Investigation of the Physico-Chemical and Mechanical Properties of Expanded Ceramsite Granules Made on the Basis of Coal Mining Waste

Yerkebulan Kocherov, Alexandr Kolesnikov, Gulnaz Makulbekova, Aigul Mamitova, Lazzat Ramatullaeva, Bahtiyor Medeshev and Olga Kolesnikova

Abstract: In this article, one of the main scientific directions was the search for ways of recycling coal mining waste to produce expanded clay granules. There are a number of scientific studies devoted to the use of various industrial wastes in the production of thermal insulation and fireproof expanded clay granules. The authors consider the production of granular porous aggregates based on pulverized fractions of igneous rocks—basalt, granite, and syenitite, as well as man-made materials of various origins, to be promising. According to the results of the conducted studies, it was found that the optimal interval of the amount of waste in expanded clay was 4.0–6.0%, and the optimal firing temperature was 1150 °C with the production of samples with a bulk density of 0.337–0.348 t/m³ and with a compressive strength of 1.37–1.51 MPa under these conditions.

Keywords: waste of coal production; environment protection; engineering; ceramsite granules; porous structure

1. Introduction

Annually, large quantities of coal production wastes are produced and stored. The disposal areas for such wastes occupy and pollute large territories, and land rehabilitation issues require significant expenses. The accumulated wastes can damage the ecological balance of territories. On the other hand, the internal mineral rocks could be used as raw material for the production of expanded clay, which does not require large investments [1–16].

In order to solve the problem of production of competitive heat-insulating materials, it is necessary to organize the production of economically efficient, high-quality, environmentally friendly, and safe raw materials [1,2,17–27].

In scientific publications, researchers have studied the methods of production of low-density, porous, and low-heat-conducting expanded clay aggregates based on changing the composition of the clay, releasing the liquid phase on the surface of the granules during firing, creating specific conditions for the firing process, and increasing the temperature range of their good porosity [1,2,28–37].

The use of various production wastes in the production of heat-insulating and fire-safe expanded clay granules is presented in many scientific publications. One of the main scientific directions of the authors was the search for ways and methods of solving the problems related to waste processing. The production of granular porous aggregates based on dusty fractions, as well as ash and slag residues of fuel of power plants, is considered by authors to be a promising method. Ash–slag waste consists of 98–99% free...
and chemically bound silicon, aluminum, iron, calcium, magnesium, potassium, sodium, and other compounds. According to phase and mineralogical composition, ash–slag residues belong to multi-component systems, including crystalline (quartz grains, hematite, magnetite) and amorphous (glass phase) components. It could be a good raw material for obtaining different construction materials. Based on the existing research, it has been observed that the migration of heavy metals from the outer layer of the samples of expanded clay depends on the structure and phase composition [38–45].

The influence of brown coal and coal production wastes on the porosity of bentonite clays was experimentally studied in order to improve the heat-insulating properties of fire-safe expanded clay granules. The exact dependence of the porosity coefficient and volume density of mixed expanded clay samples on the firing temperature is shown. A positive effect of coal production residues and lignite on the porosity of Kyngirak-Keles bentonite clays has been established. In both cases, expanded clay granules with high heat-insulating efficiency and low bulk density were obtained. These studies reveal the cost-effective ways of increasing the energy efficiency of buildings and houses, increasing the fire safety and resistance to a number of climatic conditions, and establish the quantitative compositional basis for the production of heat-insulating granules [46].

Further, the authors proposed the use of coal ash burned at a thermal power station in the production of porous fillers for structural purposes [47]. By using certain compositions consisting of the industrial wastes of coal production and additional residues formed in the process of alumina extraction, it is possible to obtain the expanded clay granules, which require appropriate preparation, forming, and firing at a temperature of about 1150 °C. The main indicators and aspects of the studied production process are given in the work of the authors [48].

In addition, the possibility of using ash and slag residues of thermal power stations in road construction has also been studied [49].

At present, ash is used very rarely because it is inconvenient in terms of processing, storage, and disposal. To solve this problem, methods of ash consolidation have been studied. In connection with these studies, a number of tests were carried out to determine the cause of thermal cracking of rapidly dewatered fly ash particles, both at high temperatures and at the optimal temperature limits determined by the optimal drying rate. This resulted in an increase in the pozzolanic activity and production of the binding mixture, with high dispersibility, good adhesion, low temperature compression, and certain thermal rupture-resistant properties. This method is simpler, cheaper, and more effective than other known methods. Dried pellets have a certain strength, which is advantageous in terms of handling, storage, and utilization. It is recommended to use the obtained particles as an additive to cement. If the drying process is carried out at a high temperature, it is recommended to use granules instead of expanded clay as a light filler [50].

Internal hardening, a widely used method of reducing early shrinkage of concrete, also gives significant advantages in terms of concrete strength. In the authors’ work, the potential of internal hardening by partial replacement of sand with finely dispersed lightweight aggregate was investigated to improve the properties of high-capacity concrete at high temperatures. This method can be effective and safe in the construction of high-rise buildings, where high-strength concrete is at risk of bursting during fire. To achieve this goal, the physical and mechanical properties of concrete samples with high internal strength under different temperatures, including mass loss, compressive strength, deformation at maximum stress, elastic modulus, stress–strain curve, impact resistance, and flexural strength, were studied. In addition, a number of equations are proposed to predict some of the mentioned mechanical properties. Replacing 10% of sand in pre-moistened fine expanded clay aggregates not only reduces the compressive strength at ambient temperature, but also reduces the risk of concrete cracking and can retain 20% of compressive strength after heating at ambient temperature up to 800 °C [51].

Scientists have proposed the practical use of mineral oil residue and oil sludge in the production of expanded clay gravel [52,53].
Inorganic porous insulating materials are generally underestimated, but when either free or mixed in with concrete, they can provide good thermal insulation, good mechanical resistance, and be a safe fire solution. This paper describes their origin, production processes, and application. The authors have described the fire resistance of these insulating materials, taking into account fire safety issues [54,55].

On the basis of research, it has become clear that to obtain expanded clay, cement, binders and finishing bricks, blast furnace slag residues, electric steel smelting slag, citrogypsum, and ferrovanadium production slag can be used [56–58].

Extensive research has been carried out on flame retardants, focused mainly on nitrogen-containing gas source compounds that release toxic gases, such as ammonia. Studies have shown that attapulgite has the ability to form a carbon layer that swells to a significant height in polymers. The conducted comprehensive studies explain its anti-fire properties and mechanisms of porosity upon heating [59,60].

A method is known for producing expanded clay by holding crushed clay at 300–400 °C for 15–20 min and further processing with petroleum product vapors in the amount of 1.2–1.5 wt.%, followed by granulation, drying, and firing [61]. The expanded clay obtained by this method has low strength, since when processing clay with fuel oil vapors totaling 1.2 wt.% at 350 °C, a keramsite with a bulk density of 200 kg/m$^3$ and a strength of 0.48 MPa is obtained. There is also a known method for producing expanded clay by crushing clay raw materials, sieving it into fractions of 0–5 mm and 5–15 mm, mixing a fraction of 0–5 mm with additional diesel fuel, mixing a fraction of 5–15 mm, granulating the mixture, and firing in a furnace [62]. The disadvantage of the obtained expanded clay by this method is the high bulk density of the product, since when adding 1 wt.% of diesel fuel to the clay fraction of 0–5 mm, expanded clay with a bulk density of 480 kg/m$^3$ and a strength of 1.5 MPa was obtained. The closest in technical essence is the method of obtaining keramsite by adding oil sludge to clay raw materials, granulating the mixture, drying, and firing [63]. The disadvantage of this method is the high bulk density of expanded clay 366–390 kg/m$^3$ and at the same time its low strength of 1.24–1.3 MPa. The authors have developed a method for producing expanded clay, which includes crushing clay rocks, adding 6–10 wt.% of oil sludge heated to 80–95° and containing 3–30% by weight of water, and the addition of water to obtain an elastic, well-mixed clay mass. Oil sludge was used as a swelling agent. It is a waste product of oil refineries collected during the treatment of wastewater from technological and sewage waters, and is a viscous liquid with a density of 0.86–0.97 g/cm$^3$ and contains water, mechanical impurities, and combustible fractions. The composition of the combustible fractions mainly includes asphaltenes, carbones and carbides, benzene, and alcohol–benzene resins. When heated, the oil sludge foams strongly, which increases its surface and allows a thin film to spread over the surface of the clay and penetrate into its pores. During the firing of granules, clay swelling occurs both due to the burning out of the organic part of the oil sludge, and due to water vapor, which is both a vaporizer and a catalyst for the processes occurring during the swelling of raw granules. With rapid firing, complete carbon burnout, with the release of gaseous oxidation products in the form of carbon monoxide or dioxide, can occur only after the completion of the dehydration process and the possibility of free access of oxygen to the particles of the material. To ensure a favorable reducing environment inside the material grains, the firing curve should be set in such a way that the final oxidation of the coke residue of organic substances moves to the area of the temperature of the beginning of swelling, which can be achieved due to the entry of raw granules into the kiln with a well-defined humidity. The most optimal humidity is a water content in the clay mixture of 16–20 wt.% [64,65].

The purpose of the following research is to determine the flexural behavior of reinforced concrete beams, taking into account the fire resistance of the partial replacement of coarse aggregates in the concrete mix with light expanded clay aggregates (LECA). LECA is a type of clay material with a hard, dense, scaly monoporous structure with fine closed pores. Four reinforced concrete compacted beams were used in the experiment. All models were identical in terms of geometric dimensions (1600 × 240 × 200 mm), fastening details,
and support positions. For each beam, the ratio of replacement of coarse aggregates by LECA material was different (0, 10, 20, and 30%). All samples were subjected to load testing at a constant temperature (500 °C) for 1 h after exposure to fire and sudden cooling. The test results showed that the number of cracks in the samples caused by fire decreased, the cracks width decreased too, and the deterioration of the beam’s ultimate load capacity and stiffness was reduced [66].

2. Materials and Methods

In research, internal mineral rocks are considered as a by-product of Lengir coal production. Nowadays, about 5–7 million tonnes of such waste are stored in waste warehouses negatively affecting the environment. The chemical oxidation composition of internal mineral rocks, in mass %, is as follows: CO—35.4; SiO$_2$—32.7; Al$_2$O$_3$—12.8; Fe$_2$O$_3$—9.9; CaO—5.1; MgO—2.3; SO$_3$—1.8.

Montmorillonite clays from the Badam field of Turkestan region were used as clay material. The type of waste is internal mineral rocks of coal production, included in the composition of the raw material mixture in the range of 1.0–10.0%. The organic part of coal residue was used as a pore-forming additive. The moisture content of the initial charge is 18–20%.

The sequence of the research work was as follows. We prepared the raw granules by using a residual mixture between 1.0 and 10.0% and preliminarily holding them at a temperature of 450 °C for 20 min. We then fired and cooled the preheated pellets at temperatures of 1150 and 1250 °C for 15–20 min. We determined the physico-chemical characteristics of the samples of burned expanded clay granules, as well as the effective amount of internal mineral rocks of coal production included in the charge.

Determination of the chemical composition of the samples of research materials was carried out by XRF-1800 (Shimadzu, Kyoto, Japan) X-ray structural analysis in an X-ray fluorescence spectrometer.

Determination of the granulometric composition of the primary raw materials was carried out by using a “Analysette 3” (Fritsch, Bavaria, Germany) vibrating sieve.

The structure of the sample and the elemental composition in the determined spectra were determined by using a high-resolution JSM-6400LV (Joel, Tokyo, Japan) raster scanning electron microscope and energy dispersive microanalysis.

The density, relative surface area, and average particle size of the research samples were determined by using the PSK-K (LLC RNPO Ruspribor, Saint Petersburg, Russian Federation) instrument.

In order to determine the processes occurring during heat treatment, differential thermal analyses were carried out on the Q1500D derivatograph (MOM Budapest, Hungary).

Research of the mineralogical composition of clay materials was carried out on the DRON-3M (NPP Burevestnic, Saint Petersburg, Russian Federation) device equipped with the source of X-ray reflection IRIS-0 and control diffractometer complex KUD-1.

3. Results

In our research, internal mineral rocks are considered as a by-product of Lengir coal production. Nowadays, about 5–7 million tonnes of such waste are stored in waste warehouses negatively affecting the environment. The chemical oxidation composition of internal mineral rocks, in mass %, is as follows: CO—35.4; SiO$_2$—32.7; Al$_2$O$_3$—12.8; Fe$_2$O$_3$—9.9; CaO—5.1; MgO—2.3; SO$_3$—1.8. Internal mineral rocks of Lengir coal production were studied in order to determine their physico-chemical parameters by generally known methods, and the results are presented in Tables 1 and 2. For the research, crushed samples were used, with the content of particles below 0.1 mm in size being up to 75%.
Table 1. Physico-chemical properties of internal minerals of Lengir coal production.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Unit of Measure</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total humidity</td>
<td>%</td>
<td>13.8</td>
</tr>
<tr>
<td>Analytical humidity</td>
<td>%</td>
<td>5.7</td>
</tr>
<tr>
<td>Ash content</td>
<td>%</td>
<td>18.1</td>
</tr>
<tr>
<td>Volatile yield</td>
<td>%</td>
<td>46.7</td>
</tr>
<tr>
<td>High heat of combustion</td>
<td>kcal/kg</td>
<td>7265</td>
</tr>
<tr>
<td>Lower combustion heat</td>
<td>kcal/kg</td>
<td>4805</td>
</tr>
<tr>
<td>Deformation initiation temperature</td>
<td>°C</td>
<td>1200</td>
</tr>
<tr>
<td>Melting point</td>
<td>°C</td>
<td>1480</td>
</tr>
<tr>
<td>Liquid melting point temperature</td>
<td>°C</td>
<td>&gt;1500</td>
</tr>
<tr>
<td>Grinding index</td>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td>Analytical humidity %</td>
<td>%</td>
<td>3.5</td>
</tr>
<tr>
<td>Total humidity %</td>
<td>%</td>
<td>33.9</td>
</tr>
<tr>
<td>Total heat %</td>
<td>%</td>
<td>15.2</td>
</tr>
<tr>
<td>Deformation initiation temperature</td>
<td>°C</td>
<td>1380</td>
</tr>
<tr>
<td>Melting point °C</td>
<td></td>
<td>1800</td>
</tr>
<tr>
<td>Liquid melting point °C</td>
<td></td>
<td>1800</td>
</tr>
</tbody>
</table>

Table 2. Fractional composition of internal mineral rocks of Lengir coal production.

<table>
<thead>
<tr>
<th>Aggregate Size, mm, and Their Content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1–0.2</td>
</tr>
<tr>
<td>9.4</td>
</tr>
</tbody>
</table>

Figure 1 shows the DTA of internal mineral rocks of Lengir coal production, which contains 35–40% carbon, up to 1.8% total sulfur, and up to 13% moisture, and the rest is up to 40–45% mineral fraction.

During the analysis, as can be seen from Figure 1, the weight loss of internal mineral rocks at a temperature of 323 °C is 41.77%. This weight loss can be explained by the fact that internal mineral rocks contain up to 70% free carbon.

In a visible space of the micrograph of waste particles, polydisperse grains are microaggregates of polymineralic phases held together by both electrostatic forces and coagulation bonds. Upon further enlargement, the irregularly shaped particles in the 20–200 nm range are also found in the sample.

During the study of the microstructure of the coal production system, the weight amounts of the elements at the points taken for quantitative and qualitative analysis are as follows (%): C—62–78; Cr—34.6; Al—0.81–3.12; K—0.1–0.26; Si—6–45; Fe—0.3–60; and S—0.23–1.81. The spectral results of the elemental analysis of internal mineral rocks carried out under a micro-element microscope are presented in Figures 2–5.
The porosity characteristics of the clay material are determined by the following analysis.

**Figure 2.** Elemental composition of internal mineral rocks of Lengir coal production (spectrum 1).

<table>
<thead>
<tr>
<th>Element</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>K</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, %</td>
<td>0.11</td>
<td>1.13</td>
<td>45.04</td>
<td>0.23</td>
<td>0.20</td>
<td>0.39</td>
</tr>
</tbody>
</table>

**Figure 3.** Elemental composition of internal mineral rocks of Lengir coal production (spectrum 2).

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Fe</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, %</td>
<td>62.72</td>
<td>0.81</td>
<td>11.30</td>
<td>0.10</td>
<td>0.52</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Figure 4.** Elemental composition of internal mineral rocks of Lengir coal production (spectrum 3).

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Al</th>
<th>Si</th>
<th>Mg</th>
<th>K</th>
<th>Fe</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, %</td>
<td>34.60</td>
<td>6.43</td>
<td>5.93</td>
<td>7.99</td>
<td>0.39</td>
<td>8.46</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.** Elemental composition of internal mineral rocks of Lengir coal production (spectrum 4).

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, %</td>
<td>2.67</td>
<td>7.11</td>
<td>0.97</td>
<td>60.12</td>
</tr>
</tbody>
</table>
Montmorillonite clays from the Badam field of the Turkestan region were used as clay material. The type of waste is internal mineral rocks of coal production, included in the composition of the raw material mixture in the range of 1.0–10.0%. The organic part of the coal residue was used as a pore-forming additive. The moisture content of the initial charge is 18–20%.

The sequence of the research work was as follows. We prepared the raw granules by using a residual mixture between 1.0 and 10.0% and preliminarily holding them at a temperature of 450 °C for 20 min. We then fired and cooled the preheated pellets at temperatures of 1150 and 1250 °C for 15–20 min. We determined the physico-chemical characteristics of the samples of burned expanded clay granules, as well as the effective amount of internal mineral rocks of coal production included in the charge.

According to its composition, the raw material of Badam clay consists of montmorillonite. Quartz in the form of dust fractions totals 5–25%, feldspar 2.5–22.5%, hydromics 1–5%, and gypsum 1–15%. The amount of organic additives is 0.39%. The results of the determination of the chemical composition are given in Table 3.

<table>
<thead>
<tr>
<th>Table 3. Chemical composition of Badam clay.</th>
</tr>
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<tbody>
<tr>
<td>SiO₂</td>
</tr>
<tr>
<td>63.45</td>
</tr>
</tbody>
</table>

The physical–mechanical properties of Badam clay are as follows: bulk density—1.92 g/cm³; plasticity—43.35; fire resistance—1250 °C; sintering temperature 1180 °C; porosity coefficient—5.4; natural humidity 25%; moisture absorption—18%; porosity index—42%; firing temperature—970 °C; compressive strength limit—13 MPa; bending strength limit—5.6 MPa; frost resistance—22 periods.

The results of the determination of the granulometric composition of Badam clay are presented in Table 4.

<table>
<thead>
<tr>
<th>Table 4. Granulometric composition of Badam clay.</th>
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<tbody>
<tr>
<td>&gt;0.001</td>
</tr>
<tr>
<td>41</td>
</tr>
</tbody>
</table>

As presented in our previous works [67], it was found, as a result of the determination of the granulometric composition, that Badam clay is finely dispersed. The determined density of Badam clay is 2.39 g/cm³, the relative surface area is 2260 cm²/g, and the average size of the particles is 10.7 microns.

The results of the determination of the elemental composition of Badam clay are presented in Table 5, and micrographs are presented in Figure 6. The indicated effective scientific research work was carried out in the laboratory of M. Auezov, South Kazakhstan University.

<table>
<thead>
<tr>
<th>Table 5. Elemental composition of Badam clay.</th>
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</thead>
<tbody>
<tr>
<td>Element</td>
</tr>
<tr>
<td>Weight, %</td>
</tr>
</tbody>
</table>
Figure 6. Micrograph of Badam clay.

The results of the differential–thermal analysis of Badam clay samples are presented in Figure 7. The thermogram revealed endothermic effects at temperatures of 160 °C, 360 °C, 560 °C, and 885 °C, as well as exothermic effects at temperatures of 450 °C and 950 °C.

Figure 7. Badam clay thermogram.

The endothermic effect associated with the loss of absorbed moisture is observed at 160 °C, and the steplike curve at 360 °C corresponds to the loss of interlayer water. The next reaction occurs at 560 °C, which leads to the loss of constitutive water in the hydroxide form characteristic of montmorillonite. At temperatures of 800 °C and higher, the layered structure is preserved. The endothermic effect at 885 °C corresponds to the process of calcite decomposition.

The exothermic effect at 450 °C in the thermogram is caused by the combustion of organic compounds, and the effect at 950 °C corresponds to the crystallization of high-temperature phases. At 900 °C, weight loss is 10%, and at higher temperatures, mass stabilization occurs.

The results of X-ray phase analysis of Badam clay are presented in Figure 8.
X-ray structural analysis shows that the main product of the crystalline phase is sodium feldspar (d, A: 3.23: 2.86: 2.45 Å), with a significant amount of silicon compounds (d, A: 4.24: 3.34: 2.45: 1.81 Å) and chlorite formations (d, A: 6.94: 4.64: 3.16 Å).

4. Discussion

The use of internal mineral rocks of coal production in obtaining expanded clay as raw material shows the following results. The influence of the amount of internal mineral rocks in the raw material mixture on the porosity coefficient and bulk density of expanded clay granulate is shown in Figures 9 and 10. It becomes clear from Figure 9 that introduction of 1–10% of waste mixture as raw material for expanded clay production and firing at 1250 °C is unfavorable. The viscosity of the ceramic mass decreases with the increase in the amount of residual mixture acting in the form of a melt, and as a result, the product is deformed during the firing process. The produced expanded clay samples have dark melting crusts. Upon interaction of the components of the charge mass, given the high firing temperature, the melts are formed upon reducing the burning temperature. By increasing the quantity of wastes, it becomes possible to obtain soft clay granules, at which point, compacted agglomerates in a pyroplastic state become impermeable to gas. The main factor that determines the intensity of the porosity process is viscosity of charge.

As can be seen from the graph curve, the samples taken at a temperature of 1250 °C have a lower porosity index. At this burning temperature, the hard melting upper layer of the charge prevents the sticking of granules, and agglomeration of the upper light melting layer upon firing reduces the gas permeability of charge granules. Gases formed in the volume of charge upon burning at a temperature of 1150 °C cannot escape through the dense surface, which makes the granule more porous. The introduction of internal mineral rocks into raw material creates the conditions for an increase in the raw granule porosity coefficient with a simultaneous increase in the temperature range. The process of burning the raw clay at a temperature of 1250 °C is accompanied by the free release of gas, which makes the prepared products more porous. The expanded clay samples with 4–6% coal residues fired at 1150 °C belong to the category of medium porous materials, with a porosity coefficient of 2.5–2.7. The expanded clay samples with 1–10% wastes and fired at 1250 °C possess a low degree of porosity (less than 2.5).
penetration of moisture into the inner layer of the granule, then expanded clay is unsuitable as a consumer material.

The total porosity of expanded clay increases with the increase in quantity of waste mixture up to 4%, and further increase in waste in the raw material up to 10% leads to a sharp decrease in porosity (Figure 11). According to the industrial requirements, the expanded clay’s total porosity should be in the range of 40–75%.

Figure 12 shows the dependence of expanded clay moisture absorption on the amount of residual mixtures introduced at different firing temperatures. The higher the moisture absorption, the higher the durability of expanded clay. If the outer layer cannot resist the penetration of moisture into the inner layer of the granule, then expanded clay is unsuitable as a consumer material.

Figure 9. The influence of the amount of internal mineral rocks in the raw material mixture on the porosity coefficient of expanded clay granulate.

Figure 10. The influence of the amount of internal mineral rocks in the raw material mixture on the density of expanded clay granulate.
The dependence of wastes, being introduced into the raw material from expanded clay strength, is given in Figure 13. Also, the decrease in strength of expanded clay with the increase in waste content in raw material is shown. This effect occurs because of the presence of a large number of pores in the structure in this case. The reason for the decrease in the expanded clay’s porosity is the structural features of the obtained expanded clay and the mineralogical composition of walls between pores.

The results given in Figure 13 show that the expanded clay strength decreases with the increase in quantity of added wastes. The increase in quantity of flux mixture leads to a decrease in the viscosity of the melt mass, which leads to deformation of the product during burning. The calcination of raw material with the flux mixture at a temperature 1250 °C is not recommended, because in this case, the melting of raw material takes place, and compressive strength decreases. The effective burning temperature is 1150 °C.
The stage of expanded clay passing through the glass phase has a negative influence on the thermal conductivity of the clay material. A decrease in the thermal conductivity causes an increase in the thermal properties, which occurs because of the increase in amorphous components upon burning. The composition of the expanded clay phase is as follows: 78.6–79.8% glassy phase and 20.2–21.4% crystalline formations at an added mixture quantity of 4–6% and burning temperature of 1150 °C. In the cross-section of the granule samples, it can be seen that regional divisions have appeared (Figure 14).

![Figure 13](image-url)

**Figure 13.** The influence of the amount of waste mixture on the strength properties of expanded clay.

The uniform porous structure is formed with the following pore sizes: up to 1 mm (Figure 14a–c), and a small pore structure up to 1.5 mm combined with large pores (Figure 14d,e). Further, as the amount of waste mixture increases, the pores inside the granule are transferred to the melt, and cavities are formed due to strong porosity (Figure 14e). The amount of residual mixture in this case is 6.0. At amounts of residual mixture of
8.0 and 10.0%, cavities with sizes of 0.8–1.8 mm are formed. The samples with residual content of 2.0 and 4.0% fired at 1150 °C are have increased strength, small uniform porosity, and a smooth structure of the walls between the pores. Due to the formation of cavities, which form due to the increasing number of micropores, a decrease in the thermal conductivity of the expanded clay occurs.

The results of the research of expanded clay inside a structure at a temperature of 1250 °C are shown in Figure 15. Due to the increase in the quantity of micropores that form the cavities in the expanded clay granules, thermal conductivity decreases. From Figure 15a,b, it is clear that at waste content quantities of 1.0–4.0%, the formed large pores are surrounded by micropores, and the interpore walls have a microporous structure (Figure 15c).

![Figure 15](image)

**Figure 15.** Structure of expanded clay sample fired at 1250 °C; amount of residual mixture, wt.%: (a)—1.0; (b)—2.0; (c)—4.0; (d)—6.0; (e)—8.0; (f)—10.0.

Upon increasing the amount of residual mixture to 6.0–8.0%, the size of the internal pores increases to 1.5–3.0 mm (Figure 15d,e), and it is compatible with the decrease in open porosity and moisture absorption of the finished material. At 10% of the residual mixture, a small amount of melt is formed in the central parts of the granule along with macropores. The formation of melts can be explained by the process of internal combustion of carbon compounds in the waste.

5. Conclusions

Based on the conducted research on the physico-chemical and mechanical properties of expanded ceramsite granules made on the basis of coal mining waste, the following conclusions can be drawn:

- There is an influence of internal mineral rocks from coal mining in the amount of 1.0–10.0% on the physico-chemical properties of expanded clay.
- The minerals of calcium and magnesium contained in the charge and the organic part of the coal residue act as a fluxing additive, which leads to the hardening of the granules.
- At the same time as the porosity of the granules decreases, the size of the internal pores increases, empty cavities form, the surface of the expanded clay granules melts, and the compressive strength decreases.
- The recommended amount of waste in expanded clay is 4.0–6.0%.
- The effective firing temperature is 1150 ̊C.
- It is possible to obtain samples of expanded clay granules with a bulk density of 0.337–0.348 t/m³ and a compressive strength of 1.37–1.51 MPa, which comply with GOST 32496-2013 (GOST 9757-90) and mark F50 with a volumetric density of 350–400 [68].

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