Selection of a rational formulation of lightened concretes on combined aggregates

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Abstract. In the difficult conditions of modern construction, the use of concretes with a combined aggregate, if the composition is rational and the formulation and technological factors act rationally, will allow solving many existing problems. In this paper, studies were carried out on the choice of a rational formulation of lightened concrete based on foamed slag, natural crushed stone and granulated blast furnace slag by varying the volume content of a porous coarse aggregate and a fine aggregate in relation to the volume of the mixture. In total, 9 series of prototypes and 1 series of control samples were manufactured and tested. One series of samples includes three cubes with dimensions of 10x10x10 cm. All samples are tested for density, compressive strength and the coefficient of constructional quality. According to the results of the study, it was concluded that the introduction of foamed slag into the composition of heavy concrete instead of a part of a dense coarse aggregate and the replacement of a fine dense aggregate with granulated blast furnace slag leads to an increase in the coefficient of constructional quality, that is, the decrease in compressive strength of concrete is compensated by an even more significant decrease in the density of the material, and therefore a decrease in mass. The increase in the coefficient of constructional quality of concrete based on foamed slag, natural crushed stone and granulated blast furnace slag in comparison with the control composition was 14%.

1. Introduction
In modern construction conditions, reinforced concrete structures, made in turn from concrete on light and low-density aggregates, acquire a special role [1-4]. The manufacture of such structures, and subsequently buildings and structures leads to the fact that the weight of such buildings and structures is significantly reduced. This, in turn, has a positive effect on the construction of multistorey and other buildings and structures for various purposes, combined with the complexity of engineering and geological conditions in a number of localities, a real lack of space for the construction of new buildings and structures, as well as with the density of urban development [5-8].

Thus, the current direction is the development of optimal formulation and technological parameters, design solutions, technology for the construction and factory production of products and structures made of lightweight and lightened concrete, that is, made with the use of porous aggregates [9-12].

Let us specify at once that in our paper the object of research will be lightened concretes on the combined aggregate, consisting of dense and porous aggregate, and the subject of research will be not
the absolute indicators, such as compressive strength and density of concrete products and structures, but the relative index, called the coefficient of constructional quality of concrete, that is known in the scientific literature as the ratio of the strength of concrete to its density.

Thus, the purpose of this work will be to choose a rational formulation and optimal technology that allows to obtain lightened concrete on combined aggregates in a rational combination that will lead to the maximum coefficient of constructional quality, while the objectives of the study will be to review and analyze the literature on lightened concretes on combined aggregates, as well as the issues of fiber reinforcement of such concretes, the choice of basic compositions of raw materials and equipment for research, the development of an experimental research program, which will be aimed at finding a rational ratio of dense and porous aggregates in the concrete body. In this case an important task will be to find the highest coefficient of constructional quality of any composition in laboratory studies due to two hypotheses, the first of which will be the maximum increase in strength, which will lead in turn to a directly proportional increase in the coefficient of constructional quality and the second option is a sharp decrease in density, while maintaining, or a slight drop in strength, but due to a sharp decrease in density we get a higher coefficient of constructional quality.

Thus, the working hypothesis of the study should be formulated as follows: with a rational combination of formulation and technological factors and the correct ratio between the dense and porous aggregate in the concrete body it is possible to replace part of the dense aggregate of heavy concrete with porous aggregate with loss in some sense of the absolute strength, but a gain in the coefficient of constructional quality and thus the acquisition of advantages when erecting buildings and structures from such concretes.

2. Materials and methods

During the research we used Portland cement without additive of PC 400 D0 brand, physical and mechanical characteristics of which are presented in Table 1.

| Table 1. Physical and mechanical characteristics of Portland cement PC 400 D0. |
|---|---|
| Name of characteristics | Value |
| Grinding fineness, passing through a sieve № 008, % | 95.8 |
| Specific surface area, cm²/g | 2988.5 |
| Standard density of cement paste, % | 26.5 |
| Setting time, h: min | |
| - start | 0: 48 |
| - end | 4: 00 |
| Compressive strength at the age of 28 days, MPa | 42.5 |

Natural crushed stone from quartzite rocks was used as a large dense aggregate, and foamed slag was used as a large porous aggregate. The physical and mechanical characteristics of a dense and porous coarse aggregate are presented in Table 2.

| Table 2. Physical and mechanical characteristics of a large aggregate. |
|---|---|---|---|
| Name | Bulk density, kg/m³ | Strength according to GOST 9758, MPa | Crushability according to GOST 8269, MPa | Grain density, g/cm³ | Voidness, % |
| Foamed slag of fraction 10-20 mm | 654 | 0.9 | - | 1.30 | 52 |
| Crushed stone of fraction 5-10 mm | 1380 | - | 75 | 2.57 | 47 |
Quartz sand was used as a fine dense aggregate, and granular slag was used as a fine porous aggregate. The physical and mechanical characteristics of a fine dense and porous aggregate are presented in Table 3.

Table 3. Physical and mechanical characteristics of a large aggregate.

| Name          | Bulk density, kg/m³ | Size modulus | Grain density, g/cm³ | Voidness, % |
|---------------|---------------------|--------------|----------------------|-------------|
| Granular slag | 1021                | 3.8          | 1.95                 | 50          |
| Sand          | 1480                | 1.4          | 2.61                 | 43.3        |

The preparation of the concrete mixture was carried out in a laboratory concrete mixer of forced action BL-10. For the production of cubes, standard forms of the 2FK-100 brand were used. Compaction of the concrete mixture during the forming of samples was carried out on a laboratory vibration platform SMZH – 539 – 220A with a mechanical attachment, the average vibration time was 60-90 seconds. On the next day after forming, the samples were decompressed and placed in a normal hardening chamber for 28 days until the design strength was set [13-15].

We also used for research: testing equipment (hydraulic press IP-1000), measuring instruments (metal measuring ruler, laboratory scales, a device for measuring deviations from flatness NPL-1, a device for measuring deviations from the perpendicular NPR-1).

In total, nine series of prototypes and one series of control samples were manufactured and tested. One series of samples includes three cubes with an edge size of 10 cm.

Compression tests of the samples were carried out in accordance with the requirements of GOST 10180 «Concretes. Methods for strength determination using reference specimens» [13-15].

3. Results and discussions

As a control composition, heavy concrete is designed on dense aggregates of class B30 with the required mark for workability P1 (cone slump 1-4 cm). The parameters of the composition of the concrete mixture obtained as a result of calculations are shown in Table 4.

Table 4. Parameters of the concrete mixture composition.

| Name of the parameter | Cement, kg/m³ | Water, l/m³ | Crushed stone, kg/m³ | Sand, kg/m³ | ρc, kg/m³ |
|-----------------------|---------------|-------------|----------------------|-------------|-----------|
| Parameter value       | 378           | 203         | 1198                 | 721         | 2500      |

The cubic compressive strength of the control composition of heavy concrete was $R_{b,cub} = 41.1$ MPa, the density was 2500 kg/m³, and the coefficient of constructional quality was $16.4 \times 10^3$ MPa·m³/kg.

The selection of the optimal volume contents of large and small porous aggregates in relation to a mixture of large aggregates was carried out by performing calculations by the method of mathematical planning of the experiment using the “MathCAD” program.

As functions, we take the following indicators that vary depending on the different volume contents of large and small porous aggregates in relation to a mixture of large aggregates: density, compressive strength and the coefficient of constructional quality.

The parameters were taken as the response function:

- $R_{b,cub}$ ($V_{fs}$; $V_{gs}$) – compressive strength, MPa;
- $\rho_{cm}$ ($V_{fs}$; $V_{gs}$) – density of lightened concrete, kg/m³
- CCQ ($V_{fs}$; $V_{gs}$) – coefficient of constructional quality, $\times 10^3$ (MPa·m³/kg).

As arguments, we will take the volume content of a large porous aggregate and the volume content of a small porous aggregate in relation to a mixture of large aggregates in absolute terms with different levels of variation. The values of the variation factors are presented in Table 5.

Table 5. The values of the PFE $2^k$ variation factors.

| №  | Factor | Physical meaning of the factor | Measure unit | Factor levels |
|----|--------|--------------------------------|--------------|---------------|
The results of experimental studies of the influence of the volume contents of coarse and fine porous aggregates in relation to a mixture of large aggregates on the density, compressive strength and the coefficient of constructional quality of lightened concrete are presented in Table 6 and in Figures 1-3.

**Table 6.** The results of experimental studies of the influence of the volume contents of porous coarse and fine aggregates in relation to a mixture of large aggregates on the density, compressive strength and the coefficient of constructional quality of lightened concrete.

| Number of experiment | Volume content of a porous coarse aggregate, % | Volume content of fine aggregate in relation to a mixture of large aggregates, % | Density of lightened concrete, kg/m³ | Compressive strength, MPa | Coefficient of constructional quality of lightened concrete, x10³ (MPa·m³/kg) |
|----------------------|-----------------------------------------------|--------------------------------------------------------------------------------|-------------------------------------|--------------------------|------------------------------------------------------------------|
| 1                    | 40                                            | 30                                                                             | 2123                                | 38.9                     | 18.3                                                             |
| 2                    | 60                                            | 30                                                                             | 1938                                | 36.1                     | 18.6                                                             |
| 3                    | 40                                            | 40                                                                             | 2132                                | 39.1                     | 18.3                                                             |
| 4                    | 60                                            | 40                                                                             | 1978                                | 37.8                     | 19.1                                                             |
| 5                    | 40                                            | 35                                                                             | 2130                                | 39                       | 18.3                                                             |
| 6                    | 60                                            | 35                                                                             | 1942                                | 36.3                     | 18.7                                                             |
| 7                    | 50                                            | 30                                                                             | 2067                                | 37                       | 17.9                                                             |
| 8                    | 50                                            | 40                                                                             | 2095                                | 37.1                     | 17.7                                                             |
| 9                    | 50                                            | 35                                                                             | 2058                                | 36.8                     | 17.9                                                             |

Based on the results of the research, the basic regression equations were obtained using the least squares method, which are presented in the form of polynomials of the 2nd degree:

When calculating the composition of lightened concrete in each experiment, the values of aggregate consumption (see Table 7) were calculated using the formulas:

\[ \sigma_{cm}(V_{fs}, V_{gs}) = 2051 - 87.85 \cdot V_{fs} + 12.84 \cdot V_{fs} \cdot V_{gs} + 7.75 \cdot V_{fs} \cdot V_{gs} - 32.86 \cdot V_{fs}^2 + 12.16 \cdot V_{gs}^2 \]  

(1)

\[ R_{bb, cub}(V_{fs}, V_{gs}) = 37 - 1.37 \cdot V_{fs} + 0.5168 \cdot V_{gs} + 0.3 \cdot V_{fs} \cdot V_{gs} - 0.0006 \cdot V_{fs}^2 + 0.3499 \cdot V_{gs}^2 \]  

(2)

\[ R_{bb, cub}(V_{fs}, V_{gs}) = 37 - 1.37 \cdot V_{fs} + 0.5168 \cdot V_{gs} + 0.3 \cdot V_{fs} \cdot V_{gs} - 0.0006 \cdot V_{fs}^2 + 0.3499 \cdot V_{gs}^2 \]  

(3)

When calculating the composition of lightened concrete in each experiment, the values of aggregate consumption (see Table 7) were calculated using the formulas:

\[ M = r \times \sum V \]  

(4)

\[ K = \sum V - M \]  

(5)

\[ K_s = V_s \times K \]  

(6)
there $M$ – consumption of fine aggregate, m$^3$/m$^3$;
$r$ – proportion of sand by volume in the mixture of aggregates;
$\sum V$ – the sum of the fractionated volumes (the total consumption of aggregates per 1m$^3$ of concrete) is taken according to the results of studies of the properties of mixtures of aggregates, m$^3$/m$^3$;
$K$ – total consumption of large aggregates, m$^3$/m$^3$;
$K_s$ – consumption of foamed slag, m$^3$/m$^3$;
$K_{cs}$ – consumption of crushed stone, m$^3$/m$^3$;
$V_s$ – proportion of foamed slag;
$V_{cs}$ – proportion of crushed stone.

Table 7. Aggregate consumption values.

| Number of experiment | Sum of the fractionated volumes, m$^3$/m$^3$ | Consumption of granular slag, m$^3$/m$^3$ | Consumption of foamed slag, m$^3$/m$^3$ | Consumption of crushed stone, m$^3$/m$^3$ |
|----------------------|---------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 1                    | 1.423                                       | 0.427                                    | 0.398                                    | 0.598                                    |
| 2                    | 1.452                                       | 0.436                                    | 0.610                                    | 0.407                                    |
| 3                    | 1.436                                       | 0.574                                    | 0.345                                    | 0.517                                    |
| 4                    | 1.479                                       | 0.592                                    | 0.532                                    | 0.355                                    |
| 5                    | 1.428                                       | 0.571                                    | 0.343                                    | 0.514                                    |
| 6                    | 1.457                                       | 0.510                                    | 0.568                                    | 0.379                                    |
| 7                    | 1.448                                       | 0.507                                    | 0.471                                    | 0.471                                    |
| 8                    | 1.467                                       | 0.440                                    | 0.513                                    | 0.513                                    |
| 9                    | 1.453                                       | 0.581                                    | 0.436                                    | 0.436                                    |

When preparing experimental mixes of concrete mixtures on a combined aggregate, the cement consumption remained unchanged, and the water consumption was adjusted until the required mobility of the concrete mixture was obtained.

Figure 1. Change in the density of lightened concrete depending on the volume contents of large and small porous aggregates in relation to a mixture of large aggregates (K – control composition; 1, 2 ..., 9 – experimental compositions).
Figure 2. Change in the compressive strength of lightened concrete depending on the volume contents of large and small porous aggregates in relation to a mixture of large aggregates (К — control composition; 1, 2 ... 9 — experimental compositions).

Figure 3. Change in the coefficient of constructional quality of lightened concrete depending on the volume contents of large and small porous aggregates in relation to a mixture of large aggregates (К — control composition; 1, 2 ... 9 — experimental compositions).

The analysis of the obtained results indicates that the introduction of foamed slag into the composition of heavy concrete instead of a part of a dense coarse aggregate and the replacement of a fine dense aggregate with granular blast furnace slag leads to an increase in the coefficient of constructional quality, that is, the decrease in compressive strength of concrete is compensated by an even more significant decrease in the density of the material, and therefore a decrease in mass.

The maximum increase in the coefficient of constructional quality of concrete based on foamed slag, natural crushed stone and granulated blast furnace slag is observed when a part of a large dense aggregate is replaced with foamed slag in the amount of 60% of the total volume of large aggregate in the concrete mixture and the volume content of fine aggregate in relation to a mixture of large aggregates in the amount of 40%.
4. Summary
As a result of our research, we made the following conclusions. The technology of combining aggregates, that is, replacing a part of a dense aggregate, in our case, crushed stone from quartzite rocks and quartz sand, with porous ones, namely, foamed slag of 10-20 mm and granulated blast furnace slag, allows achieving a significant reduction in the weight of the structure by reducing the mass and densi-
ty of concrete. This increases the coefficient of constructional quality of such concretes.

The increase in the coefficient of constructional quality of concrete based on foamed slag, natural crushed stone and granulated blast furnace slag in comparison with the control composition was 14%.

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