Technological approaches to increase the quality of lightweight concrete based on hybrid binders

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Abstract. The processes of structure formation of hardening compositions based on hybrid binders as well as the controlled change of these processes allow obtaining concretes with increased strength and durability, for example, lightweight structural concretes on porous aggregates. Control of the structure formation of such concretes allows improving the quality and operational reliability of buildings and structures, saving binders, expanding the kinds of raw materials and solving environmental and economic issues. The results of the experiments have showed that the fineness of the hybrid binder effect the properties of the contact zone between the expanded clay aggregates and the cement matrix including the formation of calcium hydrosilicates on the surface of expanded clay gravel, which increases the adhesive strength. This leads to the increase of the quality of lightweight concrete based on expanded clay gravel.

Keywords. Lightweight concrete, hybrid binder, porous aggregates, quality indicators, structure formation

Introduction

The processes of structure formation of hardening compositions based on hybrid binders as well as the controlled change of these processes allow obtaining concretes of increased strength and durability, for example, lightweight structural concretes on porous aggregates [1-5]. Control of the structure formation of such concretes allows improving the quality and operational reliability of buildings and structures [6-10], saving binders [11-14], expanding the raw materials and solving environmental and economic issues [15-18].

The change of the fineness of mineral particles of binders leads to the increase of the degree of binder hydration and improves the properties of lightweight concrete [1,2,4]. However, the published data on the effect of the fineness of hybrid binders based on slag and sulfate component as well as degree of hydration of hybrid binders on the properties of lightweight concrete based on expanded clay aggregates is not enough. The authors of the study previously state the working hypothesis according to which the use of a hybrid binder based on finely ground slag and sulfate component instead of ordinary Portland cement will have significant influence on the processes of structure formation of lightweight concrete based on expanded clay aggregates.

The aim of the paper is the scientific and practical justification of technological approaches to the regulation of the structure formation of lightweight concrete with hybrid binder to improve the quality of lightweight concrete based on expanded clay aggregates. Mixture of slag, sulfate component and hardening activator was used to develop and evaluate the properties of the hybrid binders.

Materials and methods
Expanded clay gravel of two types was used as coarse aggregate in the compositions of lightweight concrete. Gravel tests were carried out according to the standard 9758-2012 "Porous inorganic aggregates for construction. Test methods". Expanded clay sand was used as fine aggregate. Tests of sand were carried out according to the standard 8736-2014 "Sand for construction. Technical conditions".

Hybrid binder was obtained by mixing ground granulated blast furnace slag (ggbfs), sulfate component - phosphogypsum (fg) and alkaline activator - cement kiln dust (ckd). Characterization of binders was performed according to standard 30744 "Cements. Test methods using polyfractional sand".

The characteristics of all components according to the test results are given in Table 1.

**Table 1. Characteristics of the components of lightweight concrete**

| Components          | Characteristics                                                                 |
|---------------------|--------------------------------------------------------------------------------|
| Coarse aggregate    | 1. Expanded clay gravel                                                         |
|                     | — Bulk density — 480 kg/m³                                                       |
|                     | — Strength when compressed in the cylinder - 2,32MPa                            |
|                     | — Grain composition of expanded clay:                                          |
|                     | 5-10 mm - 40%                                                                  |
|                     | 10-20 mm - 60%                                                                 |
|                     | 2. Expanded clay gravel                                                         |
|                     | — Bulk density - 465 kg/m³                                                      |
|                     | — Strength when compressed in the cylinder -2,32MPa                             |
|                     | — Grain composition of expanded clay:                                          |
|                     | 5-10 mm - 30%                                                                  |
|                     | 10-20 mm - 70%                                                                 |
| Fine aggregate      | — Expanded clay sand                                                            |
|                     | — Water demand – 9,2%                                                           |
|                     | — Density — 2600 kg/m³                                                         |
|                     | — Finess modulus =1,7                                                           |
| Hybrid binder       | — Composition: 80%ggbfs+20%fg +10%ckd                                          |
|                     | — Specific surface ($S_{sp}$) - 3500 cm²/g u 6000 cm²/g                          |
|                     | — Standard consistency — 30%                                                    |
|                     | — Setting time - beginning 2 h 40 min                                            |
|                     | — Activity at the age of 28 days - $R_{ck}=40$ MPa                             |
| Mixing liquid       | Drinking tap water                                                             |

**Features of structure formation of lightweight concrete based on hybrid binder**

Samples of lightweight concrete were made on hybrid binders with $S_{sp}=3500$ cm²/g and $S_{sp}=6000$ cm²/g at the water-to-binder ratio of W/B=0.55. The tests were performed on beam samples of size 4×4×16 cm at t=20°C. Also, previously obtained data [19] that both steaming and heating of the fresh mixture over 60°C do not increase the strength characteristics of the concrete on these hybrid binders were confirmed by our experiments. It is stated that more intensive hydration of CaOfree and its binding in hydration products is observed in cement matrix based on hybrid binder with $S_{sp}=6000$ cm²/g as shown in Table 2.

**Table 2. Effect of the specific surface of binder on the hydration processes in lightweight concrete**

| $S_{sp}$, cm²/g | t, C | In cement matrix of hybrid binder | In lightweight concrete | Volumetric expansion after heat-steaming, % |
|-----------------|------|----------------------------------|-------------------------|------------------------------------------|
|                 |      | CaO total hydrated, %           | CaO bound in the hydration products, % | CaO total hydrated, % | CaO bound in the hydration products, % | In cement matrix of hybrid binder | In lightweight concrete |
| 3500            | 20   | 54.9                            | 29.0                     | 61.6                                     | 19.1                                     | 16…18                         | 14…16                      |
| 6000            | 20   | 88.2                            | 35.6                     | 90.1                                     | 50.7                                     | 6…8                           | 1.5…2.5                    |
Significant absorption of calcium oxide from the liquid phase of the cement matrix based on the binder with higher specific surface area leads to the decrease of the concentration of calcium ions in the liquid phase and thus creates favourable conditions for subsequent hydration of free non-hydrated calcium oxide contained in the binder [20]. As a result, the degree of hydration of calcium oxide increases after increasing the specific surface area of the binder.

The presence of fine fraction of expanded clay sand does not reduce the concrete strength and contributes to increased strength in case of use of the binder with higher specific surface as shown in Table 3. Increase of the ratio $R_{pt}/R_{comp}$ is characteristic of structure improvement, reduction of defects [21].

Lime binding by slag in the process of hardening of hybrid binders provides a high uniformity of the structure that is necessary for high technical properties of concrete [21]. The maximum binding of lime contained in the composition of hybrid slag binder is the necessary condition for improving the quality of lightweight concrete, which is achieved, as studies have shown, with the increase of specific surface of binder.

The features of the structure and properties of lightweight concrete on porous aggregates and the role of various technological methods to improve concrete quality are revealed taking into account modern theoretical concepts. In this case the great importance should be given to the state of the contact zone between expanded clay aggregate and cement matrix based on hybrid cement [22].

**Table 3. Mechanical properties of concrete based on different binders**

| Concrete strength class | B15   | B25   |
|-------------------------|-------|-------|
| Concrete class according to average density | D1300 | D1500 |
| Binder                  | Hybrid binder | CEM32.5 | Hybrid binder | CEM32.5 |
| $R_{pt}/R_{comp}$       | 0.27  | 0.25  | 0.24  | 0.22  |
| Strength, MPa           |       |       |       |       |
| Bending strength        |        | 4.2   | 6.9   | 6.1   |
| tensile strength        | 4.9   |       |       |       |
| $R_{pt}/R_{comp}$       | 0.30  | 0.26  | 0.26  | 0.22  |
| Cubic, $R_{cub}$        | 17.0  | 16.6  | 29    | 27.0  |
| $R_{pt}/R_{comp}$       | 17.0  | 16.6  | 29    | 27.0  |

**Note.**
1. Above the line – values for concrete with binder $S_{sp}=3500$ cm$^2$/g, under the line - with $S_{sp}=6000$ cm$^2$/g
2. The averaged values were obtained by testing of 25 series of concrete samples of each class (coefficient of variation within 4.5-6.5%)

Improving the structure of lightweight concrete based on hybrid binder is caused by changes in the conditions of structure formation. Reducing the paste viscosity due to the increase of specific surface of binder allows reducing the viscosity of fresh concrete and promotes better colmatation of open pores of coarse expanded clay aggregate. Under such conditions the contact surface of the cement matrix with aggregate increases, which contributes to the intensification of the processes of contact interactions.

The composition of hybrid binder namely the lime-gypsum medium intensifies the reactivity of the expanded clay aggregate. As a result the binding process of free lime and gypsum with aluminite phases of slag and aluminosilicate phases of expanded clay aggregate is forced. The contact zone on the aggregate surface, where the presence of hydrosilicates is stated, is formed more intensively during the contact reactions of the hydrating
hybrid binder with the expanded clay aggregate. These hydration products provide the adhesive strength increase of aggregate with cement matrix. Fine expanded clay fractions of sand contribute to the growth of hydration products in the contact zone. The intensification of contact interactions at the boundary with the expanded clay aggregate is accompanied by simultaneous change in the pore structure of hybrid cement matrix.

The change of the pore structure can be explained by the acceleration of the processes of binder hydration as a result of a more intense interaction of free lime and the amorphous phase of slag with the formation of ettringite, which in this case plays a reinforcing role. X-ray phase analysis [23] indicates a more complete binding of free lime in concrete based on hybrid binder with greater S_sp. There are no lines of diffraction reflections of Ca(OH)₂ in the mortar part of the concrete and the intensity of quartz lines increases. Complete binding of free lime and the above-stated composition of hydration products determine the increase of physical and mechanical properties of the studied concrete. The combination of these processes is contributed to a purposeful change in the concrete structure, which leads to the increase of mechanical properties and improvement of deformation characteristics as shown in Tables 3-4.

It is known that the tensile bending strength of concrete (Rₜₘₙ) and the ratio of Rₜₘₙ/Rₜₐₘₙ are more sensitive to the substitution of the binder and to changes of technological factors in concrete production. The increase of this ratio corresponds to the reduction of defects in the concrete structure [24]. The replacement of Ordinary Portland cement CEM32.5 with hybrid binder of greater specific surface in studied lightweight concrete has led to the increase of Rₜₘₙ up to 20% and ratio of Rₜₘₙ/Rₜₐₘₙ as shown in Table 3. This indicates the increase of the crack resistance of obtained concrete.

The increase in the deformability of lightweight concrete is achieved while increasing the compressive strength and is due to the following factors:

- increase of more finely dispersed components in the mortar part of concrete and, accordingly, the creation of more deformative contact layers on surface of expanded clay aggregate characterized by amount of hydrosilicate phases [26-28];
- change of concrete pore structure characterized by uniform distribution of conditionally closed pores performing in this case the role of dampers.

Table 4. Ratio of strength and deformation characteristics of lightweight concrete on hybrid binder and CEM 32.5

| Strength Average density | Rₜₘₙ¹/Rₜₘₙ² | Modulus of elasticity Eₐ¹/10³, MPA | Eₐ¹/Eₐ² | Rₜₘₙ¹/Eₐ¹ | Rₜₘₙ²/Eₐ² |
|-------------------------|-------------|----------------------------------|---------|-------------|-------------|
| B 15                    | 1,21        | 0,2 Rₜₘₙ | 0,3 Rₜₘₙ | 0,4 Rₜₘₙ | 0,2 Rₜₘₙ | 0,5 Rₜₘₙ | 1,04 | 1,07 | 1,17 |
| D1300                   |             |         |         |         |         |         |     |     |     |
| B 25                    | 1,19        | 220     | 192,5   | 166,8   | 1,06 | 1,08 | 1,13 |
| D1500                   |             |         |         |         |         |         |     |     |     |

Note: Index 1 refers to concrete based on hybrid binder with S_sp=6000 cm²/g; Index 2 refers to concrete based on CEM 32.5.

The uniform pore distribution in concrete structure improves its deformative properties and increases the resistance of the structure to internal pressure [25,34,35]. It was found that the modulus of elasticity of lightweight concrete based on hybrid binders (Eₐ) is slightly higher than the same value of lightweight concrete based on CEM 32.5. The ratio Rₜₘₙ/Eₐ indirectly characterizing the fracture toughness of concrete increases in 1.13-1.17 times as a result of use of hybrid binders as shown in Table 4.

The presence of elastic-viscous inclusions in concrete structure—low-modulus additives of damping action as internal stress relaxers and energy crack dampers—provides the increase of strength, crack resistance and frost resistance of concrete [29-33].

Heat conductivity of wall stones based on lightweight concrete
The required value of concrete density is achieved due to the maximum degree of filling its volume with expanded clay aggregate. Satisfactory performance of the structural quality of concrete due to the use of hybrid binder as a result of its grinding with optimization of concrete pore structure to improve the thermal characteristics of lightweight concrete [36,37]. The coefficient of heat conductivity is decreased by 10-12% as shown in Table 5.

Table 5. Heat conductivity of wall stones based on lightweight concrete

| Concrete                                                        | Heat conductivity W/(m·°C) at average density (kg/m³) for conditions A/B |
|----------------------------------------------------------------|------------------------------------------------------------------------|
|                                                                | 750  | 900  | 1050 | 1200 | 1350 | 1450 |
| Lightweight concrete on fine and coarse expanded clay aggregate| 0.28/ | 0.37/ | 0.38/ | 0.43/ | 0.49/ | —    |
| Lightweight concrete on coarse expanded clay aggregate and quartz sand | —    | 0.35/ | 0.41/ | 0.46/ | 0.54/ | 0.65/ |
|                                                                  | 0.39  | 0.45  | 0.51  | 0.58  | 0.69  |

Note: A - normal humidity mode of operation; B - wet mode.

Conclusions

The studies have shown that the use of hybrid slag binders with alkaline and sulphate activation as well as increased fineness of binder up to 6000 cm²/g in the presence of fine fraction of expanded clay sand provides production of lightweight concrete with guaranteed quality due to the controlled structure formation. Improving the structure of lightweight concrete is caused by changes in the conditions of its formation, namely, the decrease of suspension viscosity. This can be contributed to better colmatation of open pores of expanded clay gravel.

The contact surface of cement matrix with expanded clay gravel increases under such conditions that contribute to the intensification of the processes of contact interactions. The formation of the contact zone on the surface of expanded clay gravel is intense. The contact area is represented by hydrosilicates that increase the adhesive strength. As a result the quality of lightweight concrete increases: strength and deformation characteristics. The ongoing change of the pore structure of hardening concrete also contributes to this.

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