Ceramic products and energy-efficient systems

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Abstract. The energy efficiency concept incorporates energy conservation and durability components involved in the operation of buildings and cost considerations pertaining to the manufacturing and installation of materials. Ceramic brickwork offers the highest reliability and durability category, is not combustible and in terms of these parameters has advantages over other insulated facade cladding systems. Improving the thermophysical properties of masonry made of calcined ceramic products is possible through the use of heat-efficient ceramics and, in particular, porous ceramic stones. It is notable that the use of combustible additives does not enable the uniform distribution of porosity across the material while the high ash content of some additives reduces the quality of the ceramic crock. In this connection, it was decided that the use of exfoliated vermiculite of up to 0.5 mm fraction would be reasonable. A completed experiment made it possible to establish the optimal density of exfoliated vermiculite and a methodology based on the correlation between the properties of ceramic-vermiculite products and consumption of exfoliated vermiculite and ceramic product calcination temperature.

1. Introduction
The energy efficiency of construction processes includes two key components: saves energy during operation and reduces energy intensity of the facility. Building structures, on the one hand, must ensure heat conservation (reduction of heat losses), and, on the other hand, they must be durable which presumes the use of building materials showing high operational durability. The fire safety of building structures presuming the use of non-combustible materials [1-3] is also critical.

Ceramic brick, that is non-combustible as a calcined material, features the highest operational durability. Its features are a relatively high thermal conductivity and energy intensity during manufacturing. Therefore, a thermal resistance that does not meet the standards constitutes a disadvantage of brick structures [4-6].
The use of large-format ceramic stones makes it possible to erect building structures whose thermal resistance is close to standard values. The next step in improving the material is the manufacturing of porous ceramic products. Porosity is normally based on the combustible additives method, i.e. adding to the mixture components (sawdust, polystyrene screening dust, etc.) that form the porous structure of the ceramic crock when burned during calcination. Keep in mind that these technologies presume the use of plastic mixtures, are energy-intensive and do not allow maintaining the isotropic properties of the calcined material [7–9].

The foregoing allows presuming, on the one hand, that the use of a porous non-combustible filler as an ingredient of ceramic masses will make it possible to get materials with lower density as compared to traditional ceramic products, and, on the other hand, will enable using harsh mixtures with reduced water content thereby significantly reducing the cost of drying products while increasing the uniformity of the porous ceramic crock [10–12].

Exfoliated vermiculite was used as non-combustible filler. The choice was based on the fact that the temperature resistance of this material was 1300°C and it would not melt while ceramic products were being calcined with average density being 80–100 kg/m3. Furthermore, the plate-shaped form of crystals will have reinforcing functions which will also contribute to the increased strength and operational stability of products [13–15].

Thermal processes, and, more specifically, drying and calcination, are the main reasons behind the high energy intensity of the process of manufacturing ceramic products. When it comes to the ceramic-vermiculite products technology, the calcination mode is dictated by the properties of the clay used. This factor varies only when changing the type of clay used or introducing fusible agents [16, 17]. The drying and calcination processes designed to dry and calcine clays-based ceramic-vermiculite samples used to manufacture ceramic bricks were studied. The most energy-intensive calcination process was optimized using mathematical planning methods and processing of the experiment's results [18, 19]. The use of exfoliated vermiculite as a light non-combustible and thinning agent, on the one hand, made it possible to use harsh ceramic mixtures (with a water content not exceeding 18%), and, on the other hand, enabled the use of more rigid and shorter drying modes which also allowed to reduce the energy intensity and material consumption inherent in the technology.

2. Experimental & Results

Methods for producing fibred concrete and fiber-reinforced foamed concrete using thin polypropylene fiber, basalt fiber and expanded vermiculite were considered in the experimental procedure.

The calcination process was optimized using mathematical planning methods and processing of the experiment's results. The correlation between the properties of ceramic-vermiculite products and calcination parameters was studied in the course of running a dual-factor experiment. The average density of exfoliated vermiculite of up to 0.5 mm fraction (X1), exfoliated vermiculite consumption (X2) and calcination temperature (X3) were considered as variable factors. Response functions: product strength (Y1) and average density (Y2). The experimental conditions are shown in table 1.
The raw material was dried at a temperature of 90°C and flow rate of the heat-transfer medium of 4 m/s until the product reached its constant mass.

**Table 1. Experimental conditions**

| Factor                              | Symbol  |
|-------------------------------------|---------|
| Average density of exfoliated vermiculite, kg/m³ | X1      |
| Consumption of exfoliated vermiculite, kg/m³ | X2      |
| Calcination temperature, °C          | X3      |

| Factor | Symbol | Average factor value | Variation range, ΔXi | Factor values at levels |
|--------|--------|----------------------|----------------------|------------------------|
|        |        | X̄i                  | i                    | –1         | +1         |
| Average density of exfoliated vermiculite, kg/m³ | X1 | 80 | 20 | 60 | 100 |
| Consumption of exfoliated vermiculite, kg/m³ | X2 | 50 | 10 | 40 | 60 |
| Calcination temperature, °C | X3 | 1050 | 100 | 950 | 1150 |

The following regression equations were obtained in running the experiment and processing its results:

\[ Y_1 = 13.4 - 0.8X_1 - 1.8X_2 + 1.2X_3 + 0.8X_2X_3 - 0.5X_1^2 \]
\[ Y_2 = 1220 + 18X_1 - 64X_2 - 32X_3 + 12X_2X_3 - 10X_1X_2 \]

The analysis of the regression equations allows drawing the following conclusions. The consumption of exfoliated vermiculite has the greatest effect on both compressive strength and average density of products (coefficients at X₁, X₂, X₃ equal module ones).

An increase in the consumption of exfoliated vermiculite results in both decreased strength and decreased density of the calcined ceramic-vermiculite sample (coefficients equal –1.8 in the strength equation and –64 in the average density equation, respectively). This can be explained by the fact that exfoliated vermiculite has lower strength and density compared to a ceramic crock, which indeed is fairly obvious.

An increase in the calcination temperature results in both increased strength and decreased density of the ceramic-vermiculite sample (coefficients equal +1.2 in the strength equation and -32 in the average density equation, respectively). This can be explained by ceramic crock clinkering depth regularities, which is also a positive factor.

In analyzing the equations, synergistic effects and effects of variable factors on the result were also established suggesting an increase in the influence of the variable factors when used together. It has been established that an increase in the consumption of exfoliated vermiculite and increase in the calcination temperature result in increased strength and also slightly increased average density (coefficients at X₂X₃, respectively, equal +0.8 for strength and +12 for average density). In the context of building materials science, such effects are explained by the interaction conditions of vermiculite particles and sintered ceramic crock in the contact zone. An increase in the content of exfoliated vermiculite and increase in the calcination temperature result in the creation of thin layers of molten mass on the contact surfaces. On the one hand, this contributes to the better sintering of vermiculite (as a reinforcing component) and ceramic crock, and, on the other hand, causes contraction processes and leads to the increased average density of the calcined material. One of the samples resulting from the experiment is shown in Fig. 2.
Figure 2. Calcined ceramic-vermiculite product. Calcination temperature: 1100°C. Average density: 1150 kg/m³; compressive strength: 12.5 MPa.

An increase in the density of exfoliated vermiculite leads to decreased strength and increased density of the calcined product (corresponding coefficients at $X_1$ are $-0.8$ and $18$). Moreover, an increase in the density of exfoliated vermiculite when approaching the upper boundary of the factor variation range entails a greater decrease in strength that begins to decrease following the parabolic law (the coefficient equals $-0.5$ at $X_{12}$). There is also an antagonistic effect in terms of the average density of the product during the paired interaction of average density and exfoliated vermiculite consumption factors (the coefficient equals $-10$ at $X_1X_2$). This fact obtained via the analysis of analytical correlations is consistent with the physics of the process – the use of low density foamed vermiculite at high consumption rates leads to decreased density of the product.

3. Discussion

The nature of the regression equations (quadratic dependence on the average density of exfoliated vermiculite) allows implementing an optimization solution for factor $X_1$ (consumption of exfoliated vermiculite). Considering the analytical optimization method, the optimum value of $X_1$ is $-0.8$ (or 64 kg/m³ in physical terms). After optimization, the regression equations are as follows:

$$Y_1 = 13.6 - 1.8X_2 + 1.2X_3 + 0.8X_2X_3$$
$$Y_2 = 1206 - 56X_2 - 32X_3 + 12X_2X_3$$

Figure 3. Nomographic chart for selecting calcination temperature and predicting the properties of ceramic-vermiculite products. Compressive strength, MPa: 1 – 12; 2 – 14; 3 – 16; average density, kg/m³: I – 1150; II – 1200; III – 1250

The nomographic chart (Fig. 3) allows determining the optimal consumption of expanded perlite and recommending appropriate calcination temperature for products. After theoretical calculations are
made, the selected compositions are checked via full-size molding and calcination operations. The properties of the product can also be predicted depending on selected technological parameters. Ceramic stones made using the method described above have average heat conductivity values not exceeding 0.16 W/(mK) and can be used to achieve the effective brickwork for walls.

Bearing walls are erected using ceramic stones with subsequent plastering (Fig. 4) as the frost resistance of ceramic stones is rated from F25 which is not enough for the central regions of Russia and further Northwards and Eastwards. Masonry made of hollow porous wall stones with an outer lining made of weatherproof and frost-resistant front brick of normal format is widely used (Fig. 5). The thermal resistance of such structure along the smooth surface of the wall is at least 2.8 m²K/W with thermotechnical uniformity of at least 0.98 (due to the presence of masonry joints).

Figure 4. Ceramic stone masonry

Figure 5. Ceramic stone masonry with brick facade cladding

The construction of buildings using porous hollow ceramic stones makes it possible to ensure a good and healthy microclimate, efficient heating performance, uniformity and good sound insulation in all rooms.

The strategy for developing the building materials industry until 2020 and further prospects until 2030 approved by Decree No.868-r issued by the Government of the Russian Federation on May 10, 2016 envisages 26 greenfield construction and upgrade brick industry projects with a total capacity of about 2 billion conventional bricks per a year and investments exceeding 42 billion rubles. Preferences
are likely to be given to up-to-date effective ceramic products including large-format ceramic products and highly efficient and weather-resistant lining bricks.

4. Conclusions

Ceramic bricks and wall stones are non-combustible materials having high operational durability resulting in the high durability of building structures constructed using them. It is possible to reduce their thermal conductivity and, therefore, increase the thermal efficiency of structures by using porous ceramics, and, in particular, when using extra-light fillers compatible with ceramic crock and not worsening drying or calcination parameters. Ceramic-vermiculite materials belong to this particular class.

The properties of ceramic-vermiculite products are determined by the initial composition of ceramic mixtures, drying conditions and calcination temperatures. It has been established that the optimum drying temperature is 90°C at a flow rate of the heat-transfer medium of 4 m/s. The post-calcination properties of products are greatly affected by the consumption of vermiculite. At the same time, synergistic effects enhancing the joint effect of the consumption rate of exfoliated vermiculite and calcination temperature on both the strength and average density of products have been established. The use of hollow wall stones with a porous ceramic matrix makes it possible to come up with systemic solutions that meet the regulatory requirements in terms of thermal resistance while the use of a lining ceramic brick in the outer layer enables to make non-combustible structures that meet regulatory parameters in terms of durability.

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