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Article

Fractal model of the strength of lightweight concrete based on volcanic tuff taking into account the scale effect

Yerlan Khamza[1,*], Vladimir Selyaev[2], Maratbek Zhuginissov[1], Zhanar Zhumadilova[1]

[1]Institute of Architecture and Civil Engineering, Satbayev University, 050013, Almaty, Kazakhstan
[2]Department of Building Structures, Ogarev Mordovia State University, 430005, Saransk, Russia
*Correspondence: y.khamza@satbayev.university

Abstract. The study proposes a fractal model based on B. Mandelbrot's geometry. Mandelbrot geometry to describe the scale effect in concrete. It has been experimentally established that under-loading concrete undergoes degradation of its structure, which is expressed in the sequential destruction of fractals at different scale levels. It was found that the scale reduction leads to an increase in concrete strength: 20x20x20 mm specimens showed the highest strength among all four compositions (23.3-25.3 MPa). The average density of tuff concrete was also investigated: the smallest specimens had a density of 1961.3 kg/m³, while the largest specimens had a density of 1974.2 kg/m³, which is explained by the heterogeneity of the structure and pore distribution. The water permeability of concrete, evaluated through air permeability, showed that specimens with higher air permeability (30.2-30.5 s/cm³) had better water resistance (W14). These data indicate a correlation between air permeability and water resistance, which may be due to the denser structure and improved pore distribution. The study of air permeability makes it possible to predict the durability of concrete structures when exposed to moisture, as well as to improve the quality of building materials and reduce the cost of their operation.
Keywords: fractal dimension, compressive strength, structure, tuff, water permeability.

1. Introduction

When concrete structures (as well as other materials) fail, a characteristic roughness appears on the fracture surface. This relief depends on the material structure, strength ratio, its matrix and grains, loading rate, and other factors that can be observed in the study of different materials. According to the law of similarity, geometrically similar bodies of the same material, made and tested under the same conditions, should have the same strength. This study quantitatively analyzes the fractal and multifractal characteristics of concrete, using the theory of fractal geometry. The study utilizes fractal dimension and multifractal spectrum to describe the defect propagation in concrete. The results show that the fractal dimension effectively estimates the overall defect propagation, with a higher dimension reflecting a greater variety of defects [1].

Concrete, possessing a variety of heterogeneities, has a block-hierarchical structure, which corresponds to the principles of multiscale and self-similarity. Therefore, when describing the degradation process of a concrete structure, it is important to take into account the hierarchically of the block structure and the nesting coefficient of some blocks into others. It is assumed that the contact between the blocks can be represented as dilatant shells, which have different properties from the main body material. Research work [2] covers how the fracture processes in concrete can be analyzed at different scales and supports the view that contacts between structural blocks (dilatant shells) have distinct properties from the bulk material, influencing the material's overall behavior.

Water absorption of concrete is the ability of the material to absorb and retain water that enters it through capillaries and pores. This parameter is an important indicator of concrete quality, as it directly affects the durability, strength, and resistance of the material to various influences. The water absorption of concrete can affect its properties in the following ways: Strength: A high level of water absorption can lead to a reduction in the strength of concrete due to increased porosity and the formation of micro-cracks. Frost resistance: Concrete with high water absorption is more susceptible to failure during cyclic freezing and thawing because water freezing in the pores expands and causes mechanical stresses. Durability: Increased water absorption favors the penetration of aggressive substances such as chlorides and sulfates, which can lead to corrosion of reinforcement and concrete failure. Shrinkage and cracking: Water absorption affects shrinkage processes in concrete, which can lead to cracking and reduced concrete integrity. Thermal conductivity: Water in the pores of concrete can alter its thermal conductivity properties, which is important to consider when using the material in different climates. Including water absorption analysis of concrete in the study will allow a more complete assessment of its effect on the fractal dimension of the fracture surface and other key material properties. Relevant data are explored in a paper [3] analyzing the relationship between sorption and capillary coefficients.

However, it has been experimentally found that the strength of geometrically similar specimens depends on their dimensions. This phenomenon is called the scale effect [4], [5]. Several hypotheses have been proposed to explain the nature of the scale effect.

Other studies believe that the manifestation of the scale effect depends on the technology of manufacturing samples of different sizes [6], [7], [8], [9].

Research [10] considers a formalism designed to answer questions about Hamiltonian systems in contact with a thermal bath. The formalism is applied to a simple crack model to find, first, the rate at which a crack moves slowly through a brittle body as a result of thermal fluctuations and, second, the rate at which the crack goes from slow to fast motion. The dominant exponential behavior of these processes is calculated accurately, but the pre-factors are only approximately estimated. Some solutions cannot be considered in the traditional sense as corresponding to a saddle point transition. By considering the crack as an isolated Hamiltonian system, it is shown that irreversible behavior can occur because, although the probability of moving from the past to the present is equal to the probability of moving back from the present to the past, the probability of moving further into the future is exponentially greater.

Research [11] shows that the fractal surface has a multiscale hierarchical structure. In the research, it was found that the structure is preserved when the scale is changed from 0.01 mm to 150 mm. It was obtained that the stress-strain state in the specimen before fracture has little effect on the fractal dimension of the captured periodograms. Their processing showed that the fractal dimension, D, obtained in the splitting experiments (D=1.061) and the fractal dimension obtained in the bending experiments (D=1.057) are different and on average equal to D=1.060. The experiments were carried out on specimens with a cross-section of 100×100 mm in the range of compressive strengths from Rb=7.5÷37.5 MPa. It was found that the concrete strength does not affect the value of fractal dimension. The values of fractal dimension in the investigated specimens along the crack development and across are practically the same.

In the research [12], the fractal dimensions of the fracture surface of concrete specimens are measured using the periodograms obtained. However, there is no data on the strength of the concrete specimens studied or their composition; the paper does not contain descriptions of the physical and mechanical characteristics of the concrete materials. The only concrete characteristic mentioned in the article is the maximum size of coarse aggregate for each of the tested specimens. As can be seen, in the plastic zone, where different types of fractal-microcracks can be formed from pores and aggregate contacts, they will be partially destroyed along the bonding surfaces when the main crack is formed. When studying the structure of a material that has not yet fractured, the contact zones may be colored by Koch-type curves, which is related to the structure formation process of cement concrete in the process of gaining its ultimate strength.

The study showed [13] that after 28 days of curing, the compressive strength was highest for specimens cured under air conditions (20 ± 3°C, relative humidity 65 ± 5%) and lowest for specimens cured under conditions (20 ± 3°C, relative humidity 95 ± 5%). Analyses of the effect of sorption capacity on compressive strength demonstrated that both surface and internal sorption capacity have no apparent relationship with compressive strength. Although the samples differed in surface water absorption, the difference in internal water absorption was minimal. High surface water absorption reduces the strength of only the surface layer of concrete, while the overall strength of concrete depends on both structures - surface and internal. Consequently, the strength of concrete cannot be evaluated by water absorption alone.

The hypothesis that cement-concrete structures have fractal characteristics has been empirically substantiated. Considering that the concrete structure is subject to process cracks and the possible formation of cracks between aggregate grains, it is logical to use fracture mechanics methods to model the fracture process. The basis of the developed A. Griffith's model is formed on the concepts of Euclidean geometry. It is known that concrete has a fractal structure, which is a concept in the field of geometry. When considering the failure mechanisms of concrete, it is important to consider the invariant multiscale structure of the material. The hypothesis that concrete structure failure can be modeled as a discrete quantum process has been experimentally confirmed [14].

In light of the reviewed literature, the primary issue lies in the incomplete understanding of how concrete's block-hierarchical structure, multiscale behavior, and fractal dimensionality contribute to its fracture processes under varying conditions. While existing studies analyze concrete's structural heterogeneities and the scale effect, the relationship between water absorption and fractal dimensions remains unclear. Additionally, the impact of the scale effect and manufacturing techniques on strength variations across geometrically similar specimens needs further investigation. This gap justifies the study of these factors to improve concrete durability and performance predictions.

The purpose of this article is to investigate the fracture features of concrete structures and to study the influence of various factors on the fractal dimensionality of fracture surfaces. The study analyses geometrically similar concrete specimens, their structure and strength characteristics, and considers the scale effect and its nature. Special attention is given to the block-hierarchical structure of concrete and the principles of multiscale and self-similarity. Additionally, the paper discusses the water absorption of concrete and its effect on the physical and mechanical properties of the material.

2. Methods

2.1 Materials used in the preparation of the samples

Filler: Volcanic tuff from the Almaty region of the Republic of Kazakhstan was used as the main concrete filler for the study. Volcanic tuff is a sedimentary rock.

Binder: Portland cement of M500 grade 'Mordovcement PTS 500' of Russian production was used as a binder. Cement "Mordovcement" M500 contains mineral active impurities that determine its properties. It is characterized by the stability of characteristics. It is used in piling foundations, construction of load-bearing structures, and modern highways [15].

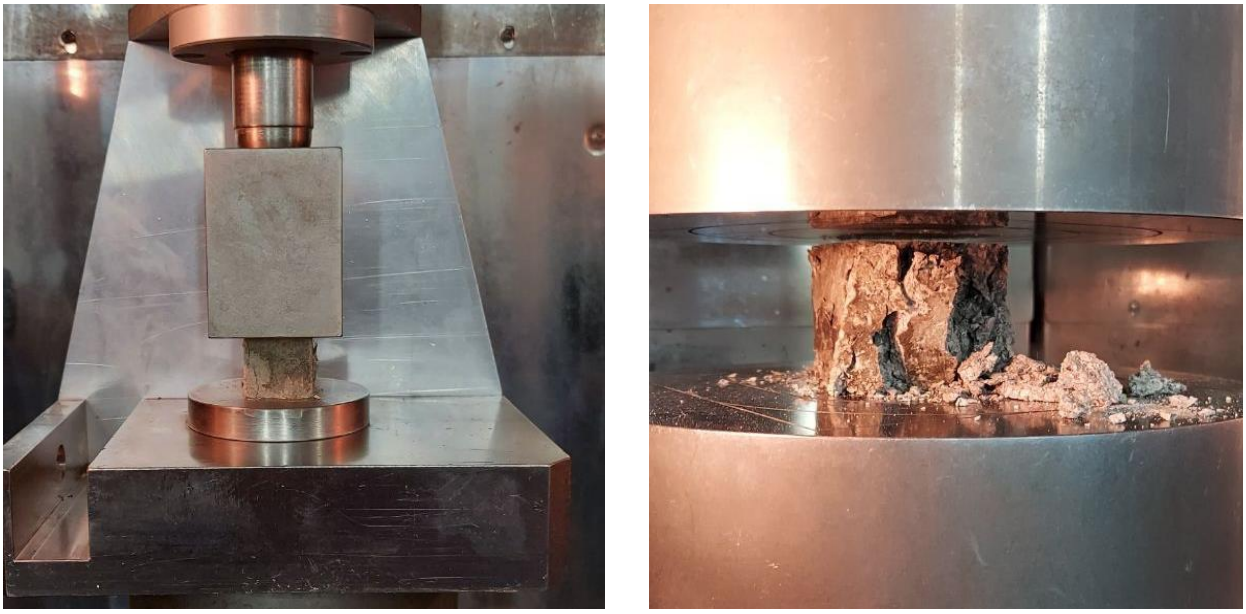
Additive: Basalt fiber Cemfibra P was also added to increase the strength. These are fibers that increase the strength of concrete and have a number of advantages over synthetic fibers as they are some of the strongest mineral fibers known to date. Basalt fiber (from roving), is designed for volumetric reinforcement of concrete, mortars, and composite materials. It is used with any dry construction mixtures, as well as concrete for self-mixing [16].

2.2 Sample Preparation

After dosage Portland cement and fillers were thoroughly mixed, first in dry form, then water was added, in the amount necessary to obtain a plastic molding mass, water-cement ratio B/C = 0.6. To study the properties of the products, standard samples were prepared with dimensions: 20 × 20 × 20 × 20 mm and 50 × 50 × 50 × 50 mm. The cube specimens were molded on a laboratory vibration platform. The samples were manufactured following the standard [17]. Also, cylindrical specimens of 100 mm diameter were made to determine the water permeability of concrete specimens.

2.3 Determination of the fractal model of concrete strength taking into account the scale effect

The possibility of explaining the scale effect on the basis of the fractal geometry of B. Mandelbrot. It is shown that the main physical essence of the scale effect lies in the scale invariance of the structure at each scale level of the concrete structure. Consequently, the properties appear to be similar. The strength (in kilo-Newtons per square centimeter, megapascals) was determined on cube-shaped specimens with dimensions of 20, 50, and 100 mm. In addition, the discrete, multilevel nature of the failure of concrete specimens with dimensions of 20, 50, and 100 mm was confirmed by the strain diagram obtained on a Wille Geotechnik testing machine (model 13-PD/104). The tests were carried out at a loading rate of 0.5 mm/min with readings recorded at a rate of 10 measurements per second. Compositions N2, N5, N17, N18 were produced. For each composition, there were 9 cube samples with rib sizes of 20, 50, and 100 mm. In Figure 1, we can observe the failure process of the samples. The strength values were also determined by standard [17].



a) Strength test of the specimen with dimensions 20×20×20 mm

b) Strength test of the specimen with dimensions 50×50×50 mm

Figure 1 – The failure process of the samples

2.4 Determination of average density

The following method was used to determine the average density of tuff concrete samples by standard [18]. For regular cubes, volume measurement was carried out using measuring tools such as a ruler and caliper, with an allowable error of no more than 1 mm. For non-uniform samples, it was recommended to use the hydrostatic method for mass determination or the volumetric method for volume measurement based on weighing.

2.5 Determination of water absorption

The AGAMA-2PM instrument was installed on the surface of the tested product using sealing mastic (Figure 2) in accordance with standard [19]. Then the piston in the chamber of the device was moved to create rarefaction, which was recorded by the pressure sensor. According to the change in pressure, the resistance of the material to air penetration was determined. The test was carried out at air temperature up to 26°C. The vacuum pressure in the chamber of the device was maintained at a minimum of 0.06 MPa. No more than 300 N of force was required to create a working vacuum in the chamber. The range of measurements included material resistance to air penetration from 0.1 to 999.9 s/cm³ and concrete water resistance grades from 0 to 20. The tolerance limit of relative error of resistance determination did not exceed 8%.

Figure 2 – Determination of water absorption on the AGAMA-2RM device

3. Results and Discussion

3.1 Determination of a fractal model of concrete strength taking into account the scale effect

The analysis confirms the multifractality and self-similarity of concrete structure as an objective manifestation of material properties that can be quantified using the fractal dimension. The graphs presented (Figure 3) demonstrate that the failure of the specimen structure is gradual rather than instantaneous. The peaks denoting the moment of fracture have an enlarged shape, showing both an increase and decrease in amplitude. However, the graph shows an oscillatory pattern as the structure gradually collapses.

Figure 3 is four enlarged sections of the same graph. The figure shows the fracture graph of 50x50x50 mm specimens of N5 composition.

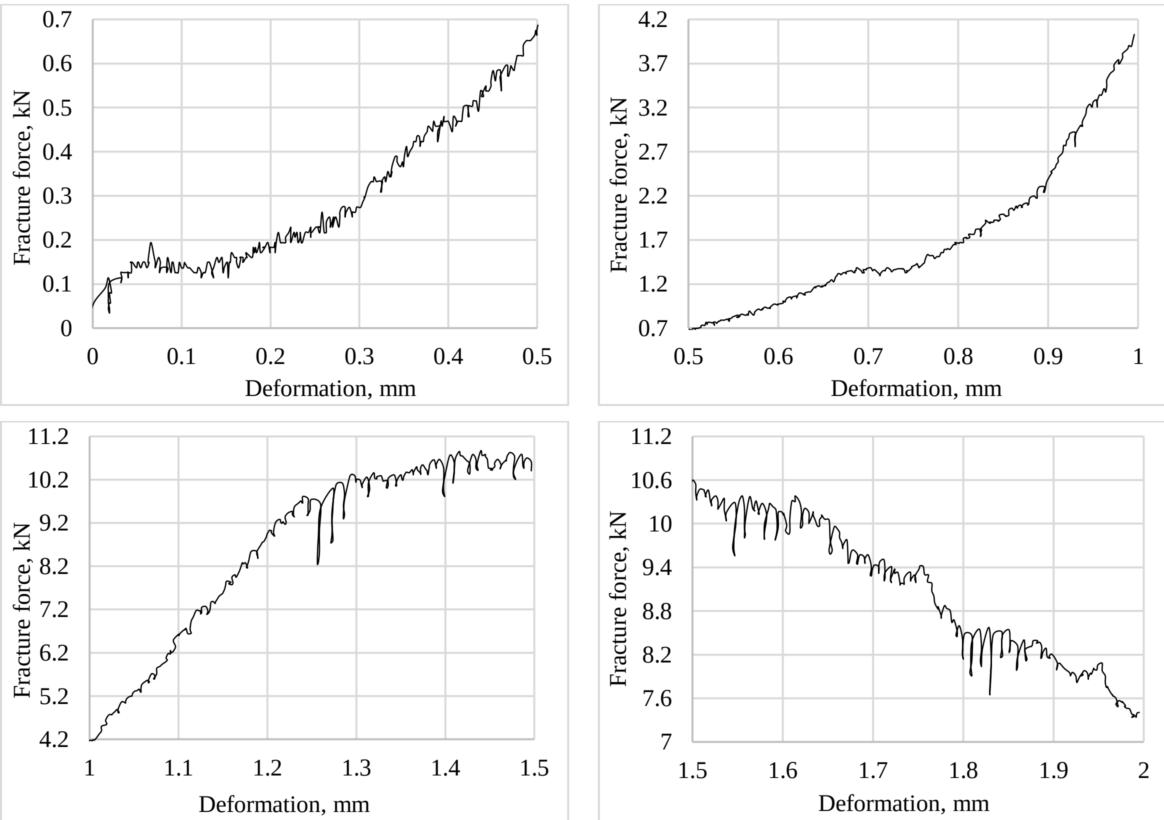


Figure 3 – Extended strain zones of a 50x50x50 mm specimen ranging from 0 mm to 2.0 mm

Table 1 shows the values after testing the specimens with the same composition at the age of 7 days. We can observe the influence of scale effect on the properties of tuff concrete depending on the size of the specimens.

Table 1 – Strength and density indices of samples depending on their size

No	20x20x20, MPa	50x50x50, MPa	100x100x100, MPa	Average density, kg/m³
N2	23.3	21.7	20.0	1961.3
N5	22.8	22.4	20.3	1851.2
N17	25.3	24.1	23.6	2085.6
N18	24.9	22.4	22.2	2128.5

Concrete consists of various components such as cement, aggregates, and reinforcing materials. Various stresses and loads can cause the bonds between these components to break, resulting in the failure of the concrete structure. The concrete matrix is a bonding material containing reinforcing materials. Exposure to load can cause failure and cracking of the concrete matrix. In Figure 4, we can observe the changes in the strength plot as a function of specimen size. We can see that in all compositions, the specimen strength increases with decreasing specimen size.

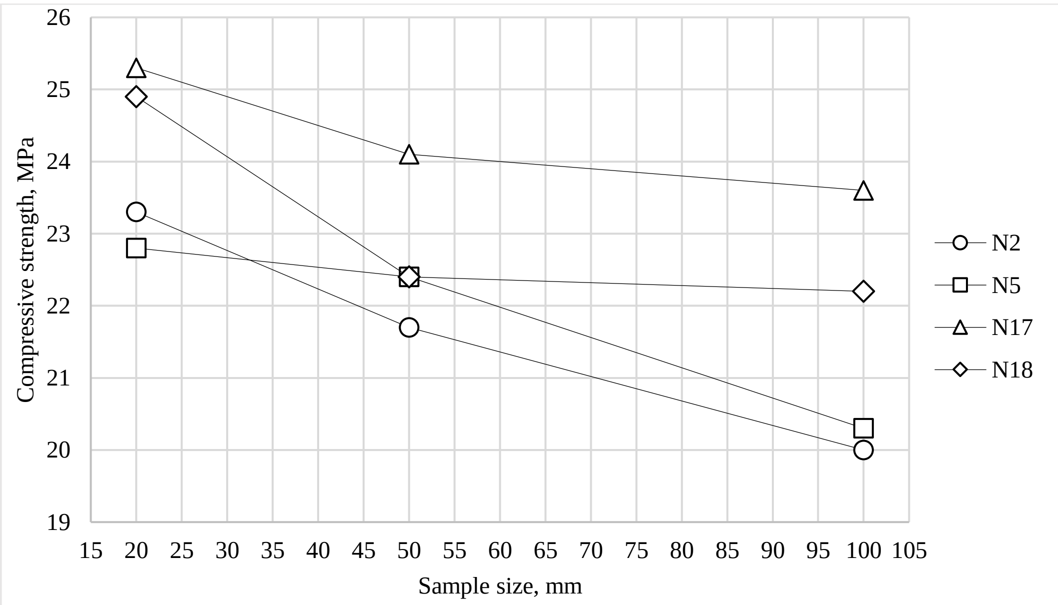


Figure 4 – Strength values of specimens depending on their size

Investigations of the compressive strength values of tuff concrete specimens of different sizes revealed a significant influence of the scale effect on the mechanical properties of the material. In particular, the 20x20x20 mm specimens showed the highest compressive strength in all four compositions, which is noticeably higher than that of larger specimens. This phenomenon is explained by the fact that smaller specimens have fewer defects and cracks, which contributes to higher strength. This supports the hypothesis of the fractal structure of concrete, where a decrease in scale leads to an increase in the strength of the material. Such results are important for the practical application of tuff concrete as they indicate the need to consider specimen size in structural design and testing.

The assumption of fractal structure of cement concrete with volcanic tuff is experimentally substantiated. The mechanism of concrete failure taking into account the invariant multifractal structure is considered. The discrete fracture process of concrete structures is experimentally confirmed. Depending on the size of tuff concrete specimens, different strength values were obtained for the same composition. The smallest size specimens showed higher strength even considering the correction factor. From the test results, an increase in strength was observed for specimens with 20 mm faces in contrast to specimens with faces of 50 and 100 mm.

3.2 Determination of average density

Measurements of the average density of tuff concrete samples of different sizes also showed interesting results. The smallest samples of size 20x20x20 mm had an average density of 1961.3 kg/m³, which was slightly higher than the average size 50x50x50 mm samples which had a density of 1958.4 kg/m³. The largest 100x100x100 mm specimens showed the highest density of 1974.2 kg/m³. The differences in density can be explained by the heterogeneity of the structure and the distribution of pores and voids in the material. The larger samples have a larger volume, which may contribute to a more uniform distribution of voids and hence a higher density. These findings emphasize the importance of careful control of density parameters in the production and application of tuff concrete, as they significantly affect the strength characteristics and durability of the final structures.

3.3 Determination of water absorption.

To determine the water permeability of concrete, the ‘air permeability’ method was used using the AGAMA-2RM device. Unlike the ‘wet spot’ method, this method does not disturb the structure of the sample.

The principle of operation of the AGAMA-2PM device is to measure the pressure in a sealed chamber where a rarefaction is created. This rarefaction increases due to the penetration of atmospheric air through pores and defects of the sample. The device provides a hermetic connection to the surface of the material through a special mastic.

The waterproofness grade of concrete (W) is determined based on the calculated parameters a and m - the resistance of the material. To obtain the result of air permeability tests, the arithmetic mean value of the air resistance of concrete measured on a set of six specimens was used.

Table 2 shows the results of the tests carried out using the AGAMA-2PM instrument.

Table 2 – Water permeability values of samples

No	Air resistance of concrete, s/cm³	Water resistance, MPa	Waterproof grade, W
N2	28.1	1.2	W12
N5	28.5	1.2	W12
N17	30.2	1.4	W14
N18	30.5	1.4	W14

The study of the water permeability of concrete based on its air permeability values is of considerable interest to modern construction technology. In the data presented, concrete grades N2, N5, N17, and N18 showed different levels of air permeability and thus water resistance. Specifically, specimens N2 and N5 have an air permeability of 28.1 and 28.5 s/cm³, respectively, and water resistance of 1.2 MPa, corresponding to water resistance class W12. On the other hand, samples N17 and N18 showed higher air permeability of 30.2 and 30.5 s/cm³, respectively, and water resistance of 1.4 MPa corresponding to water resistance class W14. These data suggest that higher air permeability correlates with higher water resistance, which may be due to the denser concrete structure and improved pore distribution.

The study [20] assesses the quality of the concrete protective layer, which is necessary for the proper maintenance of concrete structures. Concrete strength is assessed mainly by chloride penetration, neutralization and other external factors. The authors analyze the relationship between concrete air permeability and its durability indicators, such as chloride diffusion and neutralization, and propose using air permeability as an indicator of concrete durability. Experiments have shown a high correlation between air permeability, neutralization and diffusion coefficients of chlorine ions. Another study [21] also presented a method for measuring concrete permeability using the flow pump technique previously used to assess soil permeability. A new simple method for determining permeability was also proposed, based on a modification of the Valenta formula taking into account the apparent air content in concrete mixtures. Four types of concrete were studied: without additives, with an admixture to increase strength, with a superplasticizer, and with both additives simultaneously. The results showed that the proposed method provides reliable measurements in a short period of time and can be useful in engineering practice for hydraulic concrete structures, bridges, underground parts of buildings, and sealed tanks.

4. Conclusions

The study confirmed the multifractality and self-similarity of concrete structures, as evidenced by the fractal dimension. The failure of the specimens was gradual, with an oscillatory pattern in the graphs, indicating a progressive collapse rather than an instantaneous fracture.

The 20x20x20 mm specimens demonstrated the highest compressive strength: N2 with 23.3 MPa, N5 with 22.8 MPa, N17 with 25.3 MPa, and N18 with 24.9 MPa. This supports the hypothesis that smaller scales enhance material strength due to the fractal nature of the concrete.

In terms of density, the 20x20x20 mm specimens had an average density of 1961.3 kg/m³, slightly higher than the 50x50x50 mm specimens at 1958.4 kg/m³. The largest 100x100x100 mm specimens had the highest density at 1974.2 kg/m³, likely due to more uniform pore distribution.

Water permeability, inferred from air permeability measurements, showed that specimens N2 and N5, with air permeabilities of 28.1 and 28.5 s/cm³ respectively, had water resistances of 1.2 MPa (W12). In contrast, specimens N17 and N18 had higher air permeabilities of 30.2 and 30.5 s/cm³ and water resistances of 1.4 MPa (W14). This suggests that increased air permeability correlates with higher water resistance, possibly due to a denser concrete structure.

Overall, the study indicates that air permeability can reliably predict water resistance, contributing to the development of more durable and cost-effective concrete formulations. Future research could further refine these relationships to advance construction materials and practices.

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Information about authors:
Yerlan Khamza – Master of Engineering Sciences, Head of the Laboratory, Institute of Architecture and Civil Engineering, Satbayev University, 050013, Almaty, Kazakhstan, y.khamza@satbayev.university
Vladimir Selyaev – Doctor of Technical Sciences, Professor, Head of Department, Department of Building Structures, Ogarev Mordovia State University, ntorm80@maul.ru
Maratbek Zhuginissov – Doctor of Technical Sciences, Professor, Lecturer, Institute of Architecture and Civil Engineering, Satbayev University, 050013, Almaty, Kazakhstan, m.zhuginissov@satbayev.university
Zhanar Zhumadilova – PhD, Associate Professor, Vice Director, Institute of Architecture and Civil Engineering, Satbayev University, 050013, Almaty, Kazakhstan, z.zhumadilova@satbayev.university

Author Contributions:
Yerlan Khamza – concept, methodology, resources, data collection, testing, modeling, funding acquisition.
Vladimir Selyaev – concept, analysis, visualization.
Maratbek Zhuginissov – methodology, interpretation, drafting.
Zhanar Zhumadilova – analysis, visualization, interpretation, drafting, editing.

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