ATLANTIS PRESS
Atlantis Highlights in Material Sciences and Technology (AHMST), volume 1
International Symposium "Engineering and Earth Sciences: Applied and Fundamental Research" (ISEES 2019)

Technology for Production of Highly Efficient Structural Clay Tiles from Coal Refuse Processing By-Products – Screenings and Coal Slurries

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Abstract **– The paper gives a general characteristic of coal refuse processing products: intermediate fraction – coal-free screenings; small fraction – carboniferous sand containing up to 30% coal; fine fraction – silt coal containing up to 50% coal. Green and baked ceramic properties of products of processing waste coal are demonstrated. Compositions of raw mixes for items with compression strength of over 10-15 MPa with a density of below 800 kg/m^3 are substantiated, with considerations for molding with semi-rigid extrusion and requirement of minimizing baking costs. Processing properties of screenings are presented as functions of material grinding and baking temperature. A process diagram has been plotted for a possible production facility using modern equipment. Technical and economic indexes are presented, showing high profitability and promising nature of manufacturing large-size structural clay tiles from the products of processing waste coal thanks to minimal prime cost of the tiles.**

Keywords – structural clay tile; screening; coal; silt; technology; baking; strength.

I. INTRODUCTION

Large-size highly efficient structural clay tiles are finding more and more demand in modern construction. In European countries they have found its niche and take up 70-90% of the total volume of wall ceramics [1, 2]. This is thanks to advantages that structural clay tile has in comparison to other wall materials. In Russia, this indicator is currently lower [3,4]. One of its causes is a higher cost (by 10-20% on average) in comparison with gas silicate, though the latter underperforms in a number physical and technical indicators.

Reducing the price of the structural clay tile is possible by reducing its prime cost and transport expenses. Prime cost of a stoneware item depends on many factors. In the context of manufacture, they include the cost of raw materials, productivity of the production facility, processing costs, primarily energy costs, labor consumption per unit of production and other factors. Transportation costs may be reduced by shortening distance to customer and implementing logistical solutions.

Taking all this into account, the authors conducted research into possibility of manufacturing large-size high-efficiency structural clay tile using a rigid extrusion methods from the products of processing waste coals of Eastern Donbass. First, the cost of the raw materials is close to zero, at that, they contain coal that is considered a complex fuel and pore-forming component. It is interesting that often enterprises are forced to pay for storage of side products from refuse coal processing. Second, Rostov oblast that includes Eastern Donbass does not have its own facilities for structural clay tile manufacture, despite large demand and being situated at a potentially very lucrative crossing of several transportation routes. Putting the results of this research and development resulting from them into practice would make Rostov oblast a major producer of structural clay tile, covering both oblast's internal demand and demand in neighboring regions. According to preliminary calculations, the short-term demand in large-size structural clay tile will amount to 200 million items as recalculated for standard brick.

II. METHODS AND MATERIALS

Currently, the main purpose of waste coal processing is extraction of anthracite coal. Its content in those technogenic formations ranges on average from 10 to 20%. The extent of waste coal dumps in the Rostov oblast alone amounts to hundreds of millions of tons. In economic terms, it is more profitable to process waste coal than to build new mines.

Extraction of coal from waste coal results in production of several materials that may be classified by their mineral-petrographic and grain composition, as well as by coal content [5,6]. Large-grain materials with a grain size ranging from 5-6mm to 150mm are represented by sandstones and siltstone; they contain no coal, are used in construction as aggregate and are of no interest for structural clay tile manufacture. Intermediate grain materials with grain size ranging from 2 to 5-6mm (screenings), are represented by siltstone and argillite; their coal content is extremely low; they may become principal raw material for manufacture of structural clay tile. Small fraction material (carboniferous sand, cake) with prevailing grain size ranging from 0.5 to 2.5mm is also represented by siltstone and argillite and may contain up to 35% coal. However, they lack necessary plastic properties and their use in production of large-size structural clay tiles using the rigid extrusion technology is not very practical. Mainly they are used as low-calorie fuel. Fine fraction materials with a grain size of less than 0.5mm and containing over 90% of the under 0.16mm fraction are usually called silt coal, slack coal or coal slurry. Their coal content is on average about 35%. Application of modern technologies allows correcting the coal content. Mineral component in them is represented by fine argillite, thus they posses the plastic properties. On average, their plasticity is 7-10 units. The technical-economical analysis conducted has shown that it is most practical to use screenings as the main raw material with silt coal as an additive; the latter is to play a role of fuel and pore-forming additive, as well as enhancer of molding properties [7,8].

The work uses standard research methods for ceramic raw materials as stated in GOST 21216-2014 “Clay raw materials. Test methods”, as well as some authors’ own techniques that take into account the stone-like nature of the basic material and an important direct dependence of processing properties on the degree of fineness of the stone-like material [9-12].

III. RESULTS AND DISCUSSION

Research into refuse heap processing screenings has shown that they largely consist of siltstone and mudstone. It is typical, as during the processing of the refuse heap mass, the less robust rocks are transformed into fine fractions. In some cases, there may be mudstone-like clays. A ratio between the components may vary depending on the composition of the initial refuse heap [13]. Chemical composition of the screenings (Table 1) has no fundamental differences from that of clay raw materials. Characteristic features include a clear prevalence of potassium oxide over sodium oxide due to presence of mica and hydrous mica, as well as increased content of iron oxide.

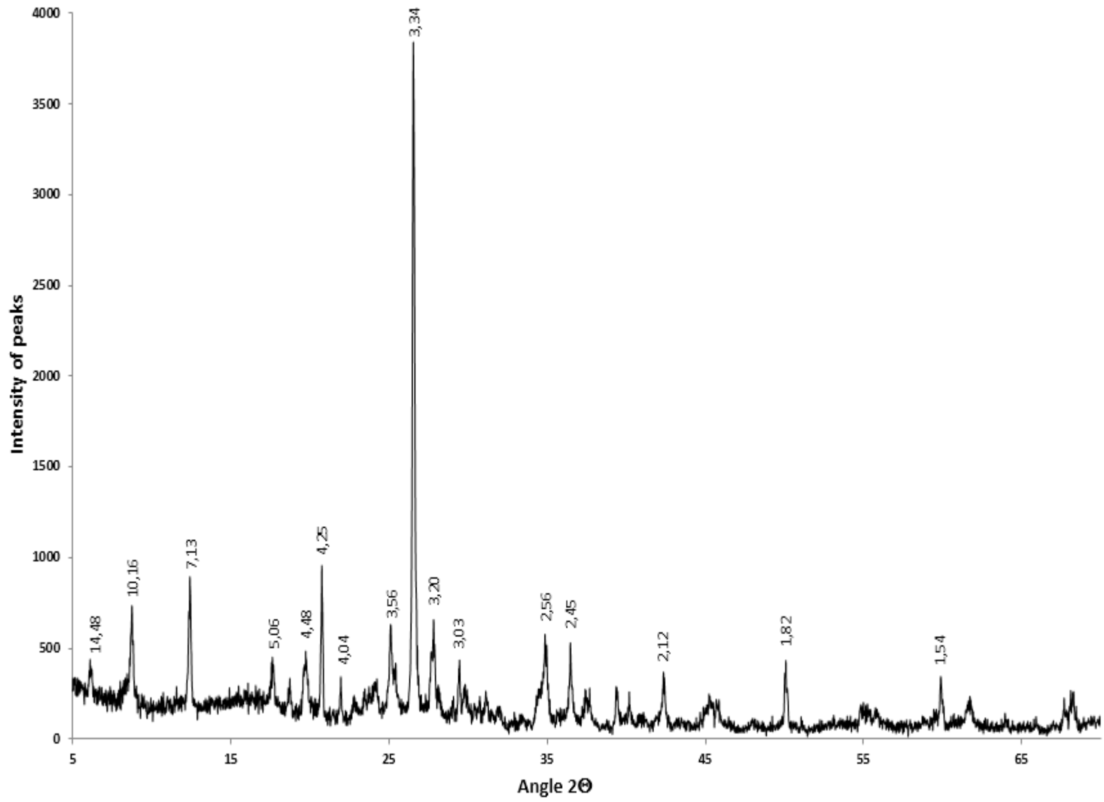

Fig. 1. X-ray diagram of screenings from processing of refuse coal in Eastern Donbass.

TABLE I. AVERAGED CHEMICAL COMPOSITION OF EASTERN DONBASS COAL WASTE HEAP PROCESSING, %WT

Loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
9-11	50-58	16-22	4-7	1-4	1-4	0.2-0.7	4-6	0.2-1.0

In addition to mica and hydrous mica, typical minerals in the screenings include feldspars, (orthoclase, albite, anorthite) that are susceptible to strong secondary changes, peach-stone, kaolinite, quartz, ferrous minerals. Figure 1 shows an X-ray diagram of typical screenings from refuse heap processing of an enterprise in Eastern Donbass. Hydrous mica (illite) and mica are detected with their diffraction peaks at 4.48, 5.06 and 10.16 Å. Feldspars and plagioclases are detected with their diffraction peats at 3,20; 4,04; 2,96; 2,51 Å. Quartz has high crystallinity and is clearly detected with its diffraction peaks at 3.34; 1.82; 1.54; 4.25; 2.45; 2.28; 2.12 Å. Minerals of chlorite and kaolinite group are detected with the peaks at 7,12; 3,53; 14,5; 4,68, 2,33 Å, etc.

Chemical and mineral composition defines ready fusibility of the screenings. At a temperature of 1000-1050 °C, they already start actively fusing, while at a temperature of 1100 °C they transition to a pyroplastic state (Fig. 2,3). It is natural, as feldspar, mica and hydrous mica start fusing at temperatures ranging 1100-1200 °C forming eutectic melts with the most hard-melting component, quartz, whose melting temperature is 1720 °C. Ready fusibility of the screenings is a favorable factor. It allows producing tiles with a required degree of caking that translates into desired physical and mechanical properties, while using relatively low baking temperatures, thus facilitating acceleration of the process and reduction in production costs.

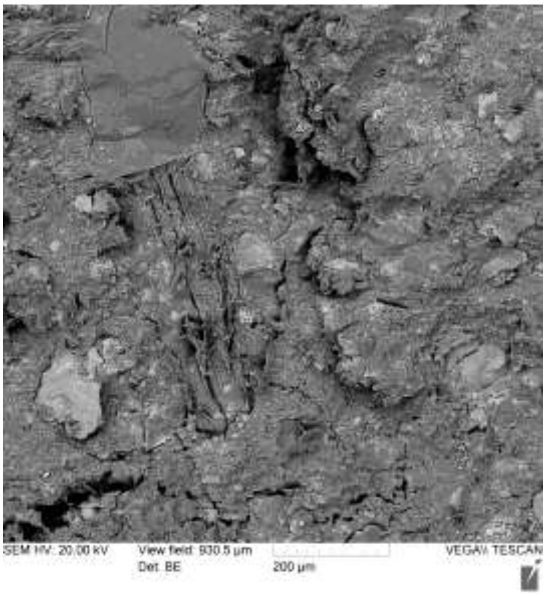

Fig. 2. Photomicrograph of a piece of screenings baked at a temperature of 1000 °C

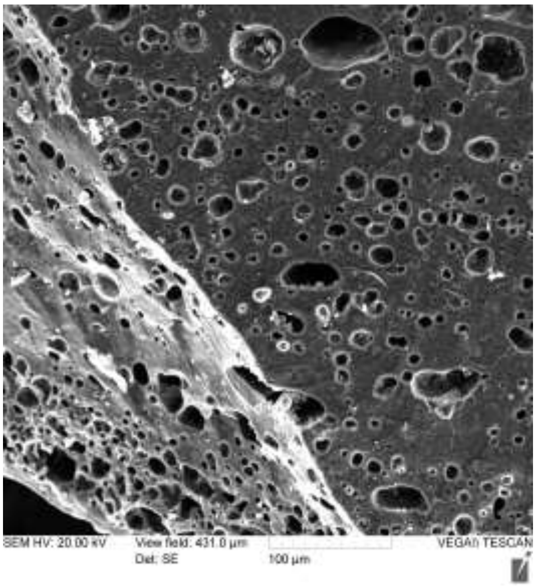

Fig. 3. Photomicrograph of a piece of screenings baked at a temperature of 1100 °C

Mineral composition and structural features of the screenings determine their specific pre-baking ceramic properties. The screenings are stiff. Their plasticity index does not exceed 5-6 units even when ground to the grain size of 0-0.16 mm, which is not enough for item molding with extrusion. They are insensitive to drying. They have low binding ability, the bending strength of dried specimens does not exceed 1 MPa. However, baked specimen from the same base have quite significant strength. At that, the strength of baked specimens strongly depends on the degree of raw material grinding and baking temperature (Fig. 4). As it is evident from the results, baking at a temperature of 950-1050 °C and grinding to a grain size of 0-0.315 – 0-0.63mm provides breaking strength of produced tiles at a level of more than 10MPa with the void coefficient of 50%.

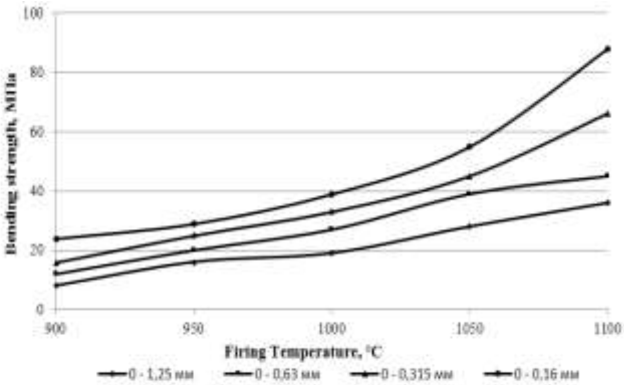

Fig. 4. Compression breaking strength of baked specimens as a function of baking temperature

Introducing slurry coal allows increasing plasticity and cohesion of the raw mass. However, as the coal slurries contain about 35% of coal, and the amount of fuel introduced together with the raw materials shall not exceed 80%, the coal slurry content shall not exceed 22%. At this level, plasticity of 7-8 units is attained, which is still insufficient for extrusion molding of tiles. The complex technological approach conditions to treating coal slurries as composite additive. Besides improving formation-related properties, they serve as a burnable fuel additive, allowing reducing the density of ceramics and significantly reducing gas consumption for baking. Cost of one calorie of released heat for coal slurries is 15-20 times lower that that of gas or pure coal. While prices for pure coal and natural gas amount to 7,000-9,000 rubles per ton, the price of coal slurry is about 200-400 rubles per ton.

Combustion of coal particles during the baking facilitates formation of porous structure in the ceramic material, thus reducing density and heat conductivity of the tiles. However, it also leads to reduced strength of the tiles. That is why determining the optimal amount of coal slurry to be introduced into the process is a challenging task. Figure 5 shows compression breaking strength of specimens containing 22% of coal slurry as a function of baking temperature for screenings ground to grain sizes of 0-0.63 and 0-0.315mm.

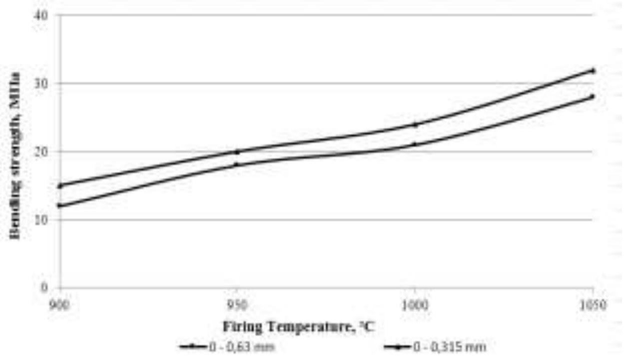

Fig. 5. Compression breaking strength of baked specimens as a function of baking temperature for coal slurry content of 22%

As it is evident, 22% of coal slurry in the raw mix is enough to achieve the strength sufficient for large-size high-efficiency structural clay tiles with the void coefficient of 50% and strength rating of M100 or higher. At that, the baking temperature shall be 950-1050 ºC, depending on the required strength. At that, the average density of ceramics is 1480-1620 kg/m^3. Taking into account the void coefficient of 50%, the average density of the tiles is going to be 750-800 kg/m^3. At that, the void coefficient may be increased further, as the safety margin of the ceramic material allows for it. Currently produced large-sized structural clay tiles a vertical configuration of voids have the void coefficient of up to 60%, while those with a horizontal configuration have the void coefficient of up to 70%, but with a significantly lower strength.

As a result from experiments, the authors recommend introduction of siliceous clays into the mass to increase plasticity of the screening-sourced ceramic mass, its structural strength and improve its molding properties. These rock types are common in the south of Russia. Their feature in the composition that includes 50-60% of montmorillonite minerals and about 30% opaline silica in the form of remains of diatoms, spicula, radiolariae. They are characterized by increased plasticity (22-28 units) and good molding properties. Ceramic material on their base has a lower average density (1550-1650 kg/m^3) by means of microporous structure of opaline silica. As an example, Table 2 shows averaged composition of siliceous clays from Malchevskoe deposit that were used in the authors' experiments.

TABLE II. AVERAGED CHEMICAL COMPOSITION OF SILICEOUS CLAYS FROM MALCHEVSKOE DEPOSIT, %WT

Loss on ignition	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**K_2O**	**Na_2O**
6-7	68-70	13-15	4-5	1-2	0.5-1	0.1-0.4	1.5-2.5	0.4-0.6

Results of the experiments, including pilot control, have shown that introduction of 10% of siliceous clays into the ceramic mass provided necessary plasticity and molding properties, while strength of baked tiles increased by 15-20% without any increase in average density. It means it is possible to bake at a temperature 20-30 ºC lower and achieve the necessary strength, if siliceous clays are introduced.

The results of our work allowed for development of an optimal process scheme, as we see it, aimed at production of large-size high-efficiency clay tiles from coal refuse processing wastes (screenings and silt coal), where the tiles are formed by semi-rigid extrusion and then dried in a drying tunnel on baking trolleys with the following ratio of the components: screenings – 65-70%; coal slurry – 20-25 %, and siliceous clay – 10 %. Figure 6 shows a diagram of the process, not showing transportation and axillary equipment.

The main pre-treatment operation of the raw mix is grinding the screenings to achieve the grain size of 0-0.315 to 0-0.63mm. To that end, it is most practical to employ a hammer mill first, followed by shaft mill, pendulum mill, globe mill or refining rolls. Coal slurry does not require grinding, as it is already in a fine state. The task is to thoroughly mix the components and strictly control the mix moisture content, which shall be within the range of 14-16% for this time of raw mass and formation method. To that end, there are two mixers and a clay muller. The tiles are formed with extruders. An SM-506M extruder (Made in Belarus) may be used for that, as well as a number of models of Western European manufacturers. Presence of fine coal is especially favorable for extrusion molding under higher pressures, as the coal serves as a kind of a lubricant in molding. The main task of a process engineer is to optimize the process parameters of mold pressing (temperature, press head pressure, extruded wad velocity, vacuum level, steam temperature, etc.) to produce tiles with sufficient strength to be placed onto baking oven trolleys. It is recommended to use robots for placing, as it is the only way to guarantee that the blocks are put onto the trolleys undeformed.

Absence of such operations as staking and removal of tiles onto and from drying trolleys significantly simplifies the process diagram of the production. At that, for raw mixes on the base of screenings, if the length of the oven is sufficient (150m or more), drying as a separate operation may be absent altogether. In baking, the main task is to provide complete burnout of the coal component and maintenance of a required baking mode. At that, the baking may be performed using only coal, following the scheme of 80% of fuel in the tiles, 20% of fuel is coal supplied through special burners. It should be noted that having fuel inside the tiles facilitates uniform baking, both through the item and through the heat treatment load. Introducing 1-2% of saw dust, straw meal, sunflower or rice husk into the mix improves the baking conditions by means of earlier ignition of coal and expanding the burning zone, as these organic materials ignite at lower temperatures (450-600 ºC) than coal does. At that, due to thermal decomposition of wood (pyrolisis) at a temperature of 250-350 °C, flammable pyrolysis gases are released and also promote expansion of the baking zone.

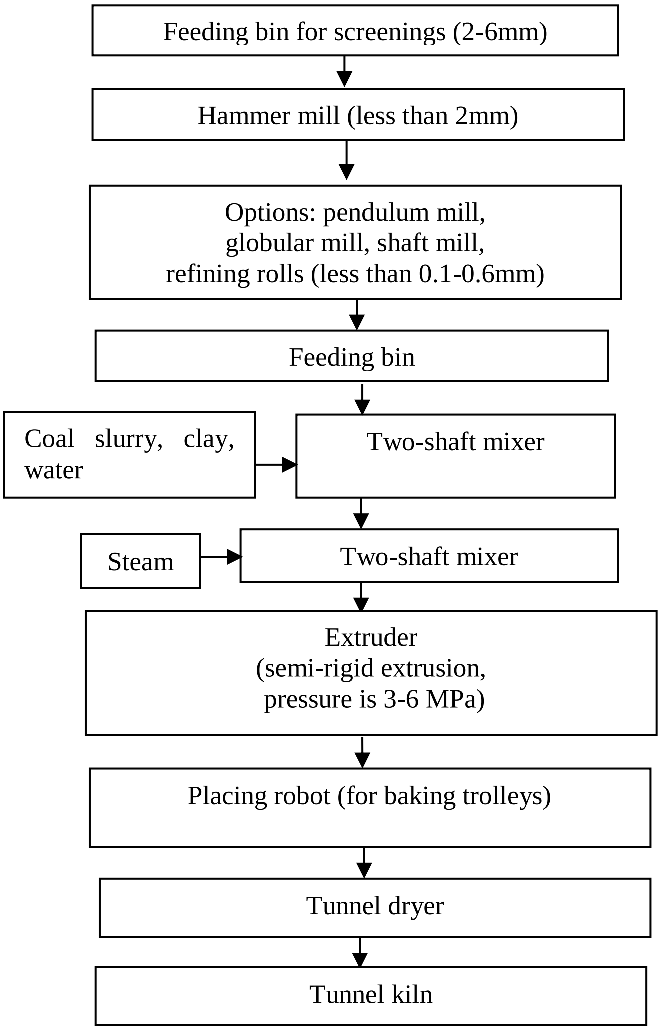

Fig. 6. Compression breaking strength of baked specimens as a function of baking temperature for coal slurry content of 22%

Most of the equipment shown in the process diagram had been made in Russia. The only major exceptions are the extruder and robots that place and remove the tiles onto and from the trolleys. Extruders are currently produced in many European countries, as well as in Turkey. Extruders manufactured by Verdes, Spain provide the optimal solutions as for price – quality ratio. The most common in the ceramic industry are robots manufactured by Fanuc (Japan) that made a good showing.

Fig. 7.

IV. Conclusion

The results of these works allowed for selection of raw materials and development of the process diagram for manufacture of high-efficiency large-size structural clay tiles with minimum prime cost. The low prime costs will be attained by means of:

– near-free raw materials;
– simplified process scheme of raw mix preparation;
– molding the tiles with a rigid extrusion method;
– accelerated drying of the tiles on baking trolleys inside the tunnel dryer;
– minimum cost of baking due to using coal slurries;
– high degree of automation with minimal involvement of manual labor.

Putting these results into practice will allow creating a highly profitalbe production and make Rostov oblast a major producer of wall ceramics.

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