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Mathematical model of polystyrene concrete structure for design of its strength characteristics

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Abstract. In the modern society a constant search is performed for the options to improve the energy efficiency of constructed residential and public buildings to reduce the cost of their operation and the human impact on the environment. One of the possible ways of the problem solution is using new construction and thermal insulation materials and products that meet modern requirements, for example, fencing and supporting construction made of polystyrene concrete. The authors carried out some research works, concerning the aforementioned improvement of deformation and strength characteristics of building material, by modeling its structure in the Institute of New Materials and Technologies of Ural Federal University. The research and mathematical modeling of the dependence of the composite material characteristics on the properties of raw materials and structure will allow predicting the strength of manufactured structures and determining the ratio and quality of raw materials of polystyrene concrete mix under production conditions.

1. Introduction

Polystyrene concrete is a composite material and one of the types of lightweight concrete which is differed by the presence of expanded polystyrene as a coarse (also a fine one often) aggregate uniformly distributed throughout the volume of concrete in its structure [1]. Concrete type mentioned above appeared in 1952 when the ‘BASF’ company produced it in industrial conditions and patented the method of production of Styrofoam concrete – the closest analogue of modern polystyrene concretes. Since the end of the 60-ies polystyrene concrete have begun to conquer the markets of the production of building materials and it is increasingly used in construction in Western Europe. From 1972 the Swiss company ‘RASTRA’ have produced heat-insulating floor slabs made of polystyrene concrete with an average density of 300-500 kg/m^3 for low-rise construction. In former USSR countries it was firstly used in production of fencing walls (wall large-format blocks) in the far North in 1970 in the Anadyr city. The successful experience was repeated while the construction of single-layer wall panels in the countryside in Chukotka. Thus, polystyrene concrete is a material that makes a significant contribution to the economic and technological development of the world construction industry for more than 60 years, being one of the most universal and accessible building materials.

2. Results and discussion

Application field and characteristics of polystyrene concrete depend on the its properties and the using of this lightweight concrete for the single-layer large-size wall panels and attic slabs manufacture, as well as small pieces of products, such as window liners and wall blocks for high-rise and low-rise construction is of the most reasonably. Modern construction technology namely 3D printing will provide a structurally reliable, architecturally diverse building with the using of polystyrene concrete structures in the possible shortest time. Currently, the physico-mechanical and deformative properties of polystyrene concrete (tensile strength in bending and compression strength, crack resistance and shrinkage) and high economic efficiency of its using have determined a large number of scientific works of this material by scientists in Europe and Asia [2-8]. The different experimental results of the influence of the characteristics of the raw materials, compositions and manufacturing technology on the properties of products and structures made of polystyrene were obtained.

At the same time, there is no necessary theoretical justification of parameter selection, analysis and summary of results. In industrial production it is possible to achieve high construction and technical characteristics of structures made of polystyrene concrete only taking into account the unique properties of the aggregate and the features of the structure listed below:

- the round shape of the expanded polystyrene granules helps to obtain a structure as close as possible to the design of the most dense cubic packaging;
- the average density of coarse aggregate granules of expanded polystyrene is close to zero and significantly reduces the weight of the structures;
- different filling of the space between the coasre aggregate granules provides the necessary density of the structure.

The space between the granules can be of three types depending on the requirements for the composite: mortar with inorganic sand of high strength to improve the strength characteristics; porous cement paste to preserve high thermal efficiency; if there is a technological possibility – mortar with a fine polystyrene aggregate, which increases both thermal and strength characteristics of the composite.

The research purpose of work carried out at the Department of materials Science in construction of UFU was the development of a mathematical model (regression parametric dependences) of deformation and strength properties (tensile strength in bending, prismatic compressive strength, Young's modulus, Poisson's ratio) based on the polystyrene macrostructure depending on the required strength characteristics of structures for using in mass production technology. The work was devoted to the studying of the polystyrene concrete behavior in various cases of loading, the detection of deformation and destruction pattern of the material and, on the basis of this, the description of its properties that determine the ability to predict its behavior under load (Figure 1).

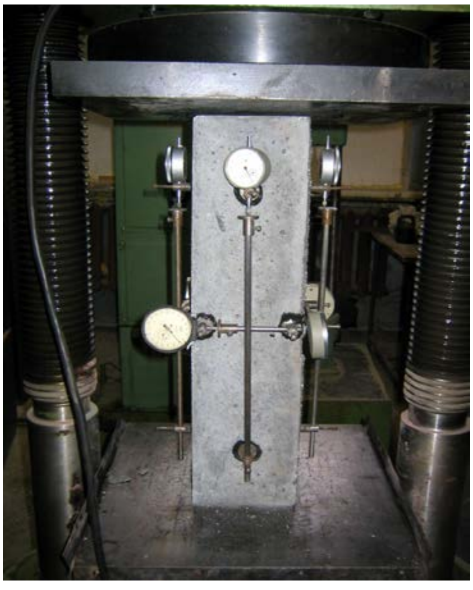

Figure 1. Compression test of a polystyrene prism sample to determine the prismatic strength and the initial modulus of elasticity.

To estimate the impact of the structural factor impact on any characteristic (for example, bending strength), its relative change was determined asl:

$$\Delta R^{bend} = \frac{R_{fb}^{bend} - R_{b}^{bend}}{R_{b}^{bend}} \times 100\%$$

where R_{fb}^{bend} – the bending strength of polystyrene concrete with these parameters of the macrostructure, MPa; R_{b}^{bend} – the basic bending strength of polystyrene concrete, MPa.

The difficulty of developing a mathematical model based on the macrostructure of polystyrene concrete is the complexity of considering a large number of properties of the initial components (binder, coarse and fine aggregates) and the composite material proper.

In the experimental part the authors introduced a number of restrictions:

- mobility and workability of the concrete mix must allow to use concrete mix both for production of monolithic and precast concrete constructions;
- parameters under investigation are only direct measured characteristics of the initial substances of the composite material obtained: geometric, deformation-strength and technological ones.

At the first stage of research only spherical granules of foamed polystyrene of narrow fractions were used as a coarse and fine aggregates namely from 1 to 2 mm, from 2 to 3 mm, from 3 to 5 mm, from 5 to 7 mm and from 7 to 10 mm. In the next stages of structure modeling the fractionated river sands will be used as a fine aggregate for the manufacture of high density polystyrene concrete.

In an ideal two-fraction hexagonal structure the layers of coarse and fine fractions of aggregates should alternate, at the same time the fine one will fill the voids between the layers of the cubic packing of the coarse fraction as much as possible. Using of monofractional aggregate forms the structure similar to a cube and the volume of the cement binder ideally tends to decrease to 26 %. The experimental results of determination of the aggregate fractions dependence on the percentage of binder for polystyrene concrete are given in table 1.

Table 1. Components content of experimental structure of polystyrene concrete.

Number of mix	Fine fraction		Coarse fraction		Binder quantity (%)
	Size (mm)	Quantity (%)	Size (mm)	Quantity (%)	
1	1-2	59	–	–	37
2	2-3	64	–	–	33
3	–	–	3-5	66	31
4	–	–	5-7	68	30
5	–	–	7-10	70	30
6	1-2	12	3-5	59	27
7	1-2	15	5-7	61	23
8	2-3	13	5-7	59	28
9	1-2	16	7-10	56	28
10	2-3	14	7-10	56	30

The aggregate content tends to an ideal estimated 74% but does not reach it due to the lack of contact between the polystyrene granules because of the spreading effect of the binder. Also in the mixing process air is always involved in the polystyrene concrete mix, which is only partially removed during the laying process.

At the first stage of research the following parameters of polystyrene concrete were chosen:

- cubic compressive strength;
- flexural tensile strength;
- coefficient of thermal conductivity at 20 °C.

After statistical processing of the experimental results it was established:

- with the increase of the aggregate size of monofractional structure of polystyrene concrete its strength characteristics monotonically decreases, and thermal insulation properties are increased not only by increasing the size of the cell polystyrene but also by reducing the content of binder required to fill the structure (Figure 2);
- in the two-fraction structure of the polystyrene concrete there is the composite with optimal quality parameters, in which the average size of the fractions is 4 times differ (Figure 3), since the grains of the fine fraction are filled the tetrahedral voids one by one.

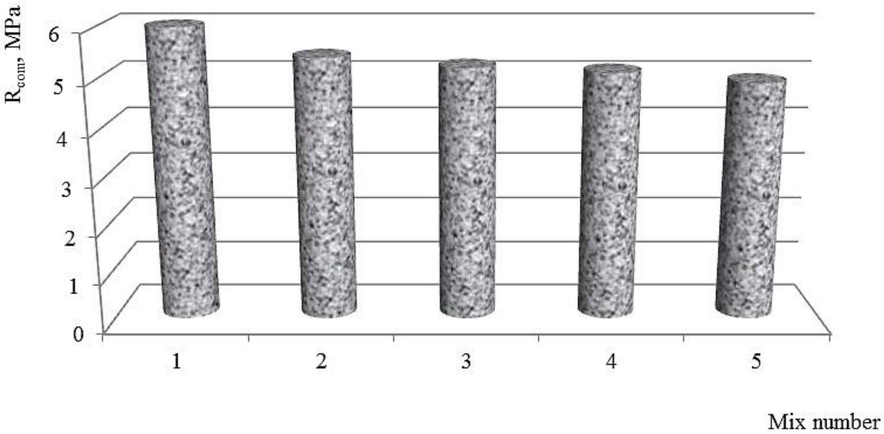

Figure 2. Compressive strength of monofractional structure.

As a result, in the second stage of research by regression analysis methods, empirical dependences of qualitative parameters (on the example of compressive strength) on the properties of the initial components were established:

$$R_c = 0.6 \times R_m \times X_m \times (\frac{D}{4d}) \times (\frac{X_D}{3X_d})$$

where R_c, R_m – compressive strength of polystyrene concrete and mortar (cement paste) at water-cement ratio used in this type of polystyrene concrete respectively, MPa;
X_m, X_D, X_d – the content of the mortar, coarse and fine aggregate in the structure of polystyrene concrete respectively, %;
D, d – the average diameter of coarse and fine aggregate, mm.

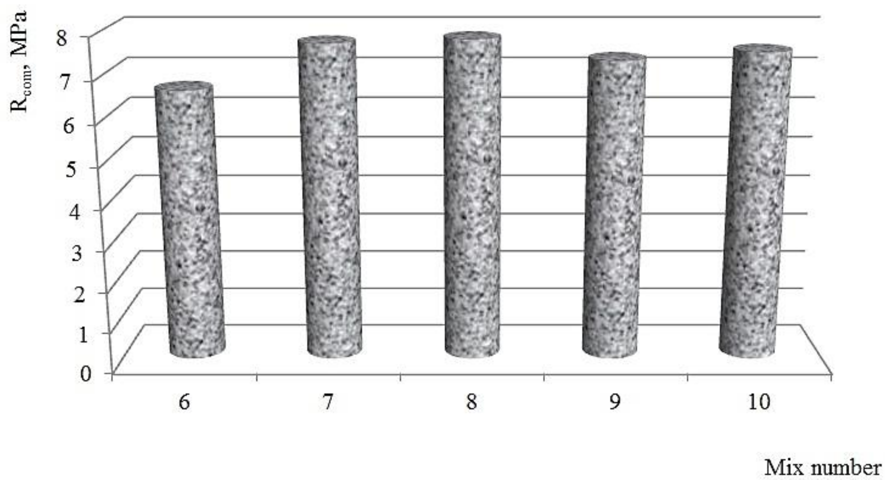

Figure 3. Compressive strength of double fractional structure.

3. Conclusion

Research works concerning the development of a mathematical model of the dependence of the deformation and strength properties of polystyrene concrete on the type of binder and fine aggregate in the structure of the composite were carried out in the Institute of new materials and technologies of Ural Federal University. The model makes it possible to select the optimal ratio of the active and inert aggregate in the composite structure based on the required strength characteristics of the structures by the calculation method. At present a general view of the model is developed, the main coefficients are determined and experimental confirmation is carried out.

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