Water-resistant gypsum expanded-clay concrete technology

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Abstract. The results of studies on the technology of preparation and hardening of the expanded-clay concrete under various conditions, prepared on the basis of a water-resistance complex gypsum binder (CGB), are presented. It is shown that CGB-based expanded-clay concrete can be used to erect the outer walls of residential and civil buildings. The optimal preparation methods and temperature and humidity conditions for hardening water-resistance CGB-based expanded-clay concrete are given.

1. Introduction

Lightweight concrete wall blocks, including made from expanded-clay concrete, are very popular in modern low-rise housing construction. Portland-cement expanded-clay concrete is mainly used. However, the use of gypsum plaster binder, that is, gypsum expanded-clay concrete, is of considerable interest. Significant advantages of these types of concretes include the high hardening rate, low energy intensity (30 - 40 kgoe/ton of gypsum compared to 200 - 260 kgoe/ton of cement), and the relative simplicity of the production of gypsum binders and concrete based on them. The energy intensity of 1 m² of the outer wall made from Portland-cement expanded-clay concrete is 32 - 37 kgoe/m² and made from gypsum-expanded clay concrete is 14 - 18 kgoe/m², [1,2]. A decrease in energy intensity by more than two times and a significant reduction in time for the production of wall elements are an obvious advantage of gypsum expanded-clay concrete compared to Portland-cement expanded clay.

Wall materials, except for the carrier one, also perform a heat-insulating function, therefore it is very important that the heat-insulating ability of gypsum stone is higher than that of cement one because of the lower density of gypsum stone, which is almost 1.5 times lower. This allows reducing the required thickness of the enclosing structures and the weight of the building as a whole.

The ability to use pigments quite effectively when manufacturing wall elements from gypsum expanded-clay concrete allows diversifying the facades of buildings under construction. The high rate of gypsum concrete strength gain allows significantly increasing the turnover of forms or formwork and reducing the duration of the manufacture of products or the construction of monolithic structures. The widespread occurrence of gypsum stone deposits, its high fire resistance, as well as the soundproofing ability and environmental friendliness of gypsum products are also important [3,4].

Materials for external walling should have a softening coefficient of at least 0.6 [4,5]. However, for gypsum-based concrete, it is only 0.4-0.5. Grade of frost resistance of gypsum concrete does not exceed F15 - F25. Thus, the low resistance to environmental influences and a sharp decrease in strength during wetting do not allow efficiently use gypsum concrete in the construction of residential buildings, industrial and agricultural structures, and, above all, as a material for external walls.

The high creep of hardened gypsum and concrete based on it should be also noted. The creep of gypsum-based concrete is almost three times higher than the creep of cement lightweight concrete. This is the reason for high deformations in the places where concentrated loads act: in the places of support of joists, trimmers, staircases and, as a result, the appearance of cracks in the wall structure. Currently, the increase in water resistance of two-water gypsum is ensured through the use of combined gypsum binders [5,6,7], mainly gypsum-cement-puzzolan ones (hereinafter - GCPB) [3,4]. However, the use of GCPB is associated with the need to study and select the composition of this
mixed binder taking into account the chemical (mineralogical) composition of cement and pozzolanic admixture. In addition, up to 25 percent of Portland cement is in the composition of GCPB, which increases its energy intensity and cost [2].

In recent years, in order to reduce the amount of clinker in the mixed binder, technologies for quick-hardening composite binder, modified with organo-mineral admixtures and concrete based on it, have been developed [7,8].

2. Materials and methods

2.1 Materials

To study the technology and properties of CGB-based expanded-clay concrete, semi-aquatic gypsum of three Russian plants (Krasnodar, Moscow, St. Petersburg) was used. The main properties of gypsum binders are presented in table 1.

| Grade | W/G$^a$ | Setting time, (min) | Compressive strength, (Mpa) |
|-------|---------|---------------------|----------------------------|
|       |         | b.s. | e.s. | Grade | Dried | Water-sat. |
| G5    | 0.50    | 5    | 15   | 5.8   | 11.9  | 5.2       |
| G7    | 0.45    | 6    | 14   | 8.7   | 16.0  | 7.3       |
| G10   | 0.40    | 7    | 12   | 10.3  | 23.2  | 11.0      |
| G13   | 0.37    | 7    | 13   | 13.6  | 25.8  | 12.4      |

$^a$ Water-gypsum ratio

To study the technology and properties of CGB-based gypsum concrete, 10x10x10 and 15x15x15 cm cubes and 10x10x40 cm prisms were made.

As a mineral admixture, biosilica from Inza diatomite plant was used. The main physico-chemical characteristics of microsilica and biosilica are shown in table 2.

| Admixture | LOI | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | K$_2$O |
|-----------|-----|---------|-------------|-------------|-----|-----|-------|
| Biosilica | 1.92| 87.0    | 6.1         | 2.8         | -   | 0.84| 1.34  |

The second component of the complex admixture was a carbide sludge, an industrial waste from the production of acetylene obtained in acetylene generators during the decomposition of calcium carbide CaC$_2$ with water. The chemical composition is shown in table 3.
Table 3. Chemical composition of carbide sludge

| Admixture       | LOI | SiO₂ | CaCO₃ | Ca(OH)₂ |
|-----------------|-----|------|-------|---------|
| Carbide sludge  | -   | 0.6  | 5.6   | 93.8    |

For comparative studies, mixtures using Portland cement CEM I 32.5 were prepared. As large aggregates, ordinary and fractionated expanded-clay gravel with a bulk density of 500 kg/m³ and expanded-clay sand with a bulk density of 700 kg/m³ were used. The sodium tetraborate in an amount of up to 0.5% by weight of the binder served as a setting retarder. C-3 superplasticizer in an amount of up to 0.75% by weight of the binder was used as a plasticizing admixture. These admixtures were mixed with mixing water.

2.1 Used methods
When studying the properties of CGB and concrete based on them, test methods regulated by regulatory documents, as well as instruments and equipment that have been verified and meet the requirements of current standards, were used. Drying to constant weight, as well as cyclic freezing and thawing were carried out in the WEISS WK3-180/70 heat/cold/humidity test chamber. Comprehensive test chambers of the WK series are designed for tests using temperature, humidity, and lighting. The chambers provide accelerated tests for protection against weathering impact, resistance at temperatures of -72 °C ÷ +180 °C, and relative humidity 10 ÷ 98%.

The storage conditions of the samples after molding and the periods of tests were set in accordance with the experimental plan. The samples were cured under normal conditions in a CURACEM normal hardening cabinet at 20 ± 1 °C and relative humidity of 95 ± 5%. The samples were cured in naturally dry conditions at 20 ± 1 °C and relative humidity 55 ± 5%. Heat and humidity treatment of the samples was carried out in a universal steam chamber KUP-1V at a relative humidity of 95 ± 5% with various indicators of the isothermal curing time and its temperature.

3. Results
To increase the water resistance and frost resistance of gypsum concrete, the compositions of a composite clinker-free waterproof gypsum binder were studied [9,10]. As an admixture, a lime-microsilica composition was used. The use of microsilica as an active mineral admixture is becoming more common in recent years [11, 12]. As a result, a binder with enhanced physical and mechanical properties that does not require special hardening conditions and has a slower setting time was obtained.

This result was obtained due to the use of the composition of the above composite binder of the active biosilica. Biosilica is a product of special combined activation of diatomite, which has undergone heat treatment at a temperature of 700 - 800 °C, with activity in relation to lime from 390 to 398 mg/g. The absorption of lime by biosilica after 30 days is up to 4 times higher than a similar indicator of natural active mineral admixtures and 40-60 percent higher than the activity of microsilica. Along with a high rate of activity at the age of 30 days, in the case biosilica, an intensive absorption of lime in the first 3 days is observed. Calcium oxide (lime) in the composite binder has been replaced by carbide sludge - a multi-ton industrial waste from the production of acetylene at acetylene stations. Carbide sludge is obtained in acetylene generators by decomposition of calcium carbide CaC₂ with water by the reaction: CaC₂ + H₂O = Ca(OH)₂ + C₂H₂. The use of carbide sludge, obtained as waste in the production of acetylene together with biosilica as components, provides a tangible environmental effect, in addition to the technical and economic one, since with an average acetylene productivity in the Russian Federation of 400 thousand tons, about 1 million 140 thousand tons of carbide sludge is formed.
To slow the setting time of the binder, sodium tetraborate was used, which allows postponing the start of setting of the initial gypsum (at a dosage of Na$_2$B$_4$O$_7$ 0.5% by weight of the binder) to 1 hour with a slight decrease in the strength of the samples. As a plasticizing admixture, plasticizer C-3 was used. Dosages of superplasticizer from 0 to 1.2% of the mass of the binder on gypsum with an activity of 13 MPa were studied. At the same time, with the consumption of binder biosilica and carbide sludge introduced into the composition within 15-20% of the gypsum mass, the normal dough density is ensured when using 0.6% S-3 superplasticizer.

Based on this binder, light expanded-clay concrete grades B3.5-B10 and higher with a softening coefficient of 0.8-0.92 and frost resistance not lower than F75 for external building envelopes were obtained [13].

3.1. The study of the basic properties and procedure of preparation of the concrete mixture

Based on the CGB, using the calculation and experimental method, the compositions of structural-thermal insulation expanded-clay concrete for low-rise construction were selected. For comparison, expanded-clay concretes uniform in both grade and composition were made based on a gypsum binder (hereinafter referred to as GB), the grade of which coincided in each experiment with the grade of GB used to prepare CGB.

To prepare a concrete mixture with a cone slump CS = 5 - 6 cm, C-3 superplasticizer was introduced into the composition of CGB in the amount of 1 - 1.2% by weight of the binder. It is established that when a concrete mixture containing C-3 superplasticizer vibrates, the influence of the latter increases significantly and accordingly reduces its required amount.

One of the important factors affecting the strength of concrete is the amount of mixing water introduced. For the experiment, CGB-based expanded-clay concrete with various consumption of binder and water-binder ratio (W/B) were prepared. Concretes with a W/B value less than 0.5 had a reduced strength due to under-compaction of the mixture. According to the results of experiments, the optimal value of the water-binding ratio was 0.56-0.58. With an increase in the water-binding ratio from 0.56 to 0.70%, the compressive strength of concrete in a water-saturated state decreases by 30 - 55%.

Investigations of the effect of the amount of the sludgy siliceous admixture added to the composition of CGB in relation to the water resistance of CGB-based expanded-clay concrete were carried out on samples of 10x10x10 cm cubes. Gypsum binder grade G5 concrete was adopted as a reference one.

![Figure 1](image_url)

**Figure 1.** Dependence of compressive strength of gypsum expanded-clay concretes on the amount of the sludgy siliceous admixture added to the composition of CGB

All samples were cured under naturally dry conditions for 14 days. Strength in a water-saturated state increases with the introduction of a sludgy siliceous admixture to an optimal value of 1.6 - 1.8 times,
and then begins to decrease (figure 1). The strength of the samples in the dried state also increases with the introduction of the admixture in 1.4 - 1.6 times.

Processes, including mixing, transportation, laying, and compaction of the concrete mixture, require delaying the setting time of the binder by less than 45-60 minutes from the mixing period of the mixture. Sodium tetraborate (STB) plays a rather effective role at a dosage of 0.45 - 0.5% by weight of the binder. In addition, when conducting studies to assess the influence of the setting retarder on the strength characteristics of the material, it was found that the above optimal dosage of STB slightly increases (up to 15%) the compressive strength of CGB-based concrete samples. Perhaps, this effect is due to better compaction of the mixture and more favorable conditions for hydration of the CGB components.

Expanded-clay gravel, used as aggregate, slightly increases the amount of mixing water required for the preparation of the concrete mixture. This is due to the fact that when preparing the expanded-clay concrete — when it is mixed — part of the mixing water is absorbed by expanded-clay gravel. However, subsequently, water-saturated expanded-clay gravel plays the role of a moisture accumulator, giving it away for a long time and contributing to the continuation of the hydration process or a sludgy siliceous admixture inside the CGB-based concrete.

Gypsum binders during hardening have poor adhesion to the aggregate, which adversely affects the strength of gypsum concrete. The use of expanded clay with a porous surface increases the adhesive bond of the mixed gypsum binder CGB with expanded clay by 1.1–1.2 times in comparison with a conventional gypsum binder [8]. This is explained both by mechanical pinching of the mineral glue in the aggregate pores and by the chemical interaction of the contacting phases. The similar chemical nature of CGB and aggregate results in increased strength of CGB-based expanded-clay concrete. In addition, expanded clay contains amorphous SiO₂, capable of chemically reacting with Ca(OH)₂, which is part of the CGB. This leads to the formation of slightly-soluble low basic calcium hydrosilicate on the contact surface, which seals the contact layer.

As studies have shown, the procedure of the preparation of concrete mixture depends on the type of CGB used: it can be either a dosage-metered dry mixture of components in sealed packages or a set of necessary components for on-site preparation of concrete mixture. Preparation of CGB-based expanded-clay concrete mixture includes the following steps:
- weight dosing and mixing of fine and coarse aggregate;
- in the case of using the carbide sludge admixture in the form of dough or paste as components of the sludgy siliceous admixture, preliminary mixing of the calculated mass of the dough (paste) in water or part of the mixing water is recommended;
- then a dosage-metered aggregate, biosilica, superplasticizer, rest of mixing water and, if necessary, setting retarder are added to this mixture;
- after mixing for 2 minutes, gypsum is poured into the mixture and the concrete is finally prepared by mixing for 4 to 5 minutes.

When using carbide sludge, dried to a constant mass, all CGB components, except gypsum, are filled together with the aggregate and mixed with water. After mixing for 2 minutes, gypsum is poured into the mixture and the final preparation of the concrete mixture is done by mixing for 4 to 5 minutes. Compaction of the mixture is carried out using a vibrating plate or vibrators for 20 to 25 seconds. After laying the mixture into a mold or formwork, several options for curing concrete are possible. The study of the strength development of the CGB-based expanded-clay concrete under various hardening conditions allows concluding that it is possible to use both heat and moisture treatment (hereinafter - HMT) and normal (hereinafter - NC) or naturally dry (hereinafter - NDC) curing conditions.

Steaming products for 10-16 hours is fastest in time and quite effective in increasing water resistance. The curing of CGB samples under normal conditions for 14 days leads to the highest strength samples in a water-saturated state, and the softening coefficient reaches 0.91. When samples are hardened in naturally dry conditions, the softening coefficient of the material is lower but its value, in this case, is not less than 0.85. This means that any of the above methods are suitable for producing waterproof
products. In addition, with a monolithic construction of buildings, the formwork removal of the structure can be carried out already 3-4 hours after laying and compacting the concrete mixture. Figure 2 shows the increase in the strength of CGB-based concrete and gypsum binder in a water-saturated state using various curing methods.

![Figure 2](image_url)

**Figure 2.** Compressive strength development of the CGB-based expanded-clay concretes and G5 grade gypsum binder in the water-saturated state and under various hardening conditions: 1 - GB, NDC; 2 - CGB, HMT at 80 °C; 3 - CGB, NC; 4 - CGB, NDC.

A similar effect of hardening conditions was found for expanded-clay concrete based on higher grades of gypsum binder: G7, G10 and G16. Frost resistance tests were carried out using an integrated test chamber. As a result, CGB-based expanded-clay concrete withstood 125 freezing and thawing cycles, which significantly exceeds the frost resistance requirements for wall materials. Normal gypsum expanded-clay concrete withstood only 25 cycles, i.e. 5 times less.

The change in the basic properties of expanded-clay concrete when replacing a gypsum binder with a complex gypsum binder is shown in table 4.

| Concrete code | Concrete grade | Density, (kg/m³) | Compressive strength in a dry state, (MPa) | Softening coefficient[^Cs], Cs | Frost resistance, cycles |
|---------------|----------------|------------------|------------------------------------------|-----------------------------|---------------------------|
| GB-1          | B7.5           | 1200             | 10.5                                     | 0.45                        | 15                        |
| GB-2          | B10            | 1310             | 12.4                                     | 0.46                        | 25                        |
| CGB-1         | B7.5           | 1220             | 13.7                                     | 0.88                        | 100                       |
| CGB-2         | B10            | 1360             | 15.0                                     | 0.87                        | 125                       |

[^Cs]: the ratio of the strength in the water-saturated state to the strength in the dry state

It is also very important that the creep strain of CGB-based expanded-clay concrete is 2.2 times lower than that the creep strain of expanded-clay concrete based on building gypsum and is at the level of cement concrete of equal grade [13].

**4. Conclusions**

The study revealed the possibility of preparing the concrete mixture on a traditional technical basis, taking into account the recommended features of the CGB preparation technology. It was established
that, with any of the above methods, increased strength, frost resistance, and water resistance of the CGB-based material, which meets the requirements for materials of building envelopes, are achieved.

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