

Magnesia Polystyrene Concrete with Porous Mineral Fillers

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Abstract – The article is concerned with the topical issue of effective lightweight concrete technology development. The objective of this study is to investigate properties of concrete mixes and lightweight magnesia concretes based on granulated expanded polystyrene and porous mineral filling materials. The following raw materials such as caustic magnesite, granulated expanded polystyrene, aluminosilicate microspheres, expanded perlite, and expanded vermiculite were used in the experiments. Concrete mixes were prepared using magnesia binder, porous fillers, and magnesium chloride solution. Technological properties of concrete mixes were determined by the Abrams cone slump; identity of the coefficient was ensured by magnesium chloride solution to caustic magnesite ratio. Concretes operating abilities were evaluated by density, strength, and strength-density ratio. Mathematical planning and processing of experimental results allowed us to develop models reflecting the dependence of magnesia concrete properties on the content and type of filling materials. Effect of each porous mineral filler on polystyrene concrete's properties was determined. Caustic magnesite and combined fillers provide homogeneous and stable lightweight concrete structure with a density of 380–840 kg/m³ and strength of 0.9–8.7 MPa. The results of the study are aimed at expanding the range and improving technical characteristics of low-density concrete.

Keywords – Caustic magnesite; lightweight concrete; polystyrene concrete; porous fillers; strength-density ratio.

1. INTRODUCTION

Construction industry accounts for approximately 40 % of global energy consumption [1], [2]. In the context of energy crisis, it creates challenges for construction technologies development. Concrete has established itself as a leader in construction materials science, providing diversity and reliability of structures. Demand for concrete is determined by its wide possibilities for composition, structure, and properties editing. One of the scientific tendencies in modern concrete studies is improving concrete's thermal insulation properties. High thermal insulation properties of concrete are considered as significant contribution to energy-efficient construction development. Concrete's thermal insulation capacity is ensured by its porous structure, which is formed primarily through the use of low-density fillers. Lightweight concretes, with a density of no more than 1800 kg/m³, possess thermal and sound insulation properties and will predominate in the construction in the coming years.

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Construction has accumulated extensive experience using lightweight concretes with porous fillers of various origins, such as expanded clay concrete [3], vermiculite concrete [4], perlite concrete [5] and concrete based on liquid glass granules [6], [7].

In recent decades, polystyrene concrete [8], [9] has been widely used, the filler is expanded polystyrene granules (polystyrene foam) with an average diameter of 1 to 8 mm [10], [11]. Depending on the material composition of the moulding mixtures, including the content of granulated expanded polystyrene, the density of polystyrene concrete can range from 550 kg/m³ to 2200 kg/m³. Polystyrene concrete compares favourably with low density, environmental friendliness, cost-effectiveness, high thermal insulation capacity, and reduced water absorption [12]. Polystyrene concrete is widely used in construction of walls, in floor systems, as part of 3D-printed fibre reinforced concrete [13], and in multilayer wall panels' structure [14]–[17]. The use of expanded polystyrene from waste packaging material reduces the cost of porous filler and ensures resource conservation of polystyrene concrete technology. Introduction of granules of expanded polystyrene into the mixtures for cellular concrete is effective [18], [19].

Despite significant benefits, concrete containing expanded polystyrene granules is subject to technological and operational problems. Granules of expanded polystyrene, having a very low density and hydrophobicity, float during preparation of moulding mixtures, causing stratification and uneven distribution of the filler in the concrete mix matrix [20]. To improve interfacial adhesion in polystyrene concrete, the technological solutions are implemented as follows: introduction of plasticizing and pore-forming additives that reduce the density of the cement paste; introduction of binders (aqueous dispersions of polyvinyl propionate, emulsified epoxy resins, lime water); chemical treatment of expanded polystyrene granules [21]. Chemical treatment of expanded polystyrene reverses the charge of granules on their surface, as consequences, the granules acquire hydrophilic properties.

Presence of expanded polystyrene filler reduces the compressive and tensile strength of concrete. Polystyrene concrete exhibits increased shrinkage, which leads to cracking of the material in the long run. Tendency of polystyrene concrete to shrink significantly is explained by low stiffness, high compressibility, and smooth, waterproof surface of expanded polystyrene granules [22], [23].

Introduction of steel and polymer fibres into the concrete mix partially compensates for the loss of strength and reduces shrinkage deformations [12], [24]. Presence of finely dispersed additives, increasing the volume of matrix in the concrete, has a positive effect on deformation properties of polystyrene concrete [25], [26].

Despite numerous studies of polystyrene concrete and a number of effective solutions for improving the properties of concrete based on expanded polystyrene granules, there are problems in this field. Concretes combining expanded polystyrene with other porous filling materials have received little study.

Concretes containing expanded polystyrene granules are typically made with cement [10], [14], [15]. Cement-based polystyrene concrete exhibits increased shrinkage strain. Cement production is characterized by high energy consumption and a significant carbon footprint [27]. Therefore, concretes based on cement-free binders are preferred, such as alkali-activated slag aerated concrete [18], [21] and magnesia concrete [28].

Detailed studies of polystyrene concrete with cement-free binders are relevant from a technical, economic, and environmental perspective.

The objective of this study is to investigate properties of concrete mixes and lightweight magnesia concretes based on granulated expanded polystyrene and porous mineral fillers.

2. MATERIALS AND METHODS

The object of this study is magnesite concretes containing porous filling materials of variable origin.

Concrete mixes containing caustic magnesite PMK-75 binder, porous fillers and magnesium chloride solution with a density of 1250 kg/m^3 were prepared to produce concretes. The saline solution ensures hardening and high strength of caustic magnesite.

Main properties of the fillers are listed in Table 1. Bulk density of porous fillers was determined as the ratio of the low-density mass in an uncompact state to the volume of this mass. The water-holding capacity of the filler was measured by the amount of water (%) retained in the mass after the free water drained off. The filling materials were saturated with water for 24 hours.

Granulated expanded polystyrene is a spherical granule with smooth, impermeable surface and an internal cellular structure. The polystyrene beads are typically impregnated with a volatile blowing agent (such as pentane), which later expands upon heating to create the cellular structure.

TABLE 1. CHARACTERISTICS OF POROUS FILLERS FOR MAGNESIA CONCRETE

Name	Particle's size, mm	Bulk density, kg/m^3	Water retentivity, %	Surface appearance
Expanded polystyrene	2.5–5.0	15	30	
Aluminosilicate microsphere	0.3–0.4	375	44	
Expanded perlite	1.25–5.0	110	155	
Expanded vermiculite	0.63–1.25	155	405	

Aluminosilicate microspheres are finely dispersed hollow particles generated as a waste product during combustion of solid fuels in thermal power plants. Aluminosilicate microspheres facilitate formation of cellular building materials [29].

Expanded perlite is a coarse porous sand obtained by expanding volcanic glassy rock. Experience has been accumulated in effective use of expanded perlite in thermal insulation building materials [5], [30].

Expanded vermiculite is loose mass of small, porous scale-like particles. Expanded vermiculite is a product of hydro micaceous mineral flame finish. Expanded vermiculite is used as a filler for thermal insulation concretes and various composite materials [4], [25].

The choice of mineral fillers' type is driven by low density and available experience in producing lightweight concretes.

Concrete mixes were prepared by adding the filler into a magnesite binder slurry (a mixture of caustic magnesite and magnesium chloride solution). When using a combined filler, the magnesite slurry was first mixed with the mineral filler, then expanded polystyrene granules were added. The moulding sands had a workability corresponding to an Abrams cone slump of 1–4 cm.

To study concrete's properties, 7-cm cube specimens were moulded. Concrete's density was determined at 7 days, after the concrete had formed a stable structure. Concrete specimens were tested for compressive strength after 28 days of air curing. Testing of the specimens was performed in a PGM-1000MG4 hydraulic press.

Mathematical planning method was used to determine the dependence of lightweight concrete properties on the composition of moulding sands (Table 2). Nine moulding sands were prepared according to the complete matrix of the two-factor experiment (Table 3).

TABLE 2. BASIC INFORMATION FOR MATHEMATICAL PLANNING OF EXPERIMENTS

Factors under study		Variation interval	Levels of variation		
Natural type	Coded type		–1	0	+1
Caustic magnesite to filler ratio	x_1	1	1:4	1:3	1:2
Expanded polystyrene content in fillers' mixture, %	x_2	50	0	50	100

TABLE 3. CHARACTERISTICS OF CONCRETE MIXES COMPOSITIONS

Composition number	Factors under study		Volume ratio of caustic magnesite to filler	Expanded polystyrene content in fillers' mixture, %
	X_1	X_2		
1	–1	–1	1:4	0
2	+1	–1	1:2	0
3	–1	+1	1:4	100
4	+1	+1	1:2	100
5	+1	0	1:2	50
6	–1	0	1:4	50
7	0	+1	1:3	100
8	0	–1	1:3	0
9	0	0	1:3	50

The following parameters were adopted for optimizing the moulding sand composition: magnesium chloride solution to caustic magnesite ratio for the moulding sand, concrete density, and concrete strength. The experiment was conducted with duplication at five zero points of the plan. Deviations between actual and calculated indicators amounted to 3–4 %. When designing moulding sand compositions, volume to volume ratios between caustic magnesite and combined filler, as well as between the different types of fillers were adopted (Table 3).

3. RESULTS AND DISCUSSION

Three series of concretes made from moulding sands containing both expanded polystyrene granules and porous mineral fillers were studied. The experimental results are presented in Tables 4, 5 and 6.

TABLE 4. PROPERTIES OF CONCRETE BASED ON EXPANDED POLYSTYRENE AND ALUMINOSILICATE MICROSPHERES

Composition	Magnesium chloride solution: caustic magnesite	Concrete density, kg/m ³	Concrete strength, MPa
M1	1.00	783	7.9
M2	0.55	840	8.7
M3	0.53	386	0.9
M4	0.43	555	2.6
M5	0.50	863	7.2
M6	0.63	603	3.6
M7	0.44	515	1.6
M8	0.70	814	8.0
M9	0.55	717	4.8

Important technological characteristic of moulding sands that determines properties of concrete is the ratio between salt solution and caustic magnesite. Requirement of moulding sands for magnesium chloride solution depends on the ability of the components to take up and adsorb the liquid phase. Mathematical models reflecting the effect of the content of concrete components on magnesium chloride solution to caustic magnesite ratio (S) are represented by regression equations for concrete of the M, P and V-series, Eqs. (1)–(3).

$$S_M = 0.631 - 0.113x_1 - 0.142x_2 + 0.043x_1^2 - 0.048x_2^2 + 0.088x_1x_2 \quad (1)$$

$$S_P = 0.621 - 0.082x_1 - 0.067x_2 - 0.075x_1^2 - 0.040x_2^2 - 0.035x_1x_2 \quad (2)$$

$$S_V = 0.973 - 0.198x_1 - 0.383x_2 - 0.001x_1^2 - 0.046x_2^2 + 0.155x_1x_2 \quad (3)$$

TABLE 5. PROPERTIES OF CONCRETE BASED ON EXPANDED POLYSTYRENE AND EXPANDED PERLITE

Composition	Magnesium chloride solution: caustic magnesite	Concrete density, kg/m ³	Concrete strength, MPa
P1	0.79	619	1.9
P2	0.57	670	2.1
P3	0.53	368	0.7
P4	0.45	501	2.4
P5	0.53	753	2.4
P6	0.72	477	1.1
P7	0.45	514	1.4
P8	0.67	705	2.3
P9	0.70	629	2.1

TABLE 6. PROPERTIES OF CONCRETE BASED ON EXPANDED POLYSTYRENE AND EXPANDED VERMICULITE

Composition	Magnesium chloride solution: caustic magnesite	Concrete density, kg/m ³	Concrete strength, MPa
V1	1.69	900	1.8
V2	0.99	1184	7.9
V3	0.53	385	0.9
V4	0.45	582	2.4
V5	0.79	997	6.0
V6	1.20	745	2.8
V7	0.48	566	1.8
V8	1.25	1000	4.4
V9	0.93	716	2.7

Geometric interpretation of the obtained dependencies is shown in Fig. 1. The colour indicates the different values of the magnesium chloride solution to caustic magnesite ratio. Analysis of the obtained results indicates that the highest consumption of magnesium chloride solution is required for moulding mixtures containing expanded vermiculite.

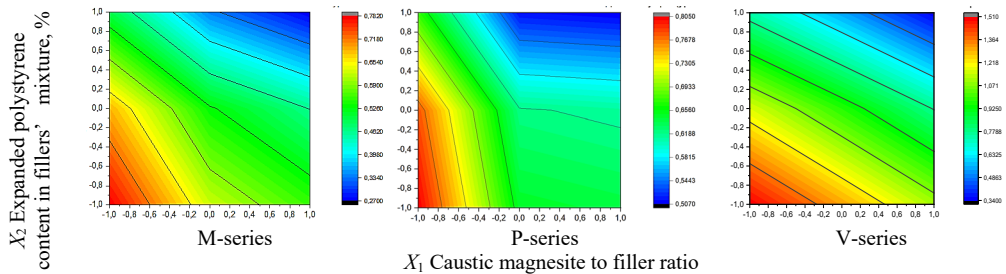


Fig. 1. Effect of caustic magnesite content and filler type on magnesium chloride solution to caustic magnesite ratio.

This is due to the fact that expanded vermiculite has an open porosity and high ability to absorb liquid (Table 1). A lower need for salt solution was noted for mixtures based on expanded polystyrene and expanded perlite, which have the largest particle size. For all the moulding mixtures studied, decrease in salt solution to caustic magnesite ratio is typical as the filler's volume decreases and proportion of a mineral filler reduces.

Density serves as an indirect characteristic of concrete structure and significantly influences material properties. The magnesite concretes studied have densities not exceeding 1200 kg/m³ and are classified as lightweight concretes. Mathematical models reflecting the effect of caustic magnesite content and filler type on concrete density (ρ) are represented by regression equations for concrete of the M, P and V-series, Eqs. (4)–(6).

$$\rho_M = 729.000 + 89.333x_1 - 155.167x_2 - 2.000x_1^2 - 70.500x_2^2 + 40.500x_1x_2 \quad (4)$$

$$\rho_P = 650.556 + 86.667x_1 - 111.833x_2 - 61.333x_1^2 - 66.834x_2^2 + 35.500x_1x_2 \quad (5)$$

$$\rho_V = 793.889 + 122.667x_1 - 258.500x_2 + 38.166x_1^2 - 49.833x_2^2 - 21.750x_1x_2 \quad (6)$$

Geometric interpretation of the obtained dependencies is shown in Fig. 2. Density values of the studied magnesite concretes depend on the amount and type of a filler. Concretes with large volume of expanded polystyrene granules have the lowest density. In increasing density, magnesite concretes based on mineral fillers are arranged in the following order: perlite concrete – concrete based on aluminosilicate microspheres – vermiculite concrete. In this case, the dependence of concrete density on filler density is not direct. High absorption capacity of scale-like particles of expanded vermiculite, with a bulk density of 155 kg/m^3 , increased the density of the concrete in comparison with the density of concrete based on aluminosilicate microspheres, with a bulk density of 375 kg/m^3 . Density of the studied concretes increases with increasing binder volume and proportion of mineral filler. For concrete containing expanded vermiculite, this dependence is the most expressive.

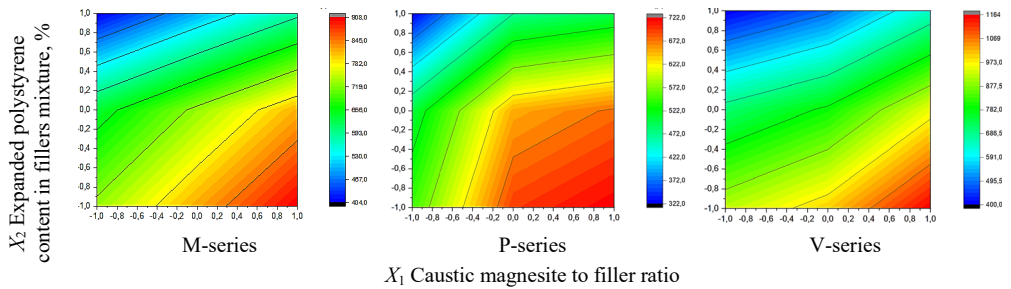


Fig. 2. Effect of caustic magnesite content and type of fillers on concrete density.

Strength is a primary performance characteristic of concrete. Strength of lightweight concrete depends on the type of porous component, the amount of binder, and the adhesion between concrete phases. Mathematical models reflecting effect of caustic magnesite content and filler's type on the concrete strength (R) are represented by regression equations for concrete of the M, P and V-series, Eqs. (7)–(9).

$$R_M = 4.970 + 1.017x_1 - 3.250x_2 + 0.350x_1^2 - 0.250x_2^2 + 0.225x_1x_2 \quad (7)$$

$$R_P = 2.089 + 0.367x_1 - 0.467x_2 - 0.333x_1^2 - 0.234x_2^2 + 0.125x_1x_2 \quad (8)$$

$$R_V = 3.789 + 2.067x_1 - 0.600x_2 + 0.066x_1^2 + 0.267x_2^2 - 0.750x_1x_2 \quad (9)$$

Geometric interpretation of the obtained dependencies is shown in Fig. 3. M-series concretes surpass other concretes in strength. The strength of M-series concretes, which increases with increasing caustic magnesite content, is highly sensitive to filler's composition and reaches its highest values with increasing proportion of aluminosilicate microspheres. P-series concretes, characterized by lower density, have low strength values. Compared to concretes of other series, P-series concretes are less sensitive to changes in the composition of the moulding sand (Table 5). The strength of V-series concretes depends on proportion of caustic magnesite and increases significantly with increasing binder content (Table 6).

However, changes in filler's composition have little effect on the strength of concrete containing expanded vermiculite.

Comparison of concretes based on combined fillers of different series shows that combination of expanded polystyrene with aluminosilicate microspheres (compositions M5, M6, and M9) provides the highest strength values. Concretes containing expanded perlite (compositions P5, P6 and P9) achieved the lowest strength values. The strength values of concretes of M and P series differ by a factor of three or more.

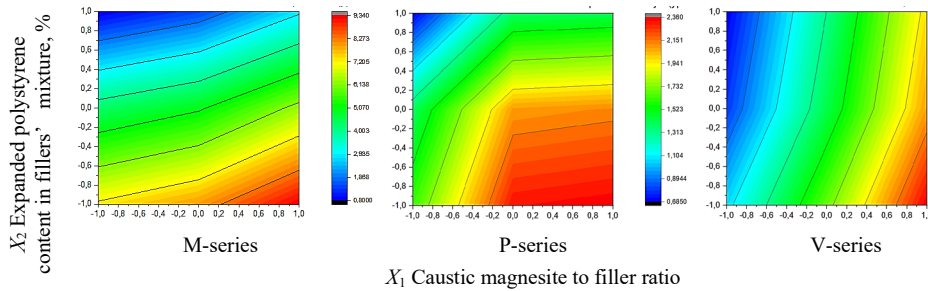


Fig. 3. Effect of caustic magnesite content and type of filler on concrete strength.

Comparing strength of concretes of M, P and V series, which have different densities, is not entirely objective. In such situations, it is preferable to compare physical and mechanical properties of concretes using the strength to density ratio (SDR). To facilitate comparison, the SDR value was increased by a factor of 100 (Fig. 4).

The highest SDR (strength to density ratio) values are characteristic of M series concretes containing aluminosilicate microspheres as the sole filler. M series concretes, containing combined filler, have superior SDR values to similar P and V series concrete compositions. Polystyrene concrete, characterized by minimum volume of caustic magnesite and the lowest density, has the lowest SDR (compositions M3, P3 and V3).

Strength of concrete depends on adhesion of the filler to the binder. Caustic magnesite is characterized by high adhesion to materials of various origins. Compared to Portland cement, adhesion of caustic magnesite to expanded polystyrene granules is more stable (Fig. 5.1 and 5.2). When using a combined filler, a fine-grained magnesite composition is located in the space between the expanded polystyrene granules, which compacts the contact zone between the components of the moulding sand, helps reduce concrete shrinkage, and strengthens the interphase bond (Fig. 5.3, 5.4 and 5.5).

Many publications consider the use of expanded polystyrene granules in cement concretes. These publications reflect the use of expanded polystyrene granules as a partial or complete replacement for dense coarse and fine aggregates [31]–[33]. Studies of magnesia concretes containing expanded polystyrene are few in number [28]. Unlike other studies, this work examines magnesia concretes, in which only porous materials serve as aggregates. The combination of granular expanded polystyrene with porous mineral fillers makes it possible to minimize or eliminate segregation of concrete mixtures.

Analysis of the research results demonstrates the possibility of adjusting technological and operational properties of lightweight magnesite concrete not only by the amount of a porous component, but also by combining fillers of different origins.

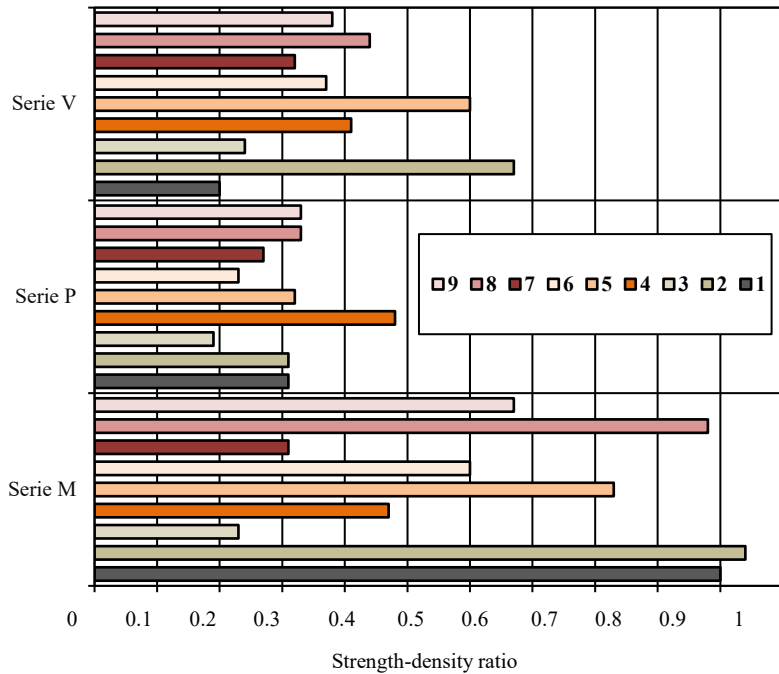


Fig. 4. Effect of caustic magnesite content and filling materials type on constructional properties of concrete (as in Tables 4, 5 and 6).

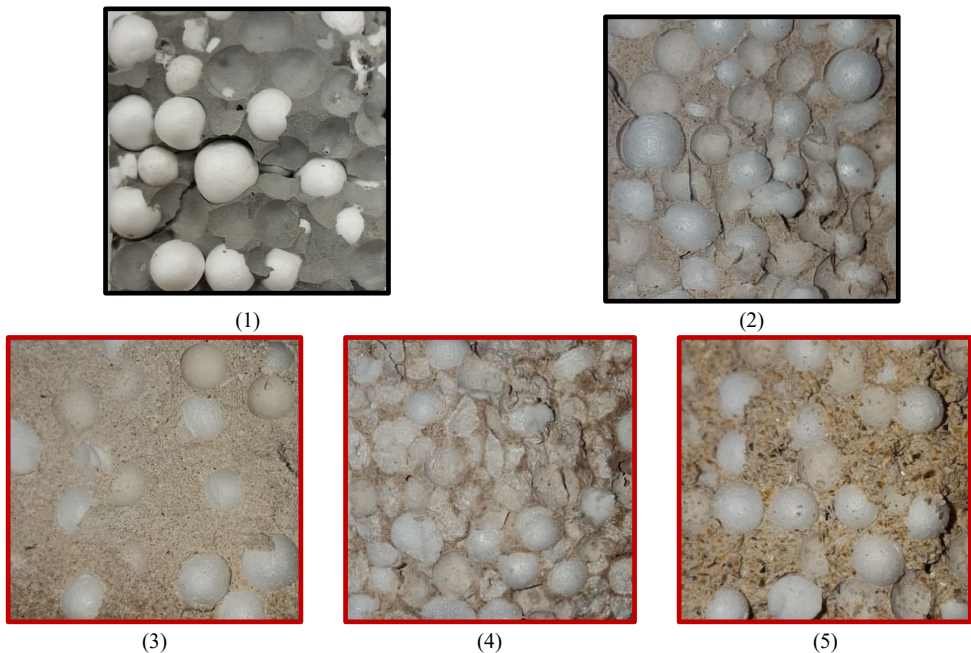


Fig. 5. Appearance of concrete structure after strength testing: 1 – cement polystyrene concrete; 2 – magnesia polystyrene concrete; 3 – magnesia polystyrene concrete with aluminosilicate microspheres; 4 – magnesia polystyrene concrete with expanded perlite; 5 – magnesia polystyrene concrete with expanded vermiculite.

4. CONCLUSION

Scientific ideas about the formation and properties of lightweight magnesia concretes based on granular expanded polystyrene and porous mineral filler have been developed.

Porous mineral fillers differ from expanded polystyrene granules in their smaller particle size and higher density. Combination of granulated expanded polystyrene with porous mineral fillers allows for targeted modification of concrete's structure and properties.

Mathematical models' study of concrete composition revealed the dependence of technological properties of moulding mixtures and performance properties of concrete on the combined effect of caustic magnesite content and the ratio of filler types.

Polystyrene concrete with aluminosilicate microspheres replacing some of expanded polystyrene is characterized by an average 50 % increase in density and gain in strength by a factor of 3–4. Magnesia concrete containing expanded polystyrene and aluminosilicate microspheres has the highest strength-density ratio. Partial replacement of expanded polystyrene with expanded perlite increases concrete density by average of 35 % and strength by 1.5 times.

Combination of expanded polystyrene granules with expanded vermiculite results in concrete compaction by average of 65 %, while increasing concrete strength by 2.5 times.

Mineral filler particles saturate the magnesite paste with pores and help reduce segregation of the moulding sand and ensure uniform distribution of the expanded polystyrene granules within the concrete structure.

Presence of porous mineral filler in the spaces between expanded polystyrene granules prevents shrinkage deformations in lightweight concretes.

The choice of mineral filler for polystyrene concrete is determined by concrete's prescribed properties and accessibility of a porous material. Effectiveness of using caustic magnesite in concretes with combined porous fillers is due, firstly, to binder's high adhesion to particles of various origins, which guarantees reliable interfacial bonding and increased strength of lightweight concretes. Secondly, magnesia binder in combination with mineral fillers can increase the resistance of polystyrene concrete to high temperatures. Thirdly, the use of low-energy magnesia binder contributes to the development of energy-saving and environmental friendliness technologies.

Homogeneous, stable structure and increased strength-density ratio of lightweight concrete with combined fillers indicate their superiority over polystyrene concrete.

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