

INVESTIGATION OF FOAM CONCRETE PROPERTIES, PRODUCED BY MEANS OF VORTEX JET APPARATUS

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Abstract. The aim of this research is to investigate the physical and the structural properties of foam concrete produced by means of new foam generating device – vortex jet apparatus (VJA). Investigations of VJA were performed at the laboratory rig having industrial scale. These investigations have included identification of an optimal foam generation regime. Foam concrete specimens with various densities were produced based on this foam, and main properties of the specimens: apparent density, compressive strength, coefficient of thermal conductivity, etc. were defined. The median pore size and pore size distribution of the foam concrete were also defined.

The correlations between compressive strength, coefficient of thermal conductivity, median pore size depending on apparent density were defined using statistical methods of data processing. The analysis of obtained results has shown that the properties of foam concrete produced by means of VJA are fully satisfy the requirements of the Russian and French standards for the foam concretes. Besides, there is no need of compressor to feed air into the VJA, thus allowing to diminish the net cost of production and to create mobile units for foam concrete production which could be used, e.g., for the private house construction.

Keywords: foam concrete, foam, vortex jet apparatus

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1. Introduction

Foam concrete is a lightweight material consisting of Portland cement paste with a homogeneous void or pore structure created by introducing air in the form of small bubbles.

Foam concrete is a building material with relatively well mechanical strength, low thermal conductivity, ease of production and application. Foam concrete is primarily used in construction for: production of building blocks, monolithic building construction, heat and sound insulation of walls, ceilings, roof slabs, etc., but is also widely used in other areas of industry such as the thermal insulation of pipelines.

Main advantages of the use of foam concrete are:

1. Low cost of works at the construction site. For example, to produce 3 – 5 m³ of the foam concrete mix no more than 1 ton of cement is required (depending on the desired density). Additionally, there is no need to use large-scale equipment, such as lifting equipment etc. Rather, it is sufficient to use a foam generator, mixer and special pump for pumping foam concrete.

2. Simple manufacturing technology that does not require skilled workers.

3. Casting of the floor with foam concrete results in their excellent equalization and the overall load on the load-bearing parts of the structure is significantly reduced (by 2.5 times in comparison with the cement or concrete).

One of the promising devices ensuring the production of foam with high technological and operational properties is the vortex jet apparatus (VJA) (Abiev, 2007); the initial studies of this promising device were published in (Abiev *et al.*, 2009; Abiev *et al.*, 2007; Abiev *et al.*, 2012).

The main advantage of the VJA is the combination of axial and tangential flows leading to a multiple increase (10-25 times compared to conventional ejectors) of the kinetic energy of the flow due to an increase in the tangential velocity in the throat of the VJA (Abiev, 2007).

This leads to an appearance of a vacuum in this zone (up to minus 98.1 kPa) (Abiev *et al.*, 2015) and high shear stresses. All this, combined with high velocities of the continuous phase (up to 25 m/s in the throat) leads to the formation of a finely dispersed gas-liquid mixture with small bubbles having a narrow size distribution. This contributes to the strength and stability of the foam, which is an obvious advantage for industrial applications, building and construction. Vacuum, created by VJA, eliminates the need for a compressor thus reduces the number of elements of the production scheme and reduces the cost of foam concrete manufacturing.

The pore structure of foam concrete, predetermined by its porosity, shape of pore and its size distribution, is a very important characteristic as it influences the properties of the material such as strength, durability and thermal conductivity. The pore parameters could therefore be a primary factor influencing the material properties of foam concrete and an in depth look into this aspect is required to establish relationships between microstructure and material properties of foam concrete. Such deeper analysis is planned for publication in our next paper. In order to evaluate these relationships it was necessary to develop parameters to explain and quantify the pore structure of foam concrete.

The aim of this research is to establish the relationship between the microstructure of foam concrete (pore size distribution, porosity, median pore size) created by means of VJA, and the material properties (strength, apparent density, coefficients of thermal conductivity and water absorption, etc.).

Hilal *et al.* (Hilal *et al.*, 2015) in similar research have obtained a clear image of foam bubbles and foam concrete pore using an optical microscope; they defined the median bubble size of foam ($d_{50} = 325 \mu\text{m}$) as being larger than median pore size of foam concrete ($d_{50} = 180 \mu\text{m}$, $175 \mu\text{m}$, $165 \mu\text{m}$ for specimens with various apparent density – 1300, 1600, 1900 kg/m^3 respectively); bubble merging in all mixtures was relatively significant, the greater merging being observed in the mixtures with lowest density; bubble splitting or shrinkage did not appear to be significant; by virtue of their size, larger bubbles contribute a significant proportion of the area (and hence volume) of voids in the concrete mixtures and are more implicated in concrete weakness.

Nambiar and Ramamurthy (Nambiar & Ramamurthy, 2007), who used river sand and fly ash as a filler, reported that the pore structure (volume, size and spacing) have influence on strength and density of foam concrete; inclusion of fly ash as a filler in foam concrete helps in achieving more uniform distribution of air voids than fine sand (fly ash being finer, helps in uniform distribution of air voids by providing a well and uniform coating on each bubble and preventing it from merging and overlapping); mixtures with a narrower air-void size distribution showed higher strength (at higher

foam volume merging of bubbles seems to produce larger voids, results in wide distribution of void sizes and lower strength); air void shape has no influence on the properties of foam concrete as all air voids are of approximately same shape and independent on foam volume.

In these and many other works, data describing the distribution of pores and bubble size, as well as the correlations between compressive strength, coefficient of thermal conductivity, median pore size and other parameters depending on apparent density were not approximated by suitable functions. The existence of such functions could facilitate further analysis of the reciprocal influence of the characteristics of foam concrete on each other; simplifies the optimization of processes and control of production technology; allows to predict the properties of foam concrete and eventually it provides the possibility to produce foam concrete with preset characteristics.

Foam concrete is divided into several types: thermal insulation foam concrete (with density between 300 and 500 kg/m³); structural thermal insulation foam concrete (density between 600 and 900 kg/m³); structural foam concrete (density is 1000 kg/m³ and higher). In the vast majority of studies attention is paid only to the material with a high density (1000 kg/m³ and higher). On the other hand, the foam concrete, as stated, is widely used in construction thanks to the great thermal insulation properties. And that is why the most common foam concrete density is below 1000 kg/m³. In this study special attention is paid to the foam concrete with densities in the range from 450 to 1000 kg/m³.

The *research task* of this paper included identification of an optimal foam generation mode through the setting of foam process parameters: foam-to-liquid ratio, foam durability, foam stability.

2. Experimental part

There are several methods for the foam concrete production and a wide range of processing units carrying out the process.

At the Department of Optimization of chemical and biotechnological equipment of St. Petersburg State Institute of Technology, the laboratory unit for foam generation has been developed (Fig. 1). The main features of the unit is that there is no need for a compressor (Abiev *et al.*, 2015), the ability to separate out foam and foaming solution, which is recycled back into a foaming solution tank (Abiev, 2007).

Foam generating technique proceeded as follows: the foaming solution was prepared in the solution tank 1; the pump 2 was launched, feeding the solution into the tangential nozzle of VJA 5; air starts to inject through the axial nozzle at the top of the VJA; two flows (foaming solution and air) were merged in the mixing chamber of VJA; foam was separated out from the foaming solution by means of the separator 6 and flowed out through the tube 7, the foaming solution was recycled back into the tank 1.

The main feature of the VJA (Fig. 2) is that the foaming solution was fed to the tangential nozzle 5, and air was injected through the nozzle 1. The flow that tangentially enters to the confuser 2 is twisted and creates an initial angular velocity of the rotational movement of the flow. Moving along the confuser to the throat 3, the flow is accelerating in accordance with the theorem of the angular momentum change. Due to the centrifugal forces, the flow is pushing to the wall of the VJA, and air vortex is forming in the middle part of it. Mixing of the solution and air takes place in the throat 3 and is accompanied by a certain increase in pressure.

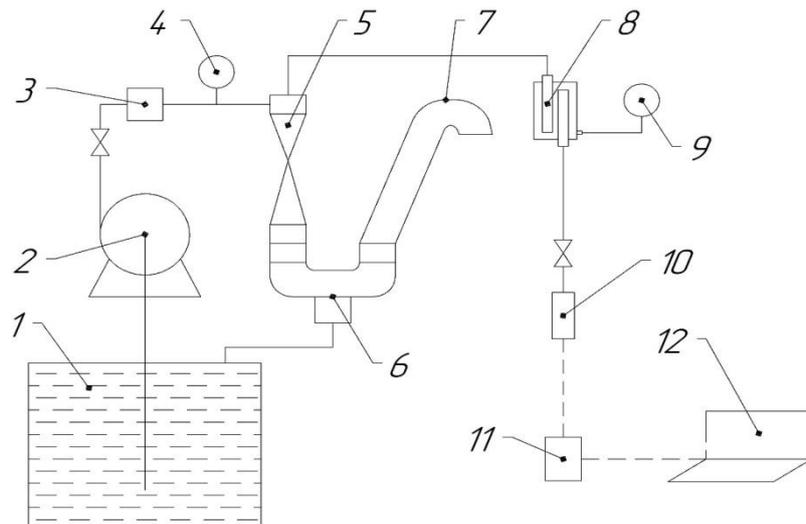


Figure 1. Scheme of experimental rig: 1 – tank with foaming solution; 2 – pump; 3 – flow-meter; 4 – pressure gauge; 5 – VJA; 6 – separator; 7 – outlet tube; 8 – separator (to protect the flow-meter 10); 9 – vacuum gauge; 10 – gas flow-meter; 11 – analog-to-digital coder; 12 – computer.

The flow enters the diffuser 4 from the throat 3, and further increase in pressure occurs. Thus, the VJA is effectively uses the change in the kinetic energy of rotational motion to increase the creating vacuum. The VJA allows to increase the kinetic energy of the flow by 25 times, compared to conventional ejectors.

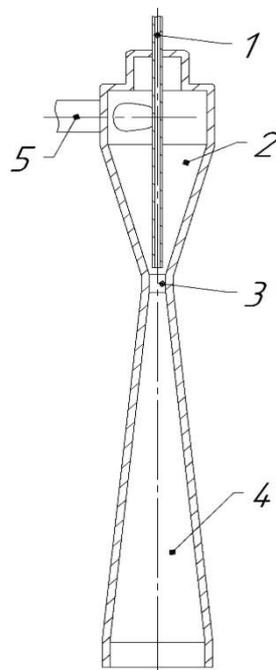


Figure 2. VJA scheme: 1 – air injection nozzle; 2 – confuser; 3 – throat; 4 – diffuser; 5 – tangential nozzle.

Optimal foam generation mode determined through the setting of foam process parameters: foam durability D_F – the property of foam to maintain its structure without destruction for a long time; foam stability S_F – time of destruction of 50% foam volume; foam-to-liquid ratio R_F – the ratio of foam volume and foaming solution volume, from which the foam was formed.

The values of optimal foam generation mode were found based on the obtained experimental data: inlet pressure $P_M = 1.5$ barg; vacuum in the throat $P_V = -30$ kPa; foaming solution flow rate $Q_S = 1.25$ m³/h; flow rate of inhaled air $Q_A = 4.6$ l/min.

Manufacturing of foam concrete specimens was performed according to the way presented in the Table 1.

Table 1. Recipe for foam concrete production used in the experiments

Apparent density of foam concrete, kg/m ³	500	600	800	1000
Sand (size lower than 2 mm, content of the clay is less than 2%), kg	1	2.1	4	5.6
Cement M500, kg	3	3.1	3.2	3.5
Water for mortar preparation, liter	1.5	1.6	1.6	1.8
Water for foam preparation, liter	0.5	0.5	0.4	0.3
Foam volume, liter	7.5	6.8	5.5	4.3

The constituent materials used to produce foamed concrete comprised of Portland cement, pulverized river sand with particles finer than 600 micrometer, tap water, and ‘fresh’ foam produced by use of VJA.

A few dozen of foam concrete specimens with densities from 500 to 1500 kg/m³ were produced, at least 3 specimens for each density. The dimension of specimens were 160x40x40 mm³.

The main properties of foam concrete – apparent density, compressive strength, thermal conductivity coefficient, etc. – were determined on the equipment available at the Materials Research Center of the Ales High Mining School, France (Center des Matériaux des Mines d'Alès, Ecole des Mines d'Alès).

Determination of pore sizes was carried out using a close-up photography (macrophotography) of the specimens' surfaces and subsequent processing of images in the graphical editor named «Kompas» (Ascon company, Russia). For preparation the surfaces for photography each original specimen was cut onto several pieces so that their dimensions became equal 10x40x40 mm³ and finally the front and back sides of each piece was cleaned and polished. Each specimen has been photographed from both front and back sides. A sampling of 700 pore size values (350 values on each side) has been performed.

The pores sizes were being processed by the MS Excel and Origin programs and distribution graphs were built; the other graphs presented in the next section were obtained by Curve Expert computer application.

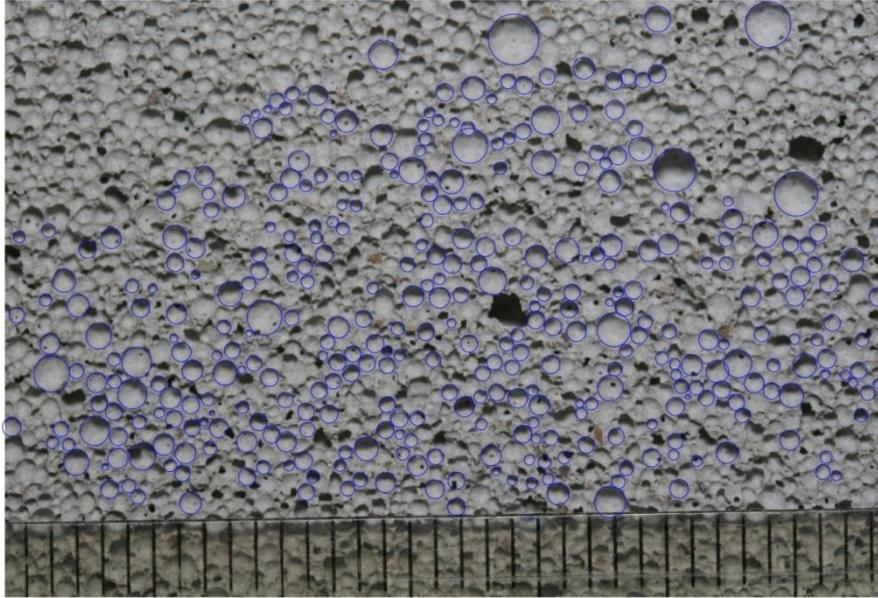


Figure 3. Macrophotography of foam concrete surface (blue circles are the samples of pore sizes; the distance between graduation mark of the ruler is 1 mm).

3. Results and discussion

It was found that for the foam produced by VJA foam durability D_F was 0.85; foam stability S_F was 7000 sec; foam-to-liquid ratio R_F was 50.

These results shows that the foam produced by VJA has excellent quality, in accordance with (Portik, 2003), therefore, VJA can be effectively used for the foam concrete production as a foam generator.

In order to understand the distribution of pores sizes in the concrete volume the probability density was calculated according to Eq. (1) and a distribution graph of pore size was drawn (Fig. 4).

$$f(d) = \frac{\Delta n}{n\Delta d}, \quad (1)$$

where d – median pore diameter in the specified interval, mm; n – amount of pore in the specified interval.

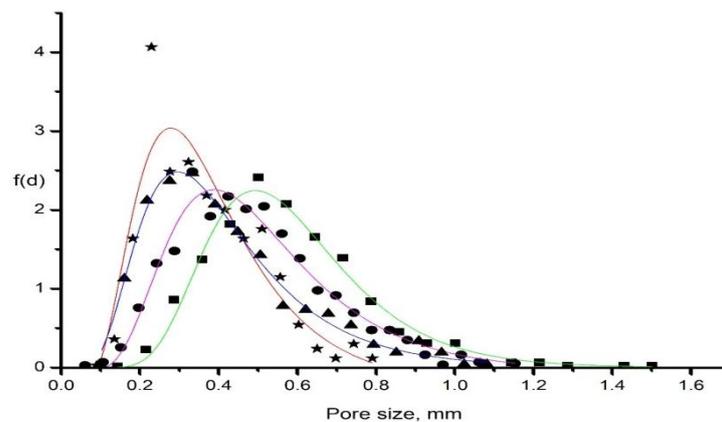


Figure 4. Numeric pore size distribution of foam concrete: ■ – 500 kg/m³; ● – 600 kg/m³; ▲ – 700 kg/m³; * – 800 kg/m³.

It was established that the distributions of pore size in the range of apparent densities of foam concrete from 500 to 1000 kg/m³ is good described by the lognormal distribution law.

Table 2 shows the main characteristics of the pore sizes distribution. It can be concluded from Table 2 that increasing density of foam concrete correlates to the reduction in the median pore diameters.

The correlation between apparent density and median pore size is shown in Fig. 5 and is well described by linear equation.

$$\rho = a - bd, \quad (2)$$

where ρ – apparent density, kg/m³; d – median pore size, m; a , b – constants (for the specified data: $a = 1752$ kg/m³; $b = 2284$ kg/m⁴).

Table 2. The value of both median diameter of pores and mode (the value that appears most often) vs. apparent density

Apparent density of foam concrete, kg/m ³	Median diameter of pores d_{50} , mm	Mode diameter of pores, mm
500	0.57	0.56
600	0.46	0.33
800	0.39	0.23
1000	0.34	0.23

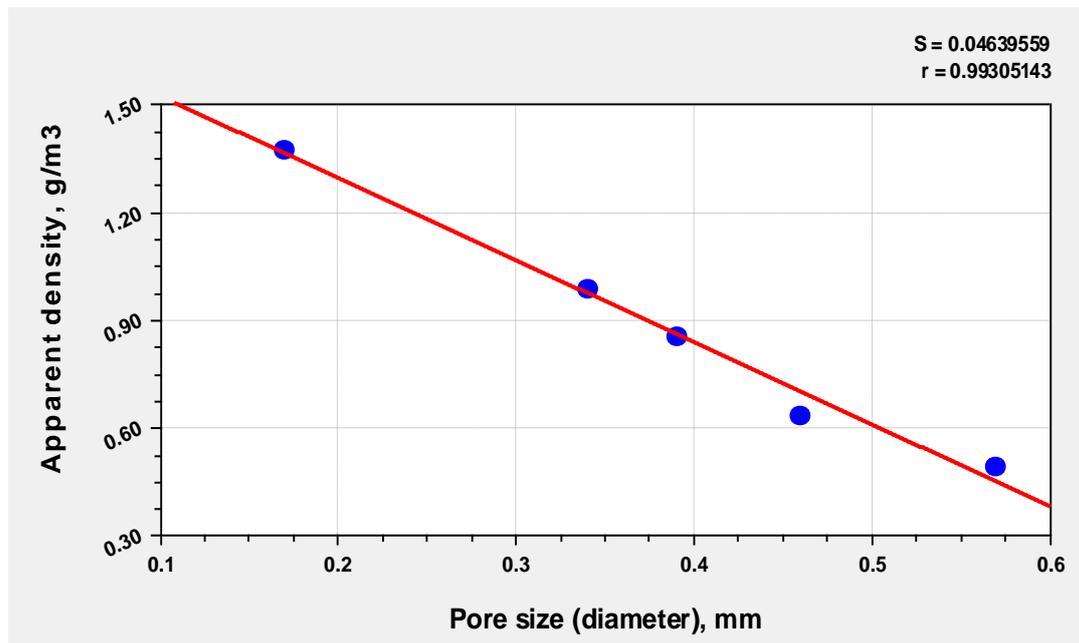


Figure 5. Apparent density vs. median pore size of foam concrete.

S – standard deviation; r – correlation coefficient.

The coefficient of thermal conductivity, one of the main parameters, obviously depends on the structure (porosity and pore size) and the apparent density of the material. Evidently, the coefficient of thermal conductivity should increase as the

apparent density increases, and decrease as the pore size increases. And that is what Fig. 6 and Fig.7 demonstrate.

These correlations are well described by following equations:

$$\lambda = c_1 f_1^p, \tag{3}$$

$$\lambda = c_2 f_2^d, \tag{4}$$

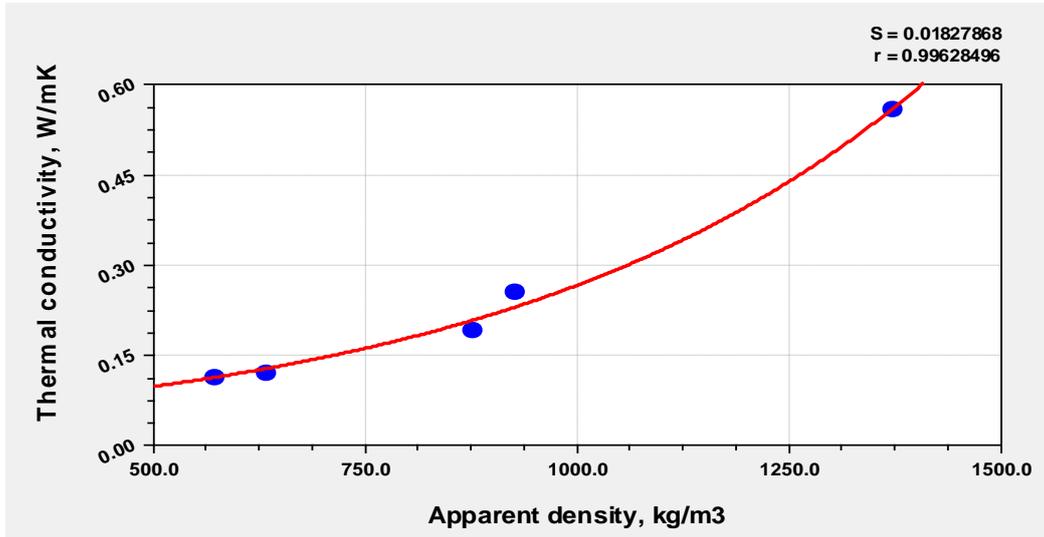


Figure 6. Coefficient of thermal conductivity vs. apparent density of foam concrete.
S – standard deviation; r – correlation coefficient.

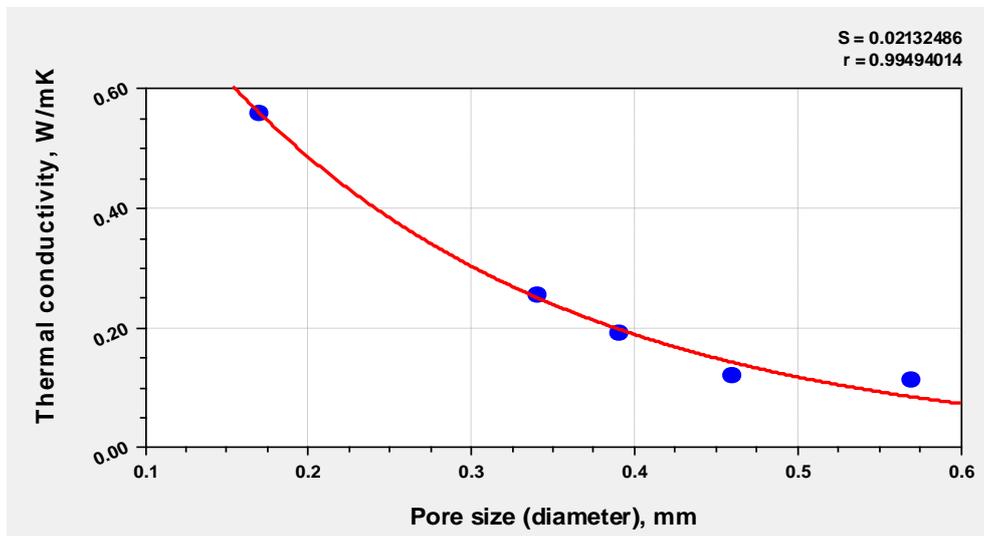


Figure 7. Coefficient of thermal conductivity vs. median pore size of foam concrete.
S – standard deviation; r – correlation coefficient.

where λ – coefficient of thermal conductivity, W/mK; ρ – apparent density of foam concrete, kg/m³; d – median pore size, mm; c_1, c_2, f_1, f_2 – constants (for the specified data: $c_1 = 3.624 \cdot 10^{-2}$; $f_1 = 1.002$; $c_2 = 1.246$; $f_2 = 8.951 \cdot 10^{-3}$).

An increase in apparent density (which is linked with reduction of pores size) leads to reduction in strength (Fig. 8). The correlation between apparent density and compressive strength described by an equation:

$$\sigma = h\rho^{kp}, \quad (5)$$

where σ – compressive strength, MPa; ρ – apparent density, kg/m^3 ; h, k – constants (for the specified data: $h = 0.245$; $k = 3.98 \cdot 10^{-4}$).

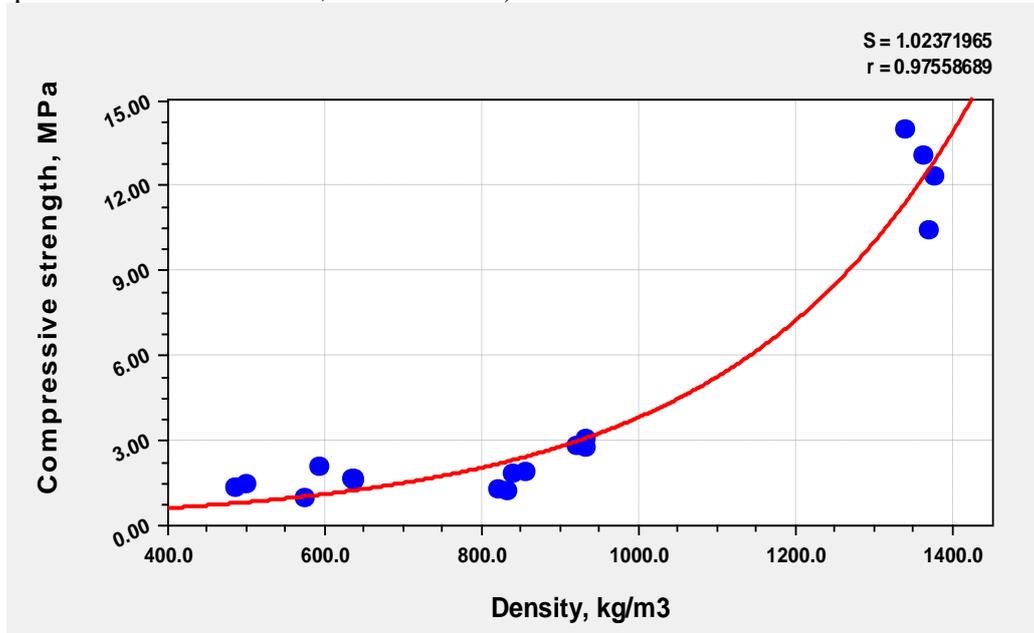


Figure 8. Compressive strength vs. apparent density of foam concrete.
S – standard deviation; r – correlation coefficient.

The values of compressive strength and coefficient of thermal conductivity of foam concrete produced by means of VJA fully meet the Russian standard «GOST 25485-89. Cellular concretes. Specifications» and French standards to the foam concretes.

4. Conclusions

The VJA as a foam generator has been investigated and the optimal foam generation mode has been determined.

Foam concrete specimens with apparent density from 500 to 1500 kg/m^3 have been produced by use of the foam generated in VJA.

The median size of pores, pore sizes distributions and its approximating functions have been identified for densities from 500 to 1000 kg/m^3 . It was found that the distributions of pore size obey the lognormal law. The median pore size varies between 0.34 and 0.57 mm depending on the apparent density.

The basic characteristics of foam concrete such as apparent density, compressive strength, coefficient of thermal conductivity have been determined.

The correlations between the pore size and basic characteristics of foam concrete were established: as the median pores size becomes smaller the density increases; an increase in median pore size leads to reduction in strength and increase in thermal conductivity.

The values of compressive strength and coefficient of thermal conductivity of foam concrete produced by means of VJA fully meet the Russian standard «GOST 25485-89. Cellular concretes. Specifications» and French standards to the foam concretes. Besides, one of the substantial preferences of the VJA as a foam generating device that there is no compressor required, that allows to reduce the number of units in the production scheme and diminish the cost of foam concrete manufacturing.

Based on the obtained data it may be concluded the VJA is an effective foam generator for foam concrete production, and determined correlations allow to produce foam concrete with preset characteristics. The knowledge about these correlations will give a good tool to control the production processes for industrial staff.

Further work will be done in the deeper understanding of the physics of foam concrete structure and explanation of the correlations found in the presented paper.

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