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Citation: AIP Conference Proceedings **1698**, 070010 (2016);
View online: https://doi.org/10.1063/1.4937880
View Table of Contents: http://aip.scitation.org/toc/apc/1698/1
Published by the American Institute of Physics

# Autoclave Foam Concrete: Structure and Properties

Alexei Mestnikov[1,a)], Semen Semenov[1], Valeria Strokova[2,b)]
and Viktoria Nelubova[2]

[1] *North-Eastern Federal University named after M.K. Ammosov, 58 Belinsky Str., Yakutsk, 677000 Russia*
[2] *Belgorod State Technological University named after V.G. Shoukhov, 46 Kostyukov Str., Belgorod, 308012 Russia*

[a)] Corresponding author: mestnikovae@mail.ru
[b)] vvstrokova@gmail.com

**Abstract.** This paper describes the technology and properties of autoclaved foam concrete taking into account practical experience and laboratory studies. The results of study of raw materials and analysis of structure and properties of foam-concrete before and after autoclave treatment are basic in this work. Experimental studies of structure and properties of foam concrete are carried out according to up-to-date methods and equipment on the base of the shared knowledge centers. Results of experimental studies give a deep understanding of properties of raw materials, possible changes and new formations in inner layers of porous material providing the improvement of constructional and operational properties of autoclaved foam concrete. Principal directions of technology enhancement as well as developing of production of autoclave foam concretes under cold-weather conditions in Russia climate are justified.

## INTRODUCTION

A significant part of the territory of Russia consists of northern regions with frigid climate. There are a lot of big and small rivers in the north of the country down by the riverside of which the basic settlements and industrial centers are located. In these conditions, the most affordable raw materials for the production of advanced autoclaved cellular concretes are river sands, related to sedimentary rocks and characterized by low content of quartz. In the paper a possibility of river sands application in the production of competitive walling materials based on autoclaved foam concrete is studied. The Lena River is the largest river in Eastern Siberia, with many tributaries of small and large rivers. It flows into the Laptev Sea. Lena's basin area is 2 490 000 km$^2$ [1]. Deposits of sands for all over the coast of the Lena River and its tributaries morphologically are large sandbars with length of 7–12 km and width of 0.2–1.2 km.

## RESULTS OF EXPERIMENTAL RESEARCH

### Raw Materials and Methods

As the binders the Portland cement CEM I 42.5N with true density $\gamma_0$ = 3100–3150 kg/m$^3$ and bulk density $\gamma_{bulk}$ = 1175–1850 kg/m$^3$; sieve residue 8–11.0 % by wt.; normal density – 24.5 cm; setting time: start – 105, end – 155 minutes; compressive strength – 51.9 MPa; tensile strength – 7.9 MPa as well as calcium quicklime are used. As silica component we used river sand from the quarries of open stock company "House-Building Factory" (Yakutsk) and limited liability company "Vilyuydorstroy" (Vilyuisk). The mineralogical and chemical compositions of Portland cement according to data of the open stock company "Yakutcement" are shown in Tables 1 and 2. The basic characteristics of calcium quicklime are presented in Table 3. As a foaming agent the protein-based foaming agent "FOAMSEM" (Italy) is used.

River sands have the following characteristics: true density $\gamma_0$ = 2650–2710 kg/m$^3$; bulk density $\gamma_{bulk}$ = =1535–1590 kg/m$^3$; the content of silt and clay particles – 2.5%; fineness modulus – 0.9–1.2; organic inclusions are absent; grain size composition is the following, % wt.: 0.315–0.63 mm – 8 %; 0.16–0.315 mm – 75 %; less than 0.16 mm – 17 %.

*Advanced Materials in Technology and Construction (AMTC-2015)*
AIP Conf. Proc. 1698, 070010-1–070010-6; doi: 10.1063/1.4937880

**TABLE 1.** The chemical composition of Portland cement

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $R_2O$ | $CaO_{free}$ | LOI |
|---|---|---|---|---|---|---|---|---|
| 21.16 | 5.45 | 4.72 | 64.85 | 2.71 | - | 0.75 | 0.15 | 0.11 |

**TABLE 2.** The mineral composition of Portland cement

| $C_3S$ | $C_2S$ | $C_3A$ | $C_4AF$ | $\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ ratio | $\frac{Al_2O_3}{Fe_2O_3}$ ratio | Saturation coefficient |
|---|---|---|---|---|---|---|
| 58.70 | 16.38 | 6.44 | 14.35 | 2.08 | 1.15 | 0.91 |

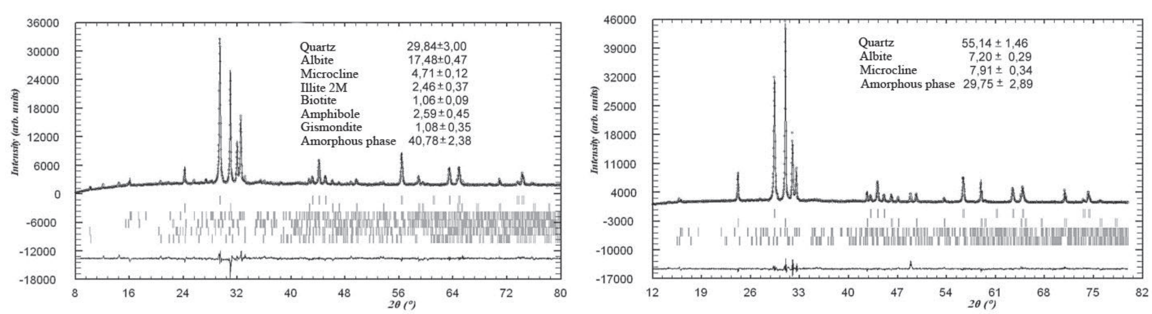
**TABLE 3.** Basic characteristics of quicklime

| Parameter | Value | |
|---|---|---|
| | Experimental | According to Russian Standard 9179 |
| Temperature of slacking, °C | 85 | 60 |
| Time of slacking, min | 6 | 4-10 |
| Content of CaO and MgO, % | 80 | > 76 |
| Specific surface area, $m^2/kg$ | 560 | Sieve residue |

Raw components and foam concrete samples were studied by using of up-to-date methods and equipment of shared knowledge centers of North-Eastern Federal University named after M.K. Ammosov (NEFU) and Belgorod State Technological University named after V.G. Shoukhov. To determine the quantitative ratios of crystalline phases (by wt. %) the full-profile quantitative X-ray phase analysis was applied. The calculations were performed with the program DDM v.1.95e in version of the Rietveld algorithm [2]. Concentration of amorphous phase (by wt. %) was determined on the basis of experimental ($C_{etalon}^{actual}$) and calculated ($C_{etalon}^{calc}$) concentrations of etalon sample by the formula [3]:

$$C_{amorphous} = \frac{100 \cdot (C_{etalon}^{calc} - C_{etalon}^{actual})}{C_{etalon}^{calc} \cdot (100 - C_{etalon}^{actual})/100}$$

Figure 1 shows the results of a quantitative full-profile XRD-analysis of the sands.




(a) (b)

**FIGURE 1.** Data of quantitative full-profile XRD-analysis of sands, wt. %:
a – from the Lena River; b – from the Viluy River

On the base of results obtained (Fig. 1) we can say about polymineral composition of sand materials, which can be attributed to the quartz-feldspar sands. Identification of the composition of the amorphous component consisting of 40 % approximately in the sands is not possible. The high content of X-ray amorphous phase allows prediction of the high reactivity of river sands to CaO contained in lime and Portland cement. High content of the amorphous phase of sand from the Lena River suggests preference of its application as a reactive pozzolanic component in cement based composite binders.

## Technological Parameters of Production

On the educational and manufacturing basis of NEFU the pilot production of autoclaved aerated concrete is organized. During optimization of the autoclaved foam concrete production process the following parameters were studied and clarified:

– dependence of yield compressive strength of foam concrete samples on fineness of lime grinding (optimal specific surface area is 580–620 $m^2$/kg);

– dependence of yield compressive strength of foam concrete samples on fineness of silica component grinding – Lena River sand (optimal specific surface of sand is 220–240 $m^2$/kg) correlate with the required bulk density of sand slurry obtained by wet grinding: 1.6–1.7 kg/l, cm.

– bulk density of foam concrete at the end of the mixing procedure should be 630–690 g/l for the foam concrete of class D500, and 750–810 g/l for class D600;

– regime of hydrothermal treatment for foam concrete cured in an autoclave is the following: 6–8 hour – preliminary curing at 30 °C to achieve plastic strength (compressive strength for the initial foam concrete of class D500 is 0.26–0.28 MPa, for foam concrete of class D600 is 0.28–0.30 MPa); increasing of temperature (up to 174–184 °C) and pressure (up to 8–0.9 MPa) – 2 hours; hardening of samples in an autoclave under pressure of 0.8–0.9 MPa and a temperature of 174–184 °C – 8 hours; pressure release – 2 hours.

The controlled technological parameters when production process are the following:

– weight feed and charging of raw materials;
– bulk density of sand slurry (1.6–1.7 kg/l);
– bulk density of the foam (70–80 g/l for the foaming agent FOAMSEM);
– bulk density of foam concrete mixture;
– spread of the foam concrete mixture according to the Suttard viscosimeter (26–30 cm);
– the temperature of foam concrete mixture (30 ± 2 °C);
– duration of foam introduction into concrete mixture, and subsequent mixing of all components;
– the temperature in the curing chamber (30–35 °C).

## Structure and Characteristics of Autoclaved Foam Concrete

The industrial composition of autoclaved foam concrete is presented for the class D500 (%, by wt.): cement – 190 kg, lime – 40 kg, sand – 290 kg, water – 210 l; the class D600: cement – 200 kg, lime – 75 kg, sand – 320 kg, water – 235 l. According to the basic characteristics the autoclave products correspond to the category I and are issued as building blocks. For example: Block I / 600×300×200 / D500 / B1.5 / F25 and Block I / 600×300×200 / D600 / B2.5 / F35 according to Russian Standard 31360-2007 (Table 4).

**TABLE 4.** The composition and characteristics of pilot series of foam concrete

| Item | D500 | D600 |
|---|---|---|
| Consumption of raw materials per 1 $m^3$ of foam concrete, kg | | |
| Cement | 190 | 200 |
| Lime | 40 | 75 |
| Sand | 290 | 320 |
| Water | 210 | 235 |
| Physical and mechanical characteristics of foam concrete | | |
| The average density of dry material, kg/$m^3$ | 536.34 | 623.68 |
| Yield compressive strength, MPa | 2.63 | 3.5 |
| Heat-conductivity coefficient, W/(m·K) | 0.109 | 0.127 |

Results of SEM-analysis of foam concrete samples demonstrate the foam concrete before autoclaving process has fine-cellular structure consisting essentially of spherical pores with size 0.291–1.15 mm. At interporous surface the microcracks and fractures with size of 0.4–1.28 mm are observed (Fig. 2a, 2c). They are attributed to accelerated drying process of experimental samples. In terms of real production cycle the foam concrete massif is kept in curing chamber at 30–35 °C up to achievement of plastic strength with further cutting and putting into the autoclave.

In foam concrete samples before autoclaving the fairly dense structure of interpore partition, containing interconnected micropores with size from 1.53 to 29.4 μm is observed. Also there are crystalline new formations and globular aggregations of non-crystallized calcium hydrosilicates phases (Fig. 3a, 3c). The binder hydration products cover quartz grains as well as fill the intergranular space, forming an integrated solid conglomerate.

After autoclaving in foam concrete a homogeneous growth of crystalline new formations takes place – low basic calcium hydrosilicates from tobermorit group in the form of crystalline sheet-like cells, accumulated into the continuous high-strength structure (Fig. 2b, 2d, 3b, 3d). The distance between the new formed sheet-like structures is 0.34–0.68 mm, the sheet's thickness is 0.05 mm at least (Fig. 4d).

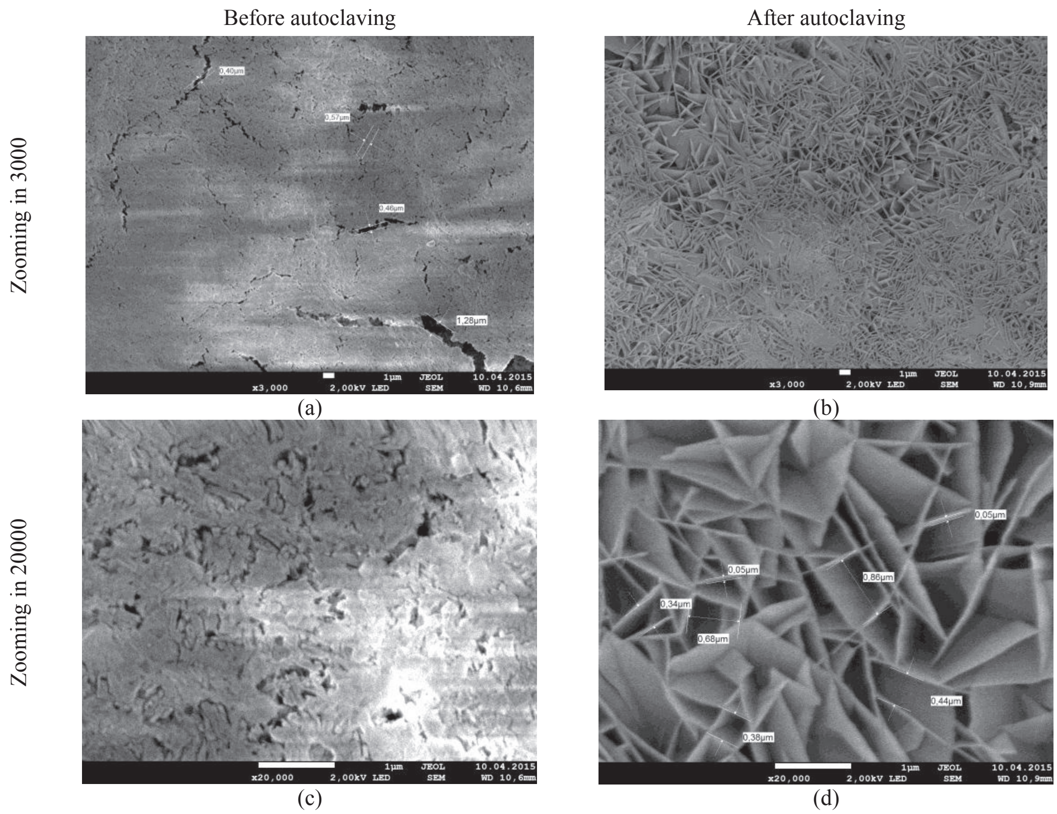
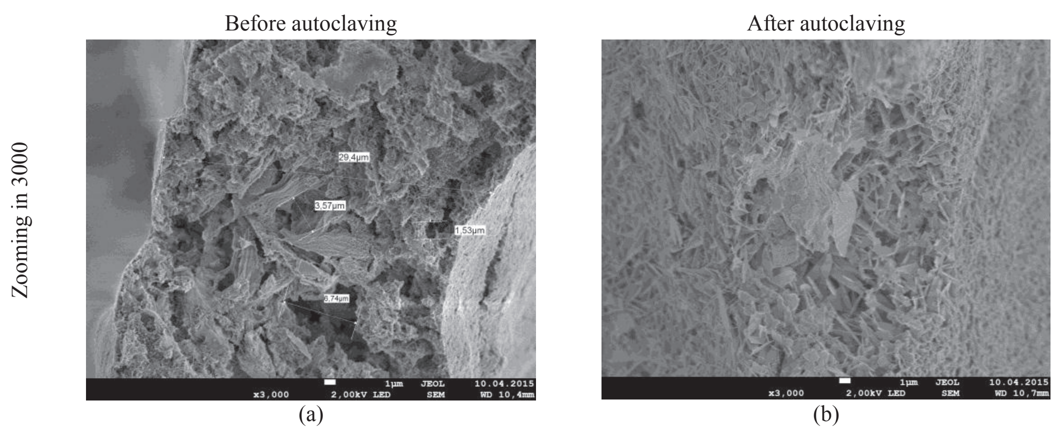



**FIGURE 2.** The microstructure of the interpore surface in foam concrete



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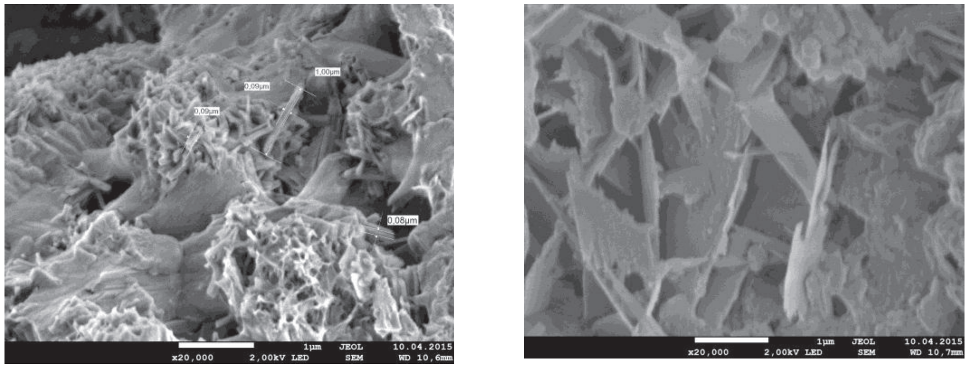

(c) (d)

**FIGURE 3.** The microstructure of interpore partitions of autoclaved foam concrete

Formation of low-basic calcium hydrosilicates, leading to increased strength of cement paste, has been studied earlier by USSR scientists [4–5]. Hydrosilicates of CSH (I)-group at high temperatures (150–200 °C) have plates with thickness up to 10–20 monomolecular layers, causing significant decreasing of specific surface of new formation vs. the surface of the same phases, formed at ambient temperatures (petal-like formations thickness of 2–3 molecular layers). The degree of crystallinity of new formations formed at 174.5–200 °C, at least, grows more intensively. Therefore, in this case the optimal regime of autoclaving for foam concretes at temperature 174–184 °C and pressure of 0.8–0.9 MPa is determined.

Mineral composition of foam concrete samples cured in ambient and autoclaved conditions is determined by quantitative XRD-analysis using X-ray diffractometer ARLX`TRA (ThermoScientic) with $Cu_{K\alpha}$-radiation (Fig. 4).

The presence of anhydrite (low-solubility anhydrite of rhombic crystal system) in the mineral composition of foam concrete is associated, perhaps, with gypsum content in the original limestone raw material used for lime production. In addition, the presence of calcium peroxide – $CaO_2$ can be attributed to some burnout of lime. The difference between the mineral composition of autoclaved-cured foam concrete and ambient-cured one is connected with presence of a crystallized form of C-S-H - 11Å-tobermorite as well as portlandite absence that is in correspondence with the results of earlier studies [6].

According to world experience [7], autoclaved foam concrete oriented factories produce such high quality products on a wide variety of density and strength values as thermal insulation materials with density class D400 and strength class B1.5–2 and construction-insulating materials with density classes D500, D600, D700 and strength classes B1.5–2.5, B2.5–3.5, B3.5–5, respectively.

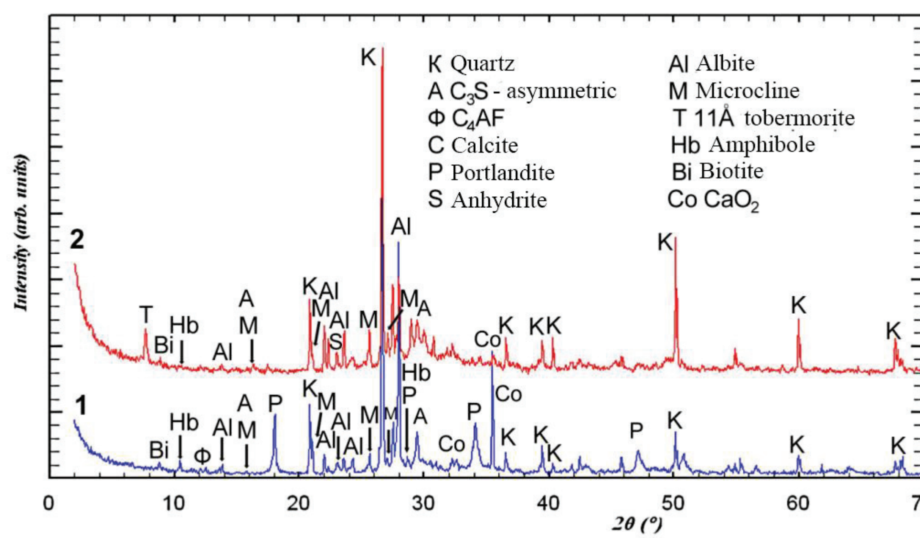


**FIGURE 4.** Diffraction pattern of foam concrete: 1 – cured in ambient conditions, 2 – cured under autoclaving

To improve the construction and operational properties of autoclaved cellular concretes, in particular, gas concretes, the different modifiers including active silica based nanostructured modifiers [6], the carbon nanotubes [8] etc. are used. However, any information about application of similar modifiers in autoclaved gas concrete oriented industries is absent. When testing of autoclaved foam concrete in plant conditions the composition's optimization was realized by varying the amount of cement, lime and sand, as well as degree of their grinding. Increasing in amount of cement leads to a fast grow of plastic strength of foam concrete, that limits the possibility of high-quality cutting of the concrete massif into blocks.

## CONCLUSION

Output product – the autoclaved foam concrete based on quartz-feldspar sand of Lena river basin – is characterized by low strength. For example, concrete of class B1.5 having density of 500 $kg/m^3$ (Table 4) refers to the lowest level in accordance with the requirements of Russian standards. A higher level of strength (class B2.5) for autoclaved foam concrete is achieved at density of 600 $kg/m^3$ (Table 4). Comparative analysis with previous studies [4] shows that the relatively low strength properties of foam concrete are connected with low quartz content in initial sands (Fig. 1). So, there is a problem of increasing the strength properties for autoclave foam concrete up to class B2.5 with density D500 and up to B3.5 with density D600, as well as of reducing the density of foam concrete to 350–400 $kg/m^3$ for class B1.5-B2.0. Primarily, application of natural mineral components activated with mechano-chemical methods is considered.


## ACKNOWLEDGEMENTS

Authors express gratitude to colleagues: senior lecturer E. Sutakova and graduate student B. Fedorov (NEFU), Ph.D., Associate Professor of BSTU named after V.G. Shoukhov I.V. Zhernovsky for personal contribution in the implementation of a number of experimental studies.


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