

A study of the strength of concrete based on industrial waste reinforced with fibre reinforcement

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Abstract

Optimizing multi-component cementitious composites requires a comprehensive understanding of not only the isolated effects of individual components but also their complex, often non-linear, inter-factor interactions. This study aims to perform mathematical modelling and evaluate the combined effect of the cement-to-fly ash ratio, fibre content, and plasticizer dosage on the compressive strength of the composite to identify optimal technological parameters. Experimental data were analyzed using one-way and multi-way analysis of variance (ANOVA). Two-factor quadratic regression equations and 3D response surface plots were generated utilizing the STATISTICA software suite. A strong synergistic effect was detected within the "Cement $\times$ Fibre" interaction system ($xy = +0.0557$). The findings demonstrate that micro-reinforcing fibres effectively enhance compressive strength only when embedded in a high-density matrix (cement-to-fly ash ratio ≥ 1.00). The interaction between the fibre and plasticizer factors exhibited a saddle-shaped response surface, indicating a drop in compressive strength below 31 MPa if the rheological balance of the mixture is disrupted. The absolute experimental maximum was identified, yielding a compressive strength exceeding 52 MPa. The derived regression models enable flexible control over the composite formulation, allowing for variations in additive dosages without sacrificing load-bearing capacity, or the targeted synthesis of materials with enhanced mechanical performance.

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1. Introduction

The historical use of fibrous fillers to modify the properties of brittle matrices extends from the use of straw in adobe and horsehair in plaster to modern composites. Technological methods for improving the mechanical properties of concrete by introducing discrete metal elements (nails, wire) began to develop in the early 20th century. However, research into dispersed reinforcement of concrete intensified in the mid-20th century, driven by the need to improve crack resistance, fracture toughness, and tensile strength. Currently, the compressive strength of concrete exceeds 100 MPa, with a theoretical maximum of up to 400 MPa. It is predicted that the tensile strength, which currently amounts to no more than 12.5% (1/8) of the compressive strength, may reach 50% of this value in the near future. Such dynamics of strength characteristics is due to the requirements for expanding the functional capabilities and increasing the economic efficiency of concrete as a universal structural material [1].

According to available data, the introduction of steel fibre provides an increase in compressive strength in the range of 15–20%, while the tensile strength during bending increases by 2.4 times [2]. The use of asbestos fibres in a concentration of 2–16% makes it possible to increase the bending strength by 1.6 times. However, the use of asbestos as a reinforcing component is significantly

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limited due to its carcinogenicity, as well as a number of technological factors: the short length of the fibres and the high complexity of the process of their desegregation (fluffing).

It has been established that the dynamic strength indicators of fibre-reinforced concrete exceed similar values for unreinforced compositions by 5–10 times. Despite the comprehensive improvement in physical and mechanical properties with the introduction of fibres, the key advantage is a significant increase in the crack resistance and fracture toughness of the material. The most popular fillers in research practice include steel, glass, polypropylene, carbon and polymer fibres [3]. The use of glass fibre helps to increase tensile strength, which allows optimizing the consumption of steel reinforcement [4]. This type of fibre increases resistance to dynamic influences and bending strength, and also transforms the nature of crack formation, helping to reduce the width of cracks [5]. It is noteworthy that the use of recycled materials in the form of industrial glass waste not only improves the strength properties of the composite, but also solves the pressing environmental problem of recycling technogenic waste [6].

The integration of polypropylene fibres does not have a significant effect on compressive strength [7], but effectively compensates for the low tensile and flexural properties of concrete [8]. Polypropylene fibre is characterized by low density, high rigidity, as well as chemical and biological inertness [9]. Research shows that an uncontrolled increase in the content of such fibres does not lead to an increase in fracture resistance; in this case, the mechanism of degradation of the reinforced matrix is described using a “two-linear softening curve” [10]. In addition, an excessive concentration of propylene additives makes it difficult to homogenize the mixture and negatively affects the uniform distribution of reinforcing elements in the volume of concrete [11]. Public spaces, including park areas and road surfaces, are subject to intense external influences, in particular shock and abrasive loads. The use of concrete modified with polypropylene fibres is advisable for objects of this type due to their increased operational resistance [12].

Dispersed carbon fibre reinforcement provides a significant increase in the material's flexural and tensile strength [13]. By micro reinforcing (“pulling together”) the edges of formed cracks, carbon fibre significantly increases the deformability of the composite [14, 15]. Although the introduction of this type of fibre does not significantly affect compressive strength, flexural strength values can increase twofold compared to control samples [16, 17]. Furthermore, the use of synthetic fibres in column structures allows for the optimization of the amount of transverse reinforcement and improves their performance under cyclic loads [18]. The integration of industrial waste, such as marble dust and ash, into non-structural elements opens up extensive opportunities for implementing sustainable construction concepts and reducing the carbon footprint (CO₂ emissions) [19, 20]. Subsoil use processes are inevitably accompanied by the formation of large-tonnage by-products in the form of overburden and associated rock. These wastes often represent valuable mineral resources suitable for recycling: fly ash, thermal power plant slag, and metal beneficiation tailings. At the Poltava Mining and Processing Plant, for example, dry magnetic separation waste is processed into crushed stone, while wet separation products (fine-grained sand) are stored in tailings dams. The rocky surface of these particles promotes strong adhesion to cement stone, which, despite their heterogeneous particle size distribution, allows them to be effectively used as fine aggregate [21]. Ash and slag waste from thermal power plants is one of the most problematic types of man-made raw materials. Currently, approximately 360 million tons of ash and slag have accumulated in the waste heaps of Ukrainian thermal power plants, covering an area of over 3,200 hectares, which has a significant negative impact on regional ecosystems. At the same time, the chemical and mineralogical similarity of these materials to natural raw materials makes them a strategic resource for the construction industry. Ash and slag recycling is considered a priority for addressing environmental issues in the industrial zones of thermal power plants, transforming the status of these materials from “waste” to the category of in-demand secondary resources.

The material composition of ash and slag from thermal power plants consists of organic and inorganic phases. The latter, in turn, includes amorphous and crystalline components [22]. The amorphous portion primarily consists of aluminosilicate glass and amorphized clay material. The crystalline component combines relict grains of primary fuel minerals (quartz, feldspars) and new

formations synthesized during high-temperature combustion, such as mullite, hematite and calcium aluminates. The pozzolanic activity of fly ash, defined by its ability to react with calcium hydroxide at ambient temperatures, is a key factor in forming insoluble hydration products. The accumulation of these hydrates governs the hydraulic hardening of composite binders based on lime or Portland cement blended with slag-fly ash mixtures. When utilized as active mineral admixtures in cement and concrete technology, the reactivity of these by-products directly regulates the setting kinetics, water demand of the cement paste, and ultimate mechanical strength of the composite.

Modern researchers are exploring the potential of using natural fibres to reinforce concrete. Due to their low weight, cost-effectiveness, higher specific strength and modulus of elasticity, and lack of health risks, natural fibres are promising reinforcing materials for use in concrete and are readily available in many countries. Common types of natural fibers include wheat straw, sugarcane fibre, sisal fibre, jute fibre, and bamboo fibre [20-27].

2. Materials and Methodology

The following industrial wastes were used in the work: waste from wet enrichment of iron ore at Poltava Mining and Processing Plant in the form of fine sand with a fineness modulus $M=1.1$ [28]; ash and slag from circulating fluidized bed boilers [29], a polycarboxylate hyper plasticizer (Fluid Premia 196), Ivano-Frankivsk Portland cement (grade 42.5), and discrete steel wire fibres with a diameter of 0.5 mm. The wire was preliminarily degreased with a solvent and then cut into individual fibres according to the calculations given below, 52 mm long. To determine the optimal fibre length, the shear stresses at the fibre-matrix interface were preliminarily determined by pulling the fibre out of a 40 mm thick sample (Fig. 1). The shear stresses were 1.03 MPa, and the tensile strength of the wire was 2148 MPa.

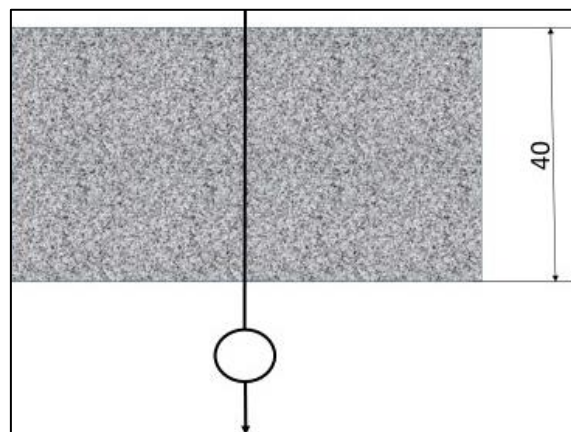


Fig. 1. Scheme for determining the shear stresses at the fibre-concrete interface

Based on the known shear stresses, the optimal fibre length was calculated using formula (1) [30]. The calculated data were used in the experimental planning matrix, the planning conditions for which are given below.

Table 1. Experimental planning conditions

Level	Variable factors			Step variation		
	X_1	X_2	X_3	X_1	X_2	X_3
Maximum	1	1	1	100%/0	0,5%	1,2%
Minimum	-1	-1	-1	70%/30%	0,1%	0,8%
Average	0	0	0	85%/15%	0,25%	1%

X_1 - cement/slag ratio; X_2 - fibre content by volume, %; X_3 - plasticizer consumption by weight of cement, %.

$$\frac{l_0}{2} = r_f \sigma_f / 2\tau \quad (1)$$

Where: l_0 – is the load transfer length from the fibre to the matrix, cm; r_f – is the fiber radius, cm; σ_f – is the fiber strength, N/cm²; τ – is the shear stress at the fiber-matrix surface, N/cm².

To determine the strength of the fibres, they were preliminarily tested for tensile strength. The volumetric fibre content at which multiple concrete failures should occur was determined from the equation adopted in the fracture mechanics of fibre composites [31,32];

$$V_f \sigma_f - \sigma'_f = \sigma_m V_m \quad (2)$$

Where V_f – is the fiber volume content, cm³; σ_f – is the fiber strength, N/cm²; σ'_f – is the fiber stress at matrix failure, N/cm². These values were calculated by pulling.

To compensate for spatial disorientation and ensure the required load-bearing capacity of the composite, the theoretically necessary volume content of the fiber, calculated according to the basic equation (2), was corrected by introducing a scale coefficient of orientation;

$$K_{or} = \frac{1}{\eta_o} = \frac{1}{0.41} \approx 2,43 \quad (3)$$

The amount of fiber obtained as a result of the calculation (increased by 2.43 times) was accepted as the zero (average) level in the planning matrix of the multifactorial experiment. The concrete composition was determined based on the volume of voids in the ore processing tailings, which were then filled with cement. The initial aggregate-to-cement volume ratio was 1:0.42. For ease of practical dosing, these values were converted to mass fractions. To minimize material variability, the concrete specimens were fabricated using a single batch of Portland cement, iron ore tailing wastes, and fly ash. All components were proportioned by mass. The concrete matrix was prepared in a laboratory-scale pan mixer (forced-action type) utilizing a strict loading sequence: iron ore tailings, cement, and fibres. The dry constituents were homogenized for 2 min, followed by the introduction of water pre-blended with a plasticizer, after which wet mixing continued for another 2 min. The water-to-cement (w/c) ratio was kept constant at 0.4 regardless of the fly ash replacement level.

All 17-specimen series were cast into rigid steel moulds and consolidated on a vibration table for 20 s within a single operating day. The casting sequence was fully randomized to eliminate systematic experimental errors. After 24 h, the specimens were demoulded and transferred to a chamber maintained at a temperature of 20 ± 2°C and a relative air humidity of 85–92%. At the curing age of 30 days, the compressive strength of the concrete was evaluated using a hydraulic testing machine with a maximum capacity of 500 kN. Precise alignment of the specimens on the bearing platens was ensured by a centering template. The loading rate was automatically maintained at a constant velocity of 0.6 MPa/s. All destructive tests were performed within a single working day. The intra-series coefficient of variation for the compressive strength ranged between $C_v = 4.5\%$ and 7.0% , demonstrating high data convergence and experimental reproducibility.

3. Test results and Discussions

Experimental design and data processing were conducted using STATISTICA, a statistical analysis software package developed by StatSoft that implements data analysis, data management, data collection, and data visualization functions using statistical methods. To assess the influence of process factors on the physical and mechanical properties of the developed material, a one-way analysis of variance (ANOVA) was conducted. The following variables were analysed: cement-to-slag ratio (%), fibre content (%), and plasticizer dosage (%). The dependent variable was the material's compressive strength, R, in MPa. Summary ANOVA statistics for all studied factors are presented in Table 2.

Table 2. Results of the ANOVA for the influence of factors on compressive strength

Variable factor	Factor level	Average value (M), MPa	95% Confidence Interval, MPa	Fisher's criterion (F)	Level of significance (p)	Statistical significance of the effect
Ratio of cement and slag, %	70	29,5	[26,5; 32,5]	18,766	0,00011	Significant ($p < 0,05$)
	85	32,7	[30,2; 35,3]			
	100	41,2	[38,2; 44,1]			
Fibre content, %	0,1	33,2	[27,9; 38,5]	1,222	0,32429	Insignificant ($p > 0,05$)
	0,25	32,8	[28,4; 37,2]			
	0,5	37,5	[32,2; 42,8]			
Dosage of plasticizer, %	0,8	36,7	[31,2; 42,2]	0,731	0,49880	Insignificant ($p > 0,05$)
	1,0	32,8	[28,5; 37,1]			
	1,2	34,3	[28,3; 40,4]			

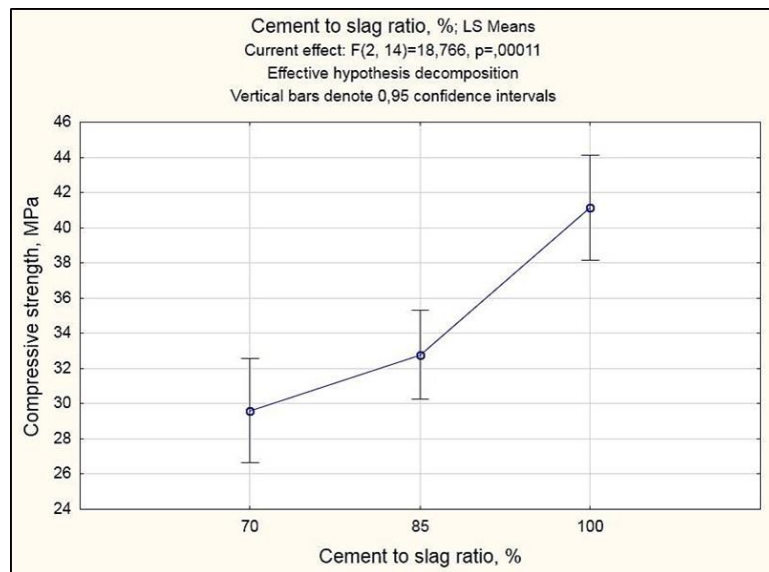


Fig. 2. Diagram of marginal averages of the dependence of compressive strength on the cement/ash ratio

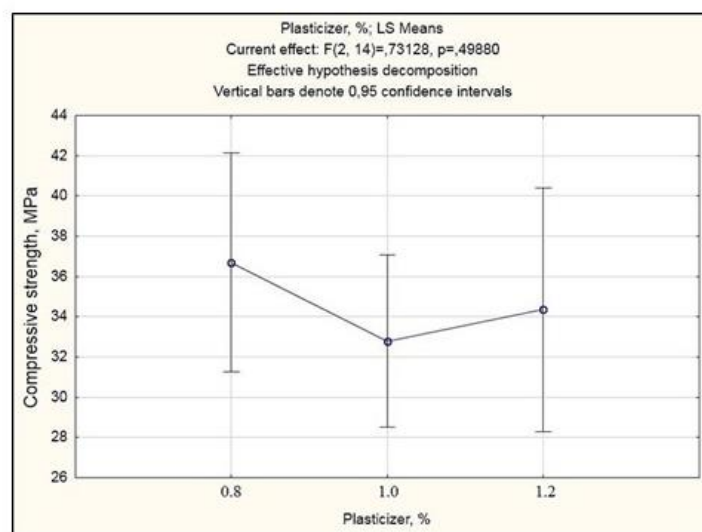


Fig. 3. Diagram of marginal means of the dependence of compressive strength on the amount of plasticizer

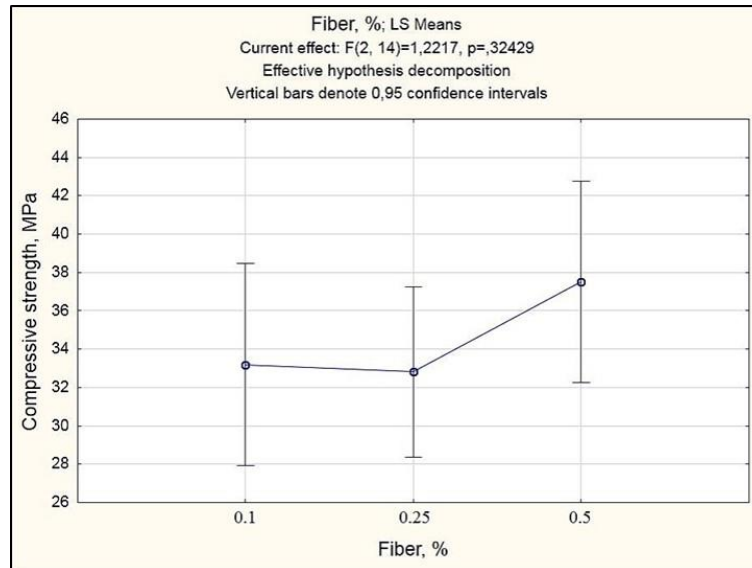


Fig. 4. Marginal mean diagram of the dependence of compressive strength on fibre content

Data analysis reveals a highly statistically significant effect of the cement/slag ratio on compressive strength ($F_{(2,14)} = 18.766$); $p = 0.00011$. A clear trend toward increased strength characteristics with increasing cement content is observed. Going from 70% to 85% cement results in a slight increase in average strength from 29.5 MPa to 32.7 MPa, with their 95% confidence intervals partially overlapping. However, the maximum strength is achieved at 100% cement content, where the average strength is 41.2 MPa. This result is statistically significantly different from that in the other groups, confirming the key role of the cement matrix in forming the material's strength framework. The plasticizer content factor in the studied range (0.8–1.2%) was found to be statistically insignificant ($F_{(2,14)} = 0.731$); $p = 0.49880$. A Fisher exact test value of less than one confirms that the variability within the experimental groups significantly exceeds the differences between them. Fluctuations in the mean strength values (36.7 MPa at a dosage of 0.8%; 32.8 MPa at 1.0%; and 34.3 MPa at 1.2%) are within the margin of error of the experiment, and the confidence intervals almost completely overlap. The obtained results indicate that a change in plasticizer consumption by 0.2% from the base level does not cause structural degradation and allows for the maintenance of stable strength properties.

Varying the fibre concentration from 0.1% to 0.5% did not show a statistically significant effect on compressive strength ($F_{(2,14)} = 1.222$); $p = 0.32429$. The change in mean values (from 32.8 MPa to 37.5 MPa) is random. The high dispersion (data scatter) and the wide overlap of the confidence intervals at all three points indicate that fibre addition at the indicated dosages neither worsens nor improves the compressive load-bearing capacity of the material. This is consistent with the classical theory of dispersed reinforcement, according to which fibre has a greater impact on tensile and flexural strength, as well as crack resistance, while having no decisive effect on pure compressive strength. Therefore, the determining factor for ensuring maximum compressive strength is optimizing the binder composition by increasing the cement content. Fibre addition and plasticizer dosage within the studied ranges can be varied based on workability or economic feasibility, as they do not have a critical impact on the final compressive strength. To study the structure of intercomponent bonds in more depth, a multivariate regression analysis was performed, which made it possible to construct a three-dimensional response surface of compressive strength from the combined influence of the cement/ash ratio and plasticizer dosage factors.

$$R=15.34+0.021x-122.15y+0.1768xy+105.4228y^2 \quad (4)$$

Analysis of the mathematical model using the regression equation shows that the positive coefficient for pair interaction (+0.1768xy) mathematically confirms the synergistic (reinforcing) effect: a joint increase in both components gives an additional increase in strength.

The quadratic term ($+105.4228x^2$) indicates a strong nonlinear (parabolic) nature of the strength growth along the cement axis.

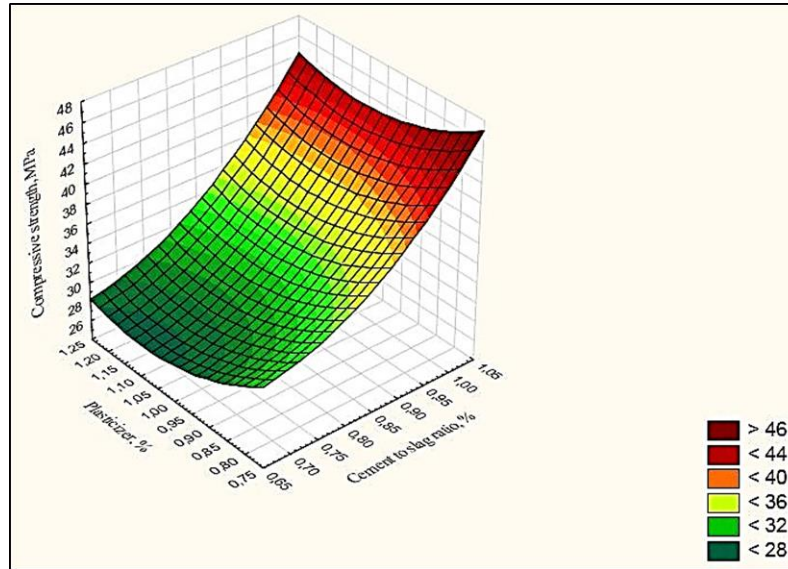


Fig. 5. Three-dimensional surface diagram of compressive strength depending on the cement/slag ratio and plasticizer

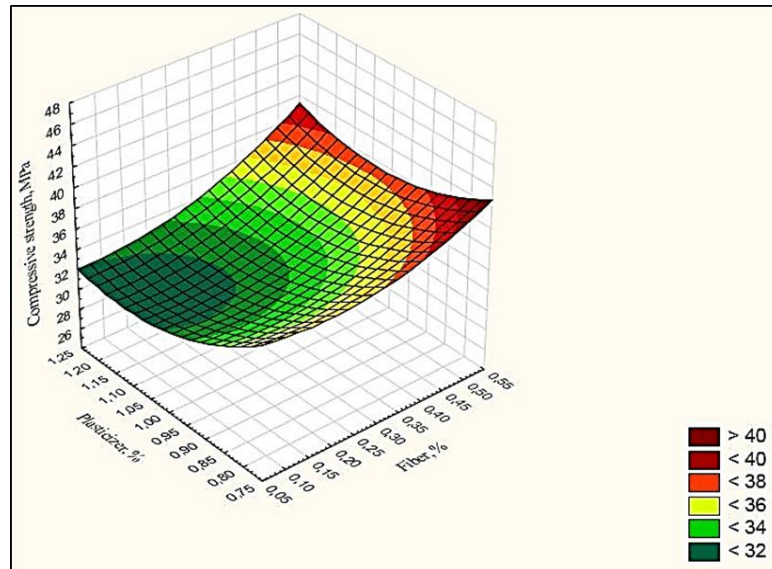


Fig. 6. Three-dimensional surface diagram of compressive strength as a function of volumetric fibre content and plasticizer consumption

The resulting response surface has the form of a nonlinear parabolic plane with a pronounced synergistic effect of component interaction, as confirmed by the positive coefficient for the paired term of the regression equation ($+0.1768xy$). It was found that the effect of the plasticizer is selective: in the low cement content region (0.65–0.80), varying the additive does not lead to a change in strength. However, when moving to the high cement content region (≥ 1.0), increasing the plasticizer consumption provides a sharp increase in the strength properties of the composite.

Analysis of the diagram shows that the plasticizer is effective only at high cement contents (from 0.95 to 1.05). As the plasticizer dosage increases in this zone, the material's strength increases significantly, reaching an extreme. At low cement contents (0.65–0.80), changing the amount of plasticizer has virtually no effect on strength. The maximum zone on the graph is reached at a cement/ash ratio ≥ 1.00 ; plasticizer $\geq 1.0\%$. Strength exceeds 46 MPa (peak in the upper right corner of the surface). This is the optimal technological region. The minimum zone is reached at a

cement/ash ratio ≤ 0.75 ; plasticizer $\leq 0.9\%$. Strength drops below 28 MPa. Thus, the maximum compressive strength values (over 46 MPa) are localized in the extreme region at the maximum studied values of the factors: a cement/ash ratio in the range of 1.00–1.05 and a plasticizer dosage of 1.0–1.2%. Additionally, the nature of the combined influence of fiber content and plasticizer dosage on the compressive strength of the composite was investigated. The resulting response surface (Fig. 6) has a nonlinear character such as a hyperbolic paraboloid (saddle-shaped surface), which indicates a strong mutual dependence of the studied factors.

$$R=59.0256-0.072x-1.1074y+0.0002x^2+0.0011xy+0.0107y^2 \quad (5)$$

Analysis of the model shows that the positive quadratic terms ($+0.0002x^2$) and ($+0.0107y^2$) mathematically describe the U-shaped concavity of the graph on both axes. As you move toward the ends of the range, strength begins to increase. The pair coefficient ($+0.0011xy$) confirms that a simultaneous increase in both parameters shifts the system into a zone of higher strength indicators.

As can be seen in the diagram, the surface has a distinct saddle shape (a hyperbolic paraboloid). This indicates a complex nonlinear interaction between the fibre and the plasticizer. Maximum strength is achieved only when both factors are at their limits (either both at their maximums or both at their minimums). If you use a large amount of fibre but little plasticizer (or vice versa), the strength of the material drops sharply. This is explained by the physics of the process: a large amount of fibre requires high fluidity of the mixture (provided by the plasticizer) for uniform distribution without the formation of voids. The absolute maximum is achieved with the maximum fibre content and maximum plasticizer. Strength in this case exceeds 40 MPa. This is also observed in the opposite corner, with minimal fibre and minimal plasticizer, strength remains at 38–39 MPa.

With a high plasticizer dosage and minimal fibre content, strength drops below 31 MPa. It has been established that the introduction of increased fibre content requires a corresponding increase in the dosage of the plasticizing additive. At the maximum saturation point of the mixture with fiber and plasticizer, a synergistic effect is observed—compressive strength reaches an extreme, exceeding 40 MPa. This is explained by the fact that the optimal plasticizer dosage ensures the necessary mixture rheology for high-quality fibre distribution without the formation of structural defects and pores. Conversely, an imbalance in the composition (for example, excessive plasticization against a background of low fibre content) leads to a localized drop in strength below 31 MPa due to possible mixture delamination or a loss of matrix density. The most pronounced inter factorial interaction was established when analyzing the combined influence of the cement/ash ratio and the fibre content (Fig. 7).

$$R=62.0378-101.1042x-0.0619y+77.624x^2+0.0557xy+0.0001y^2 \quad (6)$$

Analysis of the mathematical model shows that the significant pairwise coefficient ($+0.0557xy$) strongly suggests synergy. An increase in one factor greatly enhances the return on an increase in the other. The high coefficient for the square of cement ($+77.624x^2$) indicates a steep nonlinear slope of the response plane toward the upper right corner. The diagram shows that the resulting response surface is characterized by a sharp nonlinear rise in the region of maximum values of both factors, indicating a strong synergistic effect ($+0.0557xy$). The surface reveals a synergistic effect from all three pairs of factors. Individually, fibre did not increase strength, but when combined with cement, a cumulative, explosive increase in strength is observed. Fibre reveals its potential only in "rich," high-density cement matrices. In "lean" compositions (cement/ash ≤ 0.75), the introduction of fibre, conversely, leads to structural deterioration and a decrease in strength.

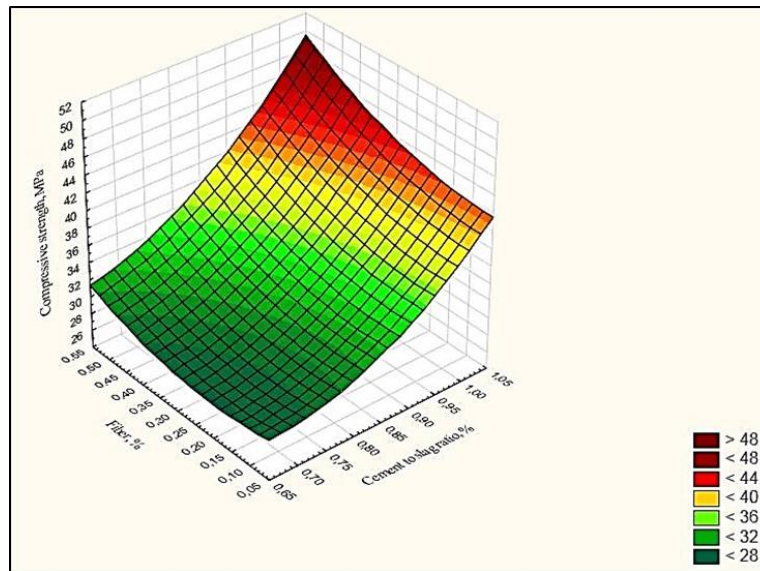


Fig. 7. Three-dimensional surface diagram of cement/ash ratio and fibre volume content

The absolute maximum of 52 MPa in the experiment is observed at a cement/ash ratio ≥ 1.00 and the maximum fibre content. This is the highest point in the entire series of experiments. At a low cement/ash ratio (0.65–0.75), the strength drops below 28–32 MPa at any fibre level. Moreover, the worst result is recorded precisely with high fibre content on lean cement. Experiments have shown that the isolated conclusion of a single-factor analysis regarding the invariance of strength with fibre content was incomplete. Fibre is capable of effective compressive strength, but only when creating a high-density cement matrix (cement-to-ash ratio ≥ 1.00), which ensures proper adhesion of the cement stone to the fibre surface and anchorage of the micro reinforcement elements. With a combination of maximum cement and fibre content, the absolute maximum composite strength over the entire study cycle was recorded—over 52 MPa. Conversely, adding fibre to compositions with low cement content (0.65–0.75) is inappropriate, as it leads to a localized deficiency of binder for fibre encapsulation, decomposition of the structure, and maintaining minimal strength (less than 32 MPa).

When designing a fibre-reinforced concrete structure, the spatial orientation of the reinforcing elements is a determining factor. Under conditions of chaotic (three-dimensionally arbitrary) fibre distribution within the cement matrix, only a certain portion of the fibres are oriented along the principal tensile stress vector. According to classical fracture mechanics of fibre composite materials [31, 32], the geometric efficiency coefficient of randomly oriented discrete reinforcement in a given loading direction is $\eta_0 \approx 0.41$ (which corresponds to the theoretical limit for a three-dimensional isotropic distribution). However, the results of physical and mechanical compression tests of fibre-reinforced concrete specimens revealed a discrepancy between classical theoretical models and the actual macro fracture behavior. Despite the standard increase in fibre content, classical rupture of the fibres themselves under load was observed exclusively in specimens with an excessive (exceeding the calculated optimum) fibre content. At the average (calculated) level of reinforcement, the destruction of the samples proceeded predominantly by the mechanism of pulling out fibres from the matrix, which is clearly illustrated by the nature of crack formation in Fig. 8.

This phenomenon is explained by fundamental principles of composite micromechanics theory. The behaviour of dispersion-reinforced systems with fibre lengths shorter than the critical length ($L < L_{crit}$) is not described by the classical linear "rule of mixtures," since the tensile stress distribution along the fibre length does not reach extreme values. The key criterion determining the tradeoff between adhesive and cohesive failure is the fiber's aspect ratio—the ratio of its length to its diameter (L/d). In the studied composite, the geometric aspect ratio (L/d) was 104. Experimental data demonstrate that for this "cement stone - fibre" system, this aspect ratio was below the critical value ($(L/d) < (L/d)_{crit}$). Due to the insufficient contact surface area of a single fibre, the shear stresses at the phase boundary reached the adhesive bond strength limit (or the

matrix yield strength) before the normal tensile stresses in the central cross-section of the fibre exceeded its tensile strength limit. Therefore, to realize the strength potential of the reinforcing material, either an increase in the fibre aspect ratio or an increase in the adhesive strength of the contact zone is required.

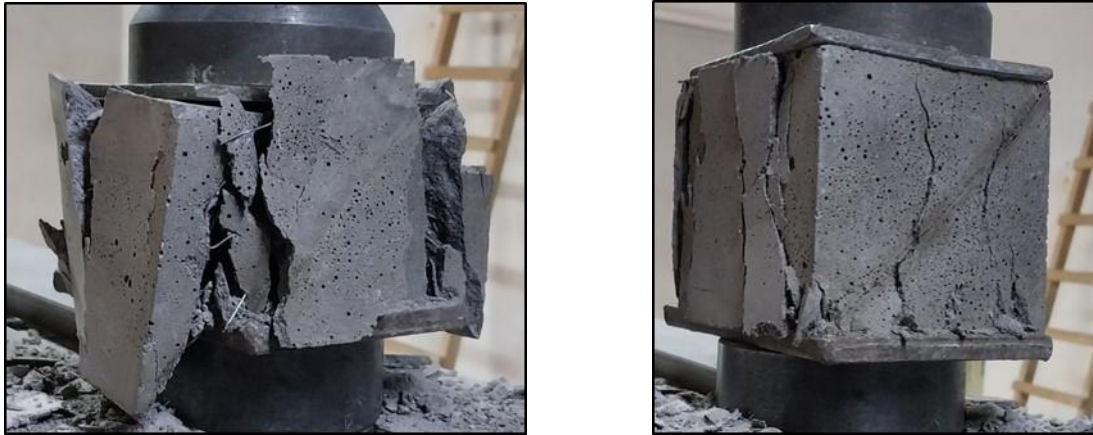


Fig. 8 Samples of fibre-reinforced concrete after compression testing

4. Conclusions

This study addressed a practical materials science problem involving the synthesis of high-strength fibre-reinforced concrete using large-scale waste: wet magnetic separation tailings from the Poltava Mining and Processing Plant and fly ash from fluidized bed boilers.

The mortar matrix design methodology is based on minimizing intergranular voids. Experiments have shown that determining the voids in man-made sand and filling them with the calculated volume of cement paste results in an optimal aggregate-to-cement ratio of 1:0.42. Converting these proportions to mass fractions guarantees highly reproducible results, stable rheology, and minimal strength fluctuations in concrete.

A single-factor analysis of variance (ANOVA) demonstrated high statistical significance for the binder structure—the cement-to-ash ratio (Fisher's exact test: $F_{(2,14)} = 18.766$; $p = 0.00011$). This confirms the leading role of the cement paste density in creating a rigid skeleton. A 100% cement content provides a peak average compressive strength of 41.2 MPa. In contrast, isolated variations in the dosage of Fluid Premia 196 hyper plasticizer (0.8–1.2%; $F_{(2,14)} = 0.731$; $p = 0.49880$) and the volume fraction of steel fibre (0.1–0.5%; $F_{(2,14)} = 1.222$; $p = 0.32429$) were statistically insignificant. The strength variations in these groups are random, which is consistent with the theory of a non-critical direct effect of discrete reinforcement on pure compressive strength. Multivariate regression analysis and 3D response surfaces revealed complex nonlinear synergistic effects of all factor pairs:

- Cement/ash and plasticizer: a positive binary interaction coefficient (+0.1768xy) and parabolic growth along the cement axis (+105.4228x²) were recorded. The plasticizer exhibits selective efficiency: in "lean" mixtures, it is invariant, while in "rich" matrices (ratio ≥ 1.0), the combined growth of the components dramatically increases strength due to optimized particle packing and hydrodynamic dispersion.
- Fibre and plasticizer: the surface have the shape of a hyperbolic paraboloid. The saddle-shaped appearance demonstrates the interdependence of the parameters: a high fibre concentration requires increased plasticizer consumption to maintain workability and prevent clumping. An imbalance in the composition (excess additive with a fibre deficiency) reduces strength below 31 MPa due to hidden defects and mixture segregation.
- Cement/ash and fibre: the strongest synergistic effect was detected (+0.0557xy). A combined increase in these factors yields an explosive increase in strength. Fibre reveals its potential only in high-density matrices (ratio ≥ 1.00), where a maximum of over 52 MPa is recorded.

In binder-deficient mixtures (≤ 0.75), fibre decomposes the matrix, reducing strength below 32 MPa.

When designing the spatial skeleton of fibre-reinforced concrete, a three-dimensional random distribution of reinforcement was taken into account. Taking into account the limit of geometric efficiency ($\eta_0 \approx 0.41$), an orientation scale factor of ($K_{or} \approx 2.43$) was introduced. However, mechanical testing revealed deviations from the linear rule of mixtures. Sample failure occurred by pulling the fibers out of the matrix without breaking the wire. The geometric elongation of the fibers ($L/d = 104$) was below the critical value. The contact area of individual fibres was insufficient, so shear stresses at the phase boundary reached the bond strength limit (1.03 MPa) before the normal tensile stresses exceeded the steel wire's tensile strength limit (2148 MPa).

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