Properties of light-weight extruded concrete with hollow glass microspheres

Dmitriy Oreshkin, Vyacheslav Semenov and Tamara Rozovskaya

Abstract

The article is devoted to the study of properties of light-weight extruded fine-grain cement concrete with hollow glass microspheres (HGMS). For improving the properties of light-weight concrete the authors suggested to use the extrusion technology. The compositions of light-weight extruded fine-grain concrete and their basic properties are shown. The deformation characteristics of light-weight fine-grain concrete with HGMS such as specific values of the energy of deformation and destruction of concrete as well as the elasticity modulus are shown. It has been proved that the extrusion reduces the water requirement of the concrete mixture with the microspheres, promotes compacting the concrete structure, significantly increases the concrete strength and crack resistance, reduces water vapor permeability and heat conductivity. The results of microstructure and X-ray diffraction analyzes of light-weight extruded fine-grain concrete are given. Based on this research work, a technology for production of light-weight extruded fine-grain cement concrete with HGMS was developed. The units produced by this technology were successfully applied in cottage construction.

Keywords: hollow glass microspheres; fine-grain concrete; light-weight concrete; extrusion; crack resistance.

1. Introduction

At present, the problem of energy efficiency and reduction of specific consumption of materials is an important one in the construction industry. The solution to this problem requires the development of efficient building
materials. It is known that the heat loss through exterior walls are up to 35 to 40% of the total heat loss of the building [1-3]. The most effective are the single-layer fencing structures, because they have a higher coefficient of heat engineering homogeneity compared with multi-layer structures and provide better thermal protection of the building [3]. Such walls can be built with cellular concrete, polystyrene concrete, porous ceramics stones and other materials with an average density within the range of 500 to 1200 kg/m$^3$ [4]. It is known that, to ensure the uniformity of heat engineering walls with small units, the average density of all structural elements - wall material, masonry mortar, window lintels, etc., should be approximately equal. In this regard, the problem of development of effective light-weight masonry mortars and concrete with average density and thermal conductivity coefficient equal to those of the wall material is urgent.

The works [3, 6-11] show a high efficiency of the use of hollow ceramics microspheres (HGMS) as a light-weight aggregate for construction and special mortars. The light-weight masonry mortars with HGMS with average density of dry stone within the range of 600 to 1200 kg/m$^3$ and the compressive strength value not less than 2.5 MPa were developed by the authors of the works [6, 9-10]. The problem of such mortars is a high water-holding capacity of the aggregate and, consequently, a low strength of the cement stone. One of the solutions of this problem, in opinion of the authors of the works [12-13], is the use of extrusion technology. In the works [14-16] the extruded fine-grain concrete were studied. The authors considered that a high specific surface of the aggregate predestinates the availability of a free surface energy, which can be used to a significant reduction of the noted drawbacks of light-weight concrete and mortars with HGMS through enhanced adhesion interaction between the aggregate surface and the cement stone.

In the works [12-13] the light-weight extruded masonry mortars with HGMS were studied. In these studies it was shown that the water demand of the mortar after extrusion is reduced by 10 to 15% as compared to non-extruded mortars (while retaining the same mobility), and the strength of the mortar somewhat increases (by the same value of 10 to 15%). The extruded mortars have a higher water-holding capacity and a lower setting time compared to non-extruded mortars. The resulting extruded masonry mortars with microspheres have a homogeneous structure. It has been found that the purification of the surface of both the cement and the aggregate particles takes place, the wetting is improved, the amount of mixing water is reduced, the reactivity of the surface of solid particles is increased during the process of extrusion. The mobility of the mortar is increased also due to a better slip when removing the gas phase [13].

According to the studies of extruded masonry mortars with HGMS, it has been suggested that the use of extruded concrete mixtures with HGMS would allow producing a material with a high uniformity, a low average density, a high strength value and a coefficient of thermal conductivity close to that of the wall material. In the works [17-20], the efficiency of application of hollow microspheres for light-weight concrete is shown. Moreover, it was found that the microspheres in the cement matrix form a honeycomb structure and fringe the pores, hardening their walls and improve the material properties [21]. In the process of production of light-weight units from such mixtures with the cone immersion of 0 to 4 cm, an opportunity exists to increase the concrete strength and the bearing capacity of units through the use of extrusion technology.

The aim of our work was the development of efficient light-weight extruded cement concrete with hollow glass microspheres.

2. Materials and testing methods

We used the Portland cement PC500-D0 (Starooskolsky cement plant) with the content of C3A equal to 3.8% according to GOST 10178-85 "Portland cement and slag cement. Specifications" as a binder. The hollow glass microspheres 3M™ Glass Bubbles, type K25 (Belgium) were used as an aggregate. Hollow glass microspheres are free-flowing white powder consisting of thin-wall balls with the diameter of 20 to 160 µm and a wall thickness of 1 to 3 µm. The microspheres have a low average density and a spherical shape, they are manufactured from sodium borosilicate glass. The average density value of the material of the microsphere wall is 2420 kg/m$^3$. The coefficient of thermal conductivity of the microspheres is 0.05 to 0.1 W/(m·°C) at the temperature of 20 °C, the temperature of softening is more than 600 °C. The superplasticizer C-3 at a dosage of 0.75% of the cement mass in terms of dry matter was used as the plasticizer.
3. Results and discussion

The extruded and non-extruded light-weight fine-grain concrete both with 15 % and 30 % HGMS from the Portland cement mass were studied. The composition variants are given in Table 1. The laboratory studies were carried out through standard procedures in accordance with GOST. The concrete with HGMS had the cone immersion of 2 to 4 cm, it was prepared in a blender and then passed through a single laboratory screw extruder with followed sealing during 3 minutes on the shaking table. The concrete strength was determined on the prismatic samples with the dimensions of 4x4x16 cm at the age of 28 days. The properties of light-weight extruded fine-grain concrete are given in Table 1.

As we can see from Table 1, the water demand of concrete mixture after extrusion process is reduced by 10 to 12 % compared to non-extruded concrete mixture, and the concrete strength increases. Reduction of the mixing water contributes to a certain increase in the average density of light-weight concrete with microspheres. When the concrete mixture passes through the extruder, the water is partly wrung and the cement paste moves closer to the surface of HGMS. This process contributes to the sealing of the cement stone structure; the water vapor penetration value and the coefficient of thermal conductivity decrease, because the flow rate of microspheres in the extruded mixtures increases due to the reduction of the water demand.

Table 1. Composition and properties of light-weight extruded fine-grain concrete with HGMS.

| Composition, mass % | Average density of dry stone, kg/m³ | Strength of masonry mortar at the age of 28 days, MPa. | Coefficient of thermal conductivity of dry stone, W/(m·°C) | Coefficient of water vapor penetration, mg/(m²·h·Pa) | Frost-resistance, cycles |
|---------------------|------------------------------------|---------------------------------|---------------------------------|---------------------------------|------------------------|
|                     | bend | compression |                     |                                  |                                      |                        |
| 100 PC + 15 HGMS + 40 Water + 0.75 SP | 993  | 5.9 | 25.9 | 0.24 | 0.0068 | 75 |
| 100 PC + 30 HGMS + 67 Water + 0.75 SP | 660  | 4.6 | 13.9 | 0.16 | 0.026  | 50 |
| 100 PC + 15 HGMS + 34 Water + 0.75 SP | 1036 | 6.6 | 29.0 | 0.23 | 0.0064 | 75 |
| 100 PC + 30 HGMS + 56 Water + 0.75 SP | 693  | 5.0 | 15.6 | 0.15 | 0.023  | 50 |

PC = Portland cement, HGMS = hollow glass microspheres, SP = superplasticizer.

Fig. 1 shows the microstructure of the extruded cement concrete with microspheres, uniformly distributed throughout the volume, and the cement matrix consisting of calcium hydroxides. The contact zone "cement stone - microsphere" consists of well-crystallized portlandite Ca(OH)₂ in the form of dense pyramids and low-basic hydroxilicate calcium with dense structure (the hydroxilicates with a ratio of calcium oxide to silicon oxide equal to 0.8 to 1.33 are called low-basic hydroxilicates).

Fig. 1. Microstructural analysis of light-weight extruded concrete with HGMS

The crack resistance of developed concrete was evaluated under the conditions of equilibrium three-point bending test. For the equilibrium tests obtaining fully equilibrium deformation diagrams (FEDD), the prismatic
samples with the dimensions of 10x10x40 cm were formed and tested according to GOST 29167-91 "Concrete. Methods for determination of fracture toughness (destruction viscosity) under static loading".

The testing machine had an elastic steel ring, which created the equilibrium conditions of deformation and destruction (Fig. 2a). Destruction mechanics methods were used [22-24]. The results of tests and data processing are shown in Fig. 2b and Table 2.

Here three main energy indices for FEDD can be identified [23]. The first index evaluates the crack resistance of the material before the start of the main crack (the rise interval for the curve to its maximum). The second index evaluates the main crack growth resistance (after the start of the crack), in which the curve goes down. The third index (the full area of the diagram) evaluates the complete destruction of the material. These three indices relating to the cross-section area of the sample form the specific values of the energy of deformation and destruction of the concrete (Gi, GL, Gc).

Fig. 2. (a) The testing machine for producing the fully equilibrium deformation diagrams (FEDD); (b) FEDD of light-weight fine-grain cement concrete with 15 % HGMS: 1 – extruded concrete mixture; 2 – non-extruded concrete mixture.

Table 2. Deformation characteristics of light-weight fine-grain concrete with HGMS

| Composition, mass %       | Specific energy consumption, J/m² | Deflection, 10⁻³ m: | Elasticity modulus, MPa² |
|---------------------------|-----------------------------------|---------------------|--------------------------|
|                           | crack initiation, Gi              | destruction, Gd     | before the start of the crack formation | after fragmentation¹ |
|                           | 0,111                             | 0,41                | 7690                     |
| Non-extruded concrete     | 0,21                              | 0,824               | 5233                     |
| 100 PC + 15 HGMS + 40 Water + 0,75 SP | 36                               | 96                  |
| 100 PC + 30 HGMS + 67 Water + 0,75 SP | 22                               | 76                  |
| Extruded concrete         | 0,060                             | 0,360               | 12132                    |
| 100 PC + 15 HGMS + 34 Water + 0,75 SP | 47                               | 116,3               |
| 100 PC + 30 HGMS + 56 Water + 0,75 SP | 29,4                             | 88                  |

¹ – fragmentation into two parts with the total destruction of the samples; 2 – the design static elasticity modulus in accordance with GOST 29167-91.

Analysis of the results from Table 2 and Fig. 2a proves a significant increase of crack resistance of extruded concrete units in comparison with non-extruded ones, which is due to the seal contact area "hollow microsphere - cement matrix."

The X-ray analysis of the light-weight extruded (Fig. 3) and non-extruded fine-grain concrete was performed at the age of 28 days. The intensity values of the peaks of alite 3CaO·SiO₂, portlandite Ca(OH)₂, calcite CaCO₃ and calcium hydroxides 3CaO·2SiO₂·3H₂O were analyzed. The results of X-ray analysis are given in Table 3.
The X-ray analysis proved that the degrees of hydration and crystallization increase for the extruded concrete in comparison with the non-extruded one. The intensity value of alite peaks decreases for all compositions with microspheres. Well-known reactions of alite hydration with the formation of low-basic calcium hydrosilicate (3CaO·2SiO₂·3H₂O) and three molecules of portlandite (3Ca(OH)₂) take place.

The peak amount of calcium carbonate in the material with HGMS increases due to a slight destruction of the microspheres under a pressure (Table 3) due to the reaction of carbonization of the portlandite Ca(OH)₂ with the formation of insoluble calcium carbonate. The calcium carbonate strengthens the stone and binds soluble portlandite. Hence, the binding of portlandite into an insoluble composition has a positive effect. The crystallization degree after the extrusion process is increased by 1.5 times. The strong low-basic calcium hydrosilicate compositions are formed and their number increases. The hydration degree is increased by 25 to 27%.

Thus, the analysis of the data obtained shows that the crack resistance of the fine-grain concrete with hollow glass microspheres produced from an extruded concrete mixture is higher in comparison with the material produced from a non-extruded concrete mixture. The crack resistance, the compressive and flexural strength values of the extruded concrete increase by 30 to 40 % compared with the material produced from a non-extruded light-weight concrete mixture with HGMS with the same mobility value. The water vapor penetrability is also reduced through a more dense structure of the extruded concrete and cement matrix, which is associated with a decrease in the quantity of tempering water.
4. Conclusion

Thus, as a result of the research, a technology of production of a light-weight extruded cement fine-grain concrete with HGMS has been developed. The use of the developed concrete was suggested for the production of window and door lintels with high heat-shielding characteristics. The technology of production of window lintels from extruded mixtures was developed as well, which comprises the flow sheet, the optimum composition of the concrete mixture, the order of mixing, the extrusion technology, sealing and storage, the quality assessment. The experimental batch of reinforced window lintels was produced in the cities of Izhevsk and Naro-Fominsk. The produced units were successfully applied in the process of cottage construction in these cities.

References

[1] V.G. Gagarin, K.A. Dmitriev, Accounting Heat Engineering Heterogeneities When Assessing the Thermal Protection of Enveloping Structures in Russia and European Countries, Construction Materials, 2013, Vol. 6, pp. 14-16.
[2] L.A. Oparina, Results of Calculation of Energy Consumption of a Building Life Cycle, Housing Construction, 2013, Vol. 11, p. 50.
[3] V.S. Semenov, Efficient light-weight masonry and plugging mortars for inclement climatic conditions, Cand. of Sc. Thesis, 2011, p. 242.
[4] G.P. Sakharov, V.P. Strelbitskiy, Materials and technologies for low-rise construction, Construction Materials, Equipment, Technologies of XXI Century, 2012, Vol. 5, pp. 22–27.
[5] V.S. Semenov, T.A. Rozovskaya, Dry masonry mixtures with ceramic hollow microspheres, Scientific Review, 2013, Vol. 9, pp. 195–199.
[6] V.S. Semenov, D.V. Oreshkin and T.A. Rozovskaya, Properties of light-weight masonry mortars with hollow glass microspheres and antifreeze additives, Industrial and Civil Engineering, 2013, Vol. 3, pp. 9-11.
[7] A.V. Klochkov, N.V. Pavlenko, V.V. Strokova and Yu.A. Belentsov, On the use of hollow glass microspheres in heat-insulating structural masonry mortars, Belgorod State Technical University Bulletin, 2012, Vol. 3, pp. 64-66.
[8] A.V. Klochkov, V.V. Strokova and N.V. Pavlenko, Structural and heat insulating masonry admixture with hollow glass microspheres, Construction Materials, 2012, Vol. 12, pp. 24–27.
[9] D.V. Oreshkin, Light-weight and superlight cement mortars for construction, Construction Materials, 2010, Vol. 6, pp. 34–37.
[10] D.V. Oreshkin, K.V. Belyaev and V.S. Semenov, Thermophysical Properties, Porosity and Vapour Permeability of Light-Weight Cement Mortars, Construction Materials, 2010, Vol. 8, pp. 51-54.
[11] D.V. Oreshkin, K.V. Belyaev and V.S. Semenov, The overall diagram of obtaining the lightened and super-lightweight cement mortars, Construction of oil and gas wells on land and at sea, 2010, Vol. 11, pp. 32-33.
[12] D.V. Oreshkin, P.V. Kaptsov, Scientific and technical preconditions for extruded lightweight cement systems, Proceedings of Moscow State University of Civil Engineering, 2012, Vol. 3, pp. 115–119.
[13] D.V. Oreshkin, V.S. Semenov and P.V. Kaptsov, Properties of masonry mortars on the basis of extruded mortar mixes, Construction Materials, 2012, Vol. 9, pp. 58–60.
[14] G.P. Sakharov, Scientific and technical preconditions for extruded fine-grain concrete, Proceedings of Moscow State University of Civil Engineering, 2011, Vol. 4, pp. 483–485.
[15] G.P. Sakharov, Chan Min Dyk, Improvement of the properties of fine-grain concrete by extruding of initial mixtures, Concrete and reinforced concrete, 2009, Vol. 11, pp. 6–8.
[16] Chan Min Dyk, Sakharov G.P., Extruded fine-grain concrete. Proceedings of higher educational institutions. Construction, 2008, Vol. 2, pp. 24–26.
[17] E.V. Korolev, A.S. Inozemtsev, Preparation and research of the high-strength lightweight concrete based on hollow microspheres, Advanced Materials Research, 2013, Vol. 746, pp. 285–288.
[18] A.S. Inozemtsev, E.V. Korolev, Hollow microspheres as an effective aggregate for high-strength lightweight concretes, Industrial and Civil Engineering, 2013, Vol. 10, pp. 80-83.
[19] F. Blanco, P. Garcia, P. Mateos, J. Ayala, Characteristics and properties of lightweight concrete manufactured with cenospheres, Cement and Concrete Research, 2012, Vol. 30, p. 11, p. 1715-1722.
[20] S.P. McBride, A. Shukla and A. Bose, Processing and characterization of a lightweight concrete using cenospheres, Journal of materials science, 2002, Vol. 37, pp. 4217–4225.
[21] D.V. Oreshkin, Problems in construction material science and production of a lightweight cement materials, Construction Materials, 2010, Vol. 11, pp. 6–8.
[22] S.N. Leonovich, Crack resistance and durability of bearing structures of NPP from the position of fracture mechanics, Proceedings of Belarusian National Technical University, 2009, Vol. 4, pp. 34–39.
[23] D.V. Oreshkin, G.N. Pervushin, Study of the crack-resistance of plugging stone with hollow glass microspheres for oil-and-gas wells after gun-fire perforation, Deformation and Fracture of Materials, 2013, Vol. 12, pp. 25–27.
[24] J. Eberhardsteiner, S. Zhdanok, B. Khoustalev, E. Batsianouski, P. Samtsou and S. Leonovich, Characterization of the influence of nanomaterials on the mechanical behavior of cement stone, Journal of Engineering Physics and Thermophysics, 2011, Vol. 84, No. 4, pp. 8–10.