High-strength lightweight concrete mixtures based on hollow microspheres: technological features and industrial experience of preparation

A S Inozemtcev

1Moscow State University of Civil Engineering, 129337, Moscow, Russia

E-mail: InozemtcevAS@mgsu.ru

Abstract. The research results concerning dependencies between technological parameters and physical properties of structural lightweight concrete are presented in the article. High-strength lightweight concrete has unique performance characteristics: low average density (less than 1500 kg/m$^3$) and high compressive strength (more than 70 MPa). Hollow alumina-silicate microspheres with nanoscale modifier are used for obtaining these properties. It is shown in the article that the preparation of high-strength lightweight concrete in industrial conditions must be implemented using a turbine mixer having six paddles and engine power more than 39.2 kW. Oscillation frequency of more than 3000 rpm, vibro-compacting time less than 15 seconds, heat-humid treatment temperature approximately 60-65 °C and heat-humid treatment time 6-7 hours are optimal for production. The results of industrial mixing-test are presented.

1. Introduction

The recognized world research trend in direction of modern building materials is development of new composites having complex properties that increases application area and provides technical and economical efficiency of new technology [1-4]. One of such materials is high-strength lightweight concrete (HSLWC). This type of concrete developed by researchers from Moscow State University of Civil Engineering has low average density (less than 1500 kg/m$^3$) and high compressive strength (more than 70 MPa). The structure of HSLWC [5] can be described as closed-packed hollow microscale spherical particles of filler evenly integrated to multifractional cement-mineral matrix. Obviously, technological factors (time and rate of mixing, parameters of vibro-compacting, mode of heat-humid treatment (HHT) and other) have influence on quality of concrete. Therefore, research the influence of technological modes on physical and mechanical properties of high-strength lightweight concrete based on hollow microspheres is relevant task for improving of construction technologies.

2. Materials, methods and equipment

Portland-cement CEM-I 42.5, hollow glass and alumina-silicate microspheres (diameter is 0-100 mkm), quartz sand fraction of 0.16-0.63 mm, stone powder with a specific surface area of 700-800 m$^2$/kg, microsilica and polycarboxylate plasticizer were used for preparation of concrete mixture. Composition of HSLWC was chosen according to [6]. The mixing of concrete was carried out using the “Automix” mortar mixer. The “Advantest 9” servo-hydraulic press was used for determination of strength in 1 day after heat-humid treatment according to ASTM C39/C39M-14. The structure of HSLWC was examined on «Eclipse MA200» microscope.
3. Results and discussion

There are different equipment parameters during preparation of the concretes at the laboratory and plants. Therefore it is required to determine the character of changes in the physical and mechanical properties of the high-strength lightweight concrete based on hollow microspheres for different technical characteristics of the manufacturing equipment. Three modes of the mixing with different rate and time were selected (Table 1).

| No | Type of mixing | Mixing time, sec |
|----|----------------|------------------|
|    |                | Mode M1 | Mode M2 | Mode M3 |
| 1  | Slow mixing    | 120     | 120     | 30     |
| 2  | Fast mixing    | –       | –       | 90     |
| 3  | Pause          | 10      | 10      | 10     |
| 4  | Slow mixing    | 90      | –       | –      |
| 5  | Fast mixing    | 30      | 120     | 120    |

Notes: slow mixing is stirrer speed about 140±5 rpm, fast mixing is about 285±10 rpm.

The inhomogeneous structure of the concrete is formed if preparation of mixture is carried out according to M1 mode. The data of the Table 1 and Figure 2 show that M1 mixing mode promotes the formation of agglomerates of cement particles which are adsorbing water only on the surface. The average density of concrete reaches 1390±5 kg/m$^3$ and compressive strength is up to 34.0 MPa (specific strength is $R_{sp}=24.5$ MPa, $R_{sp}$ – specific strength of material: compressive strength divided by relative density). Figure 2 demonstrates the structure of high-strength lightweight concrete which was prepared in accordance with M1 mode. There is loose structure with a lot of pores of different sizes and inhomogeneous zones of the cement and mineral part (region of the fuzzy image on the microphoto). The best quality of structure of the HSLWC is obtained if the preparation of the mixture is carried out with increased time of the fast mixing.

For the M2 mode, the prepared samples are characterized by almost the same density (the excess is about 2-3 %) and compressive strength (excess is 5-7 %). The structure of such concrete presented on figure 3 is more ordered system of filler/cement-mineral part. There is denser packing but still has pores of big sizes. The preparation of HSLWC compositions using a mode M3 (201 seconds of the total time of the fast mixing with stirrer speed about 285±10 rpm) allows to obtain the homogeneous and uniform structure with small numbers of small pores (Figure 4). In this case the high-strength
lightweight concrete has average density 1455±5 kg/m³ and compressive strength of more than 42.0 MPa (specific strength more than 28.9 MPa) in 1 day after HHT.

The power calculation for production mixer is carried by formula [5]:

\[ N = K_N \rho n^3 d_1^5, \]  

where \( \rho \) – density of the mixing medium, kg/m³; \( n \) – rotating speed of stirrer, sec⁻¹; \( d_1 \) – diameter of mixer, m.

For the turbulent mode there is no significant change of the parameter \( K_N \); for the laminar mode this parameter depends on the Reynolds number:

\[ R_e = \frac{n d_1^2 \varnothing^{1/2}}{\rho}, \]  

where \( \varnothing \) – kinematic viscosity of the medium, m²/sec.

It is obvious that technical parameters of laboratory and manufacturing equipment are different. Thus, for the degree of homogeneity of the concrete mixture which provides required physical and mechanical properties of HSLWC have to be:

\[ N_1 = K_{N1} \rho n_1^3 d_{m1}^5. \]  

The power of mixer allowing getting a concrete mix with similar quality:

\[ N_2 = K_{N2} \rho n_2^3 d_{m2}^5. \]  

The \( N_2 \) can be found from the equation:

\[ N_2 = K_{N2} n_2^3 d_{m2}^5 N_1^{-1} \left( K_{N1} n_1^3 d_{m1}^5 \right)^{-1}. \]  

The laboratory equipment has the following characteristics:

\( n_1 = 4.75 \) sec⁻¹, \( d_{m1} = 0.2 \) m, \( K_{N1} = 210 \), \( K_{N2} = 1 \), \( N_1 = 500 \) W, \( n_2/d_{m2} = 0.2 \), \( d_{m2} = 2.7 \) m.

For these values the \( N_2 = 39.2 \) kW.

Because quality of high-strength lightweight concrete with hollow microspheres depends on packing density and uniform distribution of cement and mineral mixture, the application of vibro-compaction is expedient for moderately mobile concrete mixtures. The optimal compaction time for concrete mixture is defined by the relation of the best strength to minimal energy expense to lay such composition. The vibro-compaction of concrete mixture for formation was carried out in layers according to the modes (Table 2) for modeling the real manufacturing processes.
Table 2. Compacting modes of HSLWC mixtures with hollow microspheres.

| No | Layer  | Compacting time, sec |
|----|--------|----------------------|
| 1  | First  | 0 5 10 15            |
| 2  | Second | 0 10 20 30           |
| 3  | Total  | 0 15 30 45           |

The results of experimental research show that vibro-compaction naturally leads to an increase of density coefficient of HSLWC mixture (table 3). It enables to increase the strength in age of one day after heat-humid treatment. The application of compaction for 15 seconds increases the concrete strength more than by 15% but modes C3 and C4 do not improve the technical characteristics of HSLWC. Moreover, the vibro-compaction for 30 and 45 seconds promotes additional entrained air, increases open porosity of products and worsens the quality of their surface.

Table 3. Influence of compacting time on physical and mechanical properties of HSLWC mixtures with hollow microspheres.

| No | Compacting mode       | Mode C1 | Mode C2 | Mode C3 | Mode C4 |
|----|-----------------------|---------|---------|---------|---------|
| 1  | Compacting time, sec  | 0       | 15      | 30      | 45      |
| 2  | Average density, kg/m³ | 1457.4  | 1463.5  | 1462.8  | 1463.8  |
| 3  | Density coefficient   | 0.971   | 0.976   | 0.975   | 0.976   |
| 4  | Compressive strength (age is 1 day after HHT), MPa | 42.8    | 49.7    | 48.5    | 48.8    |

Note: density coefficient is a ratio of the actual density to project density

Thus, vibro-compacting within no more than 15 seconds is sufficient for manufacturing of HSLWC products based on the mixture with hollow microspheres.

The heat-humid treatment is a final stage of technological processes during production the reinforced concrete products. In this research work experimental and statistical modeling was involved for study of heat treatment modes of lightweight concrete with hollow microspheres. For the approximation of the data obtained during experiment with two-factor full factorial design the linear regression model was used. The experiment was carried out for two factors: $x_1 (T)$ – temperature of the isothermal exposure, °C, $x_2 (t)$ – time of the isothermal exposure, hours. The main level for first factor is 70 °C, and for second factor is 7 hours (intervals of variation are 10 °C and 1 hour, respectively). The model represents changes the strength of HSLWC based on hollow microspheres as a function of temperature and time of the heat-humid treatment. The parameters of regression model were obtained from experiment:

$$y = 44.3 - 0.64 \cdot x_1 + 1.57 \cdot x_2$$

or

$$R_{com} = 38.28 - 0.064 \cdot T + 1.57 \cdot t,$$

where $R_{com}$ is compressive strength (age is 1 day).

The equation (5) is on Figure 5.

The plot of equation (5) and Figure 5 show that $x_1$ factor has a negative impact on strength of the investigated concrete. That is increase the temperature of the isothermal exposure up to 80°C leads to reduction of compressive strength in age of one day after HHT. It can be explained by the accumulation of the internal thermal stresses because of cement hydration processes and extra temperature gradient (the thermal conductivity of HSLWC is only 0.6 W/(m · K)). The visual examination of the specimens after heat-humid treatment (temperature is 80 °C) shows the local changing of the volume (Figure 6).
The influence of the temperature on the processes of the deformations can be decreased, in particular, by means of optimization of the HHT mode: the holding time can be varied and temperature of the products (before heat treatment stage) can be stabilized.

As it follows from the experimental results presented on Figure 5, increasing of isothermal holding time leads to small changes of the strength of the high-strength lightweight concrete. This is due to completer hydration of the cement. It is important that there are no local changes of volume of specimens of the high-strength lightweight concrete after heat-humid treatment at temperature 60 °C. The stable structure without visible cracks, bundles and other defects is observed after HHT and the samples have high coefficient of quality $k_{HHT}$, $k_{HHT}=R_{com}/T_p$, where $T_p=1$ – concrete hasn’t visual cracks or $T_p=100$ – concrete has visual cracks (Figure 7).

Thus, for manufacturing of the HSLWC products with hollow microspheres it is appropriate to use the following modes of the heat-humid treatment: isothermal holding time during 6-7 hours and temperatures are 60-65 °C.

![Figure 5](Image)  **Figure 5.** Influence of the HHT temperature and duration on compressive strength of the HSLWC.

![Figure 6](Image)  **Figure 6.** Photographs of the HSLWC samples after HHT $T=80$ °C (left) and $T=60$ °C (right).

As a result of the laboratory test the compositions of HSLWC based on hollow microspheres with design density equal to 1500 kg/m$^3$ was selected during calculation of mixture and production of the crossbars (of $1980\times370\times200$ mm) in the industrial conditions at the plant for manufacturing...
reinforced-concrete products. The preparation of the high-strength lightweight concrete was carried using by the “SB-138B” Russian mixer of a power about 37 kW and shaft speed less than 23 rpm. The laying of concrete mixture into plywood forms was made using by a concrete-stacker (Figure 8).

Formed products were subject to heat-humid treatment according to manufacturing mode with isothermal temperature of 80 °C. The compressive strength of 100 mm cubes formed from mixture of general molding was 40–42 MPa (in the age of one day after HHT). The average density of HSLWC (in the age of 28 days) was 1518 kg/m³ and compressive strength was 55±2 MPa (these values correspond to B40 grade). The photo of finished product is presented on Figure 9. Technical and economic efficiency of such materials can be evaluated according to [7].

4. Conclusions
The results of research allow making the following conclusions:
– the preparation of HSLWC compositions requires the using of a turbine mixer having six paddles and engine power more than 39.2 kW;
– the oscillation frequency have to be more than 3000 rpm, vibro-compacting time have to be less than 15 seconds, heat-humid treatment temperature have to be approximately 60-65 °C and heat-humid treatment time have to be 6-7 hours; these values correspond to optimal manufacturing technological mode (and, therefore, to the best operational properties) of the products of mixtures based on hollow microspheres.

The industrial approbation of the high-strength lightweight concrete shows that developed technology can be adapted in existing production facilities using already available industrial equipments.

References
[1] Korolev E V 2013 Principle of realization of nanotechnology in building materials science *Construction Materials* 6 60–64
[2] Payam S, Hafez G, Hilmi Bin M and Mohd Zamin J 2014 A comparison study of the mechanical properties and drying shrinkage of oil palm shell and expanded clay lightweight aggregate concretes *Materials and Design* 60 320-327
[3] Korolev E V 2013 Model of integrated nanosized modifier for asphalt *Regional architecture and engineering* 3 5–21
[4] Garkina I A and Danilov A M 2008 Materials with special characteristics quality control *Management problems* 6 67-73
[5] Inozemtcev A S and Korolev E V 2014 Structuring and properties of the structural high-strength lightweight concretes with nanomodifier BisNanoActivus *Construction Materials* 1-2 33–37
[6] Korolev E V and Inozemtcev A S 2012 Pat. RUS 2515450 *High-strength lightweight concrete* 3
[7] Bazhenov Yu M and Korolev E V 2009 Estimation of technical and economic efficiency of nanotechnologies in building materiology *Construction Materials* 6 66–67