Experimental statistical models for the study of cement-concrete for road pavements

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Abstract. The article presents the calculation and statistical analysis of the experimental statistical (ES) model of the several samples of concrete and reinforced concrete for road pavements. For the analysis, the Program (dialogue) Complex COMPEX was used, which was developed at the Odesa State Academy of Civil Engineering and Architecture by scientists of the scientific school of prof. V.A. Voznesensky. In the research of the structure and properties of rigid road pavements concrete with an optimal plan, a 4-factor experiment was carried out, in which the following factors of concrete composition were varied: X1 - the amount of Portland cement PC II / A-Sh-500, from 400 to 500 kg / m³; X2 - the amount of polypropylene fiber from 0 to 2 kg / m³; X3 - the amount of Metakaolin, from 0 to 30 kg / m³; X4 - the amount of complex action additive (polycarboxylate type) Coral ExpertSuid-5, from 0.6 to 1% of the cement mass. An increase in the amount of Coral ExpertSuid-5 additive from 0.6 to 0.8% of the cement mass is noticeable, by 10...12%, and decreases the W/C ratio of mixture. An increase in the amount of this additive of complex action to 1% causes a further, but less noticeable, decrease in W/C ratio.

1. Introduction
Rigid cement concrete pavements are widely used in the European Union, the United States and other developed countries. These pavements have shown their high-performance properties and durability, which confirmed the economic feasibility of their use. In recent years, rigid cement concrete pavements are increasingly used in domestic practice of road construction in Ukraine and other countries with temperate climates. Frost resistance is one of the main indicators of the quality of concrete pavements, ensuring the durability of materials. Nowadays, one of the most effective materials for cement concrete pavements are modified fiber concrete. These materials are able to provide both high strength and durability of the pavement. Accordingly, the task of developing modified fiber concrete rigid pavements based on domestic binders, aggregates and modifiers is actual.

2. Analysis of recent research and publications
In the conditions of constant influence of transport and weather factors, the service life of rigid road pavements is two and more times longer in comparison with asphalt concrete pavements [1]. Another important advantage of cement concrete pavement is that bitumen is not used for their production. Oil reserves for bitumen production are more limited than raw material reserves for cement production. It is also important that most of the bitumen in Ukraine is imported [2].
During the manufacture of rigid concrete pavements, the achievement of the required level of efficiency simultaneously with high durability and strength of the material is possible only when using modern additives modifiers and fiber [3, 4]. Today polycarboxylate type superplasticizers are one of the most effective concrete modifiers. For concrete pavements also an effective method of increasing durability is the use of active mineral additives of pozzolanic type [5], in particular metakaolin [6, 7]. Metakaolin significantly affects the process of structure formation of concrete. These changes in the structure increase the durability of concrete by reducing permeability and shrinkage, as well as increasing frost resistance and corrosion resistance [4-7].

Disperse reinforcement is also a known method of improving the mechanical properties of concrete [4, 5, 8, 9]. The use of fiber can increase crack resistance, frost resistance, tensile strength and wear resistance of concrete, which is important for paving materials [4, 9]. Accordingly, disperse-reinforced concrete modified with a polycarboxylate-type superplasticizer and an active pozzolanic-type mineral additive are promising materials for rigid pavements that are operated in severe conditions.

3. The purpose of this research
The purpose of this research is to determine the optimal concentrations of microsilica and superplasticizer to improve the rheological and physical-mechanical properties of plaster solutions, as well as to assess the sensitivity of the system to changes in the mineralogical and chemical compositions of microsilica.

4. Objects and methods of research
Numerical modelling based on a modern software and computational complex is an effective approach, which makes it possible to determine the composition of cement-concrete under the influence of a transport load. For the calculation and statistical analysis of experimental-statistical (ES) models of the investigated concretes and mixtures composition influence on their physical and mechanical properties, the Program (dialogue) Complex COMPEX [10, 11] was used, which was developed at the Odessa State Academy of Civil Engineering and Architecture by Head of the scientific school by prof. V.A. Voznesensky. Calculations of ES models were carried out taking into account the accepted experimental error at a two-sided risk of 10%, which means $\alpha=0.1$. For a given risk level, the hypothesis was tested about the difference in the estimates of the coefficients of the ES models from zero. The significance of the coefficients was checked. After a sequential analysis, the ES model with all significant estimates of the coefficients was tested for adequacy according to the Fisher's criterion. To calculate the ES models, a transition was made from full-scale variables to coded ones, which should be in the range from -1 to +1. For this, the usual formula (1) was used:

$$X_i = \frac{X_{i,max} + X_{i,min}}{2} - \frac{X_{i,max} - X_{i,min}}{2}$$

During research of the structure and properties of rigid road pavements concrete with an optimal plan, a 4-factor experiment was carried out, in which the following factors of concrete composition were varied:

- X1 - the amount of Portland cement PC II / A-Sh-500, from 400 to 500 kg / m³;
- X2 - the amount of polypropylene fiber from 0 to 2 kg / m³;
- X3 - the amount of Metakaolin, from 0 to 30 kg / m³;
- X4 - the amount of the complex action additive (polycarboxylate type) Coral ExpertSuid-5, from 0.6 to 1% of the cement mass.

Crushed stone of fraction 5-10 mm and quartz sand with a modulus of 2.7 were used as aggregates for fiber concretes. The compressive strength of concrete was determined according to DSTU B B.2.7-224:2009. The tensile strength in bending was determined on samples of beams with
measurements 4×4×16 cm. Frost resistance of rigid pavements concretes was determined by the accelerated method in salt water when frozen to −50°C [12].

The amount of aggregates, that is, crushed stone and quartz sand in concrete mixtures, during the experiments, was adjusted in accordance with the known methods for selecting the composition of concrete to ensure the required calculated volume of material per 1 m³, depending on the amount of cement, water, fiber and additives.

All mixtures of concrete and fiber-reinforced concrete investigated in both series of experiments had equal mobility M2 (cone slump (CS) from 6 to 8 cm), which was achieved by selecting the amount of water. This mobility was chosen to meet the most common requirements for concrete mixtures of rigid road pavements.

An extended plan of the experiment with coded samples and real values of the factors of variation of concrete and fiber-reinforced concrete of rigid road pavements are presented in Table 1.

Based on the experimental data, the ES model of the influence of composition factors on the W/C of concrete mixtures of rigid road pavements of equal mobility (2) was built:

\[
\begin{align*}
W/C & = 0.396 - 0.043x_1 + 0.015x_1^2 - 0.010x_1x_2 + 0.015x_3 + 0.015x_4 - 0.010x_1x_3 \\
& + 0.021x_2 - 0.013x_2^2 - 0.008x_2x_3 + 0.004x_3x_4 \\
& + 0.009x_3 - 0.008x_4 + 0.009x_3^2 \\
& - 0.018x_4 + 0.009x_4^2
\end{align*}
\]

5. The results of research

According to the ES model (2), one-factor diagrams were constructed and shown on Figure 1, reflecting the influence of variable factors on the W/C ratio of mixtures in the extremum zones,

Table 1. The plan of the experiment and the compositions of the concrete and fiber-reinforced concrete of rigid road pavements.

| №  | X1 (cement) | X2 (fiber) | X3 (metakaolin) | X4 (add-on) | Cement (kg/m³) | Crushed stone (kg/m³) | Sand (kg/m³) | Metakaolin (kg/m³) | Fiber (kg/m³) | Additive (kg/m³) | Water (l/m³) |
|----|-------------|------------|----------------|------------|----------------|--------------------|-------------|-------------------|-------------|-----------------|--------------|
| 1  | 0           | 0          | 0              | 0          | 450            | 1115               | 655         | 15                | 1           | 3.6             | 183          |
| 2  | -1          | -1         | 1              | -1         | 400            | 1130               | 668         | 30                | 0           | 2.4             | 191          |
| 3  | -1          | 1          | -1             | 1          | 400            | 1135               | 692         | 0                 | 2           | 4.0             | 193          |
| 4  | 1           | -1         | 1              | 1          | 500            | 1105               | 635         | 0                 | 0           | 5.0             | 168          |
| 5  | 1           | 1          | 1              | -1         | 500            | 1100               | 603         | 30                | 2           | 5.0             | 181          |
| 6  | 1           | 1          | -1             | -1         | 500            | 1105               | 621         | 0                 | 2           | 3.0             | 192          |
| 7  | 0           | 1          | 1              | -1         | 450            | 1115               | 617         | 30                | 2           | 2.7             | 206          |
| 8  | 0           | -1         | -1             | -1         | 450            | 1115               | 684         | 0                 | 0           | 2.7             | 161          |
| 9  | 0           | -1         | 1              | 1          | 450            | 1115               | 651         | 30                | 0           | 4.5             | 164          |
| 10 | 1           | 0          | 1              | -1         | 500            | 1105               | 574         | 30                | 1           | 3.0             | 203          |
| 11 | -1          | 0          | -1             | -1         | 400            | 1130               | 691         | 0                 | 1           | 2.4             | 192          |
| 12 | -1          | 0          | 1              | 1          | 400            | 1130               | 672         | 30                | 1           | 4.0             | 182          |
| 13 | 1           | -1         | 0              | -1         | 500            | 1105               | 601         | 15                | 0           | 3.0             | 199          |
| 14 | -1          | 1          | 0              | -1         | 400            | 1130               | 676         | 15                | 2           | 2.4             | 199          |
| 15 | -1          | -1         | 0              | 1          | 400            | 1135               | 702         | 15                | 0           | 4.0             | 158          |
| 16 | 1           | -1         | 1              | 0          | 500            | 1105               | 590         | 30                | 0           | 4.0             | 183          |
| 17 | -1          | 1          | 1              | 0          | 400            | 1130               | 662         | 30                | 2           | 3.2             | 189          |
| 18 | -1          | -1         | -1             | 0          | 400            | 1135               | 710         | 0                 | 0           | 3.2             | 163          |
through which the maximum (red lines) and minimum (blue lines) values pass. During constructing these graphs, the level of three factors is not reflected in each of them and were fixed at the values that provide, respectively, the maximum and minimum values of the W/C ratio of mixtures. During constructing these graphs, the level of three factors not reflected in each of them were fixed at the values that provide, respectively, the maximum and minimum values of the W/C ratio of mixtures.

An analysis of the diagrams shown in Fig. 1 shows that with an increase in the amount of Portland cement W / C, the ratio of mixtures is expected to decrease. The introduction of polypropylene fiber necessitates an increase in the W / C ratio in order to maintain the necessary mobility of the mixture. Due to the additional water requirement of Metakaolin, with the introduction of this active mineral additive, the W / C ratio of the mixture also increases. Thus, due to the introduction of the maximum amount of Metakaolin the W / C ratio increases by 8...9%.

The values of the compressive strength of concrete and fiber concrete of rigid road pavements, which were determined during a full-scale experiment, investigated at 18 points of the planned experiment on the 3rd, 7th, 28th and 180th days after hardening are given in Table 2.

**Table 2. Compressive strength of the researched concretes and fibro-concretes rigid pavements at different ages**

| №   | 3 days, $f_{ck,cube,3}$ | 7 days, $f_{ck,cube,7}$ | 28 days, $f_{ck,cube,28}$ | 180 days, $f_{ck,cube,180}$ |
|-----|------------------------|-------------------------|---------------------------|-----------------------------|
| 1   | 41.2                   | 45.3                    | 59.4                      | 69.4                        |
| 2   | 31.6                   | 36.6                    | 49.3                      | 56.3                        |
| 3   | 30.7                   | 33.2                    | 45.2                      | 51.9                        |
| 4   | 44.1                   | 49.8                    | 66.1                      | 76.9                        |
| 5   | 49.8                   | 53.9                    | 65.0                      | 77.6                        |
| 6   | 41.1                   | 43.0                    | 54.4                      | 64.3                        |
| 7   | 36.5                   | 39.6                    | 51.1                      | 61.8                        |
| 8   | 36.5                   | 41.2                    | 54.8                      | 62.3                        |
| 9   | 47.7                   | 51.2                    | 65.4                      | 75.5                        |
| 10  | 42.6                   | 45.4                    | 55.5                      | 63.8                        |
| 11  | 27.4                   | 31.2                    | 41.8                      | 47.9                        |
| 12  | 36.3                   | 38.6                    | 49.1                      | 56.0                        |
| 13  | 39.8                   | 43.6                    | 56.6                      | 63.4                        |
| 14  | 29.6                   | 34.3                    | 46.3                      | 52.8                        |
| 15  | 39.1                   | 45.2                    | 60.9                      | 67.8                        |
ES models (3,4) which are constructed according to the data given in Table 2, are presented below:

\[
f_{ck,\text{cube.3}}(\text{MPa}) = 40.9 + 5.8x_1 - 1.7x_1^2 + 0.8x_1x_2 \pm 0.8x_1x_3 \pm 0.1x_1x_4 \pm 0.2x_2 \pm 0.9x_2^2 \pm 0.1x_2x_3 + 0.6x_2x_4 + 2.1x_3 - 0.8x_3^2 + 1.0x_3x_4 + 2.1x_4 - 0.8x_4^2 \tag{3}
\]

\[
f_{ck,\text{cube.7}}(\text{MPa}) = 45.4 + 5.7x_1 - 1.5x_1^2 + 1.1x_1x_2 \pm 0.8x_1x_3 + 0.8x_1x_4 \pm 0.9x_2 + 1.2x_2^2 \pm 0.7x_2x_3 + 0.6x_2x_4 + 2.0x_3 - 1.7x_3^2 + 1.0x_3x_4 + 3.0x_4 - 1.2x_4^2 \tag{4}
\]

Based on the ES models (3,4) in the PC COMPEX, the influence of variable composition factors on the compressive strength of the researched samples of concrete and fiber concrete of rigid road pavements at an early age: 3 days, \( f_{ck,\text{cube.3}} \) (Figure 2) and 7 days, \( f_{ck,\text{cube.7}} \) (Figure 3), was modelled and presented as a three-factor volumetric diagram.

**Figure 2.** Influence of the amount of Portland cement, Metakaolin and Coral ExpertSuid-5 complex action additive on the compressive strength of fiber-reinforced concrete on the 3rd day \( (x_2 = 0) \)

**Figure 3.** Influence of the amount of Portland cement, Metakaolin and Coral ExpertSuid-5 complex action additive on the compressive strength of fiber-reinforced concrete on the 7th day \( (x_2 = 0) \)
The maximum compressive strength on the 3rd day was $f_{\text{c, cube.3, max}} = 50.5$ MPa at the point with coordinates $x_1 = x_3 = x_4 = 1$, $x_2 = -1$. The maximum compressive strength on the 7th day was $f_{\text{c, cube.7, max}} = 55.2$ MPa at a point also with close coordinates $x_1 = x_4 = 1$, $x_2 = -1$, $x_3 = 0.69$. That is, on the 3rd and 7th days, concrete has the greatest compressive strength with the maximum amount of cement and Coral additives and without fiber. The maximum strength on the 3rd day with an amount of Metakaolin of 30 kg / m$^3$ and on the 7th day - 24...25 kg / m$^3$ was observed.

Analysis of the diagrams shown on Figure 1, Figure 2 shows that with an increase in the amount of cement in the composition of concrete, its strength is expected to increase, but this effect is somewhat non-linear both on the 3rd day and on the 7th day after hardening. That is, with an increase in the amount of binder from 400 to 450 kg / m$^3$, the compressive strength of composites increased more intensively than with an increase in the amount of binder from 450 to 500 kg / m$^3$. Metakaolin, as an active mineral additive, affects the processes of structure formation, which increases strength of concrete both in the early age and in the branded age.

The strength of concrete on the 28th day can be called strength at the "standard" age, since it is this strength that determines the class of concrete or its strength grade. The minimum class of concrete for road pavements is set by the relevant regulatory documents. Therefore, it is the compressive strength on the 28th day that is largely decisive from the point of view of the possibility of using concrete in a particular structure, including rigid road pavements.

The influence of varying composition factors on the compressive strength of the investigated concretes and fiber concretes of rigid road pavements at the “standard” age of 28 days is described by the ES model (5) given below:

$$f_{\text{c, cube}} (\text{MPa}) = 59.4 + 5.9x_1 - 2.4x_1^2 + 1.1x_1x_2 \pm 0x_1x_3 + 1.1x_1x_4$$
$$- 2.0x_2 + 2.4x_2^2 \pm 0x_2x_3 - 1.0x_2x_4$$
$$+ 1.6x_3 - 3.1x_3^2 \pm 0x_3x_4$$
$$+ 1.5x_4 - 1.9x_4^2$$

The field of properties of this ES model shows the minimum strength $f_{\text{c, cube.min}} = 41.3$ MPa at the point with coordinates $x_1 = x_3 = x_4 = -1$, $x_2 = 0.43$, which corresponds to compositions with a minimum amount of cement and additive Coral ExpertSuid- 5, without Metakaolin and with a fiber amount of approximately 1.3 kg / m$^3$. The maximum strength $f_{\text{c, cube.max}} = 70.9$ MPa was observed at the point with coordinates $x_1 = x_4 = 1$, $x_2 = -1$, $x_3 = 0.24$, which corresponds to compositions with the maximum amount of cement and Coral additive, without fiber and with the amount Metakaolin 18...19 kg / m$^3$.

6. Conclusions

The results of the experiment and recommendations for the manufacture and use of modified concrete for hard road surfaces are presented. An increase in the amount of Coral ExpertSuid-5 additive from 0.6 to 0.8% of the cement mass by 10...12% reduces the W / C ratio of the mixture. An increase in the amount of this additive of complex action to 1% causes a further, but less noticeable, decrease in the W / C ratio. Due to the use of a rational number of modifiers, the strength of the investigated concretes and fiber-reinforced concretes on the 3rd day, depending on the amount of cement in their composition, reaches from 40 to 50 MPa, and on the 7th day - from 45 to 55 MPa. That is, due to the use of modifiers, concrete has an increased early strength, which, as mentioned above, makes it possible to accelerate the start of operation of the road surface. With an increase in the amount of the additive of complex action Coral, both due to a decrease in the W / C ratio of the mixture, and due to the action of the additive as a hardening accelerator, the early strength of concretes increases, while the positive effect of the additive will be more noticeable for concretes and fiber-reinforced concretes with the addition of Metakaolin. In general, mixtures were researched using an increased amount of Coral ExpertSuid-5 additive (superplasticizer) and with a limitation of up to 20 kg / m$^3$ the amount of Metakaolin have a W / C ratio of no higher than 0.40, and a strength of at least 40 MPa, for 28 days, which allows use them for rigid road pavements.
The economic effect is achieved by increasing the service life and saving materials and repair costs. In the future, it is planned to continue research with greater variability.

7. References

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