Use of Granulated Metallurgy Slag in the Raw Mix for Producing Ceramic Paving Stones: Insights from an Experiment in Kazakhstan

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Abstract

Ceramic paving stones are some of the frequently used building materials with many applications. Metallurgical slag when used in the production of ceramic pavers obtain high physical and mechanical properties, lead to environmental friendliness of the slag disposal process and save the valuable natural resource.

It has been established that an increase in blast-furnace granulated slag up to 35% will transform the ceramic mass into an insensitive mixture. Molded specimens can then be dried at an accelerated rate without cracks. An increase granulated slag upto 35%, also increases the strength of the samples at a firing temperature of 1000°C. This is 1.5 times of minimum slag content.

This research examines the raw mixture for the production of ceramic paving stones with the addition of granulated blast-furnace slag. To achieve this goal, experiments were performed on the use of granulated blast-furnace slag as part of the raw mix.

This study found that the samples fired at 1000°C, painted slag grains are crystallized by the low-temperature form of wollastonite (CaSiO3). The crystallized slag grains present in the blast-furnace granulated slag is 30-35%. These results will help in the production of ceramic paving stones, and save the exhaustible resources. And also, the results of this work satisfy the problems of the metallurgical industry for the disposal of blast-furnace slag.

Keywords: Blast-furnace slag; Loam; Bentonite; Wollastonite; Physical and mechanical properties; Microstructure.

Introduction

In recent years, in Kazakhstan, there is a focus on the construction of roads and pedestrian zones. Until 2025, it is planned to build new pedestrian zones in Almaty, at least on eight streets. Such a rapid growth in construction has created a need for quality raw materials. The most popular material in this case is ceramic paving stone, which is used for paving city squares, sidewalks, roadways, parking lots, various sites, parking alleys, areas in front of shops and restaurants, as well as for modelling borders, stairs and other architectural structures. The use of ceramic paving stones has many advantages. Firstly, the paving of pedestrian areas with paving stones has a more aesthetic appearance. It is well known that ceramic materials have high chemical resistance (98-99%) in relation to solutions of salts, acids and alkalis (Das and Das, 2021). Due to this property, the products are not destroyed by the actions of sulphate salts, acids and alkalis. Ceramic pavers also, conduct water well and have high frost resistance, since there is no excess moisture in the material. Accordingly, there is no damage at low temperatures. Ceramic pavers are highly resistant to abrasion, because they have a high density. Due to the induced properties, ceramic paving stones are quite durable, because they practically do not change their properties during operations (Bieliatynskyi et al., 2022; Tyliszczak et al., 2018).

Ceramic pavers are often made from clay material (Lee and Yeh, 2008; Mohmoudi et al., 2008), but in almost all regions of Kazakhstan, the reserves of high-quality clays are very limited. Therefore, loess-like loams, which are widespread in Kazakhstan, are used for the production of ceramic materials. However, the use of low-grade sandy loess-like loams does not make it possible to obtain a ceramic material with high physical and mechanical properties that can withstand long-term operation in open spaces. Loess-like loams are characterized by low sintering properties and the presence of undesirable impurities. Due to the unstable chemical and mineral composition of loams, when they are fired, the processes of structural formation do not fully proceed even at high temperatures (Sattinova et al., 2022). As a result, high energy and resource costs are required for their production, which are not justified by the quality of the finished product.

However, it is possible to solve this problem through the use of granulated metallurgical slag in production. Wastes of ferrous (blast furnace, steel-smelting, ferroalloy, cupola) and non-ferrous (copper-smelting, nickel, aluminium) metallurgy are classified as metallurgical slags. 1 ton of smelted metal can be formed from 0.04 to 0.7 tons of slag (Abdrakhimov and Abdrakhimova, 2000; Duan et al., 2022a; Duan et al., 2022b).

Due to the high activity towards crystallization, as well as sintering in a finely dispersed state, that is, after granulation, the slag can replace most of the clay component in the initial mass. The use of slag waste from metallurgical industries solves urgent environmental problems of preserving natural resources, rational environmental management and optimizing engineering solutions (Peleshenko et al., 2017). In addition, inter-production cooperation, leading to a reduction in the waste of some industries and an increase in the quality of products of others, is undoubtedly included in the concept of sustainable development, which stands on three pillars–economic development, social responsibility and responsibility for the environment (Dovzhenko and Zubekhin, 2010; Lisachuk et al., 2011). Therefore, new scientific and technological research is needed to obtain ceramic pavers with shapes, colours and types for the purpose of arranging sidewalks, alleys, park areas, courtyard roads, playgrounds, parking lots and other areas. These studies should consist of solving technological problems for the production of raw materials, and for the development of starting materials for optimal raw mixtures, taking into account the constituent materials at the stage of processing, moulding, drying and firing. At the same time, the issues of resource-saving and energy-saving should be resolved.

In this context, the goal of this research is to the study the raw mixture with the addition of granulated ceramic slag to obtain ceramic paving stones. Its objectives are as follows.

1. To investigate the effects of incorporating granulated blast-furnace slag into the raw mix for ceramic paving stone production.

2. To assess the physical and mechanical properties of ceramic paving stones obtained from the raw mix with varying percentages of granulated slag.
3. To evaluate the environmental benefits of utilizing metallurgical slag in the production process, particularly in terms of slag disposal and conservation of natural resources.
4. To determine the optimal percentage of granulated slag in the raw mix that would result in an insensitive mixture, allowing for crack-free drying of moulded specimens.
5. To examine the impact of increasing granulated slag content on the strength of ceramic paving stone samples after firing at a temperature of 1000°C.
6. To identify the mineralogical composition of the samples, particularly the crystallized slag grains present in the blast-furnace granulated slag.

Literature Review

Literature shows that there is a renewed interest in blast-furnace slag utilization. Many scientists are busy with the use of metallurgy waste. Blast-furnace slag is often used as a component of building materials or ceramics. Khater et al. (2022) have examined the properties of ceramics, which include blast-furnace slag, the percentage of which range from 10 to 90% by weight, in combination with ceramic slag. The samples obtained has had an average porosity of 28-40% and a density in the range from 1.613 to 2.182 g/cm^3, which confirms the relevance of using this mixture for the construction purposes. By adding blast-furnace granulated slag to the composition of ceramics, such wollastonite modifications as para-wollastonite and gehlenite have been obtained.

Wu and Zichen (2021) have shown that obtaining porous ceramics from steel slag solves not only the problem of processing steel slag, but also provides a good replacement for the main raw material of porous ceramics. The influence of the size of slag particles has also been studied. It has been found that particles of smaller dispersion improve the physical and mechanical properties of ceramics (Sobczak-Kupiec et al., 2012). De Figueirêdo et al. (2019) have studied the structural changes in composite ceramic masses using bentonite. They show that the plasticizer bentonite improves the moulding properties of the mixtures and adds mechanical resistance to size change and the formed mullite cohesive crystalline phases. Studies of the properties of loams from deposits in Ukraine, Germany, France and Portugal have shown that with the addition of slag 5-10% by weight of bentonite deposits in Sardinia, Italy (Andreola et al., 2009) provide high stability. The blast furnace slag has the potential to be used as a secondary raw material in the production of ceramic wall tiles. The utilization of BFS waste offers advantages such as improved strength and reduced thermal expansion. The SEM analysis revealed that the presence of BFS led to the formation of anorthite and a glassy phase, with higher CaO content. The inclusion of BFS resulted in higher strength and lower thermal expansion values compared to the standard samples. Notably, incorporating 33% BFS in the tile composition led to a significant 25% increase in strength (Ozturk and Gultekin, 2015).

The research by Badiee et al. (2013) aimed to explore the use of electric arc furnace steel slag as a raw material in the production of floor tiles. Experimental samples were prepared with varying amounts of slag and subjected to firing in an industrial roller kiln. The thermal behaviour of the samples was analyzed, and the major phase in the slag was identified as Wustite (FeO) using X-ray diffraction. The study evaluated the effect of slag addition on the strength of the samples through a four-point bending strength test. The sintering behaviour of the samples was also examined by measuring shrinkage, relative density, and water absorption. The results indicated that adding more than 40 wt-% of slag to the base body resulted in closed porosities due to the bloating phenomenon, which led to a reduction in bending strength. Furthermore, a wear resistance test confirmed that the samples with a high slag content could be utilized as standard floor tiles.

The existing body of research predominantly focuses on the application of slags in the production of wall ceramic materials, particularly through plastic and semi-dry moulding techniques for ceramic masses. However, it is important to note that the dimensions and specifications of these products are primarily governed by state standards, which may not be relevant for their use as ceramic paving stones.

Research Methodology

This article presents the findings derived from a comprehensive scientific and experimental study conducted to investigate the utilization of granulated blast-furnace slag in the manufacturing process of ceramic paving stones. The experimental investigation was performed using a raw material system comprising loam, bentonite clay, and blast furnace granulated slag obtained from ArcelorMittal Temirtau JSC (joint-stock company). The granulated slag, characterized as a bulk material with a grey appearance, was employed as a crucial component in the study. The loam and bentonite clay used in the research were sourced from the Turkestan region, as depicted in the Fig. 1.

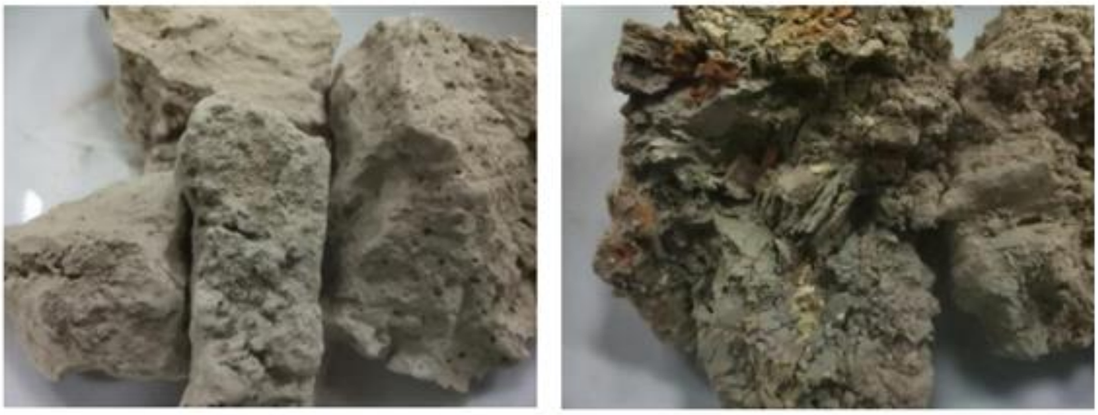


Fig. 1: Appearance of loam and bentonite clay deposits of the Turkestan region: a) loam; b) bentonite clay
Source: made by the authors.

The physical and mechanical properties of the finished product were investigated through a series of analyses. Initially, the chemical and mineralogical characteristics of the chosen raw materials were thoroughly examined. Subsequently, after the production of samples, an extensive assessment of the physical and mechanical properties of the resulting product was conducted. The investigation of the raw materials constituted a critical stage in the study, as it provided essential data on the chemical and mineralogical properties of the materials. These findings played a pivotal role in the selection and formulation of the production technology. By understanding the structural attributes of the raw materials, appropriate production techniques could be devised, ensuring the desired physical and mechanical properties of the final product.

The Table 1 provides an overview of the analytical methods and corresponding instrumentation used for the elemental and mineralogical analysis of samples. The combination of these analytical methods offers comprehensive insights into the elemental and mineralogical properties of the samples, enabling a detailed characterization and understanding of their composition. Scanning electron microscopy (SEM) brand JSM-6390LV with energy-dispersive microanalysis was used to determine the local elemental composition of the samples. ICP-MS Agilent 7500cx inductively coupled plasma mass spectrometry method was used to determine the chemical elemental composition. The X'Pert PRO MPD X-ray diffraction method was used to determine the mineralogical composition.

Table 1: Elemental and Mineralogical Analysis of Samples using SEM-EDS, ICP-MS, and XRD Techniques

Source: compiled by the authors.

Sample Analysis Methods	Instrumentation Used
Scanning Electron Microscopy (SEM) with Energy-Dispersive Microanalysis (EDS)	JSM-6390LV
Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	Agilent 7500cx
X-ray Diffraction (XRD)	X'Pert PRO MPD

X-ray phase analysis represents a fundamental approach employed in the examination of a material's structure. The underlying principle of this method involves the identification of distinct phases within the material by analyzing its diffraction pattern. The procedure involves scrutinizing a series of interplanar distances and corresponding line intensities for each element present in the material, as captured by the obtained X-ray data. To determine the granulometric composition of clays, the hydrometric method was utilized. This composition serves as a vital characteristic of the material and pertains to the distribution of various fractions within it, specifically the particle sizes. For particles smaller than 0.1 mm in clay, the areometric method is commonly employed. This method relies on assessing the rate of sedimentation of soil particles of varying sizes in water.

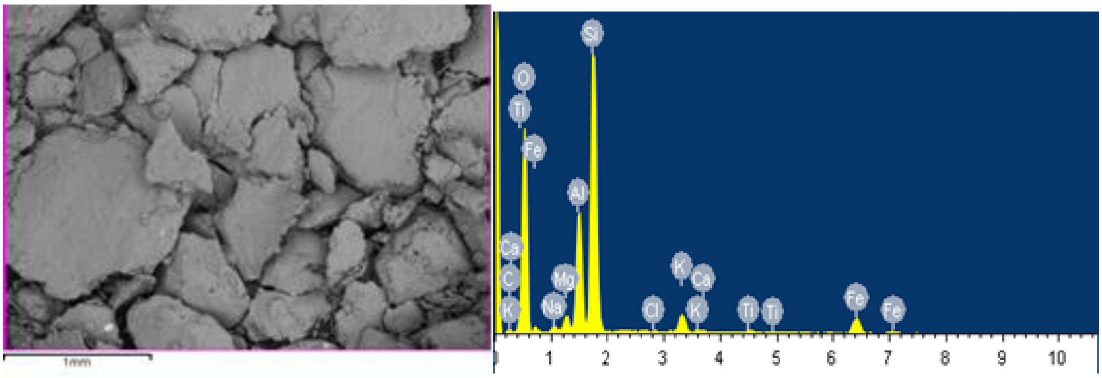
The particle size distribution is determined by passing the total mass of the material through a set of sieves with different aperture sizes. Following the characterization of the raw material, the subsequent stage involves the production of samples and the determination of their physical and mechanical properties. Sample production is conducted using powder metallurgy techniques, encompassing several key operations such as obtaining and preparing raw materials, pressing, and heat treatment or sintering. These processes ultimately confer the final physical and mechanical properties upon the material.

To assess the physic-mechanical properties of the obtained samples, a comprehensive series of investigations were conducted. The sensitivity to drying was evaluated using the Chizhsky method, which involves subjecting the samples to controlled heat flow to assess their ability to withstand shrinkage stresses. The duration until the first appearance of cracks was recorded as the indicator of sensitivity to drying, measured in seconds. Furthermore, the mechanical properties of the ceramic pavers were characterized by determining their ultimate compressive and flexural strength. The ultimate compressive strength indicates the maximum load the pavers can withstand before failure, while the flexural strength measures their resistance to bending forces.

In addition to the mechanical properties, several physical characteristics were analyzed. The average density of the samples was determined to provide an understanding of their mass-to-volume ratio. Water absorption, a crucial parameter for durability, was also assessed as it directly influences the material's resistance to moisture penetration. Lastly, the frost resistance of the samples was evaluated, taking into account the interrelation between water absorption and frost resistance. It is worth noting that lower water absorption levels correlate with higher frost resistance, indicating a superior ability to withstand freezing and thawing cycles. The combined assessment of these physic-mechanical properties provides valuable insights into the overall quality and performance of the ceramic pavers, facilitating informed decision-making in various practical applications.

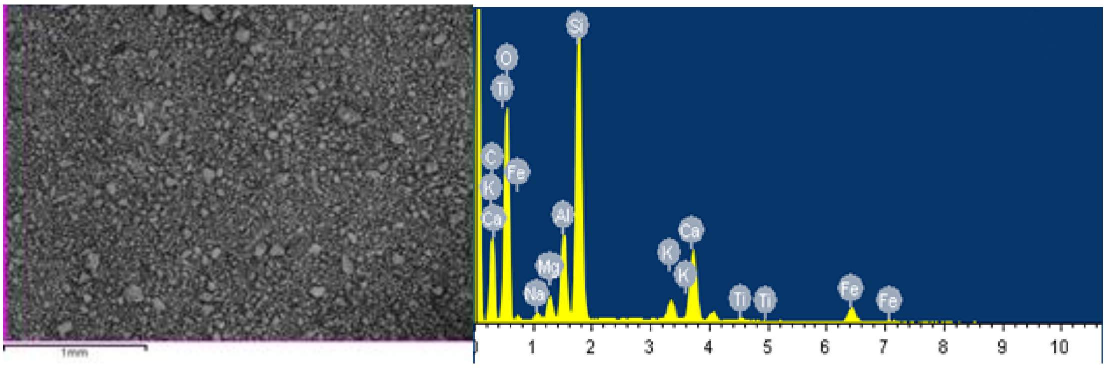
Results

At the first stage, the composition and chemical and mineralogical characteristics of the initial raw material mass, which includes loam, bentonite clay and blast furnace granulated slag ArcelorMittal Temirtau JSC, were studied. Since it is these characteristics that play a key role in the construction of a technological scheme, the choice of parameters for formation and heat treatment, and the physical and mechanical properties of the obtained materials depend on these parameters. The results of the obtained microstructure and spectra of bentonite clay and loam can be found in the Figs 2 & 3 respectively.



a) b)

Fig. 2: Microstructure and spectra of bentonite clay: a) microstructure; b) spectra
Source: Authors.



a) b)

Fig. 3: Microstructure and spectra of loam: a) microstructure; b) spectra
Source: Authors.

When determining coarse-grained inclusions, both clay materials were crushed to a size of pieces no more than 10 mm and dissolved in water during the day. After that, the residue on the No. 05 sieve was determined. The sandiness index was estimated by the residue on the sieve No. 0063. The results obtained are shown in Table 2.

Table 2: Coarse-grained inclusions and sandiness of clayey rocks
Source: Montayev et al., 2022

Property name	Content, %	
	loam	bentonite
coarse-grained inclusions	0.4	2.4
sandiness	7.8	3.4

According to the results, it was found that the granulometric composition of clays is similar to each other in terms of a significant content of silt fractions, while they differ in the clay component and the sand fraction. It should be noted that bentonite clay contains half as much clay and less sand than loam. Using the organoleptic method, the moulding moisture content of clay was determined, after which the moisture content was determined by the gravimetric method. For the studied clay materials, the forming moisture was 15.94% for loam and 31.58% for bentonite. In accordance with GOST 21216-2014 (2015), the plasticity of both clay components was determined by the balance cone method. The results are shown in the Table 3.

Table 3: Indicators of plasticity of clayey rocks of the Ordabasy deposit of the Turkestan region
Source: Montayev et al., 2022

Name of raw materials	Absolute humidity of the mass in the state of boundary limits, %		Plasticity number
	Lower yield point	Rolling border	
Loam	23.85	19.22	4.63
Bentonite clay	61.06	40.02	21.04

According to the data in the Table 2, it can be concluded that loam refers to low-plastic raw materials, and bentonite clay – to medium-plastic. The chemical composition of the slag depends mainly on the raw materials used and the overall process (Gorai and Jana, 2003). The chemical composition of the slag used in the work is presented in the Table 4.

Table 4: Chemical composition of blast furnace granulated slag ArcelorMittal Temirtau JSC
Source: Linskiy, 2010.

Name of raw materials	Content of oxides, wt.%											
	SiO_2	Al_2O_3	Fe_2O_3	CaO	FeO	MgO	SO_3	Na_2O	K_2O	CO_2	TiO_2	ShO	other
Granulated blast-furnace slag JSC ArcelorMittal Temirtau JSC	40.62	16.24	0.19-0.52	42.11	0.43	5.33-10.39	1.66	0.36-1.5	0.42-1.32	-	0.62-0.88	0.11-1.37	0.92

As a result of the research, an X-ray pattern of blast-furnace granulated slag was obtained, shown in the Fig. 4. X-ray phase analysis of heat-treated slag in the temperature range of 950-1000°C shows the presence of wollastonite, melilite and cuspidin in it.

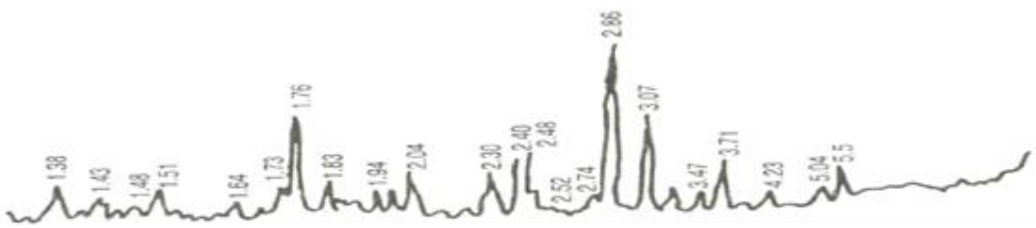
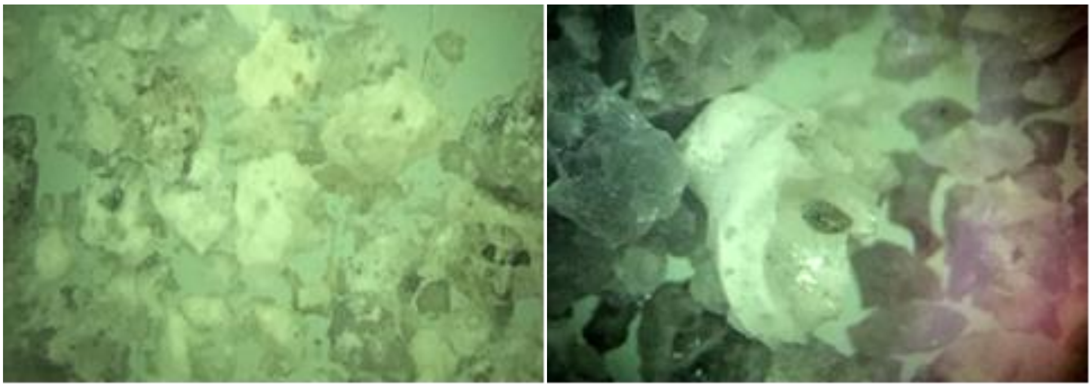


Fig. 4: X-ray pattern of blast-furnace granulated slag ArcelorMittal Temirtau JSC after heat treatment at a temperature of °C
Source: Linskiy, 2010

Micrographs of blast furnace granulated slag ArcelorMittal Temirtau JSC are shown in the Fig. 5.



a) b)

Fig. 5: Microphotographs of blast-furnace granulated slag ArcelorMittal Temirtau JSC: a) increase x 10; b) increase x 50
Source: Linskiy, 2010.

The glass phase content in ArcelorMittal Temirtau JSC slag averages 70-95%. The vitreous structure is mainly due to the rapid cooling during the granulation process. Basically, most of the metallurgical slags, for the purpose of reuse, lend themselves to the process of dry granulation (Liu et al., 2016). The next stage of the experiments was the production of samples from the prepared raw materials and their study of the physical and mechanical properties. In order to develop the most practical and high-quality composition for the production of ceramic pavers, four compositions of ceramic masses with different percentages of elements were prepared, and a control sample was made without the presence of granulated blast-furnace slag in the composition. Ceramic compositions were prepared by mixing dry powders of loam, bentonite and granulated blast furnace slag in the ratios shown in the Table 5.

Table 5: Investigated compositions of ceramic masses
Source: Authors

Content numbers	Mass fraction, %		
	loam	bentonite	blast furnace granulated slag
1	85	5	10
2	70	10	20
3	55	15	30
4	45	20	35
Control content	85	15	-

For the preparation of the ceramic samples, a standard technique of powder metallurgy was used, which consists of the following steps: drying of raw materials, grinding, dosing and mixing of the mixture, forming samples, or in other words, pressing, drying, sintering and quality control of the resulting material. Drying of the raw mass was carried out in an oven at a temperature of 70-80°C, so that the residual moisture was 5-7%. After that, the resulting mass was ground using a ball mill and sifted through a sieve with a fraction size of 1 mm. The resulting powder mixture was dosed according to the test compositions listed in the Table 1, and then stirred until a homogeneous mixture was obtained using a laboratory stirrer. Water was added to the resulting dry mixture up to 10-12% and again mixed until a homogeneous mixture was obtained, the moistened ceramic mass was kept in a desiccator for 48 hours. After the end of the aging period and the ceramic masses, cylindrical specimens with dimensions of 50x50 mm were moulded using the vibropressing method, which consists in exposing the mixture in the mold to vibration and high pressure. The vibropressing method is one of the main methods that are used in the production of building materials, including paving stones. The obtained pressed samples were placed in an oven at a temperature of 70-80°C, after which the samples went through the sintering stage, which is the main one in this technological scheme. The sintering of the samples was carried out in a laboratory electric furnace brand SNOL 58/350, the heating temperature of the furnace was 1000°C, the temperature rise rate was 150°C/hour. The resulting fired samples were cooled in the switched off furnace to room temperature.

The finished samples were tested to determine the physical and mechanical properties. The coefficient of sensitivity to drying according to the Chizhsky method, compressive and bending strength, average density, water absorption and frost resistance were chosen as the studied physical and mechanical properties. Since it is these properties of ceramic paving stones that are the main ones during operation and characterize the quality and durability of the materials obtained. The results of the studies are shown in Table 6. At the initial stage, in order to establish the regularity of changes in the physical and mechanical properties of the samples from the amount of addition of blast-furnace granulated slag, studies were carried out on raw samples, the coefficient, in order to determine the sensitivity to drying according to the Chizhsky method as a criterion for drying properties, green strength as the criterion of moulding properties and the average density as one of the criteria for the technological properties of samples.

Table 6: Physical and mechanical characteristics of materials of the loam-bentonite clay-blast-furnace granulated slag system

Content numbers	Coefficient of sensitivity to drying, seconds	Average density, g/cm³	Strength, MPa		Water absorption, %	Frost resistance, cycles
			At compression	When bending		
1	175	1.63	19.7	2.4	15.4	72
2	182	1.71	22.4	3.5	13.3	84
3	185	1.78	28.2	4.8	10.4	95
4	188	1.84	30.4	6.6	8.2	100
Control sample	110	1.58	18.5	2.2	17.5	50

To study the sensitivity to drying, the duration of the period of exposing the freshly moulded sample to the heat flow until the first crack appeared was studied. The irradiation period was determined as the arithmetic mean of the test results of the three samples and the sensitivity to drying of the ceramic mass was evaluated: highly sensitive is less than 100 seconds, medium sensitive is 101-108 seconds, low sensitive is more than 180 seconds.

According to this technique, highly sensitive ceramic masses, when irradiated, first cracks appear in them faster. With medium-sensitive and low-sensitive ceramic masses, the first cracks appear after longer irradiation. Therefore, the more sensitive the ceramic mass is to drying, the faster the first cracks appear during their thermal irradiation.

The experimental has shown that with an increase in the dispersion of granulated blast-furnace slag, the drying properties of the ceramic mass improve. In particular, the ceramic mass with the use of granulated slag powder transfers the studied mixture from the category of highly sensitive to the category of moderately sensitive, and an increase in the composition of blast-furnace granulated slag to 35% transfers the ceramic mass to the category of low-sensitivity mixtures.

This effect is apparently due to a more complete wedging of dispersed particles of bentonite loam, which are highly sensitive to drying, by more finely dispersed particles of non-plastic granulated slag. As a result, finely ground particles of granulated slag contribute to the easy transfer of moisture from the ceramic mass without defects and drying cracks. Dried cylindrical samples were also tested to determine the compressive strength in a hydraulic press according to a generally established method. Studies have shown that with an increase in the amount of granulated slag, an increase in compressive strength is observed.

Next step was to study the samples after sintering. The results of the analysis of the physical and mechanical properties of heat-treated samples at a temperature of 1000°C made it possible to establish the main patterns of their change depending on the amount of addition of blast-furnace granulated slag. With an increase in the amount of blast-furnace granulated slag, an increase in the average density and compressive and bending strength of the samples is observed. Thus, at a firing temperature of 1000°C, an increase in the average density from 1.63 g/cm^3 to 1.84 g/cm^3 is observed, and the compressive strength from 19.7 kg s/cm^2 to 30.4 kg s/cm^2. A comparative analysis shows that the increase in the strength of samples at a firing temperature of 1000°C with an increase in the amount of granulated slag addition to 35% is almost 1.5 times. Apparently, finely dispersed powders of granulated slag intensify the sintering process in a composition with clay minerals under the influence of high temperature. Due to the increased specific surface of granulated slag, the reactivity in the raw mixture is likely to increase due to an increase in the number of contacts between particles, which improves the physic-mechanical properties of the samples not only at the firing stages, but also at the moulding and drying stages. On the radiograph of the fired samples at a temperature of 1000°C (Fig. 6), there is a sharp increase in the reflections of β-wollastonite with a significant decrease in the reflection of quartz. Moreover, the absolute increase in the main lines of wollastonite is $2.97 \cdot 10^{-10}$ m.

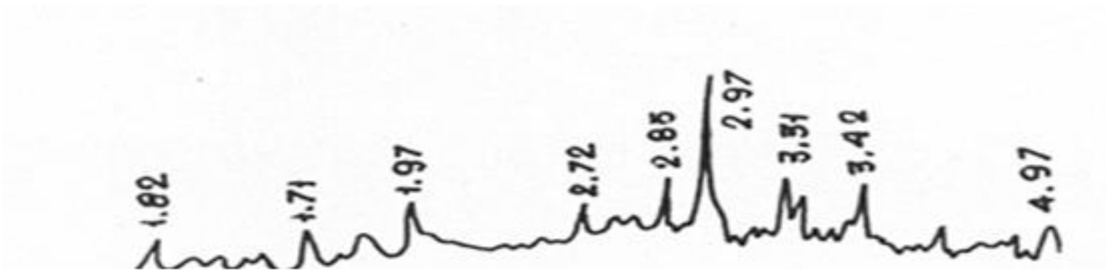
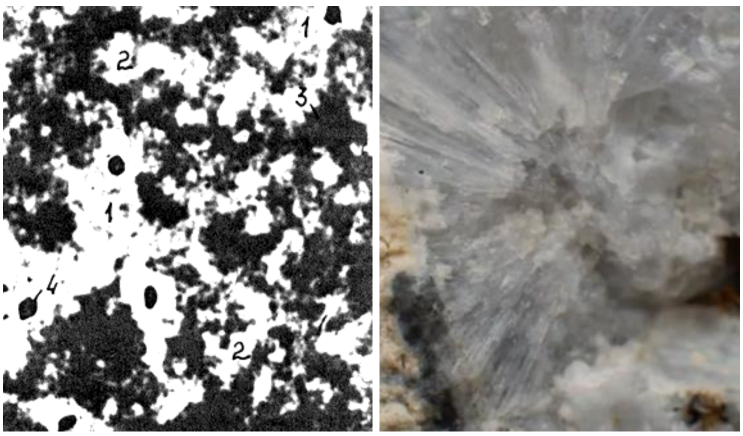


Fig. 6: X-ray pattern of fired samples at temperature of 1000°C
Source: Nair and Sairam, 2021

Behind its structure, wollastonite has an acicular structure, shown in the Fig. 7. The presence of wollastonite plays the role of a reinforcing component in the composition of the ceramic mass. Wollastonite plays an important role in the content of the slag (Nair and Sairam, 2021).



a) b)

Fig. 7: Micrographs of fired samples at T – 1000 °C: a) microstructure of the samples (1 – crystallized slag grains, 2 – quartz fragments, 3 – clay mass, 4 – pores); b) acicular wollastonite minerals crystallized from grains of granulated blast-furnace slag

Indeed, it should be noted that high strength indicators are achieved in those compositions where the highest crystallization of β-wollastonite is in the firing products. Wollastonite – the chemical formula of which is CaSiO3, is a natural calcium silicate, has a white or light grey colour. The main properties of wollastonite are micro-reinforcing and high adhesion to surfaces. Wollastonite is the main component of granulated blast-furnace slag. Under the microscope (Figure 7), fired at a temperature of 1000°C, porous slag grains are observed, crystallized with a low-temperature form of wollastonite. To a large extent, crystallized slag grains are observed in samples of compositions, where the amount of blast-furnace granulated slag is 30-35%. Between the slag grains are partially amorphized clay minerals and fragments of quartz. The appearance of glass with a refractive index of 1.500-1.520 is observed, which indicates the appearance of eutectic melts. The field state is subject to partial fracture. The next step was to study the indicators of water absorption. As the analysis of changes in water absorption indicators showed, with an increase in the amount of blast-furnace granulated slag, a significant decrease in these indicators is observed. Thus, the decrease in water absorption indicators of fired samples at a firing temperature of 1000°C ranges from 15.4% to 8.2%.

Discussion

Metallurgical slag is a solid industrial waste generated during the steel production process. It is estimated that about 0.13-0.2 tons of steel slag is produced per ton of steel. As a kind of alkali mixture, steel slag usually consists of CaO, FeO/Fe_2O_3, MgO, SiO_2 and Al_2O_3 but 88-92%, as well as minor oxides such as K_2O and Na_2O. The reuse of slag from metallurgical production is a very topical issue of the modern world, since as a result of blast-furnace production a lot of slag leaves, and the discharge or disposal of such amounts of slag causes environmental and space problems (Oge et al., 2019). Also, ever-increasing energy costs and environmental constraints are forcing researchers to focus on reusing vast amounts of industrial by-products, such as blast furnace and steel slag, in energy- and material-intensive industries such as iron and steel production and construction. Attempts to reuse metallurgical slag are very promising, often slag is used in the production of building materials (Skorokhod et al., 1994). For example, in the production of copper, up to 2.2 tons of slag is formed for each tonne of metal, respectively, the reuse of slag is very promising, the favourable physical and mechanical characteristics of copper slag can be used to produce products such as cement, filler, ballast, abrasive, aggregate, roofing granules, glass, tiles (Wang, 2016; Koval et al., 2021).

Materials based on metallurgical slag have high physical and mechanical properties, for example, building materials based on blast-furnace slags have higher bending and compressive strength. Accordingly, the results of this work confirm these properties of materials. It is also worth noting that ceramic materials based on metallurgical slag, in particular ceramic pavers, have high chemical resistance to solutions of salts, acids and alkalis, have low water absorption and high frost resistance, which was confirmed by the results of the work. Due to the induced properties, these materials have the prospect of a variety of applications. To compare the results of the study, with the aim of confirming or objecting, an analysis was made of works in this area by other authors over the past years of publication.

Studies have shown (Dovzhenko and Zubekhin, 2010) that ceramics based on blast-furnace slag and ceramic sludge have the prospect of being used as a building material. In the course of this work, nine ceramic samples were made, the percentage of blast furnace slag in which ranged from 10 to 90% by weight and ceramic sludge from 90 to 10% by weight. Various experimental methods such as X-ray diffraction, porosity, density, Scanning electron microscopy and dielectric analysis have been performed to investigate the properties of the obtained materials. X-ray phase analysis confirmed that the obtained ceramic materials mainly consist of phases of para wollastonite and gehlenite with fibrous, columnar and tabular crystals, respectively, the prospect of using blast-furnace slag to obtain these structures was obtained. The porosity of the samples was in the range of 28.83-40.50%, and the density was from 1.613 to 2.182 g/cm3, which made it possible to use them for construction purposes. It should be noted that the prepared materials were obtained in a green way without any chemical additives.

It has also been found that the prepared ceramic materials are suitable for applications in the electrical and electronic industries. Therefore, research in this area will be very relevant in order to obtain light ceramics of para wollastonite and gehlenite, which can be used in materials with a low dielectric constant in the production of electronic coatings.

The study Gorai et al. (2003) is aimed at elucidating the mechanisms of hydration, kinetics and characteristics of phosphate cement based on steel slag. Since iron oxides and calcium oxide containing compounds are expected to be the predominant reactants in steel slag, the resulting cement is called iron calcium phosphate cement (Tyliszczak et al., 2014). High strength properties of materials were obtained. It has been found that the use of large volumes of metallurgical slag as the main component can potentially bring great economic and environmental benefits in the production of phosphate cement. The aim of Ma et al. (2022) is to evaluate the effect of metallurgical slag as a partial replacement for cement on the mechanical properties and water resistance of cement-based materials in cramped conditions. The results show that, compared with wet steel slag, the setting time of the wet milled steel slag system is shortened and the free expansion rate is increased. With a content of wet milled steel slag of 10%, the ultimate compressive strength of the sample after 28 days of hardening is maximum and reaches 68.5 MPa, which is 9.3% higher than that of the free hardened sample, and water resistance is also the best. Under constrained conditions, the expansion strain created by the steel slag results in a compact sample structure and reduced porosity.

Research (Dai et al., 2022) has focused on the production of self-compacting concrete, when used in steel slag production technology. Self-compacting concrete is the main innovative material in the construction industry, which has excellent functionality and does not require an external load to fill. Cement is a vital ingredient in the production of self-compacting concrete, the main problem occurs in the environment due to the release of CO_2 gas in the production of cement, in order to solve this problem, binders such as fly ash are used as partial cement substitutes, which not only reduce consumption of cement, but also improve the properties of concrete (Sun et al., 2020; Prokopov et al., 1993). Steel slag, which is a waste product of the steel industry, can be used as a substitute for sand.

This article reports on the workability and mechanical properties of self-compacting concrete made from fly ash and steel slag. Cement is partially replaced by fly ash 5-20%, fine aggregates are partially replaced by steel slag 10-40% with an interval of 10% for a mixture of brand M30. Several tests were carried out in the fresh and hardened state, the optimal values of compressive and tensile strengths were noted at a dosage of steel slag of 40%. As a result, high physical and mechanical properties of the obtained materials have been obtained (Vaddeboina et al., 2022).

As an analysis of the literature has shown, in recent years, many studies have been carried out on the production of various materials using metallurgical slag. As can be seen from the above research information, metallurgical slag has prospects for the production of various materials with different properties. Therefore, the materials of this work can be a scientific basis for the following studies (Shishakina and Palamarchuk, 2020). The relevance of the use of blast-furnace slag in the production of ceramic pavers is confirmed by many factors. First of all, this is the environmental friendliness of blast-furnace production, since the resulting slag is reused during production. Slag disposal is a big problem, as the use of mankind is increasing, respectively, and the amount of used production resources and their waste. Sludge disposal is a major problem in urban areas as it causes severe damage to the environment. Until now, the burning of hazardous waste in landfills is one of the most common ways to dispose of waste, causing serious damage to health and the environment. Accordingly, the disposal of metallurgical slag entails many environmental problems, as a large amount of blast furnace slag is toxic and has a chemical impact on the environment.

Conclusions

Based on the analysis of the works of scientists in this field, as well as translated studies, a high relevance was established in the use of ceramic paving stones for the improvement of the pedestrian zone, public areas of the city, since ceramic paving stones are highly environmentally friendly, durable, weather resistant and have a more aesthetic appearance.

This experiment on the use of blast furnace granulated slag ArcelorMittal Temirtau JSC for the production of ceramic paving stones, as an additive, showed an improvement in the physical and mechanical properties of the product at the stage of drying and firing. It has been established that an increase in the amount of addition of blast-furnace granulated slag up to 35% will transfer the ceramic mass into the category of insensitive mixtures. This makes it possible to dry moulded specimens at an accelerated rate without drying cracks. It has been established that with an increase in the amount of granulated slag addition to 35%, the increase in the strength of samples at a firing temperature of 1000°C is almost 1.5 times compared with the minimum slag content. According to the results of X-ray phase and electron microscopic analysis, it was found that in samples fired at a temperature of 1000°C, porous slag grains are observed, crystallized by the low-temperature form of wollastonite ($CaSiO_3$). To a large extent, crystallized slag grains are observed in samples of compositions, where the amount of blast-furnace granulated slag is 30-35%. It has been proven that the presence of wollastonite in the composition of the ceramic mass plays the role of a reinforcing component. Indeed, it should be noted that high strength characteristics are achieved in those compositions where the highest crystallization of wollastonite is in the firing products.

This experimental work has proved that the feasibility of producing ceramic paving stones in the raw material system loam-bentonite-granulated blast-furnace slag meets the requirements of quality, aesthetics, environmental friendliness, resource and energy saving. The implementation of this production method yields the potential to enhance the recycling efficacy of waste generated from the metallurgical industry. The resulting material, obtained according to the technological scheme induced in this work, has prospects for industrial use, for paving sidewalks, footpaths, parking lots, various squares, park alleys and other urban needs. The utilization of metallurgical slag in ceramic material production contributes to the conservation of exhaustible natural resources employed in manufacturing while addressing the challenges faced by the metallurgical industry regarding blast-furnace slag disposal.

Further research may study other dosages of the composition of ceramic pavers, improve production technology and change the parameters of sintering and drying processes.

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Received	**Reviewed**	**Revised**	**Published**
22.06.2023	10.07.2023	12.07.2023	31.07.2023