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Fabrication of foam concrete by use of novel foam generator — vortex jet apparatus: study of foam concrete properties

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Abstract

A new method of foam concrete production by use of vortex jet apparatus (VJA) is studied. The foam produced by VJA exhibits high stability and narrow size distribution of the bubbles' diameter and the latter correlates well with diameters of foam concrete pores. VJA is a compact device allowing to generate foam without compressor, inhausting the air from the ambience resulting from vacuum in the center of vortex flow. Owing to additional opportunities (compared e.g. with usual axial ejector) like ability to suck the air, longer residence time and higher kinetic energy transformed further into dispersion of the bubbles new device lets to control the parameters of the foam and the density of the foam concrete, thus allowing to create foam with smaller diameter of the bubbles and higher stability. A mechanism of large pores isolation during water absorption tests was proposed. Main properties of foam concrete produced in this study: real and apparent densities, open and total porosities, thermal conductivity and thermal capacity, water absorption, compressive and flexural strengths have been measured; their values fully meet the requirements of Russian and French standards. The main part of pores was attributed to the open porosity because of very close values of total and open porosities. Equations characterizing relative mass of water absorbed by the foam concrete and the fraction of open porosity filled with the water were found as functions of apparent density. It was found that foam concrete production with wide range of densities (from approx. 480 till 1640 kg/m^3) is easily attainable by means of VJA. Hence, the VJA could be used as an effective tool for foam generation and foam concrete production.

Keywords

Foam concrete, foam generation, foam stability, foam concrete durability, thermal conductivity, water absorption, open porosity, pore structure

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1 Introduction

Foam concrete (to be more exact - autoclaved aerated concrete (AAC), also known as autoclaved cellular concrete (ACC)) production method was proposed and patented by a Czechoslovakian, Mr. E. Hoffman for the first time in 1889. The aeration was produced by carbon dioxide generated in the reaction between hydrochloric acid and limestone. Powdered aluminium and calcium hydroxide were used as aeration agents in cementing mixtures by Aylsworth & Dyer in the USA in 1914. Later it was perfected in the mid-1920s by the Swedish architect and inventor Dr. Johan Axel Eriksson, working with Professor Henrik Kreüger at the Royal Institute of Technology [1].

Both generation of stable foams and outlooks of foam concrete production are extensively studied in several works. In the recent review of Amran et al. [2] an extended view on the foam (or 'foamed') concrete has been done. Foamed concrete is defined in their work as a light cellular concrete which can be classified as a lightweight concrete (density of 400–1850 kg/m^3) with random air-voids created from the mixture of foaming agents in mortar. Some citation from Amran et al. review [2]: "Historically, the Romans first realized that by adding animal blood into a mix of small gravel and coarse sand with hot lime and water and agitating it, small air bubbles were formed making the mix more workable and durable. Over the past 20 years, substantial improvements in production equipment and better superplasticizers, foaming agents have permitted the use of foamed concrete in a larger scale and many efforts have been made to study the characteristics and behavior of foamed concrete comprehensively in order to simplify its usage in structural applications."

Foam concrete possesses following superior properties: 1) low density which allows to save spends to the raw materials, transportation and operations costs; 2) thermal conductivity; 3) fire resistance; 4) acoustic impedance; 5) easier operations like drilling, sawing etc.

There are two different technologies of foam concrete production in general. First one is known as AAC (autoclaved aerated concrete) or ACC (autoclaved cellular concrete) and produced with the use of gas (hydrogen) generated during any reaction between reactants added into the cement mortar (the most popular are limestone and Aluminum powder for the further reaction between CaO, Al and water). The reactions are known:

$$2Al + 6H_2O = 2Al(OH)_3 + 3H_2;$$

$$2Al + 3Ca(OH)_2 = Ca_3(AlO_3)_2 + 3H_2;$$

$$2Al(OH)_3 + Ca(OH)_2 = Ca[Al(OH)_4]_2.$$

For the production of autoclaved aerated concrete not only Aluminum, but special equipment – autoclave and additional energy is needed.

The second kind of foam concrete technology uses the mixture of cement, sand and water (cement mortar) with foam prepared beforehand. For this method a foaming agent is only compulsory component. Gas is usually an air blowing with the compressor. In this paper we will show opportunity to avoid the use of compressor and therefore to decrease the total costs of foam concrete production. Autoclave could be also used but for acceleration of foam concrete hardening some special additions could be used.

In this paper we will discuss the fact that not only foaming agents, but the method of foam production, as well as the cement mortar to the foam ratio control the concrete density through a size and distribution of air bubbles created in the cement paste mixture. Foam bubbles are defined in [2] as enclosed air-voids formed due to the addition of foaming agent. The foaming agents are commonly synthetic, protein-based, detergents, glue resins, hydrolyzed protein, resin soap, and

saponin [2], often the waste of food production or farm waste. An extended review of foam concrete preparation was performed in [2]. Some references of [2] are used hereinafter for the analysis the state of art.

The influence of foaming agent on the properties of foam concrete has been studied in [3–6]. The content of the foaming agent has a considerable effect on properties of both fresh and the hardened concrete. It is reported that the excessive foam volume results in a drop in flow [7, 8]. However, the flow is significantly affected by mixing time and therefore with the energy introduced into the flow. As reported, the greater the mixing time, the more is the amount of the entrained air, albeit, prolonged mixing may cause the loss of entrained air by dropping the air content and by destruction of the foam walls dividing the bubbles [9, 10].

As indicated in [2], the stability of foaming agent should be confirmed according ASTM C 869-91 and ASTM C 796-97 test procedures [11–13]. Typical values of the air voids range in most foamed concrete applications is between 6% and 35% of the total volume of final mix [14]. As introduced by ACI 523.3R-93 [15] the foam is produced by blending the foaming agent, water and compressed air (generated by an air-compressor) in pre-calculated proportion ratios in a foam generator calibrated for a discharge rate. Another production process was also introduced by Valore Jr. and by Taylor [16–18]. In their approach, the foam quality was influenced by the dilution ratio of the foaming agent, the process of forming, the compressed air density and pressure, and the adding and blending process with the mortar. In the presented paper we will discuss among the other issues the modified foam generation process, where the air is not to be compressed due to ability of foam generator to suck in the air from the ambient atmosphere.

The foam quality was of great importance because it represented the stability of foamed concrete and also it affected the strength and stiffness of the resultant foamed concrete [19]. In foamed concreting, the compressive strength is mostly affected by the foam content rather than its reliance upon the water/cement ratio [20]. Particularly, the compressive strength of foamed concrete is highly influenced by the type of foaming agent such as by protein based foaming agent more than synthetic foaming agent [4].

However, Wee et al. [21] reported through both experimental and numerical studies, that the inclusion of air bubbles in foamed concrete is more influential on compressive strength than on modulus of elasticity. It was recommended in general to add the foam immediately after its production in a viscous state to guarantee the stability of the foam. Stability can be further achieved by addition of foam stabilizing fluorinated surfactant into the foamed concrete [22]. In the presented work the foam with increased stability was used, therefore this problem is not so acute.

Not only foam content but water/cement and sand/cement ratios as well as quality of water [2] have strong influence on the properties of foam concrete. A water requirement in foamed concrete depends upon the constituents and the use of admixtures. Water content is also governed by the uniformity, consistency and stability of the desired mix [23, 24].

It was reported that low water content caused the mix to be too stiff and bubbles broke during mixing which resulted in an increased density [19, 25]. Similarly, at high water content, the slurry was too thin to hold the bubbles which caused segregation of the foam from the mix and consequently the final density was increased [19]. Hence, some optimal water concentration in the slurry looks as solution to retain bubbles. Valore Jr. [18]

reported that whenever the water/cement ratio was increased the sand proportion should be increased as well. He also noted that the addition of the proper amount of water in a mix should be visualized by consistency rather than by a predetermined water/cement ratio [16, 18].

It was recommended that the water to cement ratio should be minimized because the excessive volume of water causes segregation of foamed concrete during casting which affects the workability performance [26].

In general, the water to cement ratio range was suggested to be from 0.4 to 1.25 or in a range from 6.5% to 14% of the target density [27, 28]. The amount of water must be appropriate to guarantee that the workability of the premixed paste or mortar was acceptable for foamed concrete fresh design mix. Otherwise, the cement would absorb water from the foam and cause rapid degeneration of the foam [11, 28, 29]. As discussed in [2], the optimum water/cement ratio should be limited between 0.5 and 0.6 as suggested by British Cement Association [29].

The role of plasticizers used to improve workability and to stabilize the compatibility of foamed concrete is also discussed in [2]. They are practically defined as water-reducers used to increase the performance of fresh concrete by easing its mobility and plasticity; however, no significant effects on concrete segregation were observed [30, 31]. One of the most popular plasticizers in the foamed concrete production is fluorosurfactant (FS1). As mentioned in [2], the FS1 is generally used to reduce the amount of mixing water and also marginally accelerates the strength gain of the produced foamed concrete. The plasticizers content is approximately between 0.45% and 5% of foaming agent volume [32].

Fibers used in the foamed concrete are either synthetic or natural fibers, namely: alkali resistant glass, kenaf, steel, oil palm fiber, and polypropylene fiber [14, 33–35]. The volumetric fraction of these types of fibers range was lying between 0.25% and 0.4% of the total volume of mix design constituents [36]. Previously, it was reported that a significant improvement of mechanical and impact properties was observed when the foamed concrete was reinforced with polypropylene fibers [37, 38]. It was later revealed that the usage of fiber reinforcement could change the typical behavior of foamed concrete from brittle into ductile elastic–plastic [38].

In the review of Amran et al. [2] some recommendations of foamed concrete mix proportion are presented. There are no specific mix proportion methods to obtain targeted properties in foamed concrete. However, some trial and error methods are utilized to design the appropriate mix such as net water content, content of foam by percentage, and binder content. These methods are considered to be sufficient calculation techniques to propose the desired strength [33, 39]. Kearsley [40] proposed the system of two equations in order to calculate the mix proportions based on cement and the foam contents.

There are two techniques that could be used in the process of foam concreting; pre-foaming method and mix-foaming method. The pre-foaming method encompasses generating the base mix (mortar) and stabilizing the preformed aqueous foam independently. Then, the foam is completely blended into the base mix. The pre-formed foam could be produced by either so-called ‘dry’ or ‘wet’ method.

The ‘dry’ foam is generated by pushing the foaming agent solution over sequences of high density constraints and by pushing compressed air concurrently inside a mixing chamber. The dry foam is quite stable and generates bubbles with sizes smaller than 1 mm. The small sized bubbles facilitate a stable and uniformly blend of foam with the basic material in order to produce pumpable

foamed concrete [6]. The 'wet' foam is generated by spraying the foaming agent solution through a fine mesh, the 'wet' foam bubble size is generally between 2 and 5 mm and the foam produced is somehow less stable compared to the dry foam [41]. In the presented paper we will discuss the opportunity to prepare 'dry' foam by means of other technique.

In the mixed foaming method, the surface active agent is practically mixed along with base-mix constituents specifically cement slurry during the mixing process and the obtained foam results in a cellular structure in the foamed concrete [42].

For the discussion about properties of foam concrete in fresh and matured conditions and the analysis of the influencing factors we recommend to attend to the review of Amran et al. [2] as well as the papers mentioned in their work. It is worth noting to mention that an increase in water/cement ratio and reduction of the foam content proportionally increase the plastic density and reduces the consistency and rheology of foamed concrete [7]. It was reported that the consistency of foamed concrete was reduced when the foam content was added due to a higher volume of air content while addition of superplasticizers increased the flow rate [12].

An extended overview of foam formation was the topic of Pugh's paper [41]. High stability of foams prepared from detergents, proteins, long-chain fatty acids was shown. As stated in [41], lifetimes increase exponentially with concentration of surfactant and a plot of foam lifetime versus concentration, produces an S-shaped profile. In these systems, the film thinning times are relatively short (compared to the total foam lifetimes) and the stability of these systems is controlled by the balance of interfacial forces which equilibrate, after drainage has been completed. The films are usually fairly thin (within the range of the intermolecular forces), and, in the absence of external disturbances (evaporation, vibrations, temperature gradients etc.) then the foams can remain stable almost indefinitely.

The ***motivation of this paper*** is to study the advantages of recently developed vortex jet apparatus (VJA) [43 - 49] applied for foam generation with following foam concrete production. In our previous research the ability to obtain very stable foam with quite small bubbles has been shown. It is worth noting to mention that the stability of the foam (time of half-decay of the foam in the glass) was approximately 5 times higher (3200–3800 sec) than it is necessary (720 sec) according to Russian Standards (GOST) for the foam used for fire extinguishing with first used foaming agent (PO-6SP) and between 5200 and 8100 second for the foam prepared with the second foaming agent (GreenFroth frother, Italy).

The ***aims of the paper*** are to study experimentally the properties of the foam concrete obtained by the new method (first aim) as well as to build up the cause-and-effect relation between the process parameters of the foam concrete production process by means of new method and the main properties of foam concrete (second aim, see also section *Theory and calculation* for details).

2 Materials and methods

Samples have been produced by means of vortex jet apparatus (section 2.1) in the laboratory at the department of Optimization of Chemical and Biotechnological Equipment of Saint Petersburg State Institute of Technology and further experimental analysis (section 2.2) was made in the Research center of Material Science ('C2MA') of Ecole des mines d'Alès (in 2017 renamed as IMT Mines Alès).

2.1 Description of Vortex jet apparatus (VJA) and its advantages concerning foam preparation

The main feature of the vortex jet apparatus (VJA) [44] (Figure 1) compared with

conventional axial jet devices (ejectors) is that a workflow is fed into tangential inlet 5, whereby the flow is swirled. Moving from the cylindrical zone 2 in the tapered region of a confuser, adjacent to the neck 3, the radius of rotation of the workflow is reduced resulting in increase of the angular velocity as well as the increase of the tangential component of velocity. In addition, due to the tapering shape of the confuser 2 the axial component of velocity at the neck 3 also reaches its maximum.

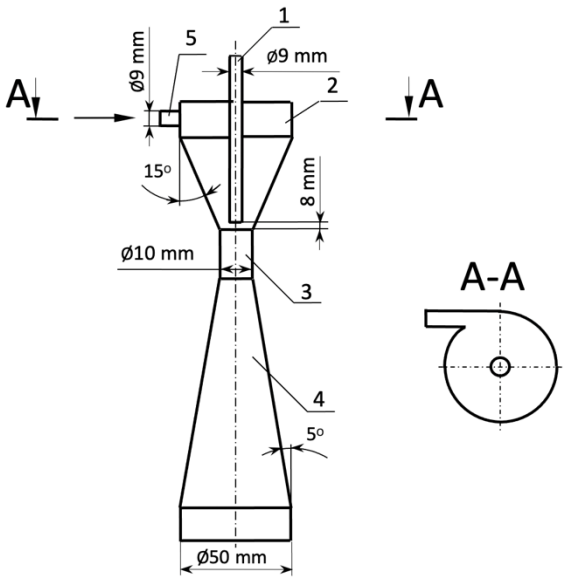


Figure 1 — Schematic of vortex jet apparatus [44]: 1 — nozzle; 2 — confuser; 3 — neck; 4 — diffuser; 5 — tangential inlet

Thus, in the entrance to the neck, axial and circumferential components of the fluid velocity have a maximum value. As a result, the kinetic energy of the flow increases in VJA more rapidly compared to the conventional jet devices (ejectors). Indeed, the specific kinetic energy in a conventional jet devices consists of only the axial velocity component w_a (see Figure 1) $E_{k.eject} = \rho w_a^2/2$. In a vortex jet apparatus, due to the tangential feed of the active flow, in addition to the axial velocity component w_a a tangential velocity component w_φ also acts, therefore the specific kinetic energy in the VJA contains both translator and rotational terms as follows: $\mathrm{E_{k.VJA}} = \rho\left(w_a^2 + w_\varphi^2\right)$. Hence the higher is tangential velocity, the larger is difference between specific kinetic energy for VJA, e.g. at typical for water in real VJA values $w_a = 5.46$ m/s, $w_\varphi = 22.38$ m/s and for usual ejector with a straight active phase supply ($w_a = 5.46$ m/s) we found

$$E_{k.VJA} = 260.2kPa \gg E_{k.eject} = 9.8kPa.$$

Because of the high fluid velocity in the annular gap, in accordance with the energy conservation law, the pressure becomes minimal in this zone. Namely, as shown by our experiments, the local pressure sinks to the value minus 98 kPa (vacuum, or 2 kPa of residual pressure), which leads to the "cold boiling" of liquid (cavitation), and the gas bubbles form a rotating conical cord in the central part of the apparatus.

One of the substantial advantages of VJA is that this device combines two impacts on the foam: so-called condensation method (i. e. creation of the bubbles by means of pressure drop lower that saturation pressure) and dispersing method (by means of high level of shear stresses, elongation of bubbles and some types of instability).

Foam is a disperse system consisting of cells — gas bubbles separated by liquid films. Usually, gas is regarded as the discontinuous phase and the liquid is a continuous phase. Properties of foams are largely determined by the conditions of their production, factors influencing their properties and destruction. There are the following main properties characterizing the foam system: foam-forming ability of the solution; multiplicity; stability (sustainability); dispersion.

Foam is widely used in many industries and in everyday life: foam detergents; in firefighting; for the production of hydro and sound insulation, foam concrete; the use of froth flotation for the beneficiation of mineral resources; it is widely used for the manufacture of heat- and sound-insulating materials, etc.

In [46] the application of vortex jet apparatus as a foam generator was investigated. For laboratory studies of VJA foam generating installation was assembled, including glass model of VJA with diameter of the widest part of diffuser and confuser of 50 mm and neck diameter of 10 mm. A copper tube with an inner diameter of 4 mm and outer diameter of 6 mm was used as a nozzle, which was furnished with the sealing unit allowing adjustment of the axial position of the nozzle. The VJA was fed with a 6% solution of foaming agent PO-6SP (synthetic hydrocarbon biodegradable frother). Foam from the VJA was fed into a cylindrical organic glass collector with a diameter of 400 mm and a volume of 30 liters. Foam stability was determined as the time of the destruction of 50% of the volume of foam in the 1 liter laboratory graduated cylinder made of glass. The results of the experiments are presented in Figure 2.

Two types of experiments have been performed: 1) with an immersion of the outlet pipe of the VJA under a layer of water; 2) without immersion. In the first case, a swirling flow moving along the walls of the diffuser in the VJA was formed, and there were additional air suction through the outlet of the VJA, i.e., through the diffuser. It also led to some reduction in performance of liquid (Figure 2).

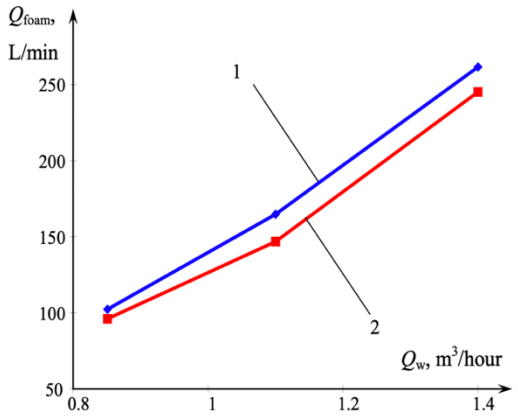


Figure 2 — The dependence of the VJA foam performance on the fluid flow rate:
1 – with immersion of VJA diffuser; 2 – without immersion of VJA diffuser

Research at this stage has led to the following results:

1) Vacuum achieved in the VJA allows injecting air into VJA without using compressor, at least for low expansion foam.

2) The ratio of the foam, or expansion ratio, or multiplicity (volume of the foam related to the volume of liquid used for foam production) obtained in the VJA in the studied range of feed water flow rates (from 0.85 to 1.4 m^3/h) ranged from 7 to 11 and was weakly dependent on the location of the exhaust pipe (immersed under the liquid level or above it).

3) It is possible to obtain quite fine foam with high stability in VJA. The stability of the foam obtained in the VJA was higher than 3200 s (at the expansion ratio of the foam of 7), and reaches 3800 s (at the expansion ratio of 11–12). This makes it possible to rely on the preservation of stability of the foam during its transportation through pipelines to process up to several tens of meters that can be used both to extinguish the fire [46], and in the production of foam concrete [49].

Pressure at the input of frother water solution (active phase) was 1.375 bar and at the entrance of air (induced phase) into the nozzle it was in the range of –4 to –4.5 kPa (vacuum). Frother water solution flow rate was kept as high as 1.25 m^3/h in all cases.

The conditions of samples' preparation are presented in Tables 1 and 2. Table 3 represents foam concrete mix proportion during experiments. GreenFroth frother (Italy, made from the animal waste) was used for foam production in further experiments.

Table 1 — Conditions of samples' preparation (samples 1–16)

Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Grade of cement	CEM I 42,5N (M500 D0*)										CEM I 32,5N (M400*)					
Raw weight of the sample, kg	0.385	0.350	0.360	0.155	0.155	0.155	0.420	0.420	0.160	0.160	0.220	0.220	0.220	0.230	0.230	0.230
Raw apparent density, kg/m^3	1500	1370	1400	605	605	605	1640	1640	625	625	860	860	860	900	900	900

*According to Russian State Standards (GOST)

Table 2 — Conditions of samples' preparation (samples 17–28)

Sample number	17	18	19	20	21	22	23	24	25	26	27	28
Grade of cement	CEM II 42,5N (M500 D20*)											
Raw weight of the sample, kg	0.130	0.130	0.130	0.170	0.170	0.170	0.370	0.370	0.370	0.240	0.240	0.240
Raw apparent density, kg/m3	507	507	507	664	664	664	1445	1445	1445	930	930	930

Table 3 — Foam concrete mix proportion for preparation in VJA

Apparent density, kg/m3	500	600	800	1000
Cement, kg	300	310	320	350
Sand, kg	100	210	400	560
Water, liter	150	160	160	180
Foam, liter	750	680	550	430

2.2 Apparent density

Apparent density was measured by two methods: 1) geometrical method and 2) open porosity method (according to the French National Norms NF P18-459).

Geometrical measurements of the samples dimensions were performed by means of sliding caliper with accuracy of 0.02 mm, their cross-section has been measured at the both ends of sample and then the mean value has been found for each of them. Before weighing and sizes' measurements the samples have been cut by diamond saw with electrical drive. The weight of the samples has been defined by means of scales 'Mettler PM 2000' (maximum weighing capacity 2100 grams, readability 0.01 gram, reproducibility 0.005 gram). The scales were placed onto stabilized table with stone tabletop. The air in

the room was conditioned: temperature was stabilized at 20.4-20.5 °C, relative humidity was held at 50%. The balance was covered with the carton box from four sides to avoid impact of air flows to the readouts of the device.

The scales has been preloaded with the piece of the concrete (574 grams) for improvement of the precision of measurement (to work in the middle range of the scales). The mass of samples lied between 112 grams and 384 grams.

Open porosity measurements method is described below in the corresponding section.

2.3 Real density

Real density of the bulk solid was measured by means of automatic pycnometer 'micromeritics AccuPyc 1330' of Micromeritics Instrument Corporation, used with helium gas after vacuumization.

The samples have been dried in a drying cabinet at 105 °C within 72 hours, and then milled in the laboratory scale vibrational mill within 8 second till the maximum size of the powder of 0.01 mm has been obtained. Scales used for the mass measurements Sartorius QUINTIX124-1S (maximum weighing capacity 120 grams, readability 0.0001 gram).

Two samples were taken from each powder; the results (mean real density of solid powder) were compared and have been very close (the difference not exceeded 0.3%). For each sample 3 measurements were made, average values and standard deviations were calculated as mean for two sets of 3 measurements.

2.4 Open porosity

Open porosity of the samples was measured according to the French National Norms NF P18-459. Samples with dimensions 40 mm × 40 mm × L (L was in the range of 60-70 mm) were dried within 36 hours in the drying cabinet at 90°C. The samples have been exposed in the vacuum chamber at 25 mbar within 4 hours, and then the water at ambient temperature was fed into the chamber. The samples have been immersed into the water within 24 hours, first under vacuum, and then the pressure was set to the atmospheric level for the full saturation of the pores in the foam concrete structure.

After saturation the samples of foam concrete have been weighed by means of scales 'Mettler PM 2000' mentioned afore in section 2.2 by two different ways: 1) on the scalepan immersed in water (so called hydrostatic weighing) and 2) by usual way after wiping with the wet cloth wringed out to prevent excess wiping of the samples. The results of weighing were calculated according to the NF P18-459 recommendations.

2.5 Total porosity

Samples with dimensions 40 mm × 40 mm × L (L = 60–70 mm) were dried within 36 hours at 90 °C and weighed after cooling down the room temperature (mass of sample M_{dry}). The samples have been exposed in the vacuum chamber at 25 mbar within 4 hours before the tap water was fed into the chamber. The samples have been submerged into the water within 24 hours. It is worth noting to mention that even after 18–19 hours of wetting of the samples some of them were not drown in the vacuum conditions in the chamber. They drowned just when the tap on the vacuum chamber has been opened, allowing the water to penetrate into the pores at ambient (atmospheric) pressure.

After full impregnation the samples have been weighing by two methods: first submerged (drawn) in the water (mass M_{water}) and then after short wiping by wet serviette of extend water (but not the capillary water in the pores) (mass M_{air}).

Scales used for the mass measurements was 'Mettler PM 2000' (for further details of the scales look at the section 2.2).

Totally open porosity of 10 samples with different density has been measured. For this aims pycnovolumetrical tests by automatic pycnometer 'micromeritics AccuPyc 1330' have been performed. Examples were milled within 8 seconds in the vibrational mill till the powder substance and dried within 72 hours at 105°C. For each powder sample 3 measurements of real density ρ_{real} were made, average value and standard deviation were calculated at once. Two samples were taken from each powder; the results were compared for repeatability. Resulting average value and standard deviation were calculated for 6 measurements set.

2.6 Thermal conductivity and thermal capacity

Thermal diffusivity being measured first by means of flash method by means of Linceis XFA device (method of transient thermal diffusivity of the heat impulse created by laser beam). For this aim the discs of foam concrete and usual concrete with thickness of 3 mm and diameter of 25 mm has been cut. Unfortunately, both for concrete and foam concrete the method gave approximately 100 folds smaller values compared with the published in the literature. This effect could be probably attributed to the non-isotropic properties of very thin samples, for which the sizes of the pores are comparable with the thickness of the samples. The other reasons could also have some impact.

For further investigations we have chosen method of transient thermal conductivity measurements using a device 'Neotim FP2C' equipped with a combined thin film sensor including small diameter V-type wire heater (heat source) and a thermocouple. The film sensor was located between two pieces of foam concrete belonging to the same piece of foam concrete (made in the same batch) and therefore having identical properties. Sizes of the pieces were 40×40×60 mm^3. Additional load (approx. 0.5 kg) to the upper piece has been applied to improve the thermal contact between thermocouple and foam concrete pieces. The software supplied with the device has been used for continuous detection of the temperature at the surface between two pieces. To control the stability of the temperature before each measurement test the temperature has been measured with the accuracy of 0.01°C; steady state was postulated if the measured temperature was constant (±0.01°C) within at least 1 minute. The power of the heat source was adapted according to the recommendations of the 'Neotim' producer concerning the expected thermal conductivity of samples. Each measurement was repeated 2–4 times to obtain acceptable repeatability. Response curves were analyzed in automatic mode by means of specialized software provided with the device, which has checked until the line in logarithmic scale could be satisfactory described by linear low, corresponding to the regular heating regime.

Totally the thermal conductivity of 14 samples (7 pairs) of different density was measured.

Thermal capacity was measured by means of Diamond DSC Perkin-Elmer device. The samples have been milled to the fine powder before measurements. Eight samples with all the range of densities have been used (numbers 2, 8, 11, 15, 19, 22, 25, 28, see Tables 1 and 2).

2.7 Compressive strength

Compressive strength was measured by use of 40 × 40 × 40 mm^3 samples (24 samples with all the range of densities were used) at the testing device launched by oil pump equipped with the QuantX 4 computer program (ver. 4) which allowed to control the instant values of oil pressure and the compressive load. Surface of the load was 16 cm^2 in all cases, the time of loading varied from 14 to 342 seconds (depending on the strength of the samples), whereas speed of loading was kept constant (0.1 MPa/s for three first

samples and 0.05 MPa/s for all the others). Preload of 0.15–0.20 kN was used before starting of measurements to ensure the tight contact between the samples' surface and the loading surfaces.

2.8 Flexural strength

Flexural strength test was performed at the Zwick/Z010 testing device with the three-point bending method (24 samples with all the range of densities were used) at velocity of loading pin of 0.002 mm/s to avoid any shock-like type of loading. The testing device was equipped with textXpert II computer program (Zwick/Roell) which was used to set the parameters of loading and to acquire the instant results of tests, i.e. load, strain and stresses. The sizes of middle cross-section of each specimen at the flexure tests were measured with 0.01 mm accuracy by sliding caliper. The breadth of samples was between 35.9 mm and 39.6 mm and the height was in the range of 35.3 mm and 41.28 mm. Maximal deformations by flexure (related to the height of the middle cross-section) were in the range of 0.534% to 2.390 %.

2.9 Water absorption

Examples with dimensions 40 mm × 40 mm × L (where L = 60–70 mm) were dried within 36 hours in the oven at 90–105 °C by two steps: 16.5 hours at 90 °C, continued 24 hours at 105 °C.

The same samples (number 1, 2, 7, 15) have been used before for open porosity experiments (see section 2.5). The new samples (number 18, 20, 24, 27) are the pieces obtained from the flexure experiments only as a rest parts of samples after crushing (from the side close to the bearing of test device, where the stresses were minimal), i.e. their structure admittedly was not changed before.

It was interesting to compare these two sets of samples to reveal the influence of preliminary saturation of the porous structure of the foam concrete with the water under pressure difference on the fraction of the pores open for the water absorption. Evidently some of the walls could be destroyed by the water both due to the impregnation into the cement-sand structure and due to the mechanical impact of pressure difference between evacuated volume of pores and outer atmospheric pressure.

Samples number 1, 2, 7 were submerged in the water for 72 hours, whereas the samples number 15, 18, 20, 24, 27 were immersed into the water for 221 hours (sample 15 used for open porosity experiments was tested together with 'new' samples to compare the effect of porous structure changes during vacuum water saturation of the foam concrete). The mass of dry samples (without paraffin wax coating M_{dry} and with coating M_{paraf}) as well as wet samples M_{wet} were weighed by 'Mettler PM 2000' scales described above. Paraffin wax coating has covered all the sides of each sample excluding one square side with the sizes approx. 40×40 mm^2 (the real sizes were measure with sliding caliper) allowing one-dimensional penetration of water into the pores of the samples.

3 Theory and calculation

As mentioned afore, the main *general* goal of this work was to investigate the mechanical and thermophysical properties of foam concrete linked with such 'basic' property like apparent density. Further step of research will be aimed to build up the logical structure and mathematical model allowing to predict the properties of foam concrete (output parameters) by the control of the flow regime, concentrations and nature of surfactants etc. (**input parameters**).

The principal *particular* aim of this paper is to investigate the main properties of the foam concrete produced with the use of new device for foam generator – vortex jet apparatus. Besides, impact of the foam to cement ratio on the main properties (hereinafter

called as '**outer properties**') of foam concrete (density, strength by compressive and bending tests, thermal conductivity, water absorption, open porosity etc.) and influence of the pore structure on the outer properties are the other important questions of this work.

Hence, our 'dream' concept is to build a chain of **Controlled parameters**: Flow regime — Flow rates ratio (Liquid/Gas) — Shear stresses — **Properties of the foam**: Bubble's size distribution in the foam etc. — Concentration of components — **Inner properties of the foam concrete**: Distribution of the pores sizes/Fraction of open pores/Thickness of the walls between pores – **Outer properties of the foam concrete**: Density/Strength (compression, bending)/Absorption of water/Frost durability (number of cycles)/Permeability by the gas/Thermal conductivity.

In this paper the background to achieve this 'dream' concept was created by experimental investigation of outer properties of the foam as a function of controlled parameters. Dependence of mechanical and thermophysical properties of foam concrete on its apparent density as a 'basic' property (though it is pointed out as one of the outer properties) is a particular task of this paper.

Figure 3 represents a 'black box approach' — a look to an impact of input parameters (preparation of foam) and process parameters on the properties of foam concrete, whereas Figure 4 depictures more detailed approach – a chain of the impact of input parameters (preparation of foam) and process parameters (transformation of foam) on the properties of foam concrete. It would be expedient in the nearest future to study also impact of Water/Cement ratio, fraction of cement, fraction of surfactant etc. at the outer properties of foam concrete, too.

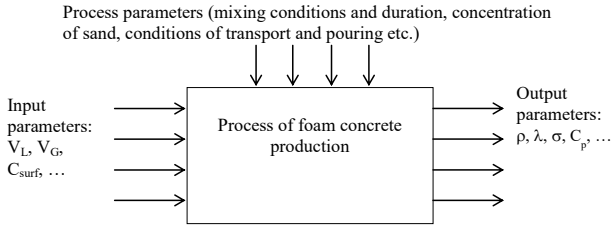


Figure 3 — General concept: scheme of the impact of Input parameters (preparation of foam) and Process parameters (transformation of foam) on the properties of foam concrete (black box approach)

The calculations have been performed as described in each of the following sections.

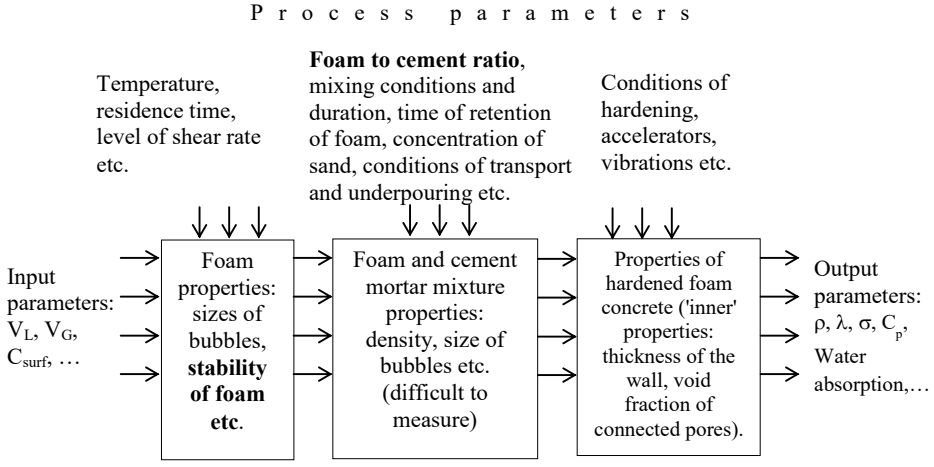


Figure 4 — Detailed concept: chain of the impact of Input parameters (preparation of foam) and Process parameters (transformation of foam) on the properties of foam concrete

3.1 Vortex jet apparatus and foam parameters

Additionally to the information presented in section 2 following parameters of foam to be discussed as necessary for further analysis.

For the flow rate of liquid $V = 1.25$ m^3/h and diameter of the inlet pipe $d_{in} = 9$ mm the mean velocity is

$$w_{\varphi.in} = 4V/\pi d_{in}^2 = 5.458 \text{ m/s}. \quad (1)$$

Specific kinetic energy at the inlet pipe could be estimated as

$$E_{k.in} = \rho\ w_{\varphi.in}^2/2 = 14.89 \text{ kPa}. \quad (2)$$

Specific angular momentum at the inlet pipe at the radius $R = 50/2 - 9/2 = 20.5$ mm

$$M_{in} = \rho\ R\ w_{\varphi.in} = 111.9 \text{ kg/(m s)}. \quad (3)$$

Tangential velocity in the neck assuming the radius of the vortex is close to the radius of the neck itself $R_{neck} = d_{neck}/2 = 5$ mm is:

$$w_{\varphi.neck} = M_{in}/\rho\ R_{neck} = 22.38 \text{ m/s}. \quad (4)$$

The axial velocity in the neck:

$$w_{a.neck} = 4V/\pi d_{neck}^2 = 4.42 \text{ m/s}. \quad (5)$$

Specific kinetic energy in the neck is a sum of the tangential and axial kinetic energies:

$$E_{k.neck} = \rho(w_{\varphi.in}^2 + w_{a.neck}^2)/2 = 260.2 \text{ kPa}. \quad (6)$$

Then, the increase of specific kinetic energy in VJA

$$\Delta E_k = E_{k.neck} - E_{k.in} = 245.3 \text{ kPa} \quad (7)$$

should be recovered by reversible pressure drop in the neck as well as by irreversible energy losses by viscous dissipation.

As it was recently shown in [50], high level of shear stresses is an attribute of VJA hydrodynamics which allows to de-agglomerate even carbon nanotubes. It was shown particularly that the maximal level of energy dissipation rate could be as high as 12000 W/kg (at the entrance to the neck) whereas the mean level in the neck is 3000 W/kg. At these conditions the level of shear stresses in the neck is in average about 10 Pa and the maximal is approx. 39 Pa.

To estimate the size d of minimal bubble forming in the VJA due to turbulent shear stresses let us consider that during the disintegration of bubbles dynamic balance of interphase tension and shear stresses takes place [51]

$$p = 4\sigma/d \approx \tau, \quad (8)$$

and the surface tension for the water with frother is $\sigma \approx 0.04$ N/m. Then, the size of the bubbles formed in the VJA are

$$d \approx 4\sigma/\tau = 4\times0.04/39 \approx 4.1 \text{ mm}. \quad (9)$$

This rough estimation correlates overestimates the real size distribution of the bubbles in the foam generated in VJA (mean diameter for the foam close to 1 mm) showing there are other mechanisms of bubble disintegration in VJA [47, 51]. Hence, some other types of impact like Kelvin-Helmholtz instability, shear stresses in the boundary layer, dynamic effects etc. could play more important role. See results of the comparative analysis in our paper [47].

3.2 Apparent density

Apparent density was calculated in all cases as follows (geometrical method)

$$\rho_{app.geo} = M/(L\times B\times H), \quad (10)$$

where M is a mass of the sample, kg; L, B, H are length, breadth and height of the sample, respectively, m. Studied foam concrete samples have had apparent density in the range from 492 till 1547 kg/m^3.

It was possible to calculate the apparent density from the open porosity measurements for five samples (see section 3.4 below).

$$\rho_{app.por} = M_{dry}\ \rho_{water}/\ (M_{air} - M_{water}), \quad (11)$$

where M_{dry} is a mass of dry sample, kg; M_{air} is a mass of the sample with the water in the

pores in the air, kg; and M_{water} is a mass of the water displaced by the sample impregnated with water, kg; ρ_{water} is a density of the water.

Index 'por' corresponds to the open porosity method and index 'geo' attributed to the geometrical method.

3.3 Real density

Mean value of real density of samples as well as standard deviation from 3 tests for each sample were calculated automatically by automatic pycnometer 'micromeritics AccuPyc 1330'.

Standard deviation of real density for two sets of 3 measurements was not higher than 3.2 kg/m^3, maximal value 2585 kg/m^3, minimal 2474 kg/m^3, i.e. the mean real density for all samples could be roughly specified as $\rho_{real} = 2553$ kg/m^3.

3.4 Open porosity

The open porosity ε_{open} of each sample was calculated as follows:

$$\varepsilon_{open} = (M_{air} - M_{dry})/(M_{air} - M_{water}). \quad (12)$$

3.5 Total porosity

Total porosity ε_{total} of the samples was calculated as:

$$\varepsilon_{total} = 1 - \rho_{app}/\rho_{real}. \quad (13)$$

3.6 Thermal conductivity and thermal capacity

Thermal conductivity values (in W/(m·K)) obtained experimentally were compared with theoretical prediction [52]

$$\lambda = 1.163\sqrt{0.0196 + 0.22\rho_{app}^2} - 0.14. \quad (14)$$

Thermal capacity of bulk concrete was measured, no additional calculation was used.

3.7 Compressive strength

Compressive strength σ_c was calculated automatically by QuantX 4 computer program during each test and was checked according to the well-known equation

$$\sigma_c = F/(L\times B), \quad (15)$$

where F is a compressive load by fracture, N; L and B are length and breadth of the sample, respectively, m.

3.8 Flexural strength

Flexural strength σf was also calculated automatically by textXpert II computer program and results were checked by equation (15) for three-point flexural tests:

$$\sigma_f = 3F_f\, L_s/(B\times H^2), \quad (16)$$

where F_f is a load at the middle of sample by fracture, N; L_s is a support span, m; B, H are breadth and height of the sample, respectively, m.

3.9 Water absorption

Relative mass of water absorbed by the foam concrete (%) was calculated as the ratio

$$WA = (M_{wet} - M_{paraf})\times 100/M_{dry}. \quad (17)$$

The fraction of open porosity filled with the water was determined as

$$\varepsilon_{wet}/\varepsilon_{open} = WA\times\rho_{app}\times 100/(\varepsilon_{open}\times\rho_{water}), \quad (18)$$

where ρ_{water} is water density, kg/m^3.

4 Results and discussion

4.1 Results of experimental investigations of Outer properties of the foam concrete

4.1.1 Apparent density

Apparent density values of the samples calculated by Eq. (10) (geometrical method) and from the open porosity by Eq. (11) are presented in Table 4 (samples 1–16); values determined only by first method are listed in Table 5 (samples 17–28). Relative error of apparent density was calculated by

$$Err\rho_{app} = \\ =(\rho_{app.por} - \rho_{app.geo})\times 100/\rho_{app.por}. \quad (19)$$

The derivation between each pair values of densities measured by different methods in

most cases was not higher than 4.14 %. Apparent density values were taken as a base values due to higher precision of measurements.

Mean value of apparent density (for each set of samples produced by identical conditions) was calculated either as an arithmetic mean from $\rho_{app.por}$ (samples 1–10, 14–16) or from $\rho_{app.por}$ (samples 11–13, 17–28) values.

It is important to mention, that the samples were prepared by following sets (letters A-J are assigned to them in Tables 1 and 2) and therefore have very similar properties within one group, hence, the properties of each sample could be attributed to the whole set.

Table 4 — Apparent density of the samples (samples 1–16)

Sample number	Apparent density $\rho_{app.geo}$ (geometrical method), Eq. (11), kg/m^3	Apparent density* $\rho_{app.por}$ (open porosity method), Eq. (11), kg/m^3	Relative error of apparent density Errρ_{app}, %	Mean value of apparent density ρ_{app}, kg/m^3	Name of the set
1	1427.9	1483.4	3.74	1420.4	A
2	1339.1	1357.3	1.34		
3	1362.1	1401.5	2.81		
4	605.6	ND	ND	634.5	B
5	593.3	637.5	6.94		
6	621.9	631.5	1.52		
7	1554.2	1600.6	2.90	1583.0	C
8	1538.9	1565.4	1.69		
9	569.8	ND	ND	573.0	D
10	576.3	599.4	3.86		
11	833.4	ND	ND	827.4	E
12	821.5	857.0	4.14		
13	831.2	ND	ND		
14	852.8	ND	ND	877.2	F
15	840.7	870.5	3.43		
16	856.1	883.9	3.14		

*ND – the density was not measured by open porosity method

Table 5 — Apparent density of the samples (samples 17–28)

Sample number	Apparent density $\rho_{app.geo}$ (geometrical method), Eq. (11), kg/m^3	Mean value of apparent density ρ_{app}, kg/m^3	Name of the set
17	501.7	494.6	G
18	487.4		
19	485.7		
20	636.3	636.5	H
21	636.7		
22	638.0		
23	1376.4	1373.6	I
24	1370.9		
25	1390.2		
26	932.1	927.2	J
27	922.3		
28	932.7		

4.1.2 Real density

Results of real density measurements are presented in Table 6.

All the values are in the narrow range of 2474 kg/m^3 (min.) and 2585 kg/m^3 (max) with mean value 2553 kg/m^3 (the estimations of standard deviation values are shown in Table 6). Hence, as expected, the real density of the bulk concrete weakly depends on the type of cement used for samples preparation as well as on the porosity of foam concrete.

Table 6 — Real density of the foam concrete samples

Sample number	Real density ρ_{real}, kg/m^3	Standard deviation of real density StD, kg/m^3	Mean value of real density ρ_{real} ± 3StD kg/m^3
1a	2566.6	1.8	2565.9±9.0
1b	2565.2	4.4	
2a	2563.3	4.2	2562.9±9.0
2b	2562.5	2.1	
5a	2581.5	4.3	2585.3±9.0
5b	2589.1	2.0	
8a	2581.7	1.4	2581.9±3.9
8b	2582.0	1.5	
11a	2551.6	3.4	2551.3±9.0
11b	2550.9	3.4	
15a	2568.2	2.2	2567.6±4.8
15b	2567.0	1.2	
19a	2472.7	3.1	2473.9±9.6
19b	2475.0	4.0	
22a	2514.2	3.5	2514.2±9.0
22b	2514.2	3.2	
25a	2559.9	2.6	2559.4±6.3
25b	2558.9	2.0	
28a	2569.2	2.0	2568.9±4.5
28b	2568.5	1.4	

4.1.3 Thermal conductivity and thermal capacity

Comparison of measured thermal conductivity (λ_{exp}) with calculated by Eq. (14) (λ_{theor}) and standard values according to Russian State Standard (GOST 25485-89) (λ_{GOST}, two points at apparent density 2400 and 2500 kg/m^3 belong to the bulk concrete according to Russian Rules for Building SNiP 23-02) are shown in Figure 5. Evidently in general thermal conductivity values of foam concrete produced by VJA comply with requirements of GOST 25485-89 and for several cases are even a bit smaller. Hence, foam concrete produced by means of VJA fully meets thermal insulation demands.

It is also clear that Eq. (14) overestimates both standard and measured results and should be corrected for further use.

Thermal capacity of eight samples with all the range of densities have been measured, showing quite close values (955±47 J/kg K).

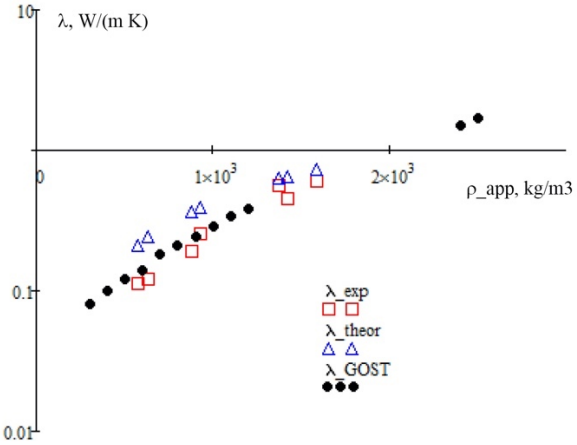


Figure 5 — Thermal conductivity of the foam concrete samples

4.1.4 Compressive and flexural strengths

The results of compressive and flexural tests are presented on Figures 6–8. Except several samples with duration of hardening exactly within 28 days all the other were matured within 3 months. As can be seen from the plots, there are a few visible differences between long term and short term matured samples. The durability of cement has an effect on the resulting strength parameters. Nonetheless, analyzing Figures 6 and 7 one can postulate that all obtained results belong to the same quite narrow ‘corridor’ of data.

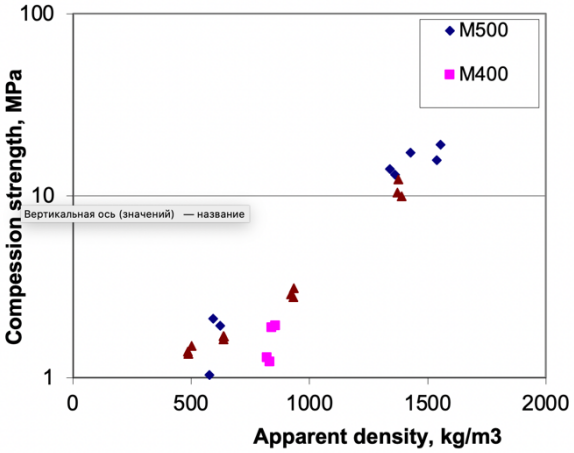


Figure 6 — Compressive strength of the foam concrete samples made with different cement types

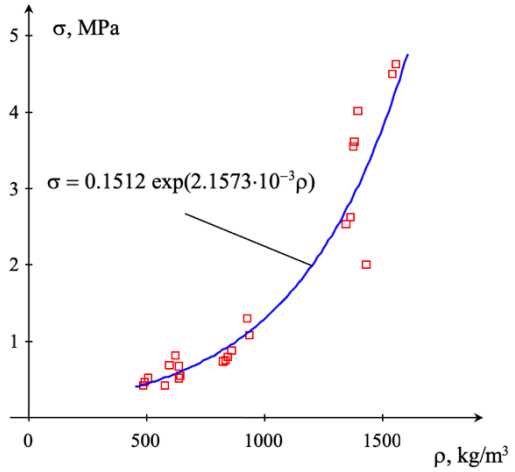


Figure 7 — Flexural strength of the foam concrete samples made with different cements

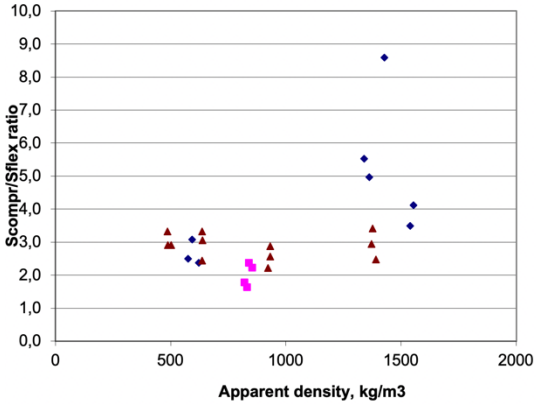


Figure 8 — Compressive to flexural strengths ratio of the foam concrete samples with different cements (the points are the same like on Fig. 6 and 7)

Concerning compressive to flexural strengths ratio of the foam concrete samples (Figure 8) one can conclude that the overwhelming majority of points lying in the range between 2.0 and 5.5, at that for each set of samples there are results very close to 3.0 in average obtained (samples hardened within 28 days). For the samples made from less durable cement CEM I 32,5N this ratio is close to 2.0 in average.

4.1.5 Water absorption

As mentioned afore, two sets of tests were performed: 1) the same samples (number 1, 2, 7, 15) have been used as for open porosity experiments before water absorption experiments, i.e. their structure could have been damaged; 2) the new samples (number 18, 20, 24, 27) have been used for open porosity experiments. The results for sample 15 were put together with second set to let easier comparison with sample 27 having similar density but tested for water absorption without being preloaded. Figures 9 and 10 represent results of the tests for samples 1, 2, 7 and 15, 18, 20, 24, 27 respectively.

The influence of density on the maximal values of relative mass of water absorbed by the foam concrete (diamond points and line 1) and the fraction of open porosity filled with the water (square points and line 2) for samples 15, 18, 20, 24, 27 is depicted on Figure 11.

The approximation of relative water mass absorbed by samples max(WA) according to Eq. (17) and $\max(\varepsilon_{wet}/\varepsilon_{open})$ as a functions of apparent density were approximated by least-squares method by following functions (see also Fig. 11):

$$\max(WA) = 1789\rho_{app}^{-0.689},\ R^2 = 0.919; \quad (20)$$

$$\max(\varepsilon_{wet}/\varepsilon_{open}) = 1.7854 + 0.0249\rho_{app},\ R^2 = 0.9545. \quad (21)$$

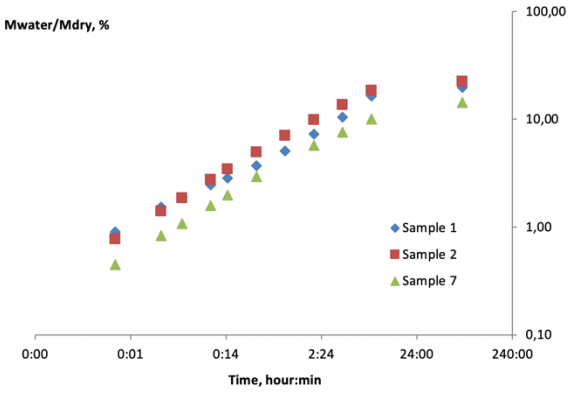
The first line (Eq. (20)) shows that the amount of the absorbed water is lower for heavier samples of foam concrete, the reason is that the own weight of the dry concrete is higher for them. But the second line

(Eq. (21)) reveals that the open porosity of the foam concrete is better 'used' (impregnated) by water namely for heavier samples, this could be attributed to the smaller sizes of the pores for the foam concrete with higher apparent density.

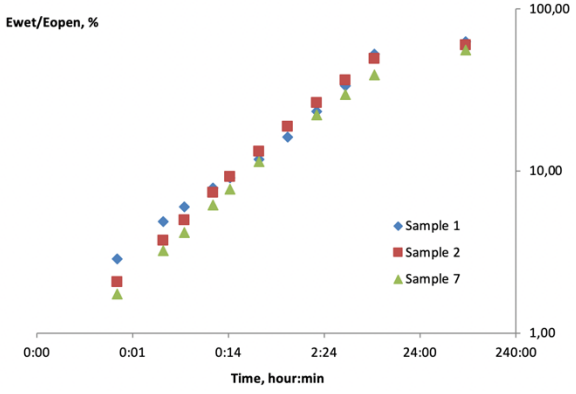
The analysis of absorption kinetics allows to conclude that samples number 18, 20 and 27 have been saturated within first 24–48 hours. These three samples having densities 487, 636 and 922 kg/m^3 respectively are the lightest among second set. In the sample 27 (1371 kg/m^3) the steady state is not reached even within 96 hours (see Fig. 10 a). This effect could be attributed to three following reasons: 1) more developed capillary microstructure in the samples with higher density, where the bubbles do not interrupt the flow in the capillary channels; 2) higher capacity of micro porous space in high density samples; 3) in the samples with lower density the diffusion of water is hindered due to lesser volume of solid body having small capillaries whereas porous structure has sizes of pores close to 1–2 mm which possess with very low capillary pressure.

According to our vision it seems that the bubbles are surrounded by the bulk concrete structure having micro pores which are impregnated with the water, i.e. the pores with gas bubbles inside are isolated one from the other, and their ability to absorb water is limited by the dissolution of air in the water (Fig. 12). The pressure in these pores is growing during impregnation process, slowly increasing the dissolution process. We have excluded samples 1, 2 and 7 from the final analysis, because they have densities in the range of 1350-1600 kg/m^3, which are rarely used in light concretes. Besides, the structure of these samples could have been partly demolished during previous test at vacuum impregnation (see discussion in the next paragraph.

It is interesting to observe that the behaviour of the absorption kinetics for samples 15 and 27 having similar densities (870.5 kg/m^3 and 922.3 kg/m^3 respectively) looks quite identical (Figure 10 a), though there are some deviations at the first stages of impregnation (Figure 10 b): in the logarithmic coordinates the rate of impregnation for sample 15 is lower than that for sample 27. This latter effect could be attributed to some rupture of structure of sample 15 during previous tests. It seems very apparent that at saturation in vacuum some part of the material could have crumbled inside of the spherical pores of the foam concrete. This assumption is corroborated by the observed crumbling of light samples of foam concrete by sawing and open porosity test exposed previously by vacuum impregnation during total porosity measurements.

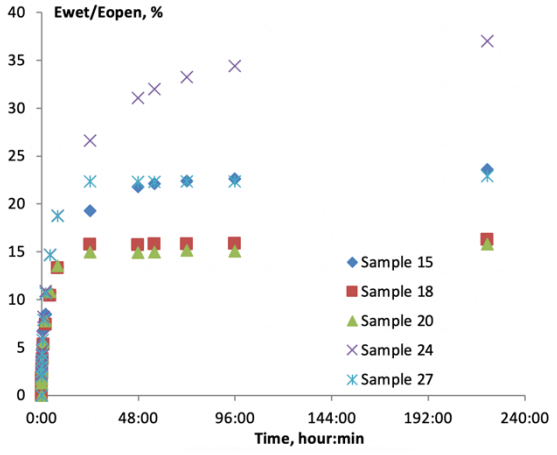


(a)

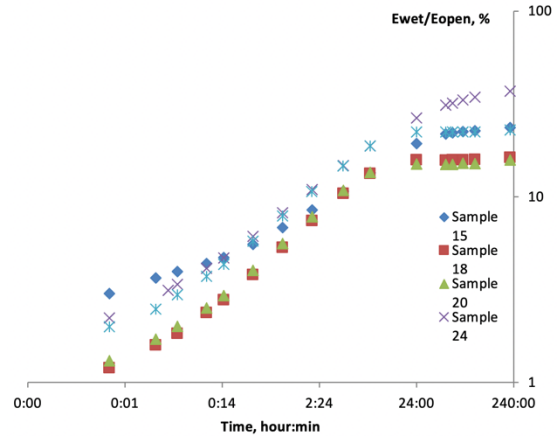


(b)

Figure 9 —Relative mass of water absorbed by the foam concrete (a) and the fraction of open porosity filled with the water (b) for samples 1, 2 and 7



(a)



(b)

Figure 10 — The fraction of open porosity filled with the water in natural (a) and logarithmic (b) coordinates for samples 15, 18, 20, 24 and 27

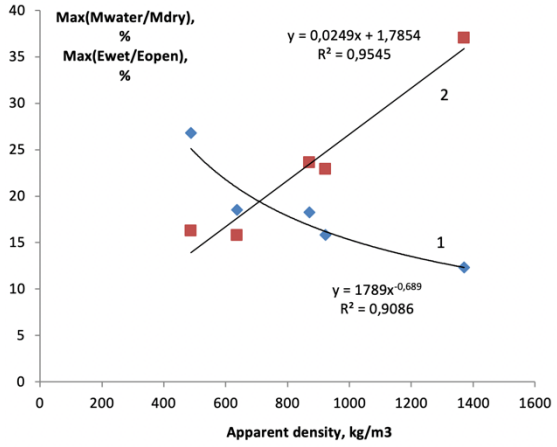


Figure 11 — The influence of density on the maximal values of relative mass of water absorbed by the foam concrete (blue diamonds and line 1) and the fraction of open porosity filled with the water (red squares and line 2) for samples 15, 18, 20, 24 and 27

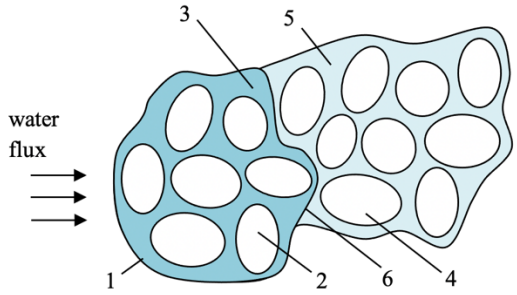


Figure 12 — Proposed mechanism of large pores isolation during water absorption tests. 1 — foam concrete body with capillary-porous walls; 2 — pores blocked around with the water; 3 — walls of concrete saturated with water; 4 — interconnected pores; 5 — walls of concrete in the dry or partly wetted part of the sample; 6 — front of impregnation

4.2 Results of experimental investigations of Inner properties of the foam concrete

4.2.1 Open, total and closed porosity

Results of open and total porosity measurements are presented in Table 7. Each set of samples has been tested at least once for total porosity and all the range of apparent densities was covered for open porosity. It is clear from the Table 7 and Figure 13 that values of open and total porosities are very close one to the other (within experimental error). Hence, the closed porosity as a difference between total and open porosity

$$\varepsilon_{closed} = \varepsilon_{total} - \varepsilon_{open} \qquad (22)$$

is negligible compared to total porosity and could not be defined with high accuracy by the methods used in this work.

Approximation of total porosity data by least-squares method gave the coefficients of Eq. (13) with determination coefficient $R^2 = 0.9978$

$$\varepsilon_{total} = 1 - 0.0004\ \rho_{app}, \qquad (13a)$$

where coefficient 0.0004 is very close to the value found by mean value of real density:

$$1/\rho_{real} = 0.395\times10^{-3}\ m^3/kg.$$

Table 7 — Open porosity of the foam concrete samples

Sample number	Name of the set	Apparent density ρ_{app}, kg/m^3	Open porosity ε_{open}	Total porosity ε_{total}
1	A	1483.4	0.448	0.422
2		1357.3	0.501	0.470
3		1401.5	0.479	ND
5	B	637.5	0.743	0.753
6		631.5	0.765	ND
7	C	1600.6	0.399	ND
8		1565.4	0.413	0.394
10	D	599.4	0.780	ND
11	E	833.4	ND	0.673
12		857.0	0.679	ND
15	F	870.5	0.673	0.661
16		883.9	0.668	ND
19	G	485.7	ND	0.804
22	H	638.0	ND	0.746
25	I	1390.2	ND	0.457
28	J	932.7	ND	0.637

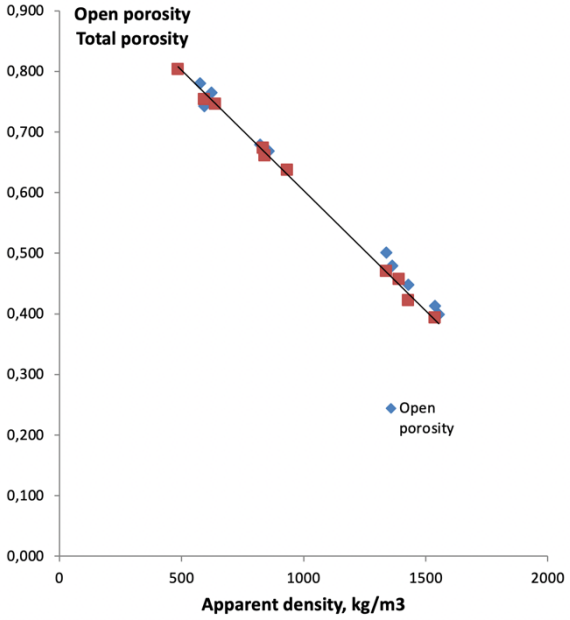


Figure 13 — Open porosity and total porosity as functions of the apparent density

This is not surprising, just confirms very small scattering of the results obtained for total porosity. Some difference between total and open porosity (the highest values of relative error 5.0–6.5% were obtained for samples 1, 2 and 8 with quite high density having therefore smallest absolute values of total porosity, for the other samples relative error was not larger than 1.8%) is attributed to the experimental procedure used in this work.

Properties of foam concrete produced by use of VJA fully meet the requirements of Russian and French standards.

5 Conclusions and outlook

A new method of foam concrete production by use of vortex jet apparatus (VJA) is described and studied. Foam produced by means of VJA is very stable and possess ability to save its properties during mixing with cement and sand. VJA is a compact device allowing to generate foam without any blowing machine, sucking the air from the ambience resulting from vacuum in the center of vortex flow, hence decreasing the both capital and operational costs of the plant. It was found that foam concrete production with wide range of densities (from approx. 480 till 1640 kg/m^3) is possible by use of VJA.

Main properties of foam concrete produced in this work: real and apparent densities, open and total porosities, thermal conductivity and thermal capacity, water absorption, compressive and flexural strengths have been measured; their values fully meet the requirements of Russian and French standards. Therefore, the VJA could be used as an effective tool for foam generation and foam concrete production.

Equations characterizing relative mass of water absorbed by the foam concrete were found as functions of apparent density.

The equations describing the total porosity (13a), maximal water absorption (20) and the fraction of open porosity filled with the water (21) are found; they have high coincidence with experimental data.

An idea to connect ‘outer’ properties of the foam concrete with its ‘inner’ properties as well as with controlled process parameters is described. A mechanism of large pores

isolation during water absorption tests was proposed.

Deeper discussions of relation between Controlled parameters, Properties of the foam, Inner properties of the foam concrete and Outer properties of the foam concrete will be performed in our next work (which is now under preparation). It is intended to build up correlations between inner and outer properties of the foam concrete in the next study.

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Исследование свойств пенобетона, полученного с использованием пеногенератора нового типа – вихревого струйного аппарата

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Аннотация

Исследован новый метод получения пенобетона с использованием вихревого струйного аппарата (ВСА). Пена, полученная при помощи ВСА, отличается высокой стабильностью и узким распределением диаметров пузырьков, который хорошо коррелирует с диаметрами пор пенобетона. ВСА - компактное устройство, позволяющее производить пену без компрессора, засасывая воздух из атмосфер благодаря разрежению, создаваемому в центре вихревого потока. Благодаря дополнительным возможностям (по сравнению, например, с обычным осевым эжектором), таким как способность всасывать воздух, более длительное время пребывания и более высокая кинетическая энергия, преобразуемая далее в диспергирование пузырьков, новое устройство позволяет контролировать параметры пены и плотность пенобетона, что позволяет генерировать пену с меньшим диаметром пузырьков и более высокой стабильностью. Предложен механизм изоляции крупных пор при испытаниях на водопоглощение. Были измерены основные свойства пенобетона, полученного в данном исследовании: реальная и кажущаяся плотности, открытая и полная пористость, теплопроводность и теплоемкость, водопоглощение, прочность на сжатие и изгиб; их значения полностью соответствуют требованиям российских и французских стандартов. Основная часть пор отнесена к открытой пористости из-за очень близких значений общей и открытой пористости. Уравнения, характеризующие относительную массу воды, поглощаемой пенобетон и доля открытой пористости, заполненной водой, находились как функции кажущейся плотности. Установлено, что производство пенобетона с широким спектром плотности (примерно от 480 до 1640 кг/м3) легко достигается с помощью ВСА. Следовательно, ВСА может быть использован как эффективный инструмент для генерирования пены и производства пенобетона.

Ключевые слова

Пенобетон, генерирование пены, стабильность пены, прочность пенобетона, теплопроводность, водопоглощение, открытая пористость, пористая структура

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