

Article

Improving Lightweight Structural Tuff Concrete Composition Using Three-Factor Experimental Planning

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Abstract: Research into lightweight structural concrete using volcanic tuff is of great importance to the construction industry. These materials have excellent thermal insulation properties, which helps improve the energy efficiency of buildings. A three-factor experimental design was used to build the statistical model. The test methods used were methods for determining the crushability of volcanic tuff, determining the average density, compressive strength and thermal conductivity of lightweight structural concrete. The influence of basalt fiber on the properties of lightweight structural concrete has been determined. The optimal compositions of lightweight structural concrete using tuff have been selected. The compressive strength of lightweight structural concrete reached 32.0 MPa. The average density range is 1754.6–2114.0 kg/m³. Good thermal conductivity values were obtained in the range of 0.653–0.818 W/m·K. The article obtained the optimal compositions of lightweight structural concrete using volcanic tuff as a filler.

Keywords: experiment planning; lightweight structural concrete; volcanic tuff; basalt fiber; thermal conductivity



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1. Introduction

An important direction in modern construction is the study of lightweight concrete. The low density and high strength of such concretes distinguish them from traditional concretes. These properties make lightweight structural concrete ideal for use in a wide variety of building structures.

One of the advantages of lightweight concrete for structural applications is its light weight. The use of such concrete can reduce the weight of structures and reduce the load on the foundation. This is particularly true when constructing a high-rise building or bridge structure.

In the study mentioned below, the advantages of lightweight concretes (average density up to 1800 kg/m³) over heavyweight concretes were demonstrated. The primary benefits are a reduction in the weight of structures by 30–40% and an increase in the compressive strength of enclosing structures. Modern lightweight concretes can exhibit increased strength at reduced weight and belong to strength classes up to B15–20 [1]. Lightweight concrete can be used in structural applications, according to the American Concrete Institute. To be considered structural lightweight concrete, the minimum 28-day compressive strength must be 17 MPa. Non-structural lightweight concrete is used for insulation and weight reduction with strengths less than 17 MPa. Benefits of lightweight concrete include improved thermal performance, fire resistance and reduced dead load, which reduces labor, transport and formwork costs. It has lower stiffness and tensile strength than conventional concrete but a reduced dead load, which compensates for the reduction in the modulus of elasticity [2].

Volcanic tuffs represent an important local raw material base that can be utilized in the building materials industry for both masonry materials and for the preparation of

masonry mortar, lightweight concrete or autoclaved aerated concrete. This paper presents the results of tests with a mathematical three-factor planning experiment conducted for lightweight structural concrete based on volcanic tuff used as an aggregate. Additionally, the incorporation of fibers, such as basalt fibers, is a crucial factor in enhancing the strength of lightweight structural concrete. The findings of the study [3] demonstrate that the incorporation of basalt fiber into concrete enhances its compressive and flexural strength, which in turn reduces the width of cracks and improves the strength and durability of concrete.

The following study [4] demonstrates the efficacy of polyfractional aggregate (sand and gravel up to 10 mm in size) derived from volcanic tuff in producing a rheologically stable self-compacting low-density concrete mix with a cone diameter of up to 90 cm. It is noteworthy that the utilization of polyfractional aggregate from volcanic tuff enables the creation of a rheological stable self-compacting low-density concrete mix. Moreover, the compressive strength of the hardened concrete ranged from 24 to 57 MPa, indicating the material's capacity to resist compressive forces. This suggests that the concrete can be utilized for structural purposes in construction. Furthermore, the average dry density of the concrete, less than 1800 kg/m³, indicates that it has a relatively low density. This can assist in reducing the overall weight of the structure, which in turn improves the material's energy efficiency. Overall, this study suggests that the use of volcanic tuff as an aggregate in the production of concrete has the potential to result in the creation of a strong, lightweight and structurally sound material.

In the aforementioned study [5], the proportions of the concrete mixture were defined as 1:2, 3:2, 2:2, which correspond to the quantities of cement, sand and tuff aggregate, respectively. Consequently, the analogous proportions for conventional concrete are 1:2, 3:3.7 by the mass of Portland cement, sand and granite aggregates, respectively, in the concrete composition. The coarse aggregates of tuff and granite, occupying the same volume of approximately 63% in the unit volume of concrete, were used to determine the aforementioned mix proportions. However, it should be noted that the aggregates have different masses. Mixtures were prepared utilizing a water–cement ratio of 0.4.

The study in [6] demonstrated that tuff fillers are suitable materials for the production of low-density structural concrete with an average density of 2038 kg/m³ and compressive strength of 26.0 MPa. The compressive strength of tuff concrete exhibited a positive correlation with an increasing water–cement ratio, reaching a compressive strength of 25.5 MPa at a B/C ratio = 0.6. The mean density of tuff concrete is 19% lower than that of conventional concrete. Consequently, it is an appropriate material for the construction of structures with enhanced earthquake resistance.

A further study of tuff concrete examines the utilization of the waste generated during the development of volcanic tuff. This waste makes up between 30 and 50 percent by volume and can be used to produce natural porous aggregates that are currently lacking in construction. These aggregates are estimated to be missing by up to 60 million m³ per year. Conversely, the cost of these materials will be significantly lower than that of similar concrete mortars on artificial porous aggregates. A high-quality and durable lightweight concrete is proposed for use in the manufacture of wall materials. This is to be formulated with the use of porous tuff aggregates as part of the mortar, specifically within the range of 0–5 mm and as a coarse aggregate within the range of 5–20 mm [7].

The findings revealed that concrete comprising a 30% ratio of volcanic tuff aggregate demonstrated a 28% reduction in tensile strength compared to conventional concrete comprising limestone aggregate ($R_{cd} = 300 \text{ kg/cm}^2$). After 28 days of curing, these observations were recorded. In concrete production, aggregates with maximum size fractions of 10, 20 and 40 mm are utilized. It is evident that these size fractions significantly influence the strength of concrete. The relationship between the strength of concrete and the size of its aggregate fraction has been quantified. Tests demonstrated that an increase in aggregate fraction resulted in a 0.2, 5 and 14% enhancement in the strength of concrete on limestone aggregate relative to volcanic tuff [8].

A further study [9] also examined the possibility of using volcanic tuff as lightweight structural concrete. In order to determine the suitability of tuff for this purpose, two specimens were subjected to a series of tests. These included a determination of the tuff's specific gravity and water absorption; the measurement of its average density and porosity, which was performed in accordance with the standards set out in ASTM C29/C29M-17a [10]; and an assessment of its readability on an abrasive machine. Tuff aggregate was employed as a replacement for limestone aggregate at varying ratios, including 25%, 50%, 75% and 100% replacement with volcanic tuff aggregate. The specimens demonstrated satisfactory porosity with a value of 0.605, corresponding to a porosity of 60.5%. The two specimens, zeolitic volcanic tuff and black volcanic tuff, demonstrated water absorption values of 8.7% and 10.2%, respectively.

In addition, the material properties, including compressive strength and thermal conductivity, were subjected to experimental evaluation. Flow table tests were conducted in accordance with the specifications set forth in EN 12350-5 [11] in order to produce lightweight concrete specimens with varying binders. Lightweight concrete with a density of less than 1000 kg/m³ was produced using expanded clay lightweight aggregate and a variety of admixtures, including limestone powder, expanded clay, tuff, fly ash and two types of sand, smooth and regular. The compressive strength of all the concretes studied was found to be above 18 MPa [12].

The average void ratio of tuff samples from the studied deposits ranges from 0.12 to 0.37, with porosity values between 10 and 27 percent. The average density of the tuff samples is between 1660 and 2250 kg/m³. These values are consistent with their use as an aggregate. The high density values of the tuff samples indicate the major textural characteristics of the rock. The high void and porosity ratios in the samples indicate low density values. The compressive strength of the material was found to decrease with the increase in the replacement ratio at seven days of age, with the percentage decrease observed being 11, 20, 45.8 and 53.6, respectively for replacement ratios of 5, 10, 15 and 20%. At 28 days of age, the compressive strength was observed to drop by 4.1, 9.4, 38.22 and 47.8, respectively [13].

Upon the addition of tuff to the mixture, a slight decrease in the density of the specimens was observed, from 1700 kg/m³ (control specimen) to 1510 kg/m³. After the specimens were subjected to firing (burning) at a temperature of 900 °C, the density was observed to decrease by 10.9% in comparison to the density recorded before the firing process [14].

The specimens containing 5% zeolite tuff exhibited the highest average compressive strength over the 7–28-day period, and the specimens from the 10% group demonstrated the highest flexural strength. With regard to the specimens tested after 56 days, the highest compressive strength was observed in the 10% zeolite group, a trend that was also confirmed for the period of 90 days [15].

The thermal conductivity of the saturated rocks was 0.79 W/m·K and 0.55 W/m·K for the white-dark tuff and the brown tuff, as stated in the above-mentioned article [16]. This value is consistent with the results of several studies on higher bulk densities of about 2000–2100 kg/m³. A comparison of the results with the standards revealed that all the tested samples exhibited a higher heat capacity than anticipated. The standards established for porous stones stipulate a specific heat capacity of 1 J/kg·K. Consequently, the results indicate that, for instance, volcanic tuff exhibits a 30% higher heat capacity than anticipated. This is of great interest, because the thermal performance of the structural system varied markedly with the specified characteristics.

Nanostructured mortars with conductivity coefficients of 0.2–0.4 W/m·K were successfully produced. With the exception of the coquina mortar, the conductivity coefficients were found to be below 0.2 W/m °C, which is consistent with the category of tuff-filled insulating mortars as defined in [17].

The research presents an investigation into the hygrothermal properties of lightweight concretes, encompassing both thermal conductivity and moisture absorption. The study

employs a combination of laboratory experiments and numerical modeling to ascertain the influence of varying concrete compositions on these properties. The study highlights the significance of selecting appropriate lightweight aggregates to achieve an optimal equilibrium between thermal conductivity and moisture absorption. It has been demonstrated that the type and quantity of lightweight aggregates exert a considerable influence on the hygrothermal characteristics of concrete [18].

In order to ascertain the optimal characteristics of concrete and concrete mixture from their composition, and to limit the number of laboratory works, experiments are conducted utilizing mathematical methods of experimentation planning and processing of their results. The planning of an optimal experimental plan is undertaken by taking into account a number of predetermined factors. Three-factor planning models are the most prevalent models for identifying the optimal values of an output quantity, such as the compressive strength of concrete [19]. The principles of experimental theory are of great significance in the modern world. Experimentation is a procedure for selecting the number and conditions of experiments necessary and sufficient to solve the problem with the required accuracy. In addition to the control of products, it is often necessary to control the parameters of technological processes. This task can be solved by testing statistical hypotheses. Nevertheless, the most significant impact can be achieved not by controlling quality parameters, but by organizing experiments in such a way. The objective of experimentation is to determine the minimum number of experiments and conditions required for their conduct, as well as the most appropriate methods for the mathematical processing of results and decision making [20]. The book *Design of Experiments for Engineers and Scientists* by J. Antony [21] describes in detail the methodology of full factorial design. This approach allows all the factors affecting the process or product under study to be systematically varied to reveal their influence on the results. The book offers both theoretical foundations and practical examples of using full factorial experimentation to achieve optimal results. Anthony's technique emphasizes the importance of statistical analysis of data, selection of representative levels of factors and interpretation of interactions between them.

The paper states that the organization of experiments is of great consequence for the establishment of the minimal number of experiments, the conditions under which they are to be conducted and the selection of methods for the mathematical processing of results and decision making. Such a goal can be achieved by subjecting statistical hypotheses to empirical testing and controlling quality parameters.

The results of the experiment plan and statistical modeling indicated that it was possible to determine the optimal compositions of lightweight structural concrete using volcanic tuff. The use of statistical methods and the design of the experiment allowed for the development of a more reliable and efficient approach to determine the optimal influencing factors and properties of concrete. The study also provided insight into the variability of the optimal parameters as well as the intervals of variation of the factors. In conclusion, the results of this study can contribute to the development of more efficient and sustainable building materials.

The purpose of this article is to study the influence of volcanic tuff on the properties of lightweight structural concrete and to determine the optimal compositions of such concrete, taking into account the use of tuff as a filler. The study involves developing a statistical model based on a three-factor experimental design and estimating parameters such as the average density, compressive strength and thermal conductivity. Additionally, the effect of adding basalt fiber on the properties of lightweight structural concrete is investigated.

The novelty of the work lies in the study of the use of volcanic tuff as an aggregate for lightweight structural concrete, which has not been studied sufficiently so far. The conducted experiments show that the addition of basalt fiber significantly improves the mechanical and thermotechnical characteristics of concrete. This approach makes it possible to create a material with high strength and excellent thermal insulation properties, which helps to increase the energy efficiency of buildings and reduce heating and cooling costs.

Basalt fiber significantly increases the compressive strength of concrete. This makes the material more resistant to loads and prolongs its service life. Fiber also helps to improve the microstructure of concrete, reducing the likelihood of cracks and other defects, which increases the durability of the material.

2. Materials and Methods

2.1. Materials

2.1.1. Tuff Aggregate

The research involved the use of crushed stone and sand obtained by crushing overburden volcanic rocks in jaw crushers. Subsequently, the grain mixture was subjected to sieving through a set of standard sieves, resulting in the formation of fractions. The fractions were 0.16–5 mm, 5–10 mm and 10–20 mm. These were formed during the extraction of volcanic tuff (Chunja village, Uygur district, Almaty region) and were of lower quality, unsuitable for the manufacture of piece products. The research employed pieces of overburden volcanic rocks with a size range of 50–150 mm. In order to create aggregates, the overburden was crushed in a jaw crusher and sieved through a set of standard sieves. Consequently, aggregates were produced from tuff in fractions. The resulting fractions were 0.16–5 mm, 5–10 mm and 10–20 mm. The first fraction corresponds to fine aggregate, which is defined as sand. The second and third fractions correspond to coarse aggregate, which is defined as crushed stone.

2.1.2. Basalt Fiber

Basalt fiber with a length of 3.2 mm was employed as a reinforcing admixture. The manufacture of basalt fiber for concrete begins with the melting of volcanic rocks at high temperatures. This process yields a high-quality natural material that is resistant to water, corrosion, fire and alkalis and chemicals. Figure 1 shows chopped pieces of basalt fiber filament yarns for concrete.



Figure 1. Chopped pieces of complex threads made of basalt fiber.

2.1.3. Cement

The binder used in the production of lightweight structural concrete was Portland cement CEM I as defined by standard EN 196-3 [22]. To ensure the stability and reliability of the results, the requisite quantity of cement for the entire series of experiments was determined and procured in a single transaction. The cement was stored in a dry environment to prevent the effects of moisture on its properties.

2.1.4. Superplasticizer

The MasterGlenium 51 superplasticizer additive was employed to reduce the quantity of water present in the concrete mortar, given that the incorporation of porous tuff tends to elevate the water–cement ratio (W/C). The additive was employed in all samples. The additive was employed in an amount equal to 0.8% of the weight of the cement.

2.2. Methods

2.2.1. Crushability of Volcanic Tuff Aggregate

The crushability of crushed stone is quantified through the measurement of grain destruction during a crushability test, in line with the standard EN 1097-2:2020 [23]. The crushability test method involved the use of a cylindrical drum with a diameter of 711 mm and length of 508 mm rotated at a frequency of 30–33 rpm. A sample of dried material weighing about 5 kg was placed in the drum, consisting of fractions passing through a 14 mm mesh sieve and remaining on a 10 mm mesh sieve, and 12 steel balls 46.8 mm in diameter were added. The drum was closed and rotated 500 revolutions. Once the rotation was complete, the contents of the drum were removed, the balls were separated, and the material was sieved through a 1.6 mm mesh sieve. The mass of material that passed through the sieve was determined and used to calculate the crushability coefficient, which allowed for estimating the mechanical strength and resistance of the material to fragmentation.

Calculation of the tuff concrete composition was carried out according to the method given by the Departmental Construction Standards (1992) [24].

2.2.2. Preparation of Tuff Concrete Specimens

From the compositions obtained by mathematical planning in laboratory conditions, cube samples with dimensions of $100 \times 100 \times 100$ mm were made. The samples were manufactured in accordance with ASTM C138/C138M [25]. The freshly mixed concrete mixture was compacted into molds by vibration or compaction. Then, the surface of the specimens was leveled and protected from evaporation. For each composition, 3 samples were made. Specialized devices were used to measure the volume and mass of the specimens and to determine the air content of the concrete.

2.2.3. Determination of the Average Density of Tuff Concrete Samples

In accordance with the Government Decree, standard ASTM C138/C138M, the average density of lightweight concrete was determined. The samples are dried to constant mass in a desiccator at 100–110 °C. The samples are then weighed on an analytical balance to determine the dry mass. They are then weighed on an analytical balance to determine the dry mass. The volume of the samples is measured by immersion in water or geometrically. The average density is calculated as the ratio of dry mass to volume. This method provides an accurate determination of the average dry density of concrete, which is important for the evaluation of its mechanical and thermal properties. In order to calculate the density index of concrete cubes of regular shape, their volume is measured using measuring tools, such as a ruler and a caliper. In this instance, the permissible error is limited to 1 mm.

To determine the moisture content and moisture transfer effect of concrete also according to ASTM C138/C138M, cubic concrete specimens of 3 pieces for each composition were initially formed and labeled for identification. The samples were then weighed to determine the initial mass, after which they were dried in a desiccator at 105 ± 5 °C until constant mass was achieved. After drying, the samples were cooled to room temperature in a protected environment and re-weighed to determine the mass in the completely dry state. The difference between the initial mass and the mass of the dry sample was used to calculate the moisture content of the concrete as a percentage. This method provides an accurate and reliable determination of concrete moisture content, which is critical to ensure its quality and durability in building structures.

2.2.4. Determination of Compressive Strength of Tuff Concrete Samples

The compressive strength of the tuff concrete samples was determined in accordance with the European Standard EN 12390-3:2009 [26]. During the compression test, the cube specimens are placed with one of the selected faces on the lower base plate of the testing machine (press) and centered relative to its longitudinal axis, using the marks on the plate of the testing machine (press) or a special centering device.

Once the test specimen has been positioned on the testing machine platens or supplementary steel plates, it is necessary to align the upper platens of the testing machine with the upper support face of the test specimen, ensuring that both surfaces are in complete contact with each other. The specimen is subjected to a constant rate of load increase (0.6 ± 0.2 MPa/s) until failure. Figure 2 presents photographic images of the tuff concrete specimen following fracture. For each composition, 3 samples of cubes were made and tested.



Figure 2. Compression test of a $100 \times 100 \times 100$ mm cube specimen.

2.2.5. Determination of Thermal Conductivity of Tuff Concrete

The thermal conductivity of tuff lightweight concrete was determined by a thermal conductivity meter, the ITP-MG4 (250), in accordance with EN 12667:2001 [27]. The tests were conducted by measuring the temperature of both sides of the samples placed between the heater at 65°C and laboratory conditions, in comparison to a reference material with known thermal conductivity. To ensure the accuracy of the measurements, the heat flux is determined under steady-state conditions, taking into account both heat conduction within the specimen and heat transfer through the air wall. This typically indicates that measurements were conducted approximately three to four hours after the commencement of the experiment. In this instance, 3 specimens for each composition with dimensions of $250 \times 250 \times 30$ mm were prepared for the purpose of determining the thermal conductivity.

In addition, the thermal conductivity was determined by determining the moisture content and moisture transfer effect in the specimens, which could affect the data obtained because the tuff filler contained in lightweight structural concrete is porous. The moisture content of the samples affected the thermal conductivity values.

2.2.6. Design of Experimental Methodology

In order to achieve this goal, it is necessary to determine the composition of the concrete mixture. This involves establishing the ratio between the components that form the material's structure and providing a given level of quality indicators.

The solution to such problems is carried out with the help of mathematical methods of the theory of planning the experiment. The use of these methods will allow us to obtain a mathematical model describing the dependence of quality indicators on the level of varying factors.

For the purposes of experimental study, it is recommended that a rotating central composite plan be employed in the matrix F, with $n = 3$.

The effect of the amount of sand and demolished stone, as well as dispersed reinforcement (fiber), on the strength, average density, and thermal conductivity of tuff concrete will be investigated.

The fundamental principle underlying the three-factor planning of experiments and the optimization of the composition of lightweight structural concrete utilizing mathematical statistics is the establishment of a mathematical relationship between the given material properties and the flow rate, the properties of constituent components and the technological factors. Table 1 depicts the variations in factors impacting the composition of concrete.

Table 1. Levels of variation of influencing factors.

No.	Factor	Components	Levels of Variation				
			−1.682	−1.0	0	+1.0	1.682
1	x_1	Tuff sand (TS)	1.318	2	3	4	4.682
2	x_2	Tuff coarse aggregate (TCA)	0.682	2	4	6	7.364
3	x_3	Basalt fiber (BF)	0.00318	0.01	0.02	0.03	0.03682

The efficacy of an experiment is contingent upon the meaningful formulation of the problem, the appropriate selection of research methodology, the identification of the primary factors and their variations and the comprehensive interpretation of the results in a physical context. The selection of factors and parameters for the optimization of lightweight structural concrete was based on the criteria of technological and economic feasibility.

A three-factor quadratic dependence experiment was planned, the planning conditions of which are presented in Table 2. For all compositions, the water–cement ratio was assumed to be $W/C = 0.4$. In the initial stages of the study, a comprehensive factor plan was developed. Subsequently, experiments 1 to 8 were conducted. Subsequently, six parallel experiments were conducted at the center of the plan, with experiments 15 to 20. The outcomes of these experiments provide compelling evidence that the model exhibits nonlinear characteristics. To provide a more comprehensive description, it is necessary to conduct experiments in star points (experiments 9–14).

Table 2. Experiment planning matrix and experimental data.

No.	Matrix of the Plan			
	x_0	x_1	x_2	x_3
1	1	−1	−1	−1
2	1	+1	−1	−1
3	1	−1	+1	−1
4	1	+1	+1	−1
5	1	−1	−1	+1
6	1	+1	−1	+1
7	1	−1	+1	+1
8	1	+1	+1	+1
9	1	−1.682	0	0
10	1	+1.682	0	0
11	1	0	−1.682	0
12	1	0	+1.682	0

Table 2. Cont.

No.	Matrix of the Plan			
13	1	0	0	−1.682
14	1	0	0	+1.682
15	1	0	0	0
16	1	0	0	0
17	1	0	0	0
18	1	0	0	0
19	1	0	0	0
20	1	0	0	0

A review of the available data suggests that the study employed an experimental design based on a full factorial plan. This involved conducting experiments at various points along the plan, as well as at the center and at the star points. The results of the center experiments demonstrated that the model is nonlinear, necessitating the conduct of additional experiments for a more comprehensive description. Consequently, experiments were conducted at the star points with the objective of enhancing the accuracy and completeness of the model. This iterative approach to experiment planning and data analysis is a common practice in scientific research, with the aim of ensuring the reliability and robustness of the results.

The significance of quadratic effects (nonlinearities) is confirmed by experimental data through the process of checking the conditions (Formulas (1)–(3)).

$$\frac{1}{8} \sum_{i=1}^{\infty} R_i = 17.5 < \frac{1}{6} \sum_{i=15}^{20} R_i = 28.0 \quad (1)$$

$$\frac{1}{8} \sum_{i=1}^{\infty} \rho_i = 1835.6 < \frac{1}{6} \sum_{i=15}^{20} \rho_i = 20.52 \quad (2)$$

$$\frac{1}{8} \sum_{i=1}^{\infty} \pi_i = 0.719 < \frac{1}{6} \sum_{i=15}^{20} \pi_i = 0.798 \quad (3)$$

Using the experimental data in Table 2, we calculate the values of regression coefficients according to Formulas (2)–(11). As a result, we obtain mathematical models describing the dependence of compressive strength, average density and thermal conductivity on the amount of sand, crushed stone and fiber in the form of Formulas (4)–(14):

$$y_i = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_{12} x_1 x_2 + a_{13} x_1 x_3 + a_{23} x_2 x_3 + a_{11} x_1^2 + a_{22} x_2^2 + a_{33} x_3^2 \quad (4)$$

$$a_0 = \frac{A}{N} \left[2\lambda^2 (n+2)(0y) - 2\lambda c \sum_{i=1}^k (iiy) \right] = 28.1 \quad (5)$$

$$a_1 = \overline{N}(iiy) = 1.3 \quad (6)$$

$$a_2 = \overline{N}(iiy) = 6.6 \quad (7)$$

$$a_3 = \overline{N}(iiy) = 1.5 \quad (8)$$

$$a_1^2 = \frac{A}{N} \left[c^2 [(n+2)\lambda - k](iiy) + c^2 (1-\lambda) \sum_{i=1}^k (iiy) - 2\lambda c(0y) \right] = 2.6 \quad (9)$$

$$a_2^2 = \frac{A}{N} \left[c^2 [(n+2)\lambda - k](iiy) + c^2 (1-\lambda) \sum_{i=1}^k (iiy) - 2\lambda c(0y) \right] = -4.0 \quad (10)$$

$$a_3^2 = \frac{A}{N} \left[c^2 [(n+2)\lambda - k](iiy) + c^2 (1-\lambda) \sum_{i=1}^k (iiy) - 2\lambda c(0y) \right] - 1.9 \quad (11)$$

$$a_{12} = \frac{c^2}{N\lambda} (iu y) = 0.9 \quad (12)$$

$$a_{13} = \frac{c^2}{N\lambda}(iuy) = -1.05 \quad (13)$$

$$a_{23} = \frac{c^2}{N\lambda}(iuy) = 1.05 \quad (14)$$

The regression coefficients of the strength, average density and thermal conductivity equations are given in Table 3.

Table 3. Regression coefficients.

y_i	a_0	a_1	a_2	a_3	a_{12}	a_{13}	a_{23}	a_{11}	a_{22}	a_{33}
R, MPa	28.1	−1.3	−6.6	−1.5	0.9	−1.05	1.05	−2.6	−4.0	−1.9
$\rho, \text{kg/m}^3$	2.05	−0.003	−0.05	−0.02	−0.005	0.001	0.01	−0.05	−0.08	−0.01
$\lambda, \text{W/m}\cdot\text{K}$	0.79	−0.02	−0.02	0.0007	−0.006	0.0004	−0.009	−0.02	−0.04	−0.002

The coded and natural values of the varied coefficients are given in Table 4.

Table 4. Coded and natural values of coefficients.

Code	Natural Values		
	$TS (x_1), g$	$TCA (x_2), g$	$BF (x_3), g$
−1	200	400	1
0	400	600	2
+1	800	1200	4

Statistical analysis of the obtained regression equations by F-criterion confirmed their adequacy.

The analysis of significance of regression coefficients established that the mathematical function of thermal conductivity can be simplified by taking $x_3 = 0$, and then it will have the following Formula (15):

$$\lambda = 0.79 - 0.02x_1 - 0.02x_2 - 0.02x_1^2 - 0.04x_2^2 \quad (15)$$

The results of the experiments shown in Table 5 allow us to determine the optimal values of the coefficients x_1, x_2, x_3 . For this purpose, we examine the obtained functions for extrema and obtain a system of equations of the Formula (16):

$$\frac{\partial y_i}{\partial x_1} = 0; \frac{\partial y_i}{\partial x_2} = 0; \frac{\partial y_i}{\partial x_3} = 3 \quad (16)$$

Table 5. Test results of cube samples after 28 days.

Experimental Data					
No.	R, MPa	$\rho, \text{kg/m}^3$	Moisture Cont., %	$\lambda_0, \text{W/m}\cdot\text{K}$	$\lambda_1, \text{W/m}\cdot\text{K}$
1	26.0	1892.0	6.1	0.757	0.898
2	29.5	1956.5	6.2	0.744	0.872
3	11.5	1201.3	6.5	0.772	0.886
4	9.0	1798.2	6.9	0.669	0.782
5	28.0	1840.0	7.0	0.774	0.864
6	17.5	1851.4	6.8	0.696	0.749
7	8.0	1754.6	6.7	0.687	0.745
8	8.0	1791.0	6.1	0.653	0.709

Table 5. Cont.

Experimental Data					
No.	R, MPa	$\rho, \text{kg/m}^3$	Moisture Cont., %	$\lambda_0, \text{W/m}\cdot\text{K}$	$\lambda_1, \text{W/m}\cdot\text{K}$
9	25.0	2083.4	6.0	0.802	0.922
10	22.0	1993.6	6.2	0.769	0.855
11	25.2	2101.0	6.2	0.781	0.860
12	12.6	1850.3	6.9	0.661	0.743
13	27.0	1951.4	6.2	0.727	0.822
14	25.0	1888.6	6.3	0.818	0.936
15	28.5	2011.0	6.2	0.810	0.928
16	29.5	2112.0	6.3	0.811	0.933
17	32.0	2097.8	6.4	0.793	0.902
18	31.6	2114.0	6.3	0.789	0.905
19	28.0	2045.6	6.4	0.799	0.921
20	29.8	2051.6	6.4	0.791	0.913

Solving these systems sequentially, we see that the highest value of strength will have the composition at values as follows (Formula (17)):

$$x_1 = -0.3; x_2 = -1.0; x_3 = -0.55; R_b = 32 \text{ MPa} \quad (17)$$

The composition will have the lowest thermal conductivity if the following is used (Formula (18)):

$$x_1 + 2; x_2 = -2; x_3 = 0; \lambda = 0.47 \text{ W/m}\cdot\text{K} \quad (18)$$

For this composition, the compressive strength will be 8.7 MPa.

A coefficient is considered to be established if its name and area of definition are specified. In the selected area of definition, it can have several values corresponding to the number of its different states. The quantitative or qualitative states of the factor selected for the experiment are called factor levels [28].

Compressive strength (Formula (19)):

$$R_{av} = 17.5 - 1.3x_1 - 6.6x_2 - 1.5x_3 - 2.6x_1^2 - 4x_2^2 - 1.9x_3^2 + 0.9x_1x_2 - 1.05x_1x_3 + 1.05x_2x_3 \quad (19)$$

Next, we find the standard deviation (S_{td1}) by expressing Formula (20):

$$S_{td1} = \sqrt{\left(\frac{\sum (x - x_1)^2}{n} \right)} \quad (20)$$

Then we find the standard deviation (S_{td2}) by expressing Formula (21):

$$S_{td2} = \sqrt{\left(\frac{\sum (x - x_2)^2}{n} \right)} \quad (21)$$

This is calculated as the root of the sum of squares of differences between the sample elements and the mean value divided by the number of elements in the sample.

Using Formulas (20) and (21), we obtain the standard deviation for the mean values of experimental and calculated data: $S_{td1} = 8.01$; $S_{td2} = 8.3$.

The adequacy of the equation is checked by Fisher's criterion. The equation is adequate, because the ratio F_{cr} thus compiled is less than the theoretical F (Formula (22)).

$$F = \frac{S_{ad}^2}{S_{rep}^2} = \frac{2.22}{0.32} \quad (22)$$

Since $F = 6.9 > F_{cr} = 0.05$, the model is considered adequate. Thus, all the coefficients are significant with 99% reliability.

The objective of this investigation is to examine the impact of various factors on the output parameters of lightweight structural concrete, with a particular focus on its average density and strength. The factors under investigation are the quantity of sand, crushed stone and dispersion-reinforcing admixture. For each test method, 3 samples were made in each composition, produced to obtain accurate experimental data and obtain average values.

3. Results and Discussion

3.1. Crushability of Volcanic Tuff Aggregate

The mass loss of the tuff following crushing was 13.5%. A special table was employed to determine the grade of the crushed rock, translating the percentage of crushability into a known grade. The grade at which it occurred is not specified. In accordance with EN 1097-2:2020, the crushability class of tuff aggregate is LA20, which means that tuff aggregate has favorable characteristics for construction work requiring durability and strength. This means that the aggregate can be used effectively in the production of concrete, asphalt and other building materials where high-quality aggregates are required. It also indicates that tuff aggregate has the potential to meet the performance requirements of engineering projects requiring durable and stable materials.

3.2. Determination of Average Density

The average density of tuff concrete, as determined by testing, is 1754.6–2112.0 kg/m³. It can be observed that the average density of formulations No. 2, 16, 18 and 20 has increased to 2114.0 kg/m³ (Table 5). As the ratio of components increased, the average density decreased. The lowest average density was observed in compound No. 7, with a value of 1754.6 kg/m³. There is no significant difference in the average density values of the concrete samples. The observed average density values are consistent with the values typically observed in lightweight structural concrete.

The moisture content of tuff lightweight structural concrete samples was higher than that of conventional concrete due to the porous structure of volcanic tuff. According to the ASTM C138/C138M standard, the moisture content of ordinary structural concrete is not more than 6% of the total mass of the sample. The values of tuff concrete specimens were in the range of 6–7% of the total mass of the specimens. The moisture content values of the samples are also listed in Table 5.

The tests conducted showed a range of average densities for the volcanogenic tuff concrete from 1754.6 to 2112.0 kg/m³. It is particularly noteworthy that compounds No. 2, 16, 18 and 20 revealed higher average densities reaching 2114.0 kg/m³. In contrast, compound No. 7 had the lowest average density of 1754.6 kg/m³. These differences in density across formulations emphasize the effect of the component ratio on the overall density of the concrete. It is worth noting that the relationship between compressive strength and density is important because it can affect the overall performance of concrete. For example, if the density of concrete is too low, it may not be able to withstand heavy loads, which can lead to structural failure. Conversely, if the density is too high, the concrete may become brittle and more prone to cracking.

3.3. Determination of Compressive Strength

The principal findings of the experiment are presented in Table 5. To obtain accurate and average values, three specimens were made for each composition. Each test was performed three times, each in accordance with the standards for that test method. The experiment revealed that certain compounds, namely, No. 2, 5 and No. 15 to 20, exhibited higher values of compressive strength. Among the formulations, No. 17 exhibited the most pronounced increase in compressive strength, reaching 31.0 MPa after 28 days. In

a comparable manner, formulations No. 2 and No. 18 demonstrated high compressive strength values of 29.5 MPa and 31.6 MPa, respectively.

Based on the information provided, it can be concluded that the optimum formulations to achieve high compressive strength values in lightweight structural concrete using volcanic tuff as filler are formulations No. 2, 5, 17 and 18. Among these compositions, No. 17 showed the highest increase in compressive strength, reaching 31.0 MPa after 28 days, followed by compositions No. 2 and No. 18, with compressive strength values of 29.5 MPa and 31.6 MPa, respectively. Hence, these compositions can be recommended for use where high compressive strength is required.

According to our analysis, compositions No. 2 and 5 showed good results due to the correct ratio of components. The correct amount of coarse aggregate, fine sand aggregate and reinforcing basalt fiber gave an optimum composition with good performance characteristics. The parallel compositions from 15 to 20 had similar proportions in the composition. These compositions have approximately the same density and thermal conductivity, although the strength values differ by 2 to 3 megapascals. From Figure 3, we can see that the strength values are higher depending on the increase in concrete density.

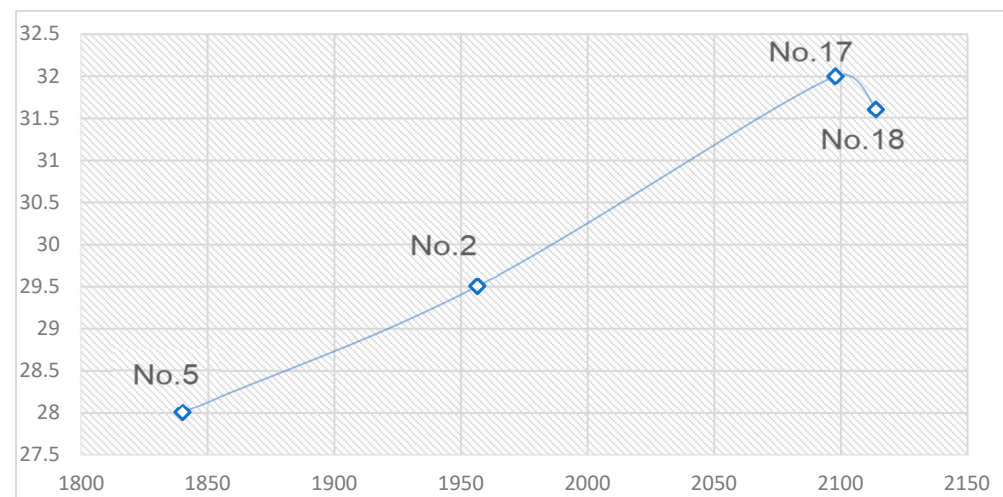


Figure 3. Average density (kg/m^3) and compressive strength (MPa) of cubic samples.

The mentioned research [29] deals with the results of compressive tests of various lightweight concrete (LWC) mixes with single-stage artificial aggregates (S-LWC) and granular lightweight aggregates (D-LWC). Compared to the reference specimen (REF), with a compressive strength of 27.84 MPa, the compressive strength of S-LWC Mix1 (16.11 MPa), Mix2 (17.64 MPa) and Mix3 (16.72 MPa) decreased by 42.13%, 36.64% and 39.94%, respectively, whereas for D-LWC Mix1 (17.03 MPa), Mix2 (19.06 MPa) and Mix3 (18.31 MPa), the decreases were 38.83%, 31.54% and 34.23%. S-LWC Mix2 and D-LWC Mix2, containing 75% fly ash (FA), showed the best compressive strength among all the specimens. The lowest strength values were observed in Mix1 mixes with 80% FA, which is due to their lowest density. The results confirm the findings of previous studies indicating that increasing the proportion of lightweight aggregates and recycled materials reduces compressive strength but improves the environmental performance of concrete.

It is hypothesized that the amount of volcanic aggregate used in the compositions may have contributed to these higher compressive strength values. In particular, as the amount of fine aggregate (i.e., volcanic tuff sand) increases, the bond between fine and coarse aggregate decreases, which could result in lower compressive strengths. However, this trend does not seem to be reflected in the results obtained for formulations No. 2, 5, 17 and 18, suggesting that other factors may be influencing the compressive strength of these formulations.

Assuming that it is still a matter of compressive strength to density ratio, it is possible that the optimum values of these properties were obtained from the studies carried out on formulations No. 2, 5, 17 and 18. Based on these results, a statistical relationship between the compressive strength and density of concrete in the dry state was obtained.

3.4. Determination of Thermal Conductivity

The thermal conductivity coefficient (λ_0) of samples dried to constant mass is in the range of 0.661 to 0.757 W/m·K, as indicated in Table 5. This value is notably less than that of heavy concrete with a density of 2100 to 2500 kg/m³, which has been determined to have a thermal conductivity coefficient of 0.9 to 1.3 W/m·K.

After determining the moisture content of the samples, we can see that the thermal conductivity values are different between the samples dried to constant weight and the samples with moisture content. Due to the porous structure of tuff filler, lightweight tuff concrete has higher water absorption than ordinary concrete, and the thermal conductivity of the samples increased by 10–15% compared to the samples dried to constant weight. Therefore, Table 5 also presents the thermal conductivity (λ_1) before drying to constant weight and determining the moisture transfer effect of the samples. Also in Figure 4, we can see the difference in thermal conductivity values of dried and wet samples clearly in the graph.

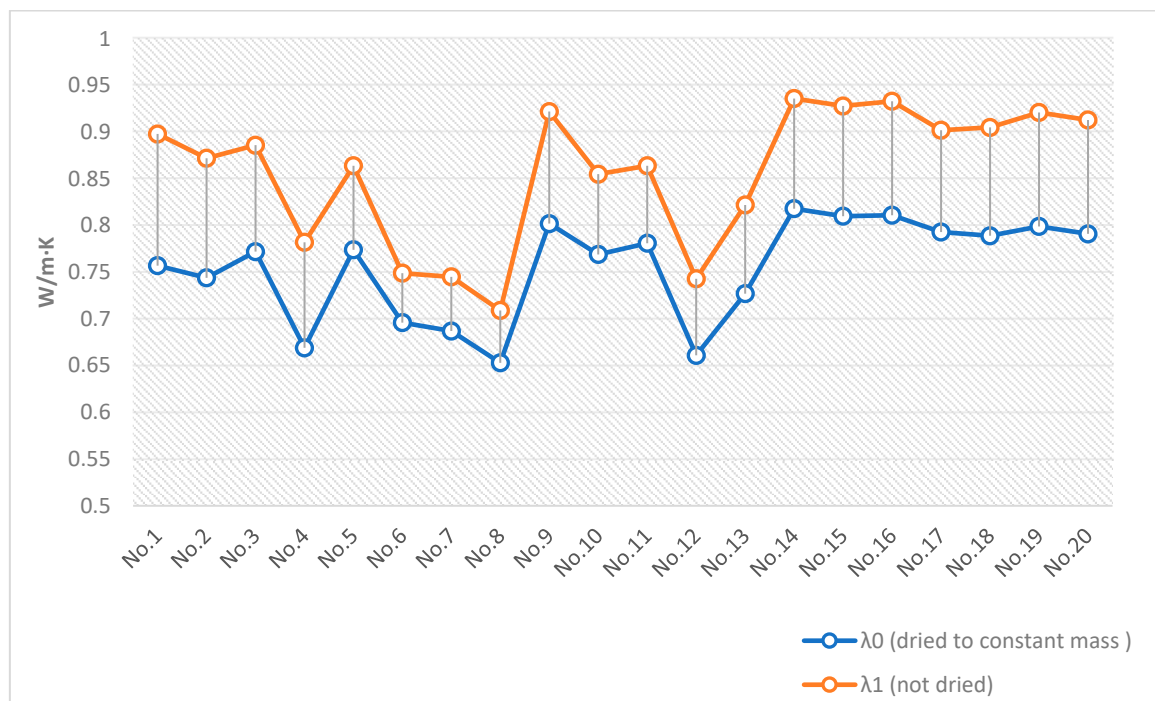


Figure 4. The difference between the thermal conductivity values of samples dried to constant mass and samples with moisture content.

Apparently, the thermal conductivity values of the manufactured concrete samples using volcanic tuff decreased with an increasing volume fraction of the tuff; their thermal conductivity was lower than that of conventional heavy concrete by about 40–50%. The thermal conductivity of concrete is not only affected by the property of volcanic tuff but also by small permeable voids, and the use of basalt fiber can also limit the heat transfer.

The paper in [29] presents the use of recycled aggregates, resulting in an average thermal conductivity reduction of 27% for S-LWC1 (0.73 W/m·K), 25% for S-LWC2 (0.75 W/m·K) and 22% for S-LWC3 (0.78 W/m·K). Similar reductions were recorded for D-LWC1 (0.78 W/m·K), D-LWC2 (0.74 W/m·K) and D-LWC3 (0.75 W/m·K), with reductions of 22%, 26% and 25%, respectively. The decrease in thermal conductivity was particularly

noticeable in S-LWC Mix1, where an increase in fly ash (FA) content resulted in a significant decrease in concrete density. In Mix1, the density decreased by more than 20% compared to the REF specimen, whereas for Mix2 and Mix3, the decrease was about 10%. The use of lightweight aggregates reduced the density and specific gravity of the concrete, resulting in lower thermal conductivity, as confirmed by other studies.

As we can see from the test results, compositions No. 7 (0.687 W/m·K), No.8 (0.653 W/m·K) and No.12 (0.661 W/m·K) have the lowest thermal conductivity values among all the specimens. We can see that as the amount of aggregate in the form of volcanic tuff increases, the thermal conductivity values decrease. But we also see that these compositions have the lowest compressive strength.

The study in [30] showed that the addition of basalt fiber to lightweight structural concrete significantly improves its thermal properties. The thermal conductivity of the specimen containing basalt fiber is 0.83 W/m·K, whereas the control specimen without fiber has a thermal conductivity of 1.17 W/m·K. This is 40% higher than that of the specimen with fiber, indicating a significant improvement in the thermal behavior of the material due to the addition of fiber. The optimum thermal conductivity values for the cement slab and the control slab are chosen to be 0.83 W/m·K and 1.17 W/m·K, respectively, which confirms the effectiveness of basalt fiber.

For the optimal composition of lightweight structural concrete with volcanic tuff, because of the optimal compressive strength and thermal conductivity, we take compositions No. 2, 5, 17 and 18.

Based on the analysis of previously obtained data using mathematical planning of experiments, the optimal compositions of lightweight structural concretes using volcanic tuff were determined. In accordance with the constructed three-factor experiment plan, actual tests were conducted, and the most optimal compositions of tuff concretes were identified. Research was conducted to determine the optimum compositions of lightweight structural concretes using volcanic tuff. Mathematical planning of experiments was used in the study to identify the most optimal tuff concrete compositions based on the results of actual tests.

The study was conducted using a rotational plan with three variables that included varying factors: sand (TS), crushed stone (TCA) and basalt fiber (BF). By manipulating these factors, the study was able to identify the most optimal tuff concrete compositions. It is likely that the results of this study can be utilized in the tuff concrete production process, helping to ensure that the final product is of high quality and meets the desired specifications. In addition, the results can be used to optimize the use of materials and resources, resulting in cost savings and increased efficiency.

When basalt fiber reinforcement was added to lightweight structural concrete using volcanic tuff, studies were conducted that included scanning electron microscope examination of the samples. The images obtained (Figure 5) provide valuable information on the microstructure and interaction of the components of this composite material. Raster image analysis allows us to study the dispersion of basalt fibers in the concrete matrix. The fibers have a fine but strong structure, which contributes to the strength and fracture resistance of the concrete. The images also show how the fibers interact with other components such as cement and aggregates to form strong bonds that can hold various loads and prevent cracking and failure.

Volcanic tuff helps to improve mechanical properties and reduce the weight of the structure. In general, the use of basalt fiber and volcanic tuff in lightweight structural concrete makes it possible to create a material with improved mechanical characteristics, increased strength and resistance to destruction. This opens new perspectives for the development of lightweight and strong building structures using innovative composite materials.

According to the results of the study, the area of the most optimal values of components of lightweight structural concrete with volcanic tuff is determined. Analyzing the above data, we take the most optimal compositions No. 2, 5, 17 and 18. Compound No. 2 has a high compressive strength (29.5 MPa), low average density and the lowest thermal

conductivity (0.744 W/m-K). Compound No. 5 has the lowest average density (1840 kg/m³) at high strength values. Compound No. 17 has the highest compressive strength (32.0 MPa) and lower average density than normal concrete.

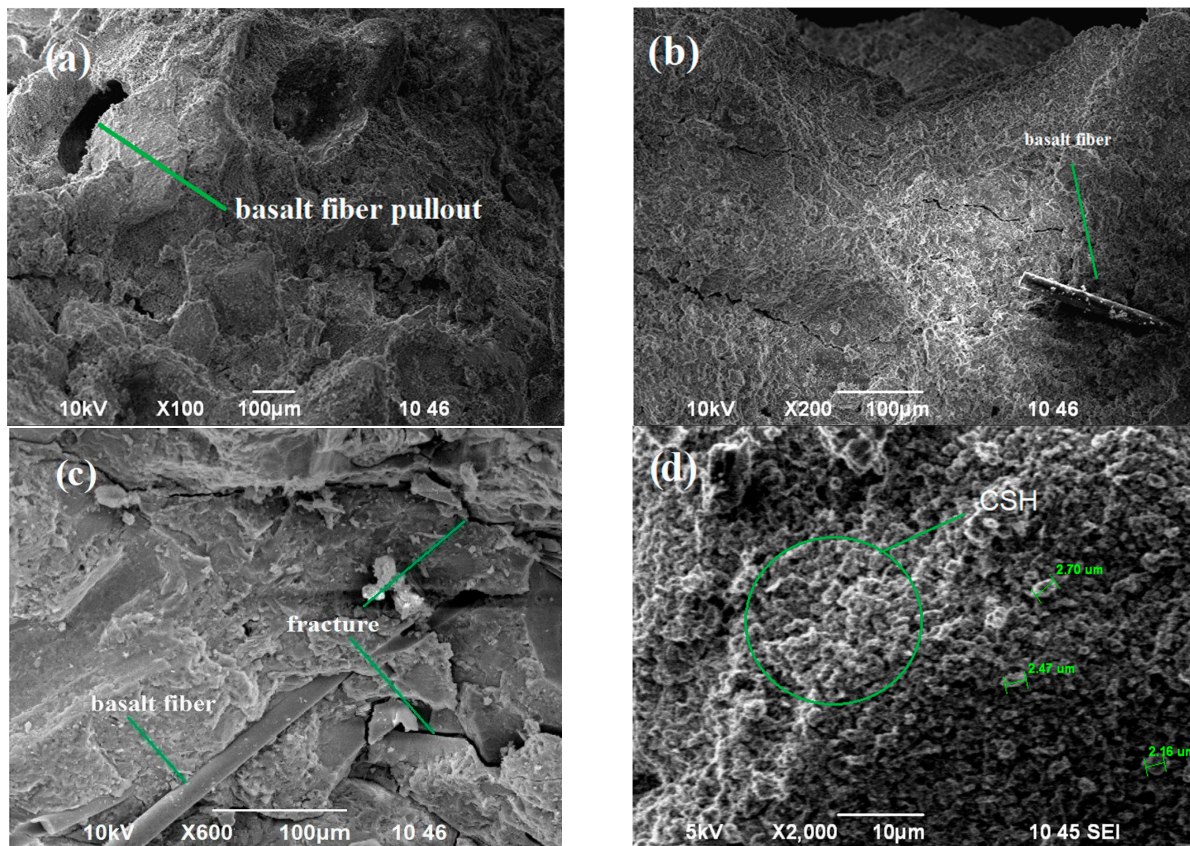


Figure 5. Scanning electron microscope photographs of the concrete structure: (a)—scanning microscope image in 100× magnification. We see the place where the basalt fiber was pulled out; (b)—scanning microscope image of the sample area in 200× magnification. On the figure, we can observe the basalt fiber; (c)—an image of the sample area obtained by a scanning microscope, at 600× magnification, where we see basalt fiber and cracks; (d)—a scanning microscope image at 2000× magnification, where we see calcium silicate hydrates (CSH).

4. Conclusions

The dependency parameters and objectives of the optimized influencing factors have been determined. The intervals of variation of the factors are selected. The plan and conditions of the experiment are chosen. Processing of the experimental results was carried out with the construction of mathematical models of the dependence of the concrete mixture and concrete properties on the selected factors. For a complete analysis of the experiment, a nomogram of optimization of the composition and technological process was constructed. The results were used to draw the following conclusions:

- In the experimental plan, the mean value of the data in the center of the plan is higher than the mean value of the obtained data in the core of the three-factor plan. This indicates the non-linearity of the constructed matrix. For this reason, star scores (+1.682; −1.682) were added to the experimental plan.
- By means of calculations and the determination of Fisher's coefficient ($F = 6.9 > F_{cr} = 0.05$) and the Student's coefficient, the adequacy of the constructed experiment plan was proved.
- As a result of the research, we also see that the moisture content of the samples with volcanic tuff is higher than that of conventional structural concrete and is in the range of 9–11% of the total mass, which significantly affected the thermal conductivity values.

- The mass loss in crush tests of tuff aggregate was 13.5%, which corresponds to the strength class of LA20.
- The average density of lightweight structural concrete using volcanic tuff was from 1754.6 to 2112.0 kg/m³. The moisture content of the samples ranged from 6 to 7%.
- The main performance properties of lightweight structural concrete with volcanic tuff filler were studied: compressive strength $R = 8.0 \dots 32.0$ MPa. Optimal compositions No.17 and 18 showed the highest strength ratings of 32.0 and 31.6 MPa, respectively.
- The thermal conductivity $\lambda = 0.653 \dots 0.841$ W/(m·K), which corresponds to the normative values and exceeds the characteristics of traditional lightweight structural concrete due to the optimized concrete structure using the developed and optimized composition. No. 2 and 5, with values of 0.744 W/m·K and 0.774 W/m·K, were selected for the optimal composition in terms of thermal conductivity. But it should also be remembered that samples not dried to constant mass had thermal conductivity values that were 10–15% higher.

Based on the experimental results and analysis of physical properties, it is concluded that the optimum compositions of lightweight structural concrete using volcanic tuff are No. 2, 5, 17 and 18. These compositions showed the highest values of compressive strength, with composition No. 17 showing the highest value of 32.0 MPa after 28 days. At the same time, the thermal conductivity values of these compositions were within the normative values and exceeded the characteristics of traditional lightweight structural concrete due to the optimized concrete structure with the use of the developed and optimized composition. Therefore, these optimized compositions are recommended for use in structural applications where high strength and thermal insulation properties are required.

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