to ensuring increased microporosity and strength of interpore partitions of foam concrete. The study was conducted in the Laboratory of Tomsk State University of Architecture and Building which is accredited in accordance with the national standards requirements. The optimal content of microsphere in the cement foam concrete mixture was 5–10 % of the cement weight. Foam concrete mixture with microsphere possesses higher flowability and concrete has reduced plastic shrinkage by 40 %. The average pores diameter in foam concrete with microspheres is reduced from 308 to 210.2 µm, mean square deviation of the pores diameter is reduced from 23.6 to 14.2 µm. The maximum effect of reducing thermal conductivity coefficient up to the value of 33 % is observed with 5 % microsphere content of the cement weight. Inclusion of microsphere within the process of mixture formation enables to increase concrete strength at the age of 28 days by 40 % and its softening coefficient by 15 %. The elaborated composition and technology of foam concrete production with aluminosilicate microsphere is intended for use in the walls structures in monolithic construction.

Аннотация. Приведены результаты исследований цементного пенобетона естественного твердения с алюмосиликатной микросферой из золошлаковых отходов Северской ТЭЦ Томской области. Актуальность исследования обусловлена необходимостью обеспечения требуемых технологических параметров смесей для транспортирования и укладки в опалубку, а также прочностных и теплофизических характеристик стеновых конструкций для строительства комфортного жилья эконом класса. Путем применение пористой микросферы из золошлаковых отходов ТЭЦ в технологии цементного пенобетона естественного твердения достигается повышенная микропористость и прочность межпоровых перегородок пенобетона. Исследование пенобетонной смеси и пенобетона проводилось в аккредитованной лаборатории ТГАСУ в соответствии с требованиями национальных стандартов. Оптимальное содержание микросферы в цементной пенобетонной смеси – 5–10 % от массы цемента. В пенобетонной смеси с микросферой повышается растекаемость смеси и снижается пластическая усадка пенобетона в среднем на 40 %. В пенобетоне с микросферой уменьшаются средний диаметр пор с 308 до 210 мкм, среднее квадратичное отклонение среднего диаметра – с 23.6 до 14.2 мкм. Максимальный эффект снижения коэффициента теплопроводности наблюдается при дозировке микросферы 5 % от массы цемента и составляет 33 %. При введение микросферы в смесь в процессе ее приготовления повышается прочность пенобетона в 28 суточном возрасте на 40 % и коэффициент размягчения в среднем на

15 %. Разработанный состав пенобетона с алюмосиликатной микросферой предназначен для устройства стеновых конструкций малоэтажных домов в монолитном домостроении.

1. Introduction

Great attention is paid to the construction of monolithic low-rise buildings using effective wall materials from local raw materials that provide the required thermal protection, comfortable conditions and ecological safety along with affordable pricing for the people in implementing the national program “Provision with available and comfortable housing and utilities of the Russian citizens” [1].

Cement based foam concrete of natural hardening is recommended to be used while construction of wall structures in individual housing [2–6]. Foam concrete has good thermal insulation properties and adequate strength for wall structures thus providing energy efficiency and durability of a residential building during operation.

Monolithic construction of low-rise buildings using foam concrete requires ensuring the necessary process parameters of mixtures for transportation and placement, as well as the strength and thermal and physical characteristics of wall structures.

It is necessary to use a system approach during the whole lifecycle of a wall structure when managing the process of structure formation of cement based foam concrete. Also it is necessary to take into account many factors starting from selection of initial components up to maintaining the given quality parameters subjected to environmental impacts during building operation [7–10]. Proper selection of a number of processing methods for establishing high quality foam concrete production is possible due to comprehension of physical and chemical processes of structure formation, particularly at the early stage. Based on the analysis of the known processing methods [3, 5–8] the authors have recommended two effective directions to form the rational structure of foam concrete and to ensure better thermal properties and maintain or increase its strength:

– strengthening of the frame (interpore partitions);

– enhancing of porous structure (type, size and pores volume).

Effective ways to increase the quality of foam concrete mixtures and foam concrete along with reduction of cement consumption and its cost is inclusion of fine-grained active mineral additives (FAMA) into the mixture [11–13].

Improving the properties of foam concrete mixture while FAMA inclusion are attributed to the chemical interaction with the minerals of hardened cement paste [12, 14–16]. Moreover, fine-grained particles of micro-filler of colloidal size could be crystallization centers of cement newgrowths the structural elements of hardened cement are clustering around, forming mixed-type clusters of a “binder-filler” type [11, 17].

The following peculiar features of FAMA's influence on the structure formation and physical and mechanical properties of foam concrete should be specified:

– reacting with calcium hydrated of crystalhydrate cement matrix which results in enlarging the volume of hydrosilicate binder [12];

– acceleration of the initial stage of structure formation of cement composition;

– strengthening of the contact zone between the hardened cement paste and fillers in concrete;

– alteration of differential porosity of foam concrete mixture with decreasing pore size (placement of filler particles between the cement particles), which contributes to the formation of cement paste with smaller size of capillary pores and strengthening of foam concretes.

To increase the microporosity and strength of interpore partitions of foam concrete, it is recommended to introduce porous FAMA into the foam concrete mixture, given as thermo-modified peat, hollow glass microspheres and ceramic microspheres [16, 18–20].

Manufacture of glass, ceramic microspheres and thermo-modified peat requires significant energy consumption thus resulting in rising prices for the ready foam concrete products.

Therefore, in the present work authors suggest using aluminosilicate microsphere as porous FAMA made from bottom ash waste, the local silica-containing raw, from Seversk Heat and Power Station (Tomsk Region, Russia) [21–24].

After burning of coals of various deposits at the temperature of 1400–1800 °C bottom ash wastes are formed; they are washed out by the water and transported along the pipeline into ash-disposal area.

Annual outlet of bottom ash wastes in Russia composes 25–30 million tons, and there are 1.2–1.5 billion tons of wastes in disposal areas. Only 8–12 % of bottom ash wastes in Russia are being used, mostly in building materials production, construction of buildings, structures and automobile roads [25]. Moreover, currently there are some difficulties with allocation of additional spaces for bottom ash wastes storage.

Microspheres have low thermal conductivity of 0.1 W/m•°C. In this regards, they are used as the initial material for production of thermal insulation ceramic products, special cements, finishing and plastering mortars for thermal insulation of external building walls [17–24]. The use of aluminosilicate microspheres, the product of the processing of ash and slag waste, in the production of foam concrete is important.

When microspheres are incremented into the foam concrete mixture, the cement matrix acquires uniformly distributed cellular structure while in interpore partitions microspheres originate micropores [19, 20]. Applying of microspheres almost does not complicate the technology of concrete mixture production, its cohesion is improved and closed porosity stable in time is provided making it possible to increase significantly frost resistance of foam concretes.

During assembling of walls from foam concrete mixture in monolithic construction shrinkage deformations of foam concrete occur, particularly at an early stage of structure formation due to physical-chemical interaction of cement particles with water. This complicates providing of the given geometrical sizes of wall structures and causes crack formation.

In the present work, on the ground of research results analysis authors made an assumption on possible reduction of foam concrete mixture plastic shrinkage and increase of its flowability, as well as improved properties of foam concrete by inclusion of porous additive given as microsphere.

The given research aims to elaborate scientifically-justified compositions and establish peculiar features of structure formation, and to determine the properties of foam concrete with mineral porous additive microsphere made from ash bottom wastes for its further application in wall structures of monolithic low-rise buildings.

2. Materials and Methods

In the present research FAMA given as aluminosilicate microsphere of bottom ash wastes from Seversk Heat and Power Station in Tomsk Region (Russia) were used. The picture of microsphere and its elemental and chemical compositions are given in Figures 1, 2 and Table 1. The basic elements of miscrosphere are Si and Al (silicon oxide and aluminium oxide). Physical properties and grain composition of microsphere are given in Tables 2, 3. Effective specific activity of natural radioactive nuclides was determined in the Accredited Laboratory of Radiation Survey of Regional Committee for Environmental Protection and Nature in Tomsk, its value is 300 Bq that makes it possible to use it in new built and reconstructed residential and public buildings.

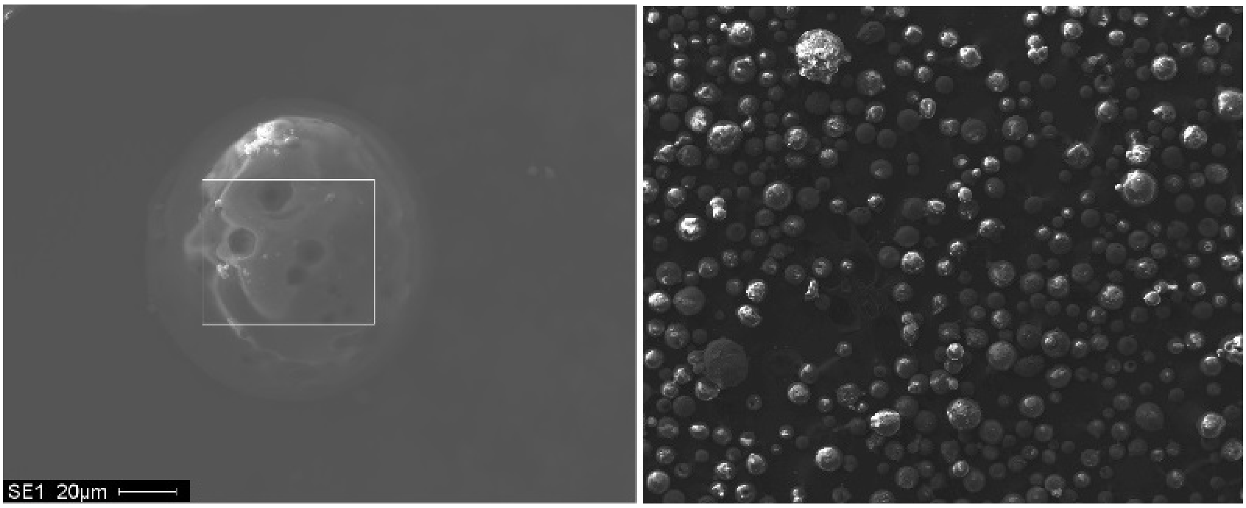

Figure 1. Microsphere (on the left – zoom x1500, on the right – zoom x100).

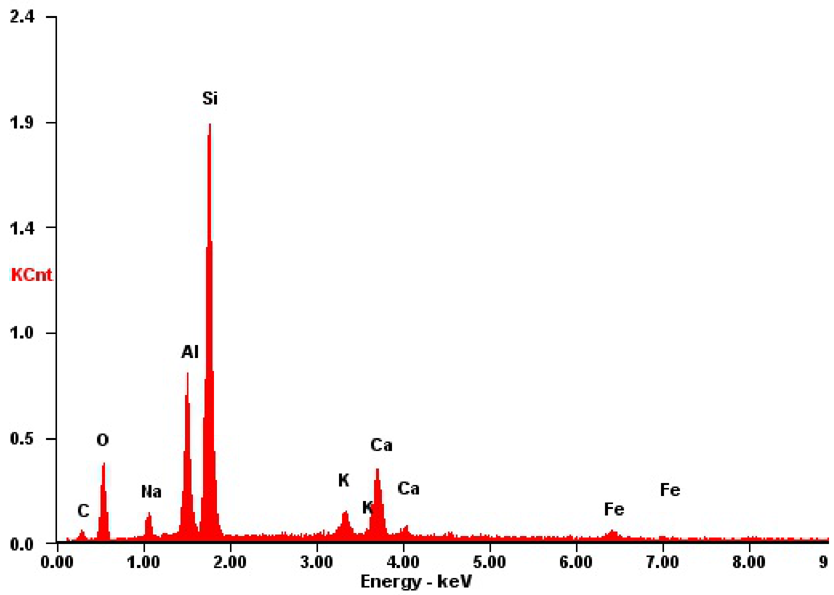

Figure 2. Elemental composition of microsphere of Seversk Heat and Power Station (Tomsk Region, Russia).

Table 1. Chemical composition of microsphere of Seversk Heat and Power Station (Tomsk Region, Russia).

Oxides content, %									
SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Mn	Na_2O	K_2O	SO_3
47.06	1.17	22.67	12.44	4.34	1.49	0.3	0.94	0.61	1.25

Table 2. Physical properties of aluminosilicate microsphere.

Colour	Bulk density, kg/m^3	Apparent density, kg/m^3	Mass humidity, %	Content of floating precipitate by weight, %
Grey	750-800	1800	0.2	0.1

Table 3. Grain composition of aluminosilicate microsphere.

Partial/complete residuals, % by weight on the sieves size, mm					External blinding admixtures
0.5	0.315	0.16	0.08	< 0.08	
0.0 0.0	0.0 0.0	0.4 0.4	23.1 23.56	76,5	Absent

Fractional composition of aluminosilicate microsphere corresponds to the requirements of Specifications 5712-089-00884306-2016.

As binders Portland cement of Topki Cement Factory (Kemerovo Region, Russia) CEM I 42.5H (Russian State Standard GOST 30515-2013) was used, sand of Kudrovskoe deposit of Tomsk Region (Russia) with fineness modulus 1.86 (Russian State Standards GOST 8736-2014 and GOST 26633-2012), water (Russian State Standard GOST 23732-2011) and foam agent PB-2000.

Foam concrete mixture formation was performed in one stage using laboratory foam concrete mixer. Physical and mechanical properties of foam concrete were defined in accordance with Russian State Standards requirements: compressive strength (GOST 10180-2012); average density (GOST 12730.1-78); water adsorption (GOST 12730.3-78). Thermal conductivity coefficient was determined using ITS-1 Thermal Conductivity Meter (Russian State Standard GOST 7076-99). Plastic shrinkage was determined within the first three hours from the moment of foam concrete mixture placement into the mould according to methodology described in [26]. The structure of pore volume of foam concretes was investigated using Quanta 200 3D Two-beam Scanning Electron Microscope. The images were obtained within the low vacuum mode at the stable accelerating voltage up to 20 kV. The images were further processed using computer program. The microscope is equipped with X-ray spectrometer to conduct element microanalysis (EDAX). In order to study porous structure of foam concrete mercury injection method was applied using

Quantachrome 33 Porosimeter. It allows obtaining the information on porous structure within the wide range of pores sizes.

Basic composition of foam concrete was selected in accordance with Russian Standard SN 277-80 “Instructions for the production of cellular concrete products” and given taking into account the actual average density of the concrete mix (Table 4) [8, 26].

Table 4. Basic composition of foam concrete per 1 m^3.

Content of microsphere in foam concrete	Components consumption				
	cement, kg	sand, kg	microsphere, kg	water, kg	foam agent, l
Basic (reference)	288.0	144.0	-	216.0	1.7
5%	289.6	146.3	14.8	217. 0	1.7
10%	282.5	144.0	28.8	218.0	1.7
15%	338.0	149.0	50.2	219.0	1.7

During the research the content of microsphere in foam concrete mixture was changing from 5 to 25 % of the cement weight. For the freshly mixed foam concrete mixture that can be transported and laid in the formwork it is required to provide good flowability along the length of the molded wall structure. It also requires conducting rheological properties assessment within the process technology of building structures production, particularly in the process of early structure formation of foam concrete.

In order to establish the ways microsphere influences the volume changes of mixture within the first hours of structure formation the studies of plastic shrinkage of foam concrete mixtures were carried out. Plastic shrinkage has a negative influence on the formation of porous structure, it causes crack formation and complicates provision of a close contact with the elements of wall structure, for instance with window and door frames [27–29].

3. Results and Discussion

It was established experimentally (Figure 3) that along with inclusion of aluminosilicate microsphere into the mixture it gets more plastic. The spread diameter of foam concrete mixture with additive was determined using Suttard’s Viscosity Analyzer and its value increased from 10 to 15.5 cm, which can be explained by decrease in the sizes of entrained air bubbles in foam concrete mixture, as well as glass-covered surface, and by the less surface area of microspheres [30]. We should also note the significant difference of the apparent density of microspheres (1800 kg/m^3) and cement paste 1750 kg/m^3 in foam concrete mixture.

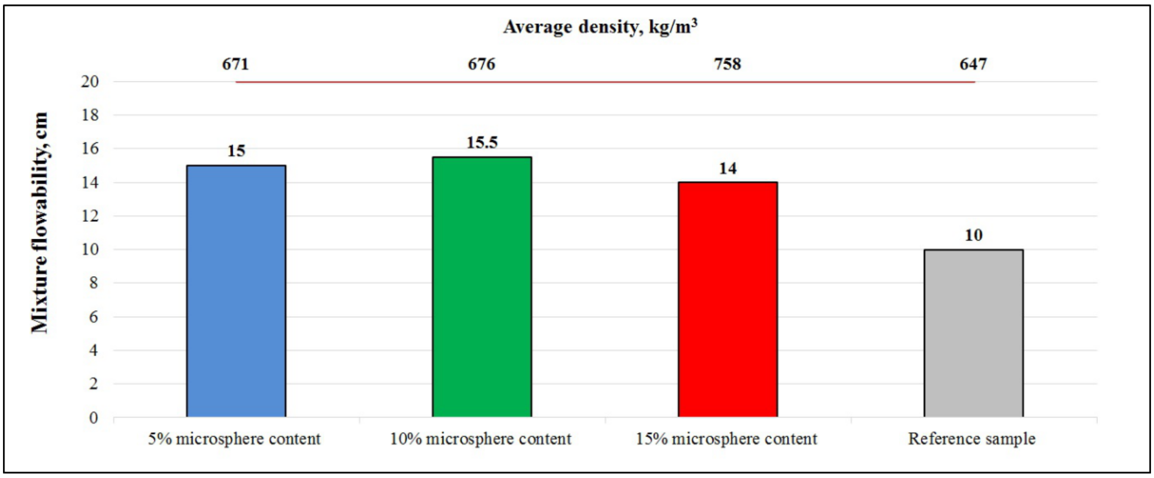

Figure 3. The influence of aluminosilicate microsphere on the flowability and average density of foam concrete mixture.

In case the content of aluminosilicate microsphere is 15 % of the cement weight, the process of foam formation deteriorates and results in reduction of volume and enlargement of the average density of the obtained foam concrete mixture by 111 kg/m^3 (up to 758 kg/m^3). Resulting from the conducted studies it was concluded to use microspheres in the amount of 5 and 10 % of the cement weight in further studies of foam concrete mixture and foam concrete.

Results of studies in plastic shrinkage of foam concrete mixtures are given in Figure 4. The assumption made by authors was proved experimentally. When aluminosilicate microsphere is applied in foam concrete mixtures in the amount of 5 % of the cement weight shrinkage decreases by 28.8 %, and in the amount of 10 % it decreases by 52.3 %. Thanks to the ideal shape and small size of microsphere particles effective filling of interpore partitions is provided. Along with that acceleration of early structure formation process occurs, homogenous fine-grained structure is formed with even distribution of pores along the whole volume; this contributes to the reduction of plastic deformation at the early stages of structure formation.

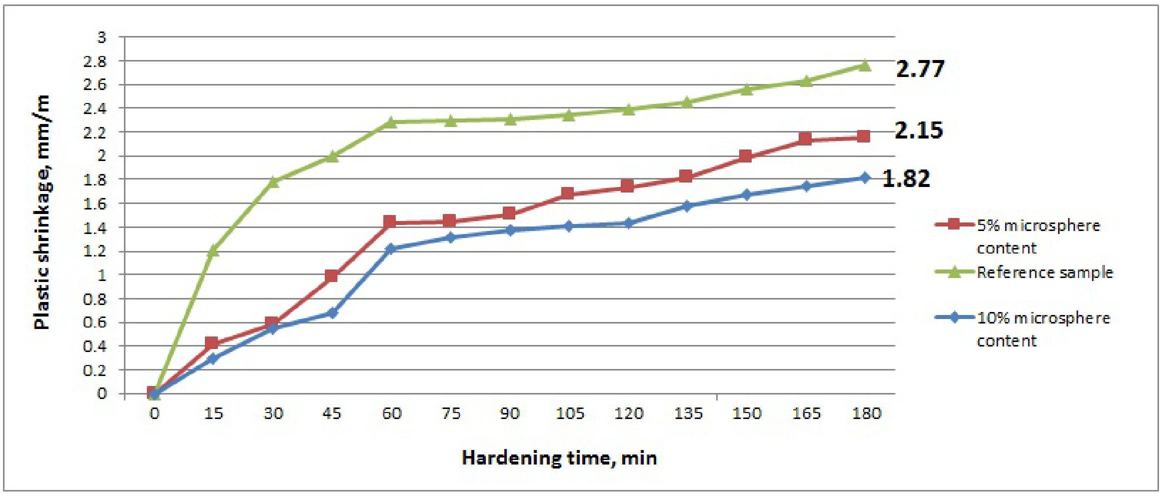

Figure 4. Plastic shrinkage of foam concrete mixture with microsphere.

The largest interest in controlling the quality of foam concrete with microsphere is taken by the studies of parameters of porous structure, namely the type, size and volume of the pores using Quanta 200 3D scanning electron microscope. Results of studies of porous structure of 28-days foam concrete samples after mechanical compressive tests are given in Figure 5 and Table 5. It is seen from the images that the basic feature of foam concrete samples with aluminosilicate microsphere is more homogenous structure; the pores are evenly distributed along the whole volume. In foam concrete without additives perforated interpore partitions are observed.

Improvement of the structure of foam concrete hardening system occurs by interaction of aluminosilicate microsphere with the cement matrix. The cluster “binder-filler” is formed due to high surface energy of filler particles which compacts the structure of interpore space of foam concrete (Figure 5, b–c). Microsphere inclusion contributed to the formation of large amount of closed pores. At the same time, general porosity of foam concrete almost does not change. Redistribution of the type and pores volume takes place.

By means of computer research the average pores diameter of a sample of cellular structure was determined, and average square deviation (δ) was defined. The average square deviation of the average pore diameter characterizes polydispersity of cellular pores, i.e. their quantity distribution by sizes. After inclusion of microsphere into foam concrete mixture in the amount of 5 and 10 % the average diameter of foam concrete pores decreases from 308 to 210 and 242 µm, the average square deviation of the average pores diameter is reduced from 23.6 to 15.5 and 8.2, the volume of open capillary pores is reduced from 20.40 % to 12.47 and 12.34 %, porosity of conventionally closed pores is increased from 22.93 % to 29.77 and 38.48 %, microporosity of foam concrete decreases from 0.05 to 0.04 and sorption humidity decreases by 16 %, accordingly. The average density of foam concrete with microspheres decreases by 1–3 %, i.e. almost does not change.

Based on test results provided in Table 6, the strength of foam concrete with 5 % microsphere content at the age of 28 days increased by 40 %. Water adsorption by weight decreases significantly in foam concrete with 5 % microsphere content from 40.0 to 25.2 % and further with microsphere content of 10 % it almost does not decrease. The values of water adsorption correlate well with the defined porosity parameters, i.e. to the content of closed pores in the foam concrete samples with microspheres. By full immersion of samples about one third of the pores volume and capillaries remain unfilled with water.

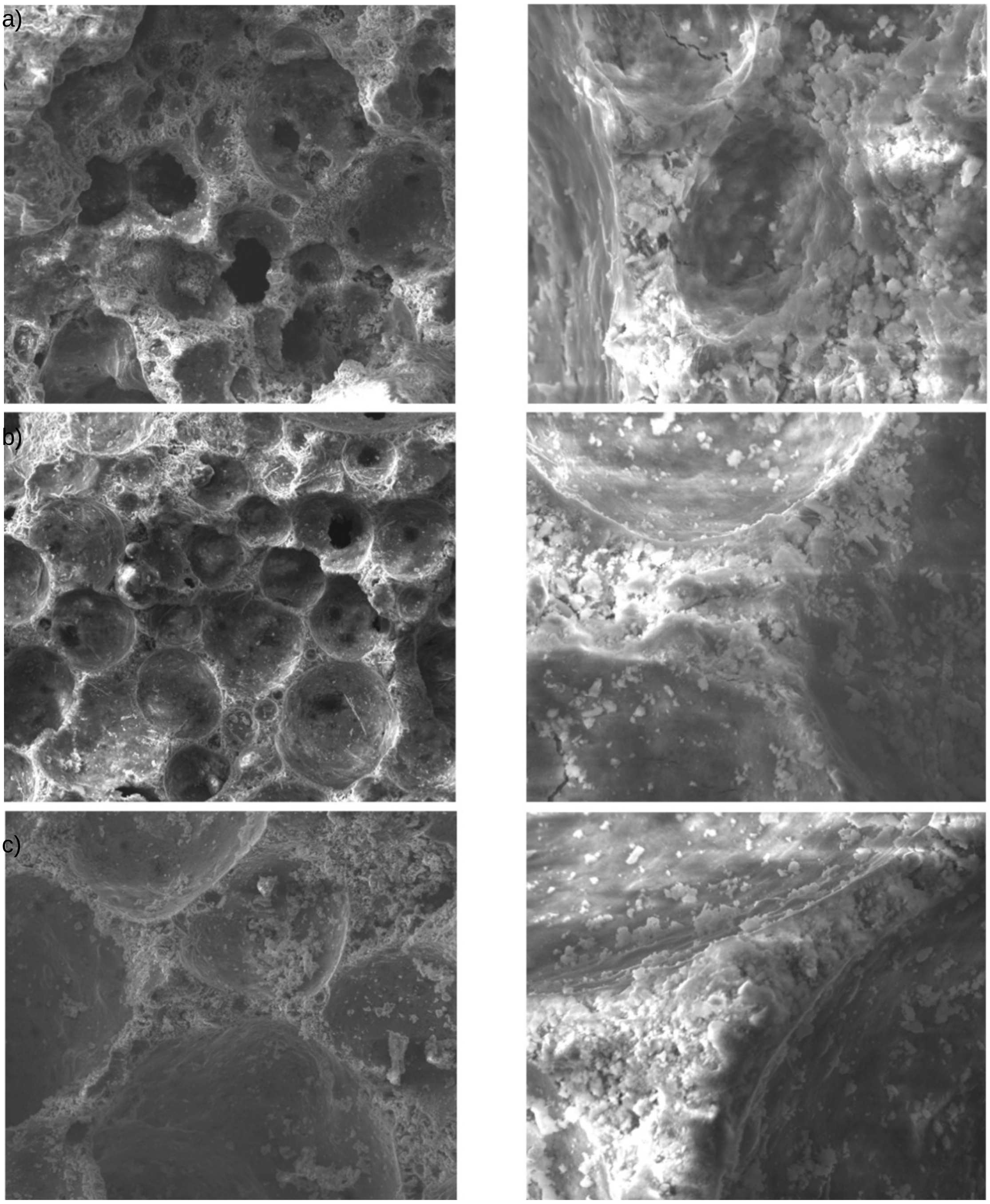

Figure 5. Structure of cement based foam concrete. On the left – zoom x250, on the right – zoom x2000: a) without additives b) with 5 % microsphere content c) with 10 % microsphere content.

Table 5. The influence of microsphere on the changing parameters of foam concrete porous structure.

Foam concrete with additives	Average density, kg/m^3	Average pores diameter, µm	δ of pores diameter	General porosity, %	The volume of open capillary pores, %	Porosity of conventionally closed pores, %	Microporosity index	Sorption humidity %
Without additive	510	308	23.6	77.83	20.40	22.93	0.05	5.8
5 % Microsphere content	495	210	14.2	78.24	12.47	29.77	0.04	4.99
10 % Microsphere content	505	242	16.3	77.46	12.34	38.48	0.04	5.2

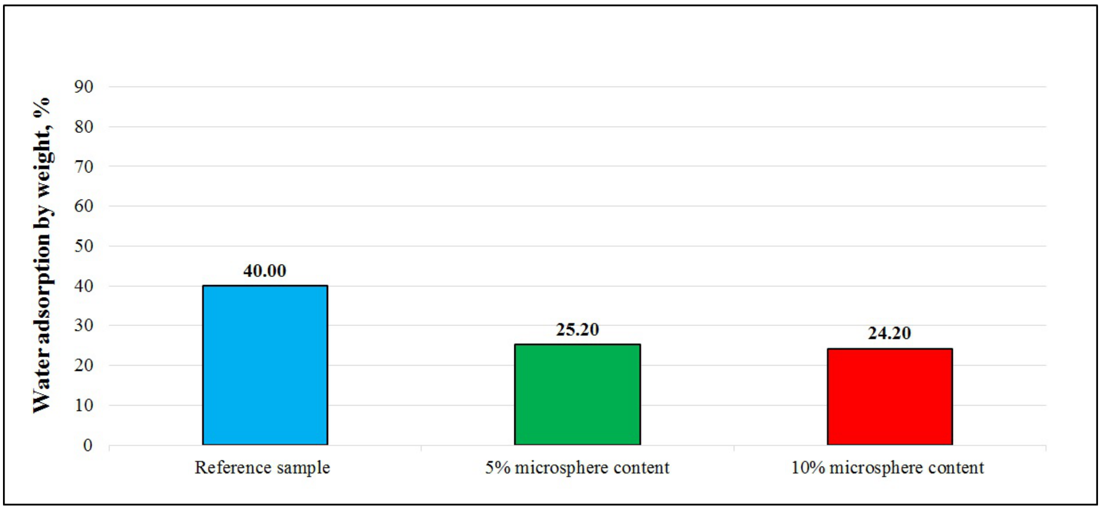

Figure 6. Influence of microsphere on water adsorption by foam concrete weight.

Table 6. Softening coefficients of foam concrete with microsphere.

Composition	Ultimate compressive strength, MPa		Softening coefficient
	prior to water saturation	after water saturation	
5 % microsphere content	1.26	1.1	0.86
10 % microsphere content	1.55	1.4	0.90
Reference sample	0.9	0.7	0.77

The capacity of porous materials to moisten while they contact with water due to capillary suction and saturate with water mainly define further operation properties of building products: strength and frost resistance. The ability of foam concrete to keep compressive strength in humid conditions is estimated by the softening coefficient. Table 6 shows softening coefficients of foam concrete samples with microspheres.

Softening coefficient of foam concretes with aluminosilicate microsphere is 13–17 % higher compared to the reference sample. This is explained by the fact that these samples acquire optimal structure with the least amount of contact pores which do not let water inside foam concrete.

The data on thermal conductivity of foam concrete samples are given in Figure 7.

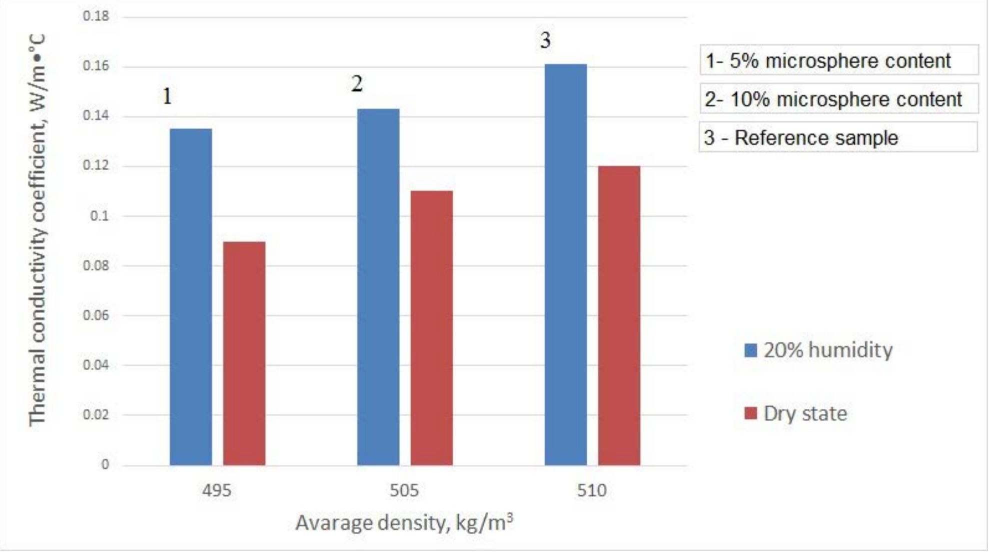

Figure 7. Thermal conductivity of cement based foam concrete samples.

Having analyzed the obtained results, it can be concluded that thermal conductivity coefficient of foam concrete in dry state with 5 % aluminosilicate microsphere content was reduced by almost 33 % and with 10 % content by 8 % compared to the reference sample. The obtained results correspond to the requirements of Russian State Standard GOST 25485-89 “Cellular concretes. Specifications” in terms of average density of the elaborated foam concrete composition.

Using the received research results authors developed actual compositions to establish resource-saving technology for production of porous cement building compositions with regulated volume changes using porous mineral additives from bottom ash wastes for their further use in wall structures of monolithic construction.

4. Conclusions

1. Optimal content of aluminosilicate microsphere made from bottom ash wastes from Seversk Heat and Power Station is 5–10 % of the cement weight in foam concrete mixture based on Portland cement, sand, water and a foaming agent. Foam concrete mixture with aluminosilicate microsphere has better flowability of mixture from 10 to 15.5 cm and reduced plastic shrinkage of natural hardening foam concrete by 28.8–52.3 %.

2. Foam concrete mixture with aluminosilicate microsphere has its average pores diameter decreased from 308 to 210 µm, average square error decreased from 23.6 to 14.2, microporosity decreased from 0.05 to 0.04, and sorption humidity decreased by 16 %. The maximum effect in reduction of thermal conductivity coefficient was observed by 5 % microsphere content of the cement weight and its value is 33 %.

3. Inclusion of microsphere into foam concrete mixture enables to increase foam concrete strength at the age of 28 days by 40 % and softening coefficient by 13–17 %.

4. Good agreement of the experimental results obtained by the authors was established while elaboration of scientifically-justified compositions of foam concrete with application of aluminosilicate microspheres made from bottom ash wastes, and that agrees with the other private research results of other authors obtained during application of glassceramic and ceramic microspheres and given in independent sources.

5. Resulting from studies recommendations were formulated on compositions of foam concrete with aluminosolicate microspheres for monolithic construction of wall structures in low-rise housing.

5. Acknowledgement

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Aleksei Steshenko,*
+7(909)5396643; steshenko.alexey@gmail.com

Aleksandr Kudyakov,
+7(913)8208554; kudyakow@mail.tomsknet.ru

Алексей Борисович Стешенко,*
+7(909)5396643;
эл. почта: steshenko.alexey@gmail.com

Александр Иванович Кудяков,
+7(913)8208554;
эл. почта: kudyakow@mail.tomsknet.ru