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STATISTICAL THEORY OF EXPERIMENTAL DESIGN FOR INVESTIGATING THE INFLUENCE OF PLASTICIZERS ON CONCRETE PROPERTIES

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The paper investigates the application of statistical experimental design theory for a quantitative assessment of the influence of plasticizers of different chemical nature and dosage on the rheological, strength, and performance properties of concrete mixtures and hardened concrete. The relevance of the study is determined by the increasing requirements for construction materials used in critical structures, particularly civil protective and fortification facilities, where a balanced combination of high strength, sufficient workability, and increased density of concrete is essential.

The feasibility of using second-order multifactor experimental designs with factor coding is substantiated, enabling the development of an exact analytical description of experimental results within the investigated factor space. Special attention is paid to the construction of polynomial models whose coefficients are determined in such a way that the calculated values exactly coincide with the experimental data at the nodal points of the experimental design. This approach eliminates the need for conventional statistical adequacy testing and allows focusing on the physical interpretation of the obtained dependencies.

The experimental factors include the type of plasticizer, its dosage, the water-to-cement ratio, and the cement class. The response variables comprise workability of concrete mixtures, compressive strength at different curing ages, average density, and indirect indicators of water impermeability. Based on the developed models, optimal regions of the factor space are identified, ensuring enhanced workability of concrete mixtures without compromising design strength. The obtained results can be effectively applied to optimize concrete mix compositions in modern construction practice and in the design of protective structures.

Key words: statistical experimental design, concrete mixtures, plasticizers, polynomial models, multifactor experiment, compressive strength, workability, concrete mix optimization.

Чепок Р. В. Статистична теорія планування експериментів для дослідження впливу пластифікаторів на властивості бетону

У статті досліджено можливості застосування статистичної теорії планування експериментів для кількісного аналізу впливу пластифікаторів різної хімічної природи та дозування на реологічні, міцнісні та експлуатаційні властивості бетонних сумішей і затверділого бетону. Актуальність роботи зумовлена зростаючими вимогами до будівельних матеріалів, що використовуються у відповідальних конструкціях, зокрема у захисних і фортифікаційних спорудах цивільного призначення, де поєднання високої міцності, пластичності та щільності бетону має вирішальне значення.

У роботі обґрунтовано доцільність використання багатофакторних експериментальних планів другого порядку з кодуванням факторів, що дозволяє отримати точний аналітичний опис експериментальних результатів у межах досліджуваного факторного простору. Особливу увагу приділено побудові поліноміальних моделей, коефіцієнти яких визначаються таким чином, що забезпечується повний збіг розрахункових і експериментальних значень у вузлових точках плану експерименту. Такий підхід дає змогу відмовитися від класичних процедур статистичної перевірки адекватності моделі та зосередитися на фізичній інтерпретації отриманих залежностей.

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Як фактори експерименту розглянуто тип пластифікатора, його дозування, водоцементне відношення та клас цементу, а як вихідні параметри – показники пластичності бетонної суміші, міцності бетону на стиск у різні строки твердіння, середньої щільності та опосередковані характеристики водонепроникності. На основі побудованих моделей визначено оптимальні області факторного простору, що забезпечують одержання бетонів з підвищеною рухомістю без втрати проєктної міцності. Отримані результати можуть бути використані для оптимізації складів бетонних сумішей у практиці сучасного будівництва та при проектуванні захисних споруд.

Ключові слова: статистична теорія планування експериментів, бетонні суміші, пластифікатори, поліноміальні моделі, багатфакторний експеримент, міцність бетону, пластичність, оптимізація складу бетону.

Problem statement. Under the current conditions of development of construction science and technologies during the period of martial law in Ukraine, the application of mathematical modeling methods and the statistical theory of experimental design (DoE) for studying the properties of construction materials becomes particularly relevant. Traditional experimental methods are often labor-intensive, costly, and do not provide the possibility of a comprehensive analysis of the simultaneous influence of multiple factors.

The use of the statistical theory of experimental design makes it possible to reduce the number of experimental runs, increase the informativeness of experiments, and obtain analytical relationships between input factors and output characteristics of materials. Experimental designs that ensure an exact analytical description of results at the design points are of particular practical value, as they minimize the need for statistical processing of deviations.

Analysis of recent research and publications. The application of the statistical theory of experimental design in studies of the properties of concrete and concrete mixtures has been actively developing over recent decades within the fields of construction materials science and engineering. A significant number of scientific works are devoted to the optimization of concrete compositions using chemical admixtures, particularly plasticizers, as well as to mathematical modeling of the influence of technological factors on the physical and mechanical properties of hardened concrete.

The works of domestic and foreign researchers widely present approaches based on single-factor and multifactor experimental designs for analyzing the influence of the water-to-cement ratio, cement type, aggregate gradation, and dosage of chemical admixtures on the strength and workability of concrete mixtures. In most cases, regression analysis methods are applied, followed by statistical verification of model adequacy using Fisher's, Student's, and Cochran's criteria.

A separate research direction focuses on studying the effectiveness of modern plasticizers, particularly polycarboxylate-based admixtures, which provide a significant increase in concrete mixture workability at reduced water-to-cement ratios. These studies demonstrate that the use of this class of admixtures makes it possible to achieve high strength and density of concrete; however, they also emphasize the complexity of accurately describing the interaction of individual technological factors using mathematical models.

At the same time, the analysis of contemporary publications indicates that a considerable portion of studies is based on classical statistical methods for processing experimental data, which assume the presence of random errors and require additional verification of model adequacy. Such an approach complicates the interpretation of results and does not always allow obtaining an exact analytical description of experimental data within the factor space.

Comparatively less attention has been paid to the application of experimental designs that ensure an exact coincidence of calculated and experimental values at the nodal points of the experimental design, as well as to the use of second-order interpolating polynomial models for describing the properties of concrete mixtures. Issues related to the practical application of such models for optimizing the compositions of special-purpose concretes, particularly for structures with increased requirements for strength, density, and placement technology, remain insufficiently covered.

The application of the statistical theory of experimental design in studies of concrete mixtures and hardened concrete is widely reflected in the works of domestic and foreign scientists. A significant contribution to the development of the methodology of mathematical modeling of technological processes in construction materials science was made by classical researchers in experimental theory, including R. Fisher, G. Box [3], G. Hunter, and S. Hunter, whose works established the foundations of factor analysis, regression modeling, and optimization of engineering processes.

In the field of applying experimental design methods to the study of construction material properties, the works of Yu. M. Bazhenov [1], V. I. Solomatov, and V. G. Batrakov are well known. Their studies are devoted to the statistical analysis of concrete compositions and the influence of the water-to-cement ratio and chemical admixtures on the strength and durability of concrete. These works demonstrate the effectiveness of multifactor experimental designs for optimizing concrete mix compositions according to multiple quality criteria.

Studies on the influence of plasticizers and superplasticizers on the rheological and strength characteristics of concrete are widely presented in the works of A. M. Neville, P. K. Mehta [4], P. Kumar Mehta, and S. Monteiro, who investigated the physicochemical mechanisms of chemical admixture action and their role in the formation of cement stone structure. Particular attention in these studies is paid to the relationship between concrete mixture workability, water-to-cement ratio, and the final strength of concrete.

A separate modern research direction concerns the use of polycarboxylate-based plasticizers. The works of K. Flatt, J. P. Scrivener, and H. Jensen show that this class of admixtures ensures effective dispersion of cement particles, which allows for a significant reduction in the water-to-cement ratio without loss of concrete mixture workability. At the same time, the authors emphasize the complexity of mathematically describing the multifactor interaction of technological parameters, which necessitates the use of advanced experimental design methods.

In the works of Ukrainian researchers, in particular M. Bordiuk and S. Solodkyi, issues related to the optimization of heavy and special concretes using statistical analysis and experimental design methods are considered. The authors note the feasibility of constructing second-order analytical models to describe relationships between technological factors and concrete properties.

At the same time, the analysis of scientific publications shows that the vast majority of studies are based on classical regression approaches followed by statistical verification of model adequacy. Significantly fewer works are devoted to the use of experimental designs that ensure exact coincidence of calculated and experimental values at the nodal points of the design and allow constructing interpolating polynomial models without applying additional adequacy criteria.

Thus, despite the significant contribution of the aforementioned scientists to the development of statistical analysis methods and the study of concrete materials, the problem of improving methodological approaches to experimental design and constructing accurate analytical models suitable for optimizing special-purpose concrete

compositions remains relevant. This determines the scientific novelty and practical orientation of the present study.

The analysis of scientific sources shows that, despite the substantial volume of research in the field of applying statistical experimental design methods in concrete science, the task of improving methodological approaches to constructing mathematical models that ensure an exact analytical description of experimental results and can be effectively used to optimize concrete mixture compositions remains relevant. This substantiates the expediency of further research in this direction and determines the scientific novelty and practical significance of this work.

Purpose of the study. The purpose of this study is to provide a scientific justification and further development of the methodology for applying the statistical theory of experimental design to construct accurate analytical models describing the influence of plasticizers on the rheological, strength, and performance properties of concrete mixtures and hardened concrete, as well as to determine, on this basis, the optimal parameters of concrete composition for use in structures with increased requirements for strength, density, and technological efficiency.

Within the framework of the stated purpose, it is envisaged to overcome the limitations of classical regression approaches based on probabilistic assessment of model adequacy by employing multifactor experimental designs that ensure complete coincidence of experimental and calculated values at the nodal points of the factor space. This makes it possible to move from an approximate statistical description to interpolating polynomial modeling suitable for a physically meaningful analysis of the effects of individual technological factors and their interactions.

The implementation of this purpose is aimed at obtaining scientifically substantiated recommendations for optimizing concrete mix compositions, taking into account the type and dosage of plasticizers, the water-to-cement ratio, and the characteristics of binding materials. This contributes to increasing the efficiency of concrete application in modern construction, particularly in structures operating under increased loads and stringent service conditions.

Presentation of the main material.

1. Theoretical Foundations of Statistical Experimental Design

Within the framework of the statistical theory of experimental design, polynomial models are widely used, as they make it possible to describe the dependence of an output parameter on a set of influencing factors. A polynomial is defined as an analytical expression that contains variables and coefficients connected by addition and multiplication operations, where the powers of the variables are natural numbers.

For multifactor experiments, factor coding is applied, which ensures their dimensionless form and convenience for mathematical processing. The transition from the natural values of factors z to the coded values x is carried out using well-known linear relationships, which makes it possible to unify the experimental space.

A distinctive feature of the proposed experimental designs is that the polynomial coefficients are determined in such a way that the calculated values exactly coincide with the experimental values at the nodal points of the design.

In modern scientific research related to the experimental analysis of complex engineering systems, methods of the statistical theory of experimental design are widely applied. However, despite the significant advantages of this methodology, it is not free from certain conceptual and practical limitations. One of the key problems is the assessment of the reliability of the obtained analytical description, namely, determining the degree of correspondence between experimental results and values obtained through mathematical modeling.

Traditionally, this task is solved by applying statistical criteria that allow analyzing the nature and regularities of error distribution between calculated and experimental data. At the same time, such an approach requires additional computational procedures and does not always ensure unambiguous interpretation of the results.

Taking these difficulties into account, specialized experimental designs have been developed within the theory of experimental design, the distinctive feature of which is the exact coincidence of experimental and analytically calculated values at specific design points. This makes it possible to abandon further statistical analysis of model adequacy within the factor space, which significantly simplifies the interpretation of results.

A key role in implementing this approach is played by the use of polynomial mathematical models. In this context, a polynomial is considered an analytical expression consisting of one or more variables and corresponding coefficients interconnected by addition, subtraction, and multiplication operations. Each term of the polynomial contains a variable raised to a non-negative integer power. Due to their universality, polynomials are widely used to formalize processes in physics, economics, and engineering sciences and serve as a fundamental tool of algebra and mathematical analysis.

Let us consider the implementation of the described approach using the example of an experimental design with two coded factors, x_1 and x_2 , which vary at three levels: (+1); 0; (-1) by transforming the natural values z_1 and z_2 using the following formulas.

This ensures the symmetry of the experimental design and facilitates further analytical description of the results.

$$x_1 = \frac{2z_1 - (z_{1max} + z_{1min})}{(z_{1max} + z_{1min})} \quad (1)$$

$$x_2 = \frac{2z_2 - (z_{2max} + z_{2min})}{(z_{2max} + z_{2min})}$$

where z_{max} and z_{min} are the maximum and minimum values of the factor z within its range of variation. When $z = z_{max}$, equation (1) yields the coded value (+1); when $z = z_{min}$, the coded value is (-1); and at the mean value

$$z = \frac{z_{max} + z_{min}}{2}$$

the coded value is (0).

The procedure for calculating the polynomial coefficients, as well as the possibility of performing calculations using analogous formulas, has been presented in our previous publications [2].

2. Experimental design with different numbers of factors

2.1. Two-factor experiment

For two coded factors varying at three levels (-1, 0, +1), a symmetric experimental design is constructed. The analytical description of the results is performed using a second-order polynomial:

$$y = b_0 + b_1X_1 + b_2X_2 + b_{12}X_1X_2 + b_{11}X_1^2 + b_{22}X_2^2$$

The polynomial coefficients are calculated directly from the experimental data, which ensures an accurate description of the results within the scope of the experimental design.

2.2. Three-factor experiment. For experiments involving three factors, a full factorial design is employed, which makes it possible to obtain a second-order polynomial that accounts for pairwise interactions between the factors. Model verification confirms a complete agreement between the analytical and experimental values at all design points.

2.3. Four-factor experiment

In the case of four factors, the experimental design is supplemented with a central point. The polynomial model includes all linear, quadratic, and interaction terms. The coefficients are determined in a manner analogous to the previous cases, which enables the methodology to be scaled to complex multifactor problems.

The proposed methodology is applied to investigate the influence of plasticizers on the properties of concrete:

1. Definition of the experimental objectives. The main objective is to establish the relationship between the dosage and type of plasticizer, the water-to-cement ratio, and the workability of the concrete mixture, as well as the compressive strength of concrete at different curing ages (7 and 28 days).

2. Selection of factors and their levels. To construct a multifactor experimental design, the following main variables are selected:

x_1 – type of plasticizer (lignosulfonate-based, naphthalene-formaldehyde-based, polycarboxylate-based);

x_2 – plasticizer dosage (% by mass of cement, e.g., 0.3; 0.6; 0.9);

x_3 – water-to-cement ratio (w/c) (0.4; 0.5; 0.6);

x_4 – type of cement (Portland cement, slag Portland cement).

The factor levels are coded according to the following scheme: -1 (minimum value), 0 (mean value), and $+1$ (maximum value).

3. Experimental design.

For two factors, a central composite design is applied (Table 1), which allows a second-order polynomial to be obtained:

$$y = B_0 + B_1X_1 + B_2X_2 + B_{11}X_1^2 + B_{22}X_2^2 + B_{12}X_1X_2$$

where y denotes the indicator of workability or compressive strength of concrete.

Table 1

№	1	2	3	4	5
x_1	+1	-1	+3	-1	0
x_2	+1	+1	-1	-1	0
y	y_1	y_2	y_3	y_4	y_5

For three factors, a full factorial design 3^2 or 3^3 is applied (Table 2), which yields the following equation:

$$y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 + B_{12}X_1X_2 + B_{13}X_1X_3 + B_{23}X_2X_3 + B_{123}X_1X_2X_3$$

Table 2

№	1	2	3	4	5	6	7	8	9
	+1	-1	+1	-1	+1	-1	+1	-1	0
x_2	+1	+1	-1	-1	+1	+1	-1	-1	0
x_3	+1	+1	+1	+1	-1	-1	-1	-1	0
y	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9

For four factors, the experimental design is constructed according to Table 3, with additional terms included in the model. $x_1 x_2 x_3 x_4$.

Table 3

№	x_1	x_2	x_3	x_4	y	№	x_1	x_2	x_3	x_4	y
1	+1	+1	+1	+1	y_1	9	+1	+1	+1	-1	y_9
2	-1	+1	+1	+1	y_2	10	-1	+1	+1	-1	y_{10}
3	+1	-1	+1	+1	y_3	11	+1	-1	+1	-1	y_{11}
4	-1	-1	+1	+1	y_4	12	-1	-1	+1	-1	y_{12}
5	+1	+1	-1	+1	y_5	13	+1	+1	-1	-1	y_{13}
6	-1	+1	-1	+1	y_6	14	-1	+1	-1	-1	y_{14}
7	+1	-1	-1	+1	y_7	15	+1	-1	-1	-1	y_{15}
8	-1	-1	-1	+1	y_8	16	-1	-1	-1	-1	y_{16}
						17	0	0	0	0	y_{17}

The polynomial providing an exact description of this design has the following form:

$$y = B_0 + B_1x_1 + B_2x_2 + B_3x_3 + B_4x_4 + B_{11}x_1^2 + B_{22}x_2^2 + B_{33}x_3^2 + B_{44}x_4^2 + B_{12}x_1x_2 + B_{13}x_1x_3 + B_{14}x_1x_4 + B_{23}x_2x_3 + B_{23}x_2x_3 + B_{24}x_2x_4 + B_{34}x_3x_4 + B_{1234}x_1x_2x_3x_4.$$

3. Conducting the experiments: Concrete mixtures are prepared using different combinations of the selected factors. The workability indicators (slump and flow spread) are determined. Control specimens are produced to determine the compressive strength at 7 and 28 days.

1. Analytical description of the results: The polynomial coefficients are calculated using the formulas presented in the methodological framework:

$$B_0 = y_0; B_1 = 1/4 (y_1 - y_2 + y_3 - y_4); B_{11} = 1/8 (y_1 + y_2 + y_3 + y_4) - 1/2 y_0$$

By substituting the experimental data, an exact analytical description is obtained without the need for statistical analysis of deviations.

4. Analysis and optimization. Using the obtained equations, optimal combinations of factors (for example, the type of plasticizer and its dosage) are determined, ensuring maximum workability of the mixture with minimal loss of strength.

Model verification is carried out using control experiments.

Expected results:

Quantification of the influence of plasticizers of different types on the workability of concrete mixtures.

Development of analytical models describing the relationships between dosage and concrete properties.

Determination of optimal parameters for producing concrete with enhanced workability and high strength.

Practical recommendations for the application of plasticizers in construction.

5. Application of the statistical theory of experimental design to the study of special-purpose concrete mixtures.

5.1. Formulation of the experimental research problem.

Modern operating conditions of concrete structures, particularly civil defense protective facilities (shelters), impose increased requirements on the complex of properties of concrete properties. The key requirements include high compressive strength (not lower than C30/37–C40/50), enhanced impact and crack resistance, sufficient plasticity of the concrete mixture to ensure proper placement under confined-space conditions, high density and reduced permeability to provide protection against fragment and shock-wave loads, as well as stability of properties under varying curing conditions.

The objective of the experimental study is to quantitatively determine the influence of plasticizers of different chemical nature and dosage on the комплекс of properties of concrete mixtures and hardened concrete using methods of the statistical theory of experimental design.

Selection of experimental factors

Four main factors were selected for modeling:

x1 – type of plasticizer: lignosulfonate-based (LS), naphthalene–formaldehyde-based (NF), polycarboxylate-based (PC);

x2 – plasticizer dosage, % by mass of cement (0.4–1.2%);

x3 – water-to-cement ratio (w/c) (0.38–0.48);

x4 – cement class (CEM I 42.5R; CEM I 52.5N).

Response variables (system outputs).

The following performance criteria were selected:

Y1 – slump (plasticity), cm;

Y2 – compressive strength of concrete at the age of 7 days, MPa;

Y3 – compressive strength of concrete at the age of 28 days, MPa;

Y4 – average density of concrete, kg/m³;

Y5 – water impermeability (indirectly assessed through the w/c ratio and density).

5.2. Experimental methodology.

Experimental design. A full second-order factorial design was used, which makes it possible to account for the individual effects of each factor, quadratic effects, and pairwise interactions between factors (for example, plasticizer type × w/c ratio).

The factors were coded within the ranges [–1; 0; +1], which ensured the universality of the mathematical model.

Preparation of concrete mixtures. Concrete mixtures were prepared under laboratory conditions in strict accordance with standard procedures: cement – Portland cement of the specified class; aggregates – crushed stone with a fraction of 5–20 mm and quartz sand; plasticizer – according to the experimental design; water.

After mixing, the following were determined: workability (slump) using a standard method, as well as visual homogeneity and segregation resistance.

Strength testing. For each experimental series, 100 × 100 × 100 mm cubes were produced. Testing was carried out at the age of 7 days to assess early strength and at 28 days to evaluate design strength.

Curing was performed under standard conditions simulating real construction conditions of protective shelters.

Example of an experimental result. For a mixture with the following parameters: polycarboxylate-based plasticizer; dosage – 0.9%; w/c = 0.40; cement – CEM I 52.5N, the following results were obtained: slump – 18–20 cm (high plasticity); compressive strength – 42 MPa at 7 days and 62 MPa at 28 days; density – above 2400 kg/m³.

These characteristics are critically important for massive concrete elements of protective structures.

5.3. Analytical description of results and optimization of concrete properties.

Development of mathematical models.

For each response variable (Y₁–Y₅), a second-order polynomial of the following form was constructed:

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j$$

where:

b₀ – is the constant term of the polynomial;

b_i – are the coefficients of the linear effects of the factors;

bii – are the coefficients of the quadratic terms representing the nonlinear effects of the factors;

bij – are the coefficients of pairwise interactions between the factors;

xi, xj – are the coded values of the factors.

A distinctive feature of the applied methodology is the approach used to determine the polynomial coefficients. They were calculated in such a way that the analytical model fully interpolates the experimental data; that is, the values obtained by substituting the coded factors into the polynomial exactly coincide with the experimental results at all nodal points of the experimental design.

This implies that the developed model is not an approximate regression relationship in the classical statistical sense but rather serves as an exact analytical description of the experimental results within the investigated factor space. Under these conditions, there is no need to apply additional model adequacy criteria, since the error between the experimental and calculated values at the design points is equal to zero.

The application of polynomial models of this type makes it possible not only to formally describe the obtained experimental data but also to perform an analytical analysis of the influence of individual factors and their interactions on the properties of concrete mixtures. In addition, the model enables prediction of the response variables for any combinations of factors within the investigated ranges of variation and can be used as a tool for optimizing the concrete composition according to specified criteria.

The polynomial coefficients were determined so that the analytical values exactly matched the experimental ones at the nodal points of the design, which increases the reliability of the model.

Analysis of factor effects.

Analysis of the developed models showed that the type of plasticizer has a significant effect on plasticity and early strength; a reduction in the water-to-cement ratio is a key factor in increasing strength and density; polycarboxylate-based plasticizers provide the best balance between plasticity, strength, and density; excessive plasticizer dosage may reduce early strength, which is taken into account in the model.

Optimization of concrete composition for protective structures.

Based on the developed models, optimal regions of the factor space were identified that ensure:

concrete mixture workability corresponding to classes S4–S5;

concrete strength $\geq C40/50$;

increased density and reduced permeability.

Such compositions are advisable for use in monolithic civil defense protective structures, where high load-bearing capacity, resistance to dynamic loads, and technological feasibility of concrete placement are required.

Based on the experimental results, the polynomial coefficients were determined. The developed models make it possible to quantitatively evaluate the influence of each factor, determine optimal parameters of the concrete composition, and predict the properties of concrete mixtures within the investigated factor space.

The study establishes the regularities of the influence of plasticizers on concrete properties, develops exact analytical models of the “composition–properties” relationships, and formulates practical recommendations for optimizing concrete mixtures.

Conclusions. The application of the statistical theory of experimental design to the study of the influence of plasticizers on concrete properties makes it possible to obtain an exact analytical description of the results without the need for additional statistical error analysis. The proposed methodology is an effective tool for optimizing concrete

compositions and can be recommended for use in both scientific and applied research on construction materials.

Modern specialists in various fields (architects, civil engineers, structural engineers, etc.) are increasingly faced with tasks that, in addition to professional qualifications, require knowledge of methods for processing observational data, experimental design, mathematical modeling, and optimization of research processes. Therefore, a contemporary professional should possess not only deep domain-specific expertise but also a certain level of competence in scientific research, including mastery of the methodological foundations of research work, the ability to collect and process data, develop research programs, analyze the obtained results, and present them in the form of a scientific report.

The proposed experimental design allows for an exact description of the data at the design levels and therefore does not require statistical analysis of deviations between experimental and calculated values.

The experimental designs presented in Tables 1 and 2 can be applied in the process of building design, as well as in laboratory work related to technical mechanics, machine elements, and engineering and computer graphics. The design presented in Table 3 can be used in the preparation of graduation theses, where, for example, the influence of different plasticizers on the workability of concrete mixtures and the strength of concrete is investigated.

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