Investigation of the technological factors’ influence on the formation of the repair compositions’ properties

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Abstract. Power transmission lines (PTL) belong to strategic facilities, on the reliability of which the life support of the country depends. Most of the currently operated PTLs were put into operation in the twentieth century, and now there is a problem of assessing their technical condition, repairing, if necessary, and maintaining them in working order. The defects appeared during the operation of PTL reinforced concrete elements have different localization and manifestation degree, but destruction of the concrete surface layer with reinforcement exposure is a characteristic, more often at the base of the PTL frame. The aim of the work is to select the optimal composition of the repair mortar based on non-shrinking and expanding cements, ensuring reliable adhesion of the repair mortar to the concrete of the structure, which will allow restoring the bearing and operational characteristics in the repaired PTL reinforced concrete elements at the design level.

Introduction

The considerable experience accumulated at present in the operation of power transmission lines (hereinafter PTL) both in our country and around the world gives an opportunity to judge the practical operational reliability of all PTL elements [1].

Most of the currently operated PTLs were commissioned back in the twentieth century, and over the past few decades, the deterioration of high voltage power grids, according to most experts, has increased by 40%. Taking the high degree of deterioration of existing facilities into consideration it is necessary to periodically carry out diagnostic measures in order to maintain them in working condition, [2], as well as repair work.

The search for the new solutions for the PTL technical condition effective restoration and the problem of timely diagnosis of damage are the urgent tasks of the modern electric power industry [2, 3].

The measures known to date to restore the operational reliability of PTL reinforced concrete elements in most cases, they require significant expenditures of materials and special repair compositions [4]. These activities are very time consuming. Their implementation requires special equipment and appropriately trained personnel. In addition, the complexity is caused by the diversity of the raw material base for the repair compounds’ manufacture in different climatic regions of the country, and often the low quality of the raw materials used [5].
The relevance of this work is due to the fact that PTL, representing a complex technological and constructive complex containing a significant number of components, refer to strategically important facilities in any country and the country’s life support depends on their reliability.

We have carried out the experimental studies on the effective repair compositions’ development for the restoration of the operated reinforced concrete PTL frames. These structural elements perform the main load-bearing function in the PTL composition and the long-term and trouble-free operation of the entire PTL. Destruction of PTL support frames can lead to early failure of the entire line, which will require its partial or complete dismantling.

Defects appearing during the PTL reinforced concrete elements’ operation can have different localization and manifestation degree [5]. Outwardly, this can manifest itself in the form of various destructions (Figure 1).

![Solid PTL frames](image1.png) ![Centrifuged frames PTL](image2.png)

**Figure 1.** Defects that appeared at the stage of operation of PTL reinforced concrete elements

An alternative to replacing PTL individual structural elements or even the entire sections, the restoration of reinforced concrete structures as a result of repair work can serve. Bearing and performance characteristics in restored PTL reinforced concrete elements can be maintained at the level of design indicators, provided that the repair restoring compounds adhere to the restored structures.

The experience accumulated to date in the use of conventional mortars or sand concretes based on Portland cement or grouting precast reinforced concrete structures indicates that such compositions do not sufficiently provide the required structures’ solidity. This is mainly due to the fact that such compositions undergo shrinkage during the setting and hardening process. In this regard, the problem of creating expandable and non-shrinking cements for the designated purposes is urgent.

In the 70s of the last century [6], a method for the preparation of expandable waterproof cements, which are characterized by the fact that they are subject to shrinkage during the hydraulic hardening process, was developed. The cement used in this case has a high setting rate and the achievement of the required strength degree. The used binder is obtained from a mixture of aluminate cement, two-water gypsum stone (CaSO₄·2H₂O) and tetra calcium aluminate, which are finely ground in a ball mill. The tetra calcium aluminate is obtained by autoclaving a mixture of alumina cement and lime in a mass ratio of 1: 1 with a water-solid ratio W / T of 0.30. Next, the resulting product is dried and milled. The advantage of the developed expanding cement is that its expansion degree can be regulated within a fairly wide range by changing the ratio between the components.

It should be noted that the formation of a hydro sulfaluminate framework when cement is mixed with water occurs during the induction period of the cement stone structure formation, when coagulation
processes still prevail in it. Therefore, expansion occurs without breaking the continuity of the structure, which ensures the achievement of the required strength and density for the resulting material.

The disadvantage of this cement is the complexity of storage due to its high hygroscopicity, as well as technological difficulties due to its fast setting. In addition, the negative properties of this cement include the fact that the expansion degree depends on the temperature and humidity conditions of hardening, as well as the reduced ability, in comparison with Portland cement, to protect the steel reinforcement of reinforced concrete.

The widespread use of expanding composites based on aluminate cement is constrained by its high cost, as well as technological difficulties during the construction work. These difficulties are caused by the shortened setting time and the high sensitivity of the cement in relation to changes in the temperature and humidity conditions of hardening.

The characteristic disadvantages of expanding cements based on alumina high-aluminate components are largely overcome when using expanding composites based on Portland cement [7].

When developing the expanding compositions based on Portland cement, the principle of compensated expansion was put forward and substantiated [6, 7]. According to this principle, in such formulations, expansion occurs mainly due to the inclusion of a small amount of aluminum powder additive in the mixture. The latter enters into chemical interaction with the resulting hydration products of Portland cement, as a result of which many small bubbles of hydrogen gas are formed in the mixture. At the same time, the external volume of the system increases, ensuring its expansion. To prevent a decrease in the strength characteristics and water resistance of the resulting expanding composite, in addition to aluminum powder, chemical additives are additionally introduced into the mixture [8-11]. These additives include calcium chloride, aluminate sulfate and a surfactant - sulfite-alcohol mash SAM (currently not produced by the pulp and paper industry).

Thus, expanding Portland cement contains a four-component complex additive with the following ratio of components in percentage: by weight of cement consumption - 0.01 aluminum powder; 2.0 aluminum sulfate; 2.0 calcium chloride; 0.15 sulfite-alcohol mash SAM. These components are introduced into the concrete mix together with the mixing water. The presence of additives and SAM provides uniform distribution of finely dispersed aluminum powder in a concrete or mortar mixture without first removing the paraffin film from its particles. The positive effect of the SAM additive lies in the fact that the calcium lignosulfonate included in its composition is deposited on the surface of the aluminum powder particles, which contributes to their uniform distribution in the form of a suspension in the liquid phase. That is why, if usually a system of interconnected capillaries and pores is formed in the cement stone, then in this case, the smallest closed gas pores are formed in the cement stone, evenly distributed throughout the cement stone volume.

Aluminum sulfate and calcium chloride are included in the expanding additives, they enter into chemical interaction with the hydrating cement, contributing to the partial filling of the above-described gas pores with crystalline neoplasms. These components of the expanding additive provide clogging (filling) of the pores of the cement stone by such crystallizing complex salts as hydro sulfa aluminites and calcium hydro chloro aluminites. This results in a very dense cement stone in which the smallest partially sealed pores are evenly distributed. As a result, the strength indicators, water resistance and frost resistance of the resulting material are significantly increased, which is confirmed by the comprehensive studies [12-14].

At the same time, along with all the advantages of the considered expanding binders based on Portland cement, it is also necessary to note their certain disadvantage, which consists in the technological complexity of dosing and the practical use of a four-component expanding complex additive. In this case, the SAM plasticizer is already out of production.

**Targets and goals**
The purpose of this work is to study the possibility of creating effective expanding compositions intended for carrying out repair and restoration measures on the PTL reinforced concrete supports in
operation, based on Portland cement, local fine sand contaminated with impurities of dusty and clay particles, and the components of a complex expanding additive available in regional conditions.

When setting the problem, we proceeded from the following considerations. In all known expanding cements, both based on alumina cement and based on Portland cement, such neoplasms as calcium hydro sulfite aluminate play a decisive role. Calcium hydro sulfite aluminate can influence the structure formation processes of cement stone in two ways, depending on the time factor of its formation in the system. One of the first to come to this conclusion was Lafuma, who formulated the fundamental proposition that in the process of direct interaction of substances in the solid phase, dangerous deformations can appear in the hardening cement stone. This is due to the fact that when crystallization of neoplasms on the interconnected structural particles’ surfaces, the structure of the cement stone as a whole is damaged. The reaction of calcium hydro sulfite aluminate formation in the liquid phase proceeds in a different way. In this case, neoplasms crystallize in the free gaps of the structure, leading to its compaction and strengthening [15].

When hardening ordinary Portland cement, there are always the above-mentioned conditions for the formation of calcium hydro sulfite aluminate. In particular, in the hydration process of the prevailing mass content in the composition of the clinker mineral CaS (tricalcium silicate) lime is inevitably formed in the form of portlandite Ca(OH)₂. In the production of cement, gypsum is compulsorily added, which is a regulator of the cement setting time.

To achieve the expansion effect of the formed Portland cement stone, the necessary increase in the amount of the formed hydro sulfite aluminate calcium should be ensured in the earliest period of structure formation.

It is possible to directionally regulate the composition of Portland cement clinker, increasing the content of clinker minerals such as tricalcium aluminate involved in the formation of calcium hydro sulfite aluminate C₃A, or tricalcium silicate C₃S, only when cement is manufactured in the factory. Naturally, it is not possible to control the kinetics of calcium hydro sulfite aluminate formation in this way when making mixtures for carrying out repair and restoration work in relation to the PTL supports.

The content of gypsum in cement can be increased by adding it while mixing the repair mixture, however, it is practically difficult to distribute it in cement in the field without having additional appropriate mixing equipment, which is equipped with conventional stationary concrete mixing units.

It is known that it is possible to increase the gypsum content with its uniform distribution in the hardening system under normal conditions by adding easily dissolving sulfate-containing substances to the mixing water, for example, Glauber’s salt Na₂SO₄ (sodium sulfate CH) [14-15].

**Experimental part**

The use of aluminum powder as an expanding component in the complex additive composition is associated with the difficulties of its dosage and uniform distribution in the mixture. This is explained by the fact that finely ground particles of metallic aluminum in the process of its production are covered with a paraffin protective film in order to avoid its oxidation and spontaneous combustion. This paraffin coating prevents wetting of the aluminum powder particles, which complicates its uniform distribution in the mixing water volume when preparing mixtures. In order to eliminate this phenomenon, the aluminum powder is freed from the paraffin film by introducing surfactants into the mixing water.

In this work, we studied the possibility of using for this purpose the additive of the superplasticizer ST 2.1, which is introduced into the mixture in a ratio with aluminum powder by weight 1:1.

It was decided to use sodium sulfate SS in the expanding additive composition as a sulfate-containing component. To obtain an expanding composition based on Portland cement, the content of the gas-forming additive of aluminum powder in the composition of the complex developed additive was taken equal to 0.01% of the Portland cement mass.

In order to establish a rational amount of sodium sulfate SS as a part of the expansion additive developed for the repair and restoration work of PTL frames, a special calculation was made. The calculated amount of the addition of sodium sulfate in the composition of the expanding additive is determined from the condition that the contraction shrinkage of the hardening Portland cement stone is
compensated due to the formed calcium hydro sulfa alinate. At the same time, clogging of the so-called "open" capillaries and pores in its structure should be ensured. The quantitative ratios of both the reagents and the products of the formation reaction in the solidifying system of calcium hydro sulfa alinate after the corresponding chemical reaction completion were determined from the process conditions.

Calculations have shown that the sodium sulfate content in the composition of the developed expanding additive should be in the range of 1.5-2.5% of the cement mass. As a result of the analysis, for further experimental studies of expanding compositions based on local substandard raw materials, it seemed expedient to use the proposed expanding additive in the composition of repair mixtures, including 0.01% by weight of cement additive ST 2.1, aluminum powder and 1.5-2.5% sodium sulfate.

When studying the formulation effect on the construction and technical properties of sandy concrete used as a repair material for the restoration of PTL frames, a set of indicators was adopted as the optimized response functions:
- from the condition of ensuring the uniform strength of concrete materials for PTL frames and their restored sections, the requirement was formulated to achieve a branded strength of at least 30 MPa (class B22.5 in strength);
- as a criterion for operational reliability under typical operating conditions of supports PTL cyclic aggressive environmental influences, such as alternating moistening and drying, freezing and thawing, etc., in experimental studies, strength characteristics of concrete were taken - compressive strength at the age of 7, 28, 250 days, MPa; tensile strength, MPa; elastic modulus.

To obtain the experimental data, we used Samara sand of the Rostov region and Portland cement of Sebryakov cement PC500 D0. To prepare repair compositions, cement-sand mixtures of the composition cement: sand were used in a ratio of 1:2 at a W / C ratio in the range of 0.4-0.6, in combination with the introduction of the proposed complex expanding additive into the mixture. From the mixtures obtained, beams of standard sizes 4x4x16 cm were molded, tested at the age of 28 and 250 days of normal hardening. Features of the manufacturing full-scale samples’ technology are presented in the work [12].

Age and conditions for their hardening (water, air-dry, etc.) have a significant impact on the formation of the structure and properties of concrete. It is well known that expanding cements have the potential to gain design strength in a shorter time frame when providing moisture care. We assume that it is not possible to provide a special temperature and humidity regime of hardening to restore the operated PTL frames in natural conditions. In this regard, the dynamics of strength gain by the investigated expanding composition over time under averaged conditions for temperature and humidity is of interest; therefore, we included a factor that takes into account the age of the concrete of the repair composition into the test plan.

Investigated factors:
\( X_1 \) – W/C ratio – 0.4-0.6;
\( X_2 \) – sodium sulfate additive content, % by cement weight – 1.5-2.5;
\( X_3 \) – aggregate grain spread ratio – 1.1-1.6;
\( X_4 \) – dosage of aluminum powder, % by cement weight – 0.005-0.015;
\( X_5 \) – concrete age, day – 7-250.

The main mechanical and deformative properties of concrete were selected as responses:

Feedback:
\( Y_1 \) – compressive strength at the age of 7, 28, 250 days, MPa
\( Y_4 \) – tensile strength, MPa
\( Y_5 \) – elastic modulus.

In the work, a factorial experiment was implemented according to the Hartley-5 (Na-5) design. Number of plan points - 27. Number of points in the center of the plan - 1. The number of coefficients in a second-order polynomial with five factors is 21. The analysis of the Ha-5 design was carried out using the Matcad statistical package. The reproducibility variance was determined from the results of parallel experiments at each point of the design.

To describe the results, a second-degree polynomial of the form was used:
As a result of mathematical processing of experimental data, adequate models of the studied response functions were obtained. Experimental Statistical Model Coefficients (ESM) the response functions of the main mechanical characteristics of concrete are presented in Table 1.

**Table 1.** The main mechanical characteristics response functions experimental-statistical models’ regression equations coefficients of form \( Y = B_0 + \sum B_i X_i + \sum B_{ij} X_i^2 + \sum B_{ij} X_i X_j \)

| Polynomial coefficients | \( Y_1 \) | \( Y_2 \) | \( Y_3 \) | \( Y_4 \) |
|-------------------------|---------|---------|---------|---------|
| \( B_0 \)               | 25.97   | 40.3    | 48.2    | 42.2    |
| \( B_1 \)               | -0.76   | -6.8    | -5.94   | -6.12   |
| \( B_2 \)               | 0.004   | -0.01   | -1.92   | -2.6    |
| \( B_3 \)               | -2.71   | -2.8    | -0.73   | -1.6    |
| \( B_4 \)               | -0.11   | 1.12    | 2.12    | 2.5     |
| \( B_5 \)               | 11      | 1.6     | 2.85    | 0.8     |
| \( B_{11} \)            | -0.95   | 0.48    | -0.93   | 0.97    |
| \( B_{22} \)            | 2.65    | -1.12   | 0.56    | 2.01    |
| \( B_{33} \)            | 2.4     | 1.33    | -0.34   | -0.13   |
| \( B_{44} \)            | -3.56   | -0.17   | -3.1    | -3.3    |
| \( B_{56} \)            | 2.38    | -2.39   | 2.16    | -1.3    |
| \( B_{12} \)            | 0.91    | 0.93    | 2.19    | 1.3     |
| \( B_{13} \)            | -0.3    | -0.83   | -0.74   | -1.4    |
| \( B_{14} \)            | 1       | 1.1     | 1.1     | 0.7     |
| \( B_{15} \)            | -1.53   | -0.7    | -0.9    | 0.9     |
| \( B_{23} \)            | 0.76    | 1.46    | 0.3     | 0.96    |
| \( B_{24} \)            | 1.11    | -0.61   | -1.6    | -0.7    |
| \( B_{25} \)            | -0.21   | -0.35   | -1.5    | -0.6    |
| \( B_{34} \)            | 0.93    | 0.95    | 1.3     | -0.3    |
| \( B_{35} \)            | 0.999   | -1.32   | -0.44   | -1.4    |
| \( B_{45} \)            | 0.163   | -0.99   | 0.54    | -0.3    |

Geometric images of the studied response functions were constructed using the regression equations using the linear algebra methods. The geometric images’ analysis of the investigated response functions made it possible to establish the optimal limits of variation of the main input parameters for obtaining concrete for repair compositions with an expanding additive. The analysis of the factor space subregions allowed us to recommend the sodium sulfate expanding additive component content concentration - 2.4%, aluminum powder - 0.010%. The ages of hardening of repair compounds for concrete optimal for various production purposes have been determined.

**Summary**

The tests carried out showed that the proposed expanding additive of compounds for repair compounds for restoration of PTL frames provides an increase in the strength of the resulting material, increases the restored structure’s durability and reliability degree (Table 1).

Experimentally, using the methods of mathematical planning, it was found that the developed expanding complex additive significantly increases the frame resistance and strength of sandy concrete and improves its structure. This may be the basis for using the proposed solutions when performing PTL repair work.
Evaluation of the repair and restoration works quality, carried out in accordance with the methodology described in [13], confirmed the high rates of adhesive adhesion of the developed four-component repair composition with concrete of the PTL frame structure.

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