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Study of Moulding Sands to Create Three-Layer Magnesium Concrete

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***Abstract* – The article is devoted to the problem of creating energy-efficient building materials for enclosing structures. The aim of the research is to develop a recipe and a method for moulding sands placing to create heat-insulating concrete of a multilayer structure. The three-layer magnesium concrete containing layers of different densities is an object of a scientific research. Compositions of moulding sands for concrete's central and surface layers have been developed and studied. Materials specially developed were used as raw materials for moulding sands; they are as follows: composite magnesial binder and porous filler obtained by low-temperature firing of a granular mixture based on sodium liquid glass and thermal energy waste (fly ash from thermal power plants, aluminosilicate microsphere). Possibility of regulating moulding sand's properties for concrete's central layer by varying the content and fractional composition of porous granules has been shown. There has been proposed the moulding sand for surface layers of three-layer magnesium concrete containing crushed porous sand. The related composition of moulding sands favours with adhesion of concrete's different layers. Various technological methods for producing magnesium concrete of a complex structure have been studied. The research reveals technological and operational characteristics of three-layer magnesium concrete obtained by horizontal and vertical deposition of moulding sands.**

***Keywords* – Aluminosilicate microsphere; caustic magnesite; fly ash from thermal power plants; magnesium moulding sand; multilayer concrete; porous granules.**

1. INTRODUCTION

The sector of modern construction accounts for almost a third of global energy [1]–[3]. High energy consumption at the stage of construction and operation of construction projects is accompanied by significant carbon dioxide emissions; its content reaches 40 % of the total volume [3].

A rational choice of materials for roofing and cladding elements is necessary to reduce energy consumption in the construction industry. This requires solving conflicting problems: on the one hand, it is necessary to increase heat-protective properties of enclosing due to materials of a porous structure with low thermal conductivity; on the other hand, it is important to ensure the required strength by means of materials with a dense structure.

Promising solution to this problem is transition to a layered structure of cladding products by combining materials with different properties. Coating slabs, layered wall panels and blocks have become widespread in the construction. Technology development for producing and using multilayer products indicate high interest of designers, technologists and builders

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in this group of innovative materials. Raw material base of layered products is expanding due to natural and technogenic resources [3]–[8], and active including materials of plant origin [3], [6], [8]. There is growing number of developments to improve heat-shielding properties of multilayer products through the use of highly porous materials [4], [5], [7]–[12]. However, multilayer cladding structures made from materials of different origins are often characterized by low adhesion strength of layers. As a result, «thermal bridges» are formed in enclosing structures, which contribute to increase in energy losses.

Multilayer structures made of concrete of different densities make it possible to increase operational properties of structures without increasing material consumption and technological costs [2], [4]–[6], [13]–[17]. A number of researches [2], [6], [18]–[20] provide convincing arguments confirming advantages of products with high number of layers. For example, in a three-layer section the layers of heavy concrete perceive the main tensile and compressive forces; the middle layer of lightweight concrete, ensuring the joint work of the outer layers also absorbs some of the forces.

Along with the achievements in creating multilayer concrete, the problems of layer integration and durability of the contact zone remain problematic. Information about technology of forming layered products is limited and often contradictory [21]–[24]. Difficulties often arise in ensuring the calculated values of layers' thickness, which is due to expansion of denser materials when increasing the products' structure.

Multilayer concretes are the basis for the manufacture of wall panels and blocks. Combination of concrete's layers of different densities and regulation of layers' thickness can provide specified mechanical and thermal characteristics of the product [25]. For example, to ensure thermal resistance of residential building's wall equal to 3.279 (m^2 °C)/W, the central layer of a wall block measuring 400×200×200 mm is 80 %, the two outer layers occupy 20 % of product's volume.

Research aimed at developing moulding sands that meet the conditions for manufacturing products with complex structures is relevant for implementing multilayer concrete technology.

The aim of the research is to develop a recipe and a method for moulding sands placing to create heat-insulating concrete of a multilayer structure.

Priorities of modern construction are focused on technologies with a low carbon footprint, low-energy processes and widespread use of man-made materials.

Materials based on caustic magnesite are characterized by intense hardening and high strength. The activating ability of magnesium oxide and chloride mixture allows even latent substances to be involved in the processes of structure formation and hardening. Magnesial binders have high adhesion to materials of various origins.

The object of a scientific research is three-layer magnesium concrete containing layers of different densities.

The subject of the research is compositions and methods of moulding sands laying and properties of concrete based on them.

The working hypothesis is: magnesia moulding sands containing porous filler made from liquid glass granules are capable of providing high adhesion and reliable adhesion of layers, as well as specified strength and thermal conductivity of multilayer concrete.

2. METHODS AND METHODOLOGY

Three-layer magnesium concrete was produced from moulding sands of various compositions and structures. Composition of moulding sands included a composite magnesial binder, porous filler and magnesium chloride solution (Fig. 1).

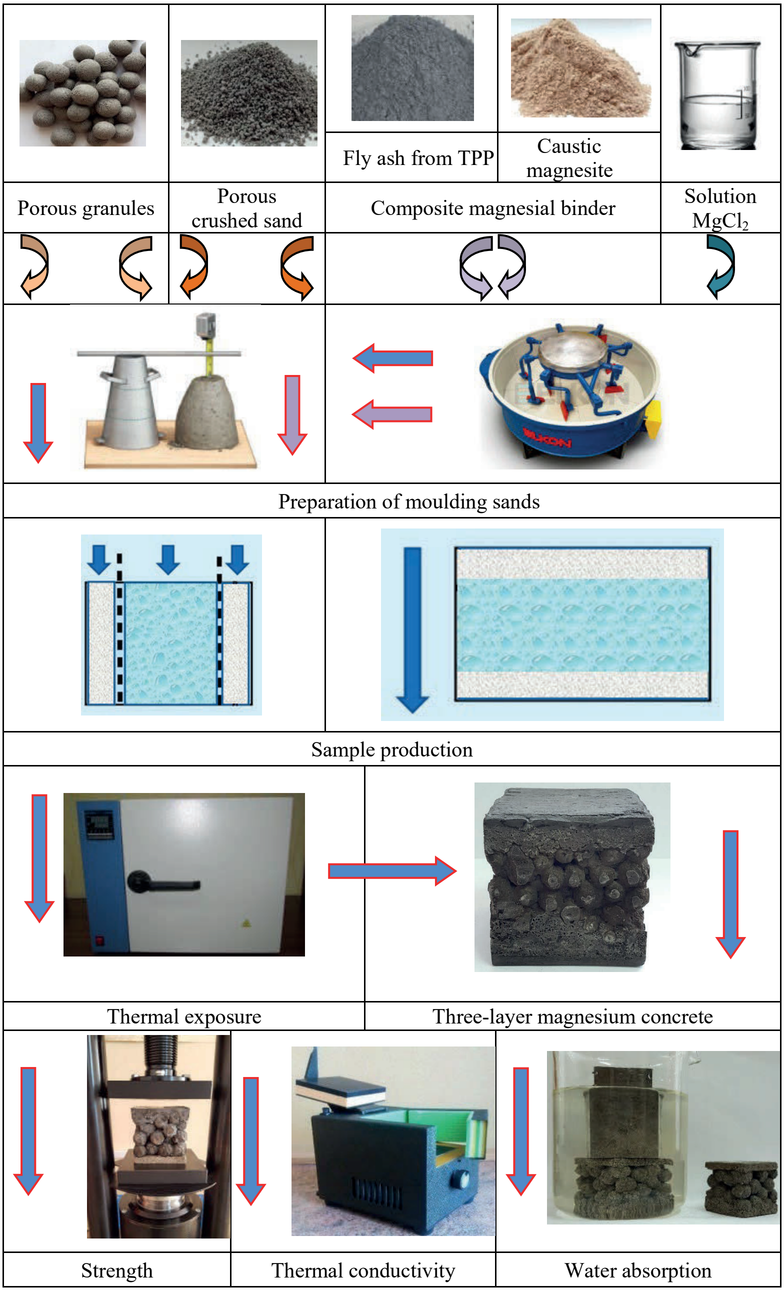


Fig. 1. Scheme for preparing and testing three-layer magnesium concrete.

Composite magnesial binder is a mixture of caustic magnesite and fly ash from thermal power plants (TPP), which was subjected to mechanical activation in 'E-max' high-speed grinding mill. The specific surface of the binder is 420 m^2/kg. Structural strength of plastic binder mass was determined using a mechanical plastometer. The effectiveness of composite magnesial binder has been confirmed in the study of materials based on wood waste [26].

Concrete layers' density was adjusted by changing the content, size and structure of filler.

Two types of specially developed fillers were used in the experiments; the experimental batches were obtained in the laboratory conditions. The first type of filler is 5–20 mm porous granules with a bulk density of 220–230 kg/m^3. Porous granules were obtained by firing a mixture of sodium liquid glass, ash microsphere and fly ash from thermal power plants at a temperature of 300 °C. To form the granules there was used a drum-type granulator. The coefficient of thermal bloating of granules was 1.20. Porization of granules occurs with the participation of liquid glass and due to aluminosilicate microsphere. Bloating of the mixture due to liquid glass provides the granules with correct spherical shape. Hollow particles of aluminosilicate microspheres are a carrier of porosity and ensure stability of expanded samples structure, performing a frame-forming function.

The second type of filler is porous crushed sand obtained by grinding porous granules; 1.25–2.5 mm fraction, 290 kg/m^3 bulk density. The liquid component of moulding sands is magnesium chloride solution with a density of 1230 kg/m^3.

Magnesium moulding sands were prepared in the following order: a composite binder was mixed with magnesium chloride solution and stirred for 2 minutes. Porous granules (porous crushed sand) were loaded into the resulting magnesium suspension and stirred for 3 minutes to uniformly distribute the binder dough between filler's particles.

Workability of moulding sands was assessed using the Abrams cone. Moulding sands containing granular filler were characterized by a cone settlement of 2–4 cm. Moulding sands based on porous crushed sand showed a cone settlement of 1–2 cm.

Three-layer magnesium concrete was moulded in the form of samples measuring 100×100×100 mm. Central part of three-layer samples with a thickness of 80 mm is made of moulding sand based on porous granules; the surface layers with a thickness of 10 mm are made of a moulding sand based on porous crushed sand.

Two methods of laying moulding sands were used in the experiments. The horizontal moulding method provided that layers of different compositions were laid parallel to the bottom of the mould; each laid layer was vibrated for 20–30 s.

When packing vertically, the layers of moulding sands were sequentially filled perpendicular to the bottom of the mould. To avoid displacement of moulding sands of different compositions, the mould was equipped with removable partitions. After depositing all the layers, the partitions were removed from the mould, and the sample was vibrated for 40 s. After preliminary curing for 1 hour, the samples of magnesium concrete were subjected to heat treatment at a temperature of 50 °C. Thermal exposure lasted for 5 hours, ensuring achievement of 80 % of the design strength.

Compressive strength of concrete was determined by testing samples after heat treatment. The tests were carried out on a PGM-1000MG4 hydraulic press. The load of the hydraulic press was directed parallel to the layers of the concrete sample.

Adhesion strength of multilayer concrete layers was assessed using an adhesion meter tearing off the contact layers. The method is based on measuring the separation force of one layer from a three-layer sample. The force is transmitted to the test sample through the traverse of the gripper. The strength of the adhesion of the layers is calculated by the magnitude of the force.

Water absorption of concrete was determined taking into account the mass of the original sample and the mass of the sample saturated with water for 1 day. Thermal insulation properties of three-layer concrete were calculated taking into account individual layers' thermal conductivity, determined by ITP-MG4 device. The structure of concrete was studied by electron microscopy.

3. Results

It is necessary to ensure adhesion of the layers when moulding multilayer products and at the same time prevent destruction of the previous layer's structure of the moulding sand. Technological properties of moulding sands are determined by binder's characteristics. Combination of caustic magnesite with fly ash from thermal power plants reduces consumption of magnesium chloride solution and makes it possible to obtain a binder with high water resistance while reducing the proportion of the firing component. However, the addition of a technogenic component slows down magnesium binder hardening in the early stages [26].

Influence of TPP fly ash content on structural strength of magnesium plastic mass was studied to optimize the composite binder's composition (Fig. 2). The research results indicate preference for a composite binder containing 40 % fly ash from thermal power plants, which is characterized by comparable structural strength indicators to caustic magnesite.

Moulding sands containing granular filler of various diameters were studied (Table 1).

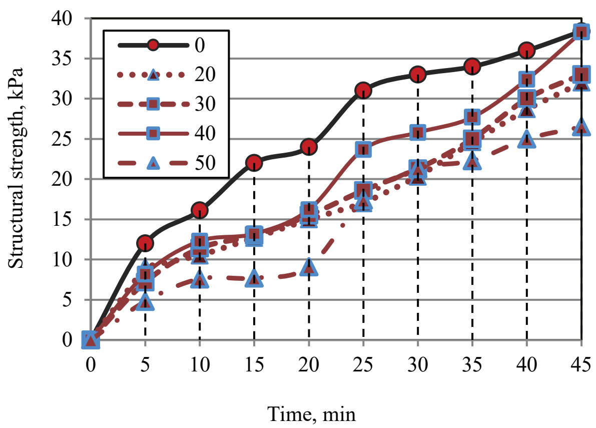
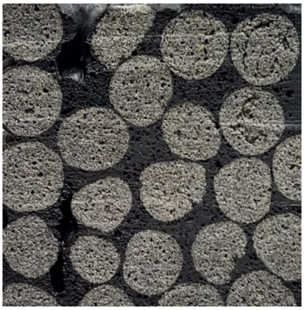
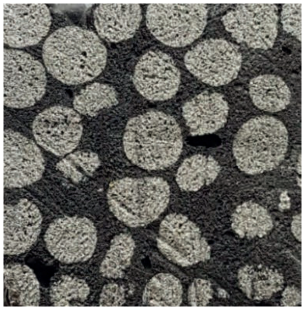


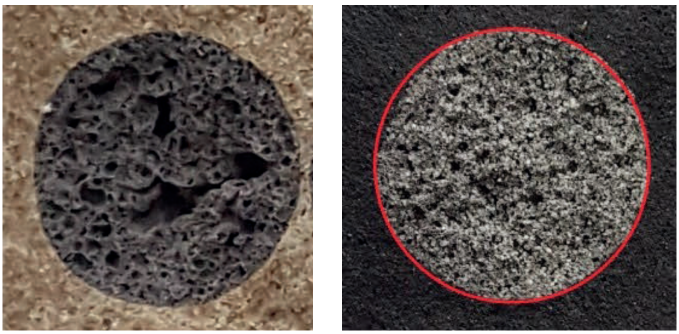
Fig. 2. Effect of thermal power plant fly ash content on the structural strength of magnesial binder.

The filling coefficient of the moulding sand C_f, equal to the ratio 'volume of binder dough: volume of filler', was 0.53. The ratio of magnesium chloride solution to the mixture of solid components, equal to 0.4, ensured the required mobility of the moulding mass. Research results indicate that varying the fractional composition of granules affects the density and strength of concrete. The density of concrete increases as the proportion of binder in the sample structure increases (Table 2) and the voids between the granules increase (Table 1). The lowest density is typical for concrete containing porous granules of various diameters (d = 15–20 mm and d = 10–15 mm at a ratio of 70:30 %).

State of the contact zone between the binder stone and the filler was studied. Absence of obvious defects in the structure of contact zone of concretes with different caustic component's contents indicates that adhesive properties of the composite binder are comparable to those of caustic magnesite (Fig. 3). The composite binder forms a dense environment around the porous granule (Fig. 3b), this is similar to the state of the porous granule in the structure of concrete of caustic magnesite (Fig. 3a).

TABLE 1. EFFECT OF FRACTIONAL COMPOSITION OF GRANULES ON THE PROPERTIES OF MAGNESIUM CONCRETE

Fractional composition of granules		
		
d = 15–20 mm	*d* = 15–20 and *d* = 10–15 mm	*d* = 15–20 and *d* = 5–10 mm
		
Density 785 kg/m^3 Strength 8.5 MPa	Density 720 kg/m^3 Strength 7.1 MPa	Density 810 kg/m^3 Strength 9.7 MPa



(a) (b)

Fig. 3. Chips of concrete made from various binders: a) – caustic magnesite 100 %; b) – caustic magnesite 60 % and fly ash from thermal power plants 40 %.

Fig. 4. Nature of concrete destruction during strength testing.

Nature of concrete destruction during strength testing confirms the reliability of the adhesion of the matrix of a composite binder with filler granules (Fig. 4).

High adhesive and strength properties of the composite magnesium binder make it possible to use moulding sands with lower values of the filling coefficient C_f and obtain low-density concretes (Table 2).

A directional change in the coefficient C_f value makes it possible to obtain concretes of various structures: concrete of dense structure (Fig. 5a), concrete with partial filling of the space between granules (Fig. 5b), large-porous concrete (Fig. 5c).

Composition of the moulding sand based on porous crushed sand was adopted on the basis of comparative tests of samples with different filler contents. The specified indicators of concrete (compressive strength of at least 8 MPa, density not more than 700 kg/m^3) are provided by the moulding sand containing, wt.%: composite binder – 45, crushed sand – 34, magnesium chloride solution – 21.

TABLE 2. CHARACTERISTICS OF MOULDING SANDS WITH POROUS GRANULES

Composition of the moulding sands, wt.%			Density, kg/m^3	The filling coefficient of the moulding sand, C_f
Composite magnesial binder	porous granules (*d* = 15–20 mm and *d* = 10–15 mm at a ratio of 70:30 %)	solution $MgCl_2$		
60.8	15.0	24.2	720	0.63
56.7	20.5	22.8	650	0.53
51.8	27.3	20.9	580	0.43
43.2	35.4	21.4	510	0.33

Technological methods for horizontal and vertical production of three-layer magnesium concrete based on the moulding sands studied have been developed.

Horizontal moulding was carried out in the following order: a layer of crushed sand was placed on the bottom of the mould and vibrated for 20 s; after 10 min, the moulding sand containing porous granules was placed and vibrated for 30 s; after a 15-minute pause, the third layer of moulding sand containing crushed sand was laid and vibrated for 20 s. The interval between layering moulding layers depends on the condition of the layer placed, which must maintain the specified layer thickness and at the same time ensure penetration of the newly placed layer to a depth of 1–2 mm.

(a) (b) (c)

Fig. 5. Structure of concrete with different filling ratios of the moulding sand: a) $C_f = 0.63$; b) $C_f = 0.43$; c) $C_f = 0.33$.

With the vertical method of producing concrete, layers of moulding sands were placed in mould compartments formed by removable partitions. Placement of the moulding layers was carried out in the following order: first, the central compartment was filled with moulding sand containing porous granules; then the outer compartments were simultaneously filled with moulding sand based on crushed porous sand. After all layers were deposited, the partition was removed and the sample was vibrated for 50 s.

Comparative analysis of technological methods for moulding three-layer products allows us to note the following: horizontal moulding takes longer due to the need for intervals between layers depositing. The horizontal method provides precise control of layers thickness. The vertical method requires more intensive compaction of the layers to avoid «hanging» of the mass in the mould compartments. Vertical moulding provides an even and smooth surface to the working surfaces of the product. Implementation of the vertical method requires additional form's elements such as dividing partitions.

Comparison of performance characteristics of three-layer concrete produced using different technologies indicates the superiority of horizontal moulding. Horizontally moulding concrete differs from vertically moulded concrete in having lower density, lower thermal conductivity and increased strength (Table 3).

TABLE 3. PROPERTIES OF THREE-LAYER MAGNESIUM CONCRETE OF VARIOUS MOULDINGS

Characteristics	**Values for moulding methods**	
	horizontal	vertical
Average density, kg/m^3	570	590
Compressive strength, MPa	6.4	6.1
Water absorption, %	12	11
Thermal conductivity coefficient, W/(m °C)	0.115	0.119
Cleavage strength of contact layers, MPa	0.51	0.48

However, differences in values of concrete's characteristics studied are small, which does not exclude the possibility and feasibility of using different methods for moulding multilayer concrete. The results of electron microscopy confirm reliability of adhesion of three-layer concrete's components, noted during physical and mechanical tests of the samples (Fig. 6).

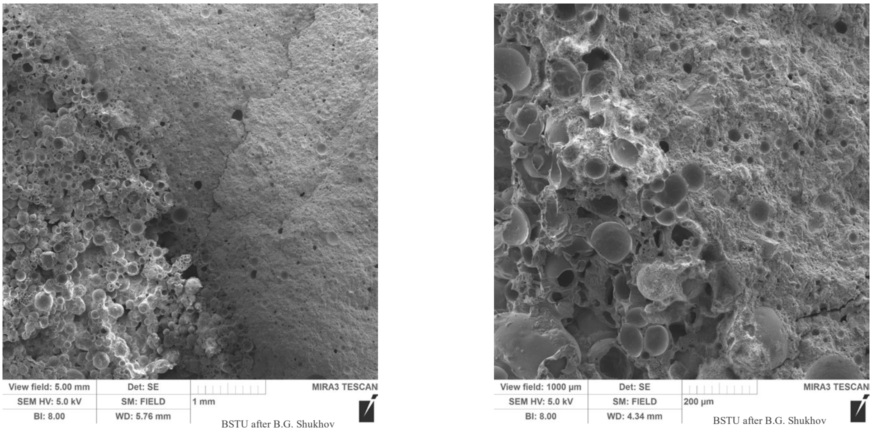


Fig. 6. Microstructure of magnesium concrete.

4. CONCLUSION

Compositions of moulding sands for producing heat-insulating multilayer concrete have been proposed, including composite magnesial binder and porous filler obtained by low-temperature firing of granular mixture of sodium liquid glass and thermal energy waste.

The nature of structure formation and adhesive ability of the composite magnesial binder, containing 40 % fly ash from thermal power plants, ensure reliable adhesion of moulding sands components and possibility of deposing in layers within technologically acceptable time.

Changing fractional composition of porous granules and the ratio of volumes of moulding sands components makes it possible to obtain concrete with a wide range of density values. Concrete with a large-porous structure, characterized by low thermal conductivity, is advisable to use as a central thermal insulation layer of three-layer concrete. Presence of two surface layers of concrete, obtained from moulding sand with crushed porous sand, provides necessary strength to the three-layer structure and serves for a heat-insulating layer as protection from external influence.

Technological methods for producing three-layer magnesium concrete have been developed. Possibility of horizontal and vertical laying of moulding sands with minor advantages of the horizontal method is shown.

Three-layer magnesium concrete with a density of 570–590 kg/m^3 is characterized by a compressive strength of 6.1–6.4 MPa, has thermal protection properties and resistance of the structure to mechanical damage and saturation with water.

The proposed technology of three-layer magnesium concrete is characterized by low energy consumption of production, which makes it possible to efficiently dispose of multi-tonnage waste of thermal energy.

The research results will contribute to the development of multilayer concrete technology with a controlled stable structure and specified technical characteristics.

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