Improving crack resistance of concrete when using expanding cements

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Abstract. The possibility of enhancing the basic properties of concrete products by using a mixture of Portland cement and sulfoalumoferrite clinker as a binder is considered. It was established that upon hydration of the binder, aluminate and ferruginous ettringite are formed, which increase the strength properties of concrete during normal hardening and thermal and wet processing by increasing the strengthening structure. The main sign of hydration of sulfoalumoferrite clinker is the stability of ferrous ettringite, which ensures the compaction of the concrete structure. The dense structure of the structure of concrete, especially the contact zone, when using sulfated clinker, ensures the non-shrinkage of concrete and eliminates shrinkage deformations and, thereby, increases the crack resistance of concrete samples.

1. Introduction
Cement concrete products and structures are exposed to many factors that determine their durability. [1-10]. This problem has received much attention from many scientists. It is shown that the most important factors determining the durability of concrete are the crack resistance [1,11-13], watertightness [2,14-18] and frost resistance [1,2,19,20]. Since cement is the most vulnerable component of concrete, its composition and properties ensuring the required quality of concrete are still the subject of research. [21-23]. Basically, two factors are considered: the mineralogical composition and dispersion of cement. In the first direction, the main discussion concerns the content of tricalcium aluminate, the amount of which in the clinker is proposed to be reduced. However, it should be noted that in many cement plants, due to the nature of the chemical composition of raw materials, it is very difficult to obtain low-alumina clinker. Moreover, according to data known in the literature, cement with the composition indicated has a high porosity due to slow hydration, which leads to the fragility of the cement stone [2,19].

In recent years, the creation of high-strength and durable concrete is associated with the modification of the concrete structure with chemical additives: plasticizing and air-entraining [1,2]. Currently, the term "modification" is used for a wider range of additives used both in concrete and cement technology, and, if necessary, to improve the properties of the products. Among the additives that improve the properties of concrete should be attributed, and expanding components [24,25].
The straining cement proposed by V.V. Mikhaylov [26] is widely used to create crack resistant waterproof concrete in various areas of construction [27-32]. Industrial production of straining cement was organized, which required the creation of expanding components [33, 34]. Usually either sulfoaluminate clinker or a mixture of alumina cement with calcium sulphate is used to create non-shrinkable and straining cements [31, 32]. When these compounds are hydrated, ettringite is formed, which ensures the consolidation of the structure of the hardening stone, eliminates shrinkage. However, the lack of high-quality aluminates raw materials does not allow organizing large-scale production of these expanding components. An alternative is sulfoalumoferrite clinker technology [34, 35]. The phase composition of sulfoalumoferrite clinker obtained by burning a ferrous raw material mixture at 1250–1300 °C is represented in calcium sulfoaluminous ferrites of various degrees of basicity and belite. The high content of sulfated calcium aluminoferrites in clinker provides the possibility of obtaining stress and expanding cements [35-36]. The use of sulfoalumoferrite clinker as an expanding component of cement is due to the fact that the properties of calcium sulfoaluminoferrites hydrates are in many respects similar to those of hydrates based on aluminates phases. Expansion of cement stone when sulfoaluminous ferrite clinker is added to portland cement is due to the formation of both aluminates and ferruginous ettringite during hydration of solid solutions of aluminoferrites modified with calcium sulfate [35].

The purpose of this research was to study the properties of concrete using a composition of portland cement and sulfated clinkers containing calcium sulfoaluminate and calcium sulfoaluminoferrite.

2. Experimental procedure
For the study were used Portland cement clinker following mineralogical composition (%): C₃S = 57; C₂S = 21; C₃A = 8; C₄AF = 14. Sulfoaluminate (SAC) and sulfoaluminoferrite clinkers (SAFC) were used as expanding additives, the chemical composition of which is presented in Table 1.

| Clinker | Content of oxide, % |
|---------|---------------------|
|         | SiO₂       | Al₂O₃       | Fe₂O₃       | CaO      | SO₃      | other |
| SAC     | 10.5       | 34.53       | 3.5         | 45.27    | 5.0      | 1.75  |
| SAFC    | 10.0       | 7.07        | 32.6        | 41.45    | 6.2      | 2.6   |

In the laboratory, produced joint grinding of clinkers. Grinding fineness of cement was evaluated by the specific surface, which was S = 350 m²/kg. Determination of the physical and mechanical properties of cement was carried out in accordance with current standards. For the preparation of concrete used natural sand with a modulus of size M = 2.5 and voidness 45.2 %. The content of dust particles in it was 2%. Granite crushed stone of fraction 5-10 and 10-20 mm was used as a coarse aggregate.

3. Experimental results and discussion
Determination of the setting time of cements with additives of sulfoaluminate and sulfoaluminoferrite clinkers showed that in the first case, the beginning of the setting of cement occurs within 20-30 minutes, in the second - within 2-3 hours. Based on these data, taking into account that cement with the addition of SAC is rapidly gaining strength: after 1 day it has a strength in the range of 20-25 MPa. This composition is of interest as a material for repair work, for example, road pavements and in metro construction. Further studies of the cement were carried out using sulfoaluminoferrite clinker as an additive.
Determination of the strength of the samples was carried out in accordance with the specifications for the straining cement with a cement : sand ratio of 1 : 1 and W / C = 0.35. The amount of SAFC introduced into Portland cement ranged from 5–20% (Table 2).

Expansion and self-stress were determined for all cement formulations. Tests have shown that on the first day cements are characterized by a linear expansion within 0.06–0.10% and self-stress - within 0.6–1.0 MPa. The composition of the products of hydration in the first stages of hardening according to x-ray phase, differential thermal analysis and electron microscopy is presented by $C_3A\cdot3CS\cdotH_{31}$, $C_4(A,F)H_8$, iron and aluminum hydroxides. During the subsequent hydration, the recrystallization of low-base hydroalumoferrite into $C_4(A,F)H_{19}$ and the formation of glandular ettringite – $C_3F\cdot3CS\cdotH_{31}$.

Table 2. The results of determining the strength of the modified PC.

| No | Cement composition, % | Flexural strength, MPa | Compressive strength, MPa |
|----|------------------------|-------------------------|---------------------------|
|    | PC SAFC gypsum 1 day 7 days 28 days 1 days 7 days 28 days |
| 1  | 90 5 5 7,2 11,2 12,3 46,8 82,4 89,8 |
| 2  | 80 10 10 6,5 7,8 12,0 45,5 74,0 84,3 |
| 3  | 75 15 10 6,0 7,5 11,7 38,7 73,5 82,4 |
| 4  | 70 20 10 5,5 7,4 10,7 37,0 66,9 77,1 |

The main feature of hydrating calcium sulfoalumoferrites of various degrees of basicity is the stability of iron ettringite. With prolonged hardening (more than 7 days) due to the formation and growth of ettringite crystals (Figure 1), the expansion increases to 0.15–0.2%, and self-stress reaches 2.5–2.9 MPa, depending on the composition of cement.

Figure 1. Cement stone microstructure, SEM, magnification - 2000x: a - portland cement; b - modified cement

In order to study the effect of the mineralogical composition of cement and the conditions of hardening on the kinetics of hydration, the degree of hydration of sulfoalumoferrite-containing cement produced at JSC "Podolsk Cement" was determined as well as the kinetics of binding of SO$_3$ under normal conditions of hardening and heat and moisture treatment. The process of binding water and SO$_3$ in normal hardening specimens proceeds more smoothly, but less intensively than with steaming.
The effectiveness of steaming and plasticizing additives investigated on concrete samples of the same cements (Table 3).

The increased strength of the experimental concrete compared to concrete based on ordinary Portland cement is due to the difference in their structure. The dense structure of the structure of concrete, especially the contact zone, when using sulphated clinker, simultaneously ensures the non-shrinkage of concrete. This provides increased crack resistance of concrete. Determination of crack resistance was performed on cement rings hardened in air. Crack resistance was evaluated in days before the appearance of cracks. Tests have shown that Portland cement has a crack resistance of 16 days, and cement with an expanding additive - more than 30 days. Increasing the crack resistance of cement stone predetermines the increased frost resistance of the stone.

![Figure 2](image.png)

**Figure 2.** The influence of the type of binder and the duration of hardening on the hydration of cement stone: 1 – sulfoalumoferrite-containing cement with normal hardening; 2 – normal cement hardening; 3 – sulfoalumoferrite-containing cement during steaming (2 + 3 + 6 + 2 h); 4 – portland cement at steaming (2 + 3 + 6 + 2 h)

**Table 3.** Strength characteristics of concrete based on portland cement and with sulfoalumoferrite additive.

| Binder                          | Cement consumption, kg / m³ | W/C, % | 1 day, heat and moisture treatment | 28 days, heat and moisture treatment | 28 days, normal hardening |
|---------------------------------|-----------------------------|--------|-----------------------------------|-------------------------------------|--------------------------|
| Portland cement                 | 300                         | 0.67   | 12.5                              | 21.0                                | 20.5                     |
| Sulfoalumoferrite-containing cement | 300                 | 0.66   | 19.9                              | 31.6                                | 31.3                     |
| Portland cement                 | 400                         | 0.45   | 30.2                              | 39.5                                | —                        |
| Sulfoalumoferrite-containing cement | 400                 | 0.42   | 34.3                              | 39.4                                | —                        |
| Portland cement                 | 450                         | 0.41   | 29.4                              | 40.9                                | —                        |
| Sulfoalumoferrite-containing cement | 450                 | 0.43   | 36.9                              | 45.7                                | —                        |

Frost resistance was determined on the beam-samples of 4x4x16 cm in size from a cement-sand solution of 1: 3 (cement : sand) at the W / C = 0.4. After 28 days of storage in water, the samples were subjected to alternate freezing and thawing. After every 25 cycles, the samples were weighed and tested in compression and bending. The samples were hardened in water for comparison. The results
showed that the samples of cements with the addition of sulfoalyumoferritny clinker were kept without loss of weight and strength drop 300 cycles of alternate freezing and thawing.

The industrial batch of this cement was successfully applied to concreting the pavement, according to the results of which a permanent production of this type of cement was organized at OJS Podolsk-Cement.

4. Conclusion
The production and use of sulphated clinker as an expanding additive to Portland cement helps to save material and technical resources at all stages of the technological process from the production of clinker to use in concrete.

The formation of ettringite and ferruginous ettringit during the hydration of sulfated clinker minerals provides compaction of the structure of cement stone and concrete, increasing strength and with normal hardening, and during steaming, eliminates shrinkage deformations. This provides increased crack resistance of cement mortars and concretes.

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