Journal of
Composites Science

MDPI

Article

Eco-Friendly Concrete with Improved Properties and Structure, Modified with Banana Leaf Ash

Sergei A. Stel'makh [1], Evgenii M. Shcherban' [2], Alexey N. Beskopylny [3,*], Andrei Chernilnik [1] and Diana Elshaeva [1]

[1] Department of Unique Buildings and Constructions Engineering, Don State Technical University, 344003 Rostov-on-Don, Russia; sergej.stelmax@mail.ru (S.A.S.); chernila_a@mail.ru (A.C.); diana.elshaeva@yandex.ru (D.E.)
[2] Department of Engineering Geometry and Computer Graphics, Don State Technical University, 344003 Rostov-on-Don, Russia; au-geen@mail.ru
[3] Department of Transport Systems, Faculty of Roads and Transport Systems, Don State Technical University, 344003 Rostov-on-Don, Russia
* Correspondence: besk-an@yandex.ru; Tel.: +7-863-273-8454

Abstract: The reduction of carbon footprint, the recycling of agricultural waste, and the development of novel environmentally friendly building materials are urgent matters that necessitate innovative solutions. The objective of this study is to explore the feasibility of utilizing banana leaf ash (BLA) as a partial substitute for cement in conventional density concrete technology. The BLA-modifying additive was produced under laboratory conditions. Its chemical, phase and granulometric composition was assessed. To determine the degree of effectiveness of BLA, eight concrete compositions were developed, where the BLA content varied from 0% to 14% with an interval of 2%. The properties of fresh concrete, such as density and slump, as well as compressive strength, flexural strength, water absorption, and microstructure of hardened concrete, were studied. It has been determined that the BLA additive exhibits pozzolanic activity, with a SiO_2 content of 50.83%. It is recommended that the replacement of cement with BLA does not exceed 10% for optimal results. Concrete modified with 6% BLA had the best properties and structure. The study revealed a significant 7.42% increase in compressive strength, a 7.01% increase in flexural strength, and a notable 9.28% decrease in water absorption. Thus, the obtained result proves the possibility of using BLA as a modifying additive in the technology of cement composites. The developed concrete has improved properties and is a more environmentally friendly building material than conventional concrete.

Keywords: composite; banana leaf ash (BLA); strength; pozzolanic activity; concrete; concrete microstructure

check for updates

Citation: Stel'makh, S.A.; Shcherban', E.M.; Beskopylny, A.N.; Chernilnik, A.; Elshaeva, D. Eco-Friendly Concrete with Improved Properties and Structure, Modified with Banana Leaf Ash. *J. Compos. Sci.* **2024**, *8*, 421. https://doi.org/10.3390/jcs8100421

Academic Editor: Yanshuai Wang

Received: 22 August 2024
Revised: 24 September 2024
Accepted: 11 October 2024
Published: 13 October 2024

1. Introduction

Currently, cement is the main raw material component of the construction industry in all countries of the world. The construction of civil and industrial infrastructure requires a large amount of this building material [1]. It is a well-established fact that cement manufacturing relates to a significant amount of energy, resulting in a substantial detrimental impact on the climate and the environment due to the release of significant amounts of CO_2 [2–4]. According to calculations by the international research project for monitoring greenhouse gas emissions, the Global Carbon Project, carbon dioxide emissions worldwide have increased by 4.9% in recent years, amounting to 36.7 billion tons. The Carbon Brief organization has published the results of an analysis of the total volume of carbon dioxide emissions by countries since 1850. The study showed the countries that bear the greatest historical responsibility for the climate emergency: the United States is recognized as the largest polluter on planet Earth, followed by China and Russia. The following countries are more evenly distributed in terms of total volumes: Brazil, Indonesia, Germany, India, the United Kingdom, Japan, and Canada. Carbon dioxide remains in the atmosphere for centuries, and the cumulative volume of CO_2 emissions is closely related to the +2 °C warming that has already occurred in the world. Thus, in order to reduce the negative impact on the environment, it seems logical to use alternative materials with astringent properties [5–8]. A significant amount of research in the global scientific community is devoted to assessing the possibility of using various technogenic wastes in the form of slags and fly ash as materials that can reduce cement consumption and improve the environmental situation [9–19]. For example, studies [9–12] prove the possibility and rationality of using ground granulated blast furnace slag (GGBS) up to 40% as a pozzolanic material, replacing part of the cement. GGBS concrete has the required strength properties and is resistant to various types of aggressive influences. In addition to GGBS, alternative types of slag can also be utilized as a partial substitute for cement in concrete manufacturing. As an illustration, in reference [13], the inclusion of up to 20% ferronickel slag enabled the production of concrete with enhanced compressive and splitting strength. The use of manganese slag [14] in high-strength concrete has increased its resistance to salt erosion. Fly ash is also an effective pozzolanic additive. In [15], with a degree of replacement of up to 20% by fly ash, concrete was obtained that has the best resistance to freezing and thawing in seawater. With an identical level of replacing part of the cement with fly ash, 20%, in [16], an environmentally friendly composite with improved compressive and flexural strength was obtained. Studies [17–19] further substantiate the efficacy of utilizing fly ash in cement composites.

Currently, more and more researchers are switching to studying agricultural waste as a modifying additive in the production of cement composites [20–24]. Rice husk ash (RHA) is the most popular [25–28]. Replacing cement with 10% RHA [24] made it possible to obtain concrete with a 10.26% higher compressive strength and reduced thermal conductivity compared to concrete without RHA. The self-compacting concrete with 20% RHA developed in the study [26] has increased compressive strength and increased the resistance to chloride migration by three times. In [27], with a 10% replacement of cement with RHA, cellular concrete had compressive strength, splitting tensile strength and flexural strength higher in comparison with the control composition by 22.16%, 20.41% and 22.31%, respectively. Other studies [28–34] have also verified the efficacy of RHA. An equally popular type of plant ash used in cement concrete is sugarcane bagasse ash (SCBA) [24]. In a study [35], the addition of 3% SCBA improved the properties of high-strength concrete. Compressive, bending, and splitting strengths increased by 11.1%, 14.8%, and 8.5%, respectively. Replacing part of Portland cement with up to 30% SCBA [36] allows one to obtain concrete with the required mechanical properties and good resistance to sulfuric and hydrochloric acid. The incorporation of 10% SCBA [37] increased compressive strength by 12% and flexural strength by up to 8%. The positive effect of using SCBA is confirmed by works [38–41]. Another common type of plant ash used as a binder replacement is palm oil ash (POFA) [42]. For example, in [43], the inclusion of POFA into concrete increased its acid resistance. A study [44] proved the effectiveness of using POFA as a cement replacement by up to 50%. The incorporation of 5–15% POFA [45] resulted in an environmentally sustainable and cost-effective composite with improved properties. Studies [46–49] confirm the effectiveness of using POFA as a modifying additive that replaces part of the binder. In addition, the effective usage of corn cob ash and sunflower seed husk ash in concrete is known [50–52].

Among the above-mentioned types of plant ash, the use of banana leaf ash (BLA) remains the least studied issue. BLA is obtained from banana trees, bananas being one of the most popular and traded fruits worldwide [53]. Accordingly, the large volumes of banana production and cultivation led to the emergence of a significant amount of plant waste. It would be interesting to find a sustainable and cost-effective way to recycle banana leaf waste. Burning banana leaves produces plant ash, which, like other types of plant ash mentioned earlier, can be used as an active pozzolanic additive in cement composites [54,55]. For example, in [56,57], replacing part of the cement with up to 10% BLA indicates the possibility of its use without a significant decrease in strength properties. Research [58] suggests the potential of using BLA in ranges from 5% to 20% without significant loss of concrete strength.

However, there is a dearth of detailed studies on the efficacy of banana leaf ash in cementitious composites. There are still risks of insufficient understanding of the characteristics of concrete with BLA. The scientific novelty of this study is the determination of new dependences of the characteristics of concrete with BLA on the parameters and proportions of its composition.

The aim of this work is to reveal the structure and properties of concrete with BLA as a partial replacement for cement in the production technology of normal density concrete and to determine the optimal level of this replacement.

The objectives of the study are to develop an experimental research program establishing minimum and maximum levels of replacement of part of cement with BLA; select and calculate experimental concrete compositions taking into account the characteristics of the raw materials used; prepare concrete samples with different BLA contents and evaluate the properties of concrete mixtures and hardened concrete, including density, compressive strength, flexural strength, water absorption and study the microstructure using electron microscopy; analyze the obtained results and determine the optimal level of BLA replacement, as well as perform a comparison with other types of plant ash used in cement concrete technology.

2. Materials and Methods

2.1. Materials

Portland cement CEM I 42.5N (CEMROS, Moscow, Russia), quartz sand (Don Resurs, Kagalnik, Russia) and granite crushed stone (JSC "Pavlovsk-nerud", Pavlovsk, Russia) were applied as the raw materials for the production of experimental concrete samples. The features of the listed raw materials can be found in Tables 1–3.

Table 1. Properties of Portland cement CEM I 42.5N.

Indicator	Actual Value
Specific surface area (m^2/kg)	341
Setting times (min) -start -end	 160 240
Standard consistency (%)	29.7
Compressive strength at 28 days (MPa)	49.7
Bending strength at 28 days (MPa)	5.6
C_3S (%)	73.4
C_2S (%)	7.9
C_3A (%)	5.5
C_4AF (%)	11.6
CaO_{fr} (%)	1.6

Table 2. Properties of quartz sand.

Indicator	Actual Value
Bulk density (kg/m^3)	1365
Apparent density (kg/m^3)	2569
The content of dust and clay particles (%)	0.03
Content of clay in lumps (%)	0.04
Organic and contaminant content (%)	No

Table 3. Properties of crushed granite stone.

Indicator	Actual Value
Bulk density (kg/m^3)	1438
Apparent density (kg/m^3)	2665
Resistance to fragmentation (wt%)	11.2
The content of lamellar and acicular grains (wt%)	6.8

Sieving curves for quartz sand and crushed granite are presented in Figure 1.

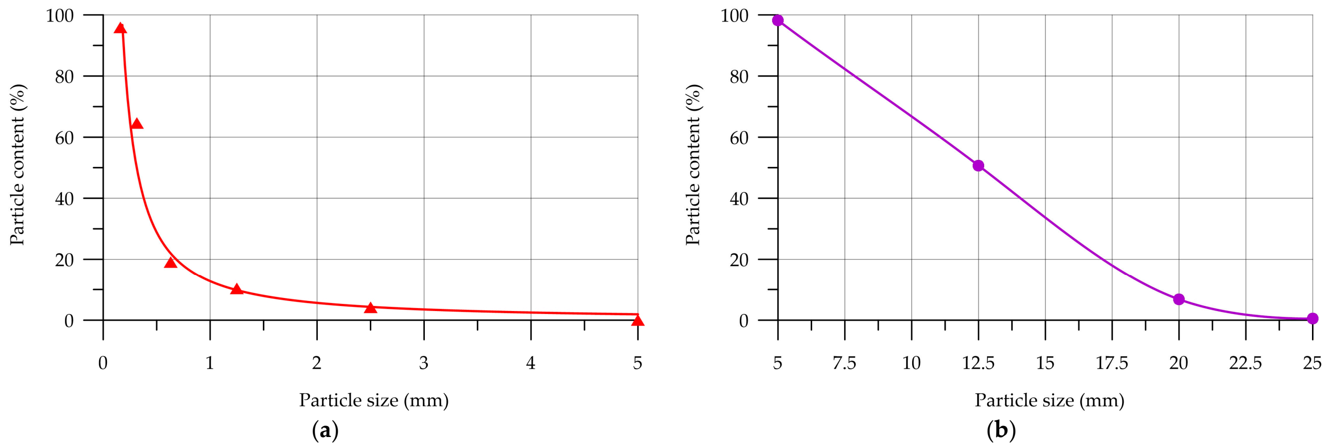


Figure 1. Particle size distribution curves: (**a**) quartz sand; (**b**) crushed granite.

The fineness modulus of the quartz sand was 1.94 (Figure 1a). The grain size of crushed stone was limited from 5 to 25 mm (fraction over 5 to 20 mm) (Figure 1b).

Banana leaf ash was used as a modifying additive, replacing part of the cement. The ash was produced in a laboratory setting by burning dry banana leaves in a laboratory oven. Banana leaves were exposed for 60 min to temperatures of approximately 600 °C. After combustion, the ash was sifted through a 0.16 mm sieve to remove large particles. The prepared ash was further crushed by grinding in an Activator-4M planetary ball mill at 400 rpm for 60 min. Then the crushed ash was sifted through a 0.08 mm sieve and part of the banana leaf ash that passed through the sieve was used as an additive. The appearance of the resulting BLA additive is illustrated in Figure 2. Figures 3 and 4, along with Table 4, showcase the key properties of BLA.

Table 4. Chemical composition of BLA.

	SiO_2 (%)	CaO (%)	Na_2O (%)	K_2O (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)
BLA	50.83	35.89	1.98	0.89	5.61	3.09	1.71

The photo presented in Figure 2 illustrates the appearance of banana leaf ash.

Figure 3 shows a radiograph of the BLA.

X-ray phase analysis showed the presence of such phases as quartz, altered halite, and sylvite in BLA.

It should be noted that not all of the SiO_2 contained in BLA participates in the pozzolanic reaction. An important parameter is the determination of the quartz content in SiO_2 using the Rietveld method. Using the Rietveld method, the quartz content was determined to be 29%.

Figure 2. Appearance of BLA additive.

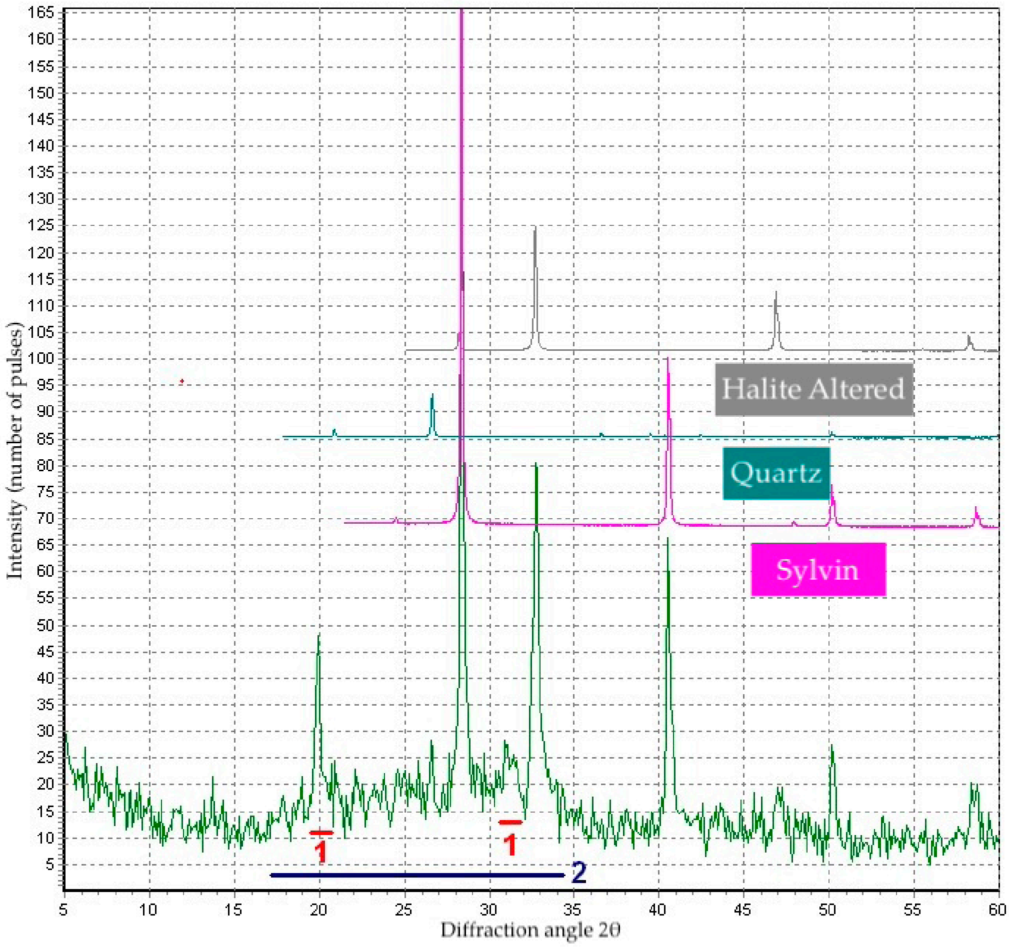


Figure 3. X-ray pattern of BLA: (1) peaks unidentified; (2) amorphous silica phase.

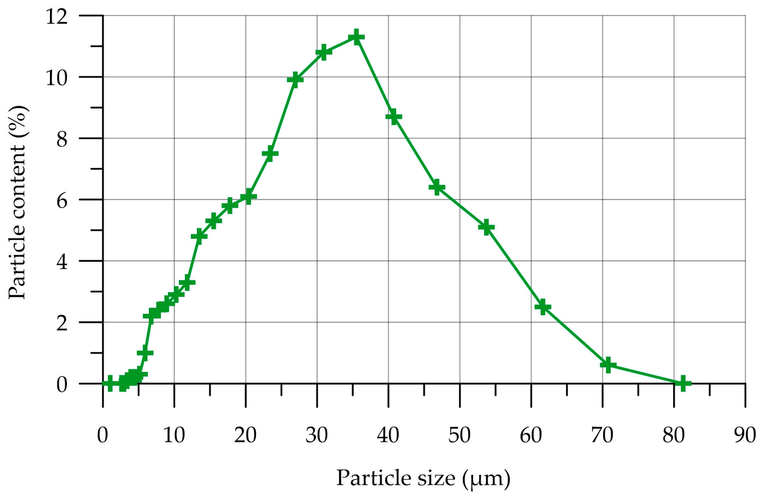


Figure 4. BLA particle size distribution curve.

The chemical composition of the BLA-modifying additive is presented in Table 4.

As is known [59], SiO_2 is a key component in pozzolanic materials. Its presence in BLA in an amount of 50.83% will ensure the occurrence of chemical reactions, namely, when silicon dioxide interacts with calcium hydroxide, compounds with cementing properties—calcium hydrosilicates—will be formed. Thus, BLA has binding properties inherent in cement. These compounds can fill voids in concrete, thereby increasing its strength.

The size distribution curve of BLA particles can be observed in Figure 4.

Figure 4 illustrates that a significant proportion of BLA particles, specifically 81.7%, exhibit sizes within the range of 11 to 60 μm. The peak BLA distribution of 11.3% occurs at particles 35.5 μm in size.

Also, a polycarboxylate-based plasticizing additive PK1 (Poliplast, Russia, Moscow) was additionally used.

2.2. Methods

To assess the impact of BLA on concrete properties and determine the ideal dosage, concrete mixtures were formulated and documented in Table 5. Figure 5 illustrates the complete program of experimental studies.

Table 5. Compositions of concrete mixtures.

Composition	PC (kg/m^3)	QS (kg/m^3)	GCS (kg/m^3)	Water (L/m^3)	PK1 (kg/m^3)	BLA	
						(kg/m^3)	% by Weight of Cement
0BLA	397	793	1050	194	3.97	0	0
2BLA	389.1	793	1050	194	3.97	7.9	2
4BLA	381.1	793	1050	194	3.97	15.9	4
6BLA	373.2	793	1050	194	3.97	23.8	6
8BLA	365.2	793	1050	194	3.97	31.8	8
10BLA	357.3	793	1050	194	3.97	39.7	10
12BLA	349.4	793	1050	194	3.97	47.6	12
14BLA	341.4	793	1050	194	3.97	55.6	14

Note: BLA—banana leaf ash, PC—Portland cement, QS—quartz sand, GCS—granite crushed stone, PK1—polycarboxylate-based plasticizing additive.

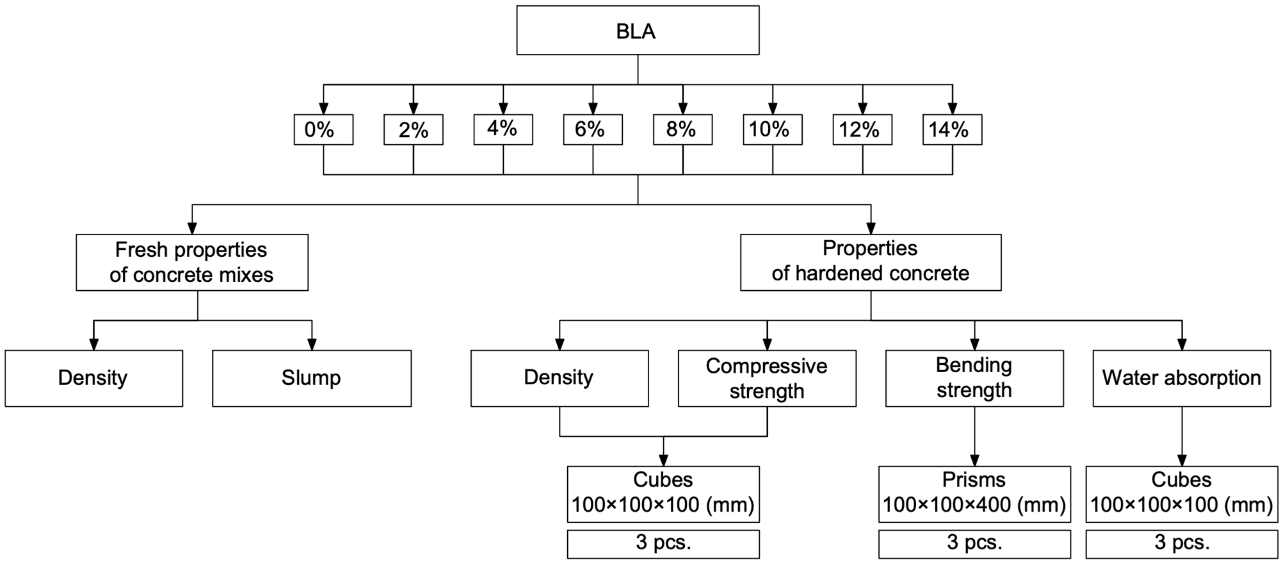


Figure 5. Experimental research program.

Forty-eight cube specimens and 24 prism specimens were prepared to determine the density, compressive strength and water absorption, and 24 prism specimens were prepared to determine the flexural strength.

The compositions of concrete mixtures used in the study are presented in Table 5.

The process of producing concrete samples incorporating the BLA additive involved the following primary stages:

- dosage of raw materials in the required quantity;
- loading of raw materials into the concrete mixing plant BL-10 (ZZBO, Zlatoust, Russia) in the following sequence: cement, sand, BLA and water with a plasticizing additive dissolved in it; mixing this mixture until a homogeneous consistency, introducing crushed stone and additional mixing until the finished concrete mixture is obtained;
- loading the concrete mixture into metal cube molds and prisms and compacting them on a laboratory vibrating table SMZh-739M (IMash, Armavir, Russia);
- smoothing and leveling the surface of compacted samples and keeping them for 1 day (curing conditions of concrete: air temperature—20 ± 2 °C, relative humidity of the surrounding air not less than 90%);
- demolding and extraction of samples, keeping them in a normal hardening chamber for 27 days until they reach the age of 28 days.

Before pouring the concrete mixture into the molds, their density and slump were determined. According to the method [60], the density of concrete mixtures was determined as one of the fundamental property. The finished mixture was poured into a two-liter metal vessel, which was then weighed.

The slump of the mixture was determined according to the method [61]. To carry out the test, a metal cone, a bayonet and a flat metal sheet were used. Before testing, all equipment was wiped with a damp cloth, the cone was placed on a sheet and the concrete mixture was loaded into it in three stages. For each stage, 1/3 of the cone was filled and compacted with 25 bayonet strikes. After compaction, excess mixture was removed and the cone was lifted upward in the vertical direction. The cone settlement was approximated by subtracting the height of the settled concrete mixture's highest point from the height of the form.

The method outlined in reference [62] was employed to determine the density of hardened concrete. After 28 days of hardening, the samples were removed from the normal hardening chamber KNT-1 (RusPribor, Saint Petersburg, Russia), kept under laboratory conditions and then weighed.

The determination of compressive and bending strengths was carried out in accordance with the specified methods [63–67]. Samples in the form of cubes were installed in a Press P-50 laboratory unit (PKC ZIM, Armavir, Russia); the load increased at a rate of 0.6 ± 0.2 MPa/s. Using the formula, we determined the compressive strength of concrete:

$$R_c = \alpha \frac{F}{A} \quad (1)$$

Here, F is the breaking load (N); A—sample working section area (mm^2); α is a coefficient taking into account the dimensions of the samples (for samples with a side of 100 mm α = 0.95).

When testing for bending, samples of concrete were first installed in a special laboratory installation, the load was applied at a rate of increase of 0.05 ± 0.01 MPa/s. Flexural strength was calculated using the formula:

$$R_{c\,bt} = \delta \frac{F\,l}{a\,b^2} \quad (2)$$

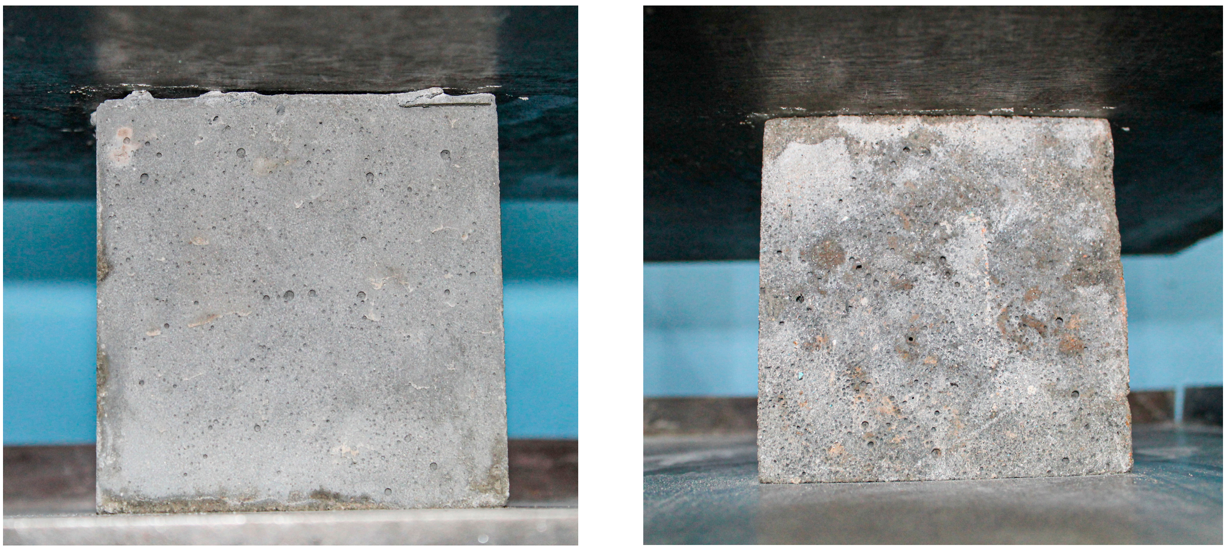
Here, F is the breaking load (N); a, b, l—characteristic dimensions of the cross-section of samples and the length of the line between supports when testing samples for tension and bending (mm); δ—coefficient taking into account the dimensions of the samples (for samples with a side of 100 mm δ = 0.92).

The assessment of water absorption in concrete was conducted in compliance with the specifications outlined in references [68,69]. The formula employed for calculating water absorption is as follows:

$$W = \frac{m_w - m_d}{m_d} \times 100 \quad (3)$$

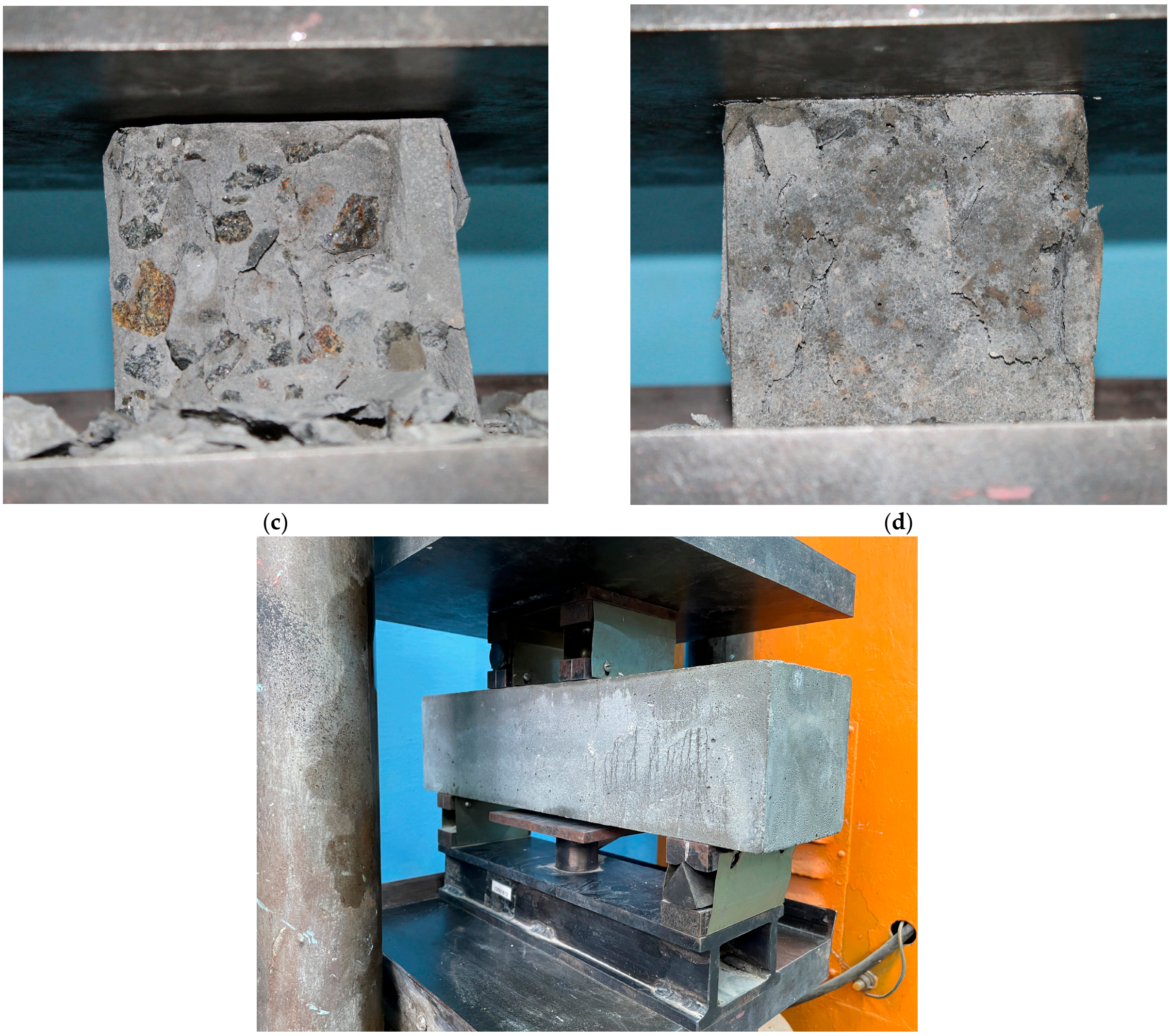
Here, m_w is the mass of the sample saturated with water (g); m_d is the mass of the dry sample (g).

The process for determining the compressive strength of concrete is presented in Figure 6.



(**a**) (**b**)

Figure 6. *Cont.*



(**c**) (**d**)

(**e**)

Figure 6. Determination of the compressive strength (**a**–**d**) and flexural strength (**e**) of concrete samples: (**a**,**c**) control composition before and after failure, respectively; (**b**,**d**) composition with 6% BLA before and after destruction, respectively.

X-ray phase analysis was performed on a DRON-7 diffractometer (NPP Burevestnik, St. Petersburg, Russia) using radiation from a copper anode.

The analysis of concrete structure was conducted by employing a 20 kV accelerating voltage electron microscope VEGA II LMU (Tescan, Brno, Czech Republic). The acquisition of all the images was performed through reflected electrons (BE), wherein phases containing higher average atomic weight are portrayed in lighter shades. A carbon coating is sprayed onto the surface.

3. Results and Discussion

Figures 7 and 8 show the results of determining the properties of fresh concrete modified with BLA. Figure 7 shows the dependence of fresh concrete density (ρ_{fc}) on the amount of BLA additive.

Fresh concrete density (ρ_{fc}) data obtained experimentally are well approximated by a linear dependence on the BLA proportion (x in the regression equation)

$$\rho_{fc} = 2436.4 - 1.488\,x,\ R^2 = 0.989 \tag{4}$$

here, R^2 is the coefficient of determination.

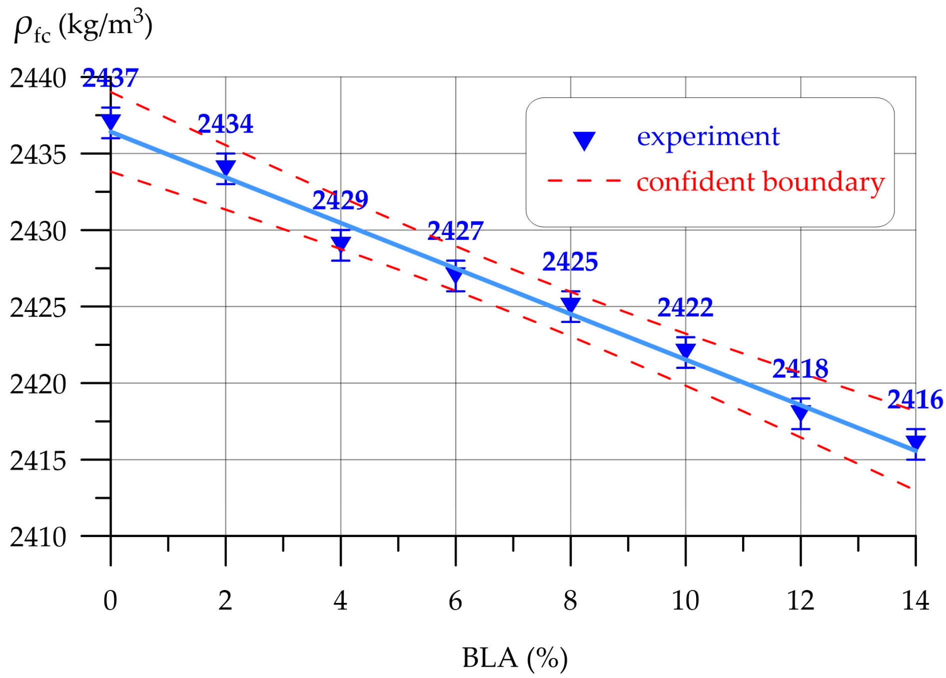


Figure 7. Fresh concrete density (ρ_{fc}) values at different BLA contents.

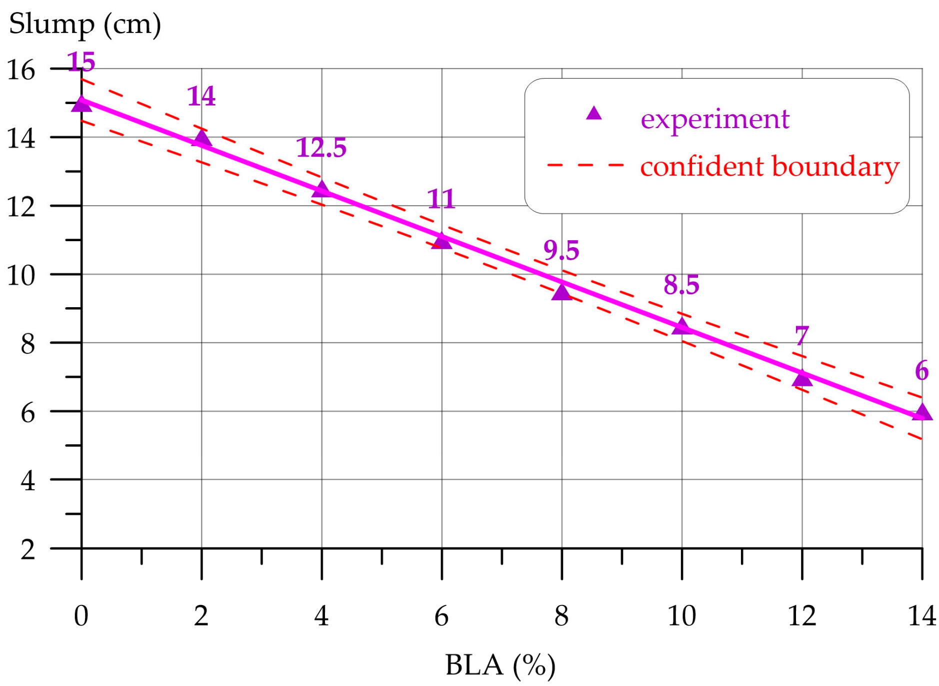


Figure 8. Cone slump values of fresh concrete at different amounts of BLA.

The data presented in Figure 7 illustrates a clear inverse relationship between the density of fresh concrete and the content of BLA. Replacing a part of the cement with BLA up to 14% leads to a slight decrease in density to 0.86%.

Figure 8 depicts the correlation between the slump of fresh concrete and the quantity of BLA additive.

Cone slump data obtained experimentally are well approximated by a linear dependence on the proportion of BLA

$$Slump = 15.1 - 0.663\,x,\ R^2 = 0.997 \quad (5)$$

Modification with the BLA additive affects the slump of concrete mixtures. Figure 8 shows the decrease in the fresh concrete slump as BLA increases. The maximum reduction in slump of the mixture was 60%. The decrease in the slump of the concrete mixture can be explained by the porous structure of ash particles and their increased water demand, which also agrees well with the studies of other authors [25,33,35].

Figures 9–11 show the properties of BLA-modified concrete. Figure 9 shows the dependence of the composite density (ρ) on the amount of BLA additive.

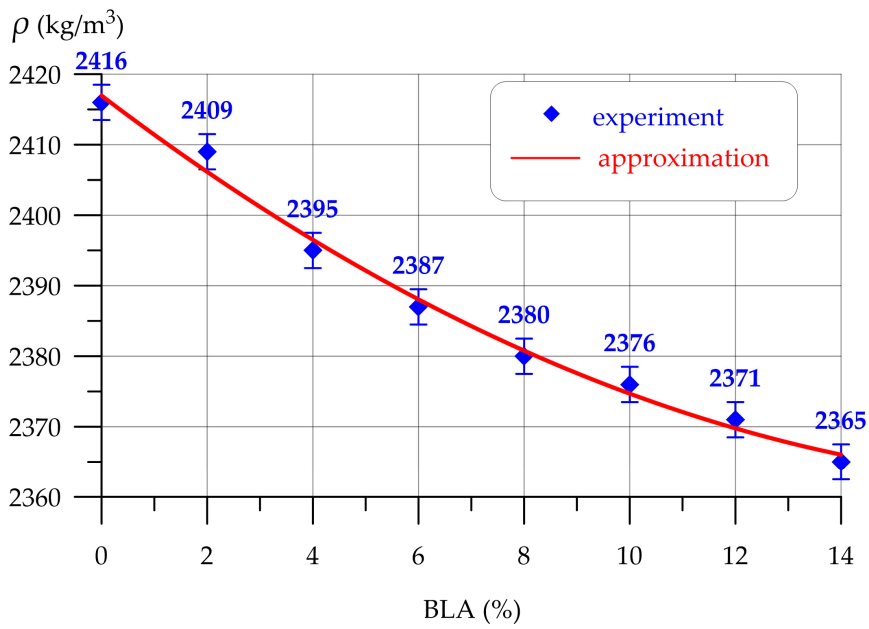


Figure 9. Concrete density (ρ) values for different amounts of BLA.

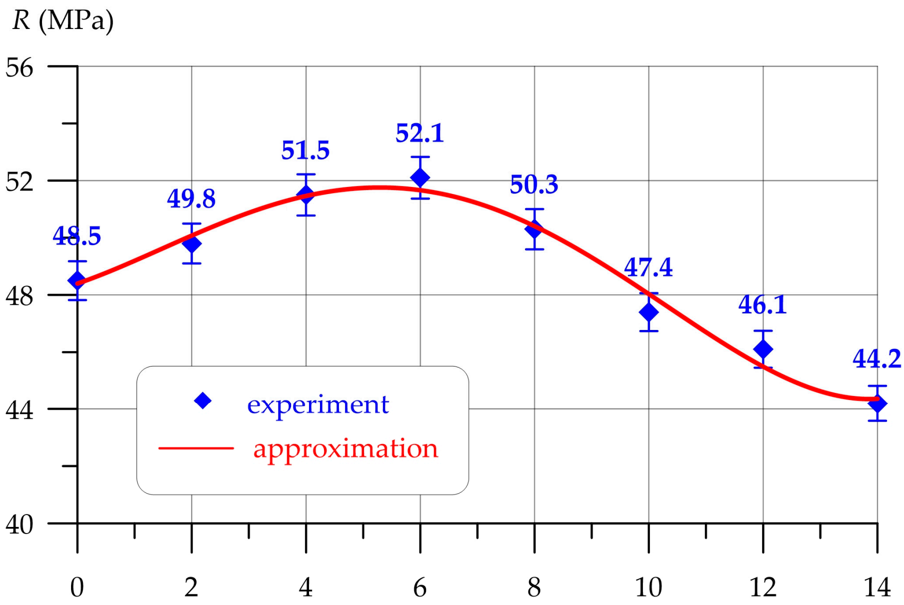


Figure 10. Concrete compressive strength (R) values for different amounts of BLA.

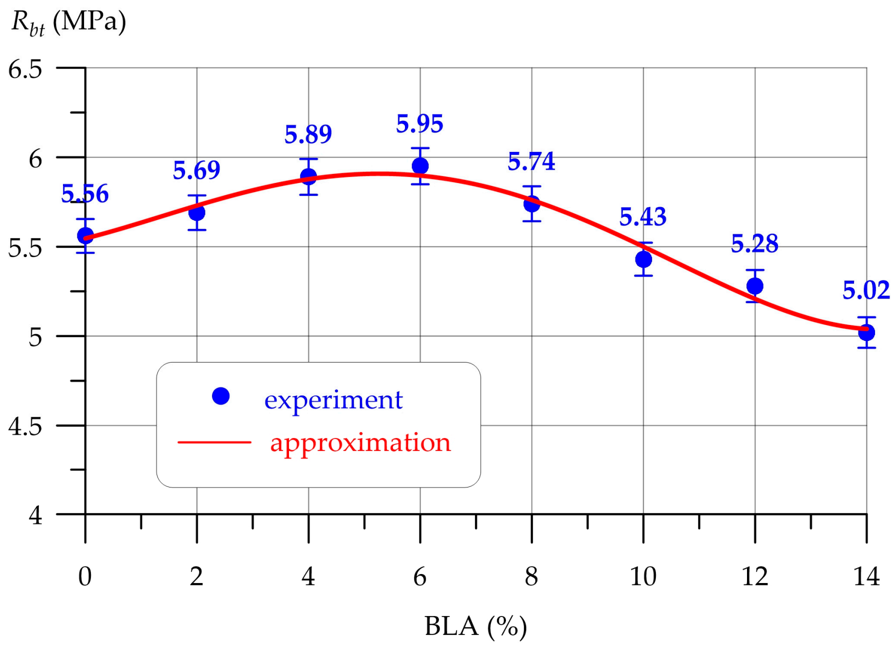


Figure 11. Concrete flexural strength (R_{bt}) values for different amounts of BLA.

Concrete density (ρ) data obtained experimentally have a more pronounced nonlinear dependence on the BLA proportion (x in the regression equation) and are well approximated by the parabola equation

$$\rho = 2417.0 - 5.699\,x + 0.147\,x^2,\ R^2 = 0.992 \quad (6)$$

As with the density of fresh concrete, the density of hardened concrete tends to decrease as the amount of BLA increases. Concrete with 14% BLA had a density value, which is 2.11% less than the control. BLA, like other types of plant ashes, have bulk density values lower than the bulk density of cement [38,56–59]. Accordingly, replacing part of the Portland cement with such ash will lead to a slight decrease in the average density of the composite.

Figure 10 illustrates the correlation between the amount of BLA and the compressive strength of concrete (R).

Concrete compressive strength (R) data, obtained experimentally in accordance with the methodology in Section 2, have a pronounced nonlinear dependence on the BLA proportion (x in the regression equation) and are well approximated by a 4th degree polynomial

$$R = 48.0 + 0.687\,x + 0.145\,x^2 - 0.0378\,x^3 + 0.0016\,x^4,\ R^2 = 0.979 \quad (7)$$

The positive impact of BLA on compressive strength can be observed in Figure 10, where it replaces up to 8% of cement. The highest value was recorded with 6% BLA: the compressive strength was 7.42% higher than the strength of concrete of the control composition (without BLA). The compressive strength change curve can be described by three characteristic sections. The initial section displays an escalation in compressive strength as the BLA content ranges from 0% to 4%. Subsequently, the subsequent section exhibits a pinnacle at 6% BLA, while the final section showcases a decline in strength as the BLA content ranges from 8% to 14%. It should be observed that the inclusion of BLA at levels of 10%, 12%, and 14% results in a significant weakening of the concrete's strength as opposed to the control formulation. The compressive strength experienced a maximum reduction of 8.87% in comparison to the control composition.

The flexural strength of concrete (R_{bt}) is illustrated in Figure 11, demonstrating its correlation with the quantity of BLA.

The concrete flexural strength (R_{bt}) data, obtained experimentally in accordance with the methodology in Section 2, also has a pronounced nonlinear dependence on the BLA proportion (x in the regression equation) and is well-approximated by a 4th degree polynomial

$$R_{bt} = 5.55 + 0.0783\,x + 0.0138\,x^2 - 0.00380\,x^3 + 0.000160\,x^4,\ R^2 = 0.977 \quad (8)$$

The dependence of the change in bending strength on the BLA content, presented in Figure 11, has a similar character to the dependence in Figure 10. At 0–6% BLA, an increase in flexural strength is observed. The flexural strength value at 6% BLA reached a maximum of 5.95 MPa, representing a 7.01% increase compared to the flexural strength of the ordinary concrete. And the minimum value of flexural strength with a decrease of 9.71%, compared to concrete without BLA, was recorded at 14% BLA.

Having analyzed the changes in the concrete characteristics from BLA content, expressed in the obtained dependencies in Figures 7–11, we can conclude that replacing part of the cement with BLA up to 10% is optimal and allows one to obtain concrete with the required strength properties. The increase in compressive and flexural strength at 6% BLA can be associated with the pozzolanic properties of this modifying additive. During the course of hydration reactions, SiO_2 particles, the content of which in BLA is 50.83%, actively interact with calcium hydroxide and form additional cementing compounds that fill the pores in concrete and prevent deterioration of strength and structural parameters in comparison with conventional concrete. Due to the porous structure and good hygroscopicity, unreacted BLA particles can retain free water [70]. The presence of such free water ensures that later hydration reactions occur. These results are in good agreement with the results of other authors, who also studied the effect of replacing part of the binder with ash of plant origin. For example, in [57], it was proven that replacing part of the cement with 10% BLA is optimal and makes it possible to obtain concrete with improved performance characteristics. Studies [58,71,72] indicate that the optimal replacement level is no more than 20% BLA by weight of cement. The resulting concretes with a maximum BLA content of 20% have characteristics comparable to concretes of the control composition. If we talk about rice husk ash, its chemical composition is characterized by a large amount of SiO_2, starting from 80%, and, accordingly, this ash has greater pozzolanic activity than BLA. For example, in [73,74], rice husk ash showed good pozzolanic activity, and replacing part of the cement by up to 20% made it possible to obtain a concrete composite with improved strength properties. The introduction of RHA [75] in an amount of 10% improved the flexural strength to 59.1%. Studies [76,77] have proven that replacing Portland cement up to 30% with sugarcane bagasse ash (SCBA) is rational. In [19], the introduction of 10% SCBA improved the strength properties of cement mortars. BLA has lower pozzolanic activity than RHA and SCBA. This has a certain phenomenological nature and is demonstrated in practice. At the same time, there is currently insufficient evidence of this phenomenon in the scientific literature, so the study of this issue can be defined by us as a prospect for the development of this research in the future. However, at the moment it can be stated that in this way we can conclude that BLA is less effective compared to RHA and SCBA. However, this fact is logical due to the fact that BLA has less pozzolanic activity.

Subsequently, Figure 12 illustrates the correlation between concrete water absorption (W) and the quantity of BLA.

Water absorption data obtained experimentally also have a pronounced nonlinear dependence on the BLA proportion (x in the regression equation) and is well approximated by a 4th degree polynomial

$$W = 5.15 - 0.0162\,x - 0.0352\,x^2 + 0.00582\,x^3 - 0.000223\,x^4,\ R^2 = 0.957 \quad (9)$$

The data depicted in Figure 12 illustrates the relationship between the change in water absorption of concrete and its dependence. It is evident that the addition of BLA up to 8% yields a beneficial impact by reducing water absorption. The minimum water absorption value was recorded for concrete with 6% BLA, which is 9.28% compared to the control. Concrete modified with 14% BLA has the highest water absorption value, which is 5.61% higher compared to the control composition. Lower water absorption values when modifying concrete with BLA additive are explained by the fact that the composite structure has fewer capillary pores, since BLA particles act as a microfillers and provide this effect. This gives the structure greater cohesion and slightly affects the density of concrete compared to concrete without BLA. Similar effects associated with a decrease in water absorption of a composite when plant ashes are introduced into its composition are reflected in works [78–80]. Figures 13–15 depict photographs illustrating the microstructure of concrete samples for the ordinary composition, the composition with 6% BLA, and the composition with 14% BLA.

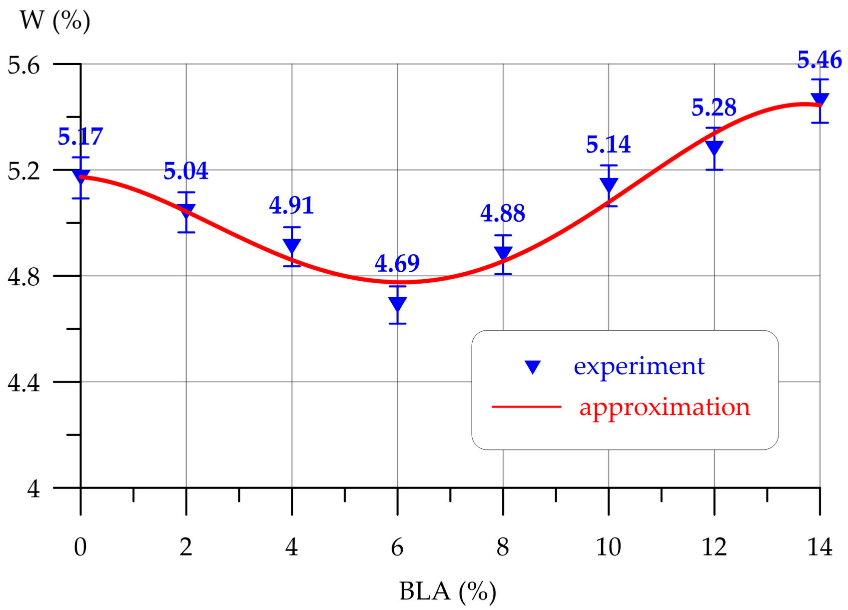


Figure 12. Water absorption values of concrete (W) at different amounts of BLA.

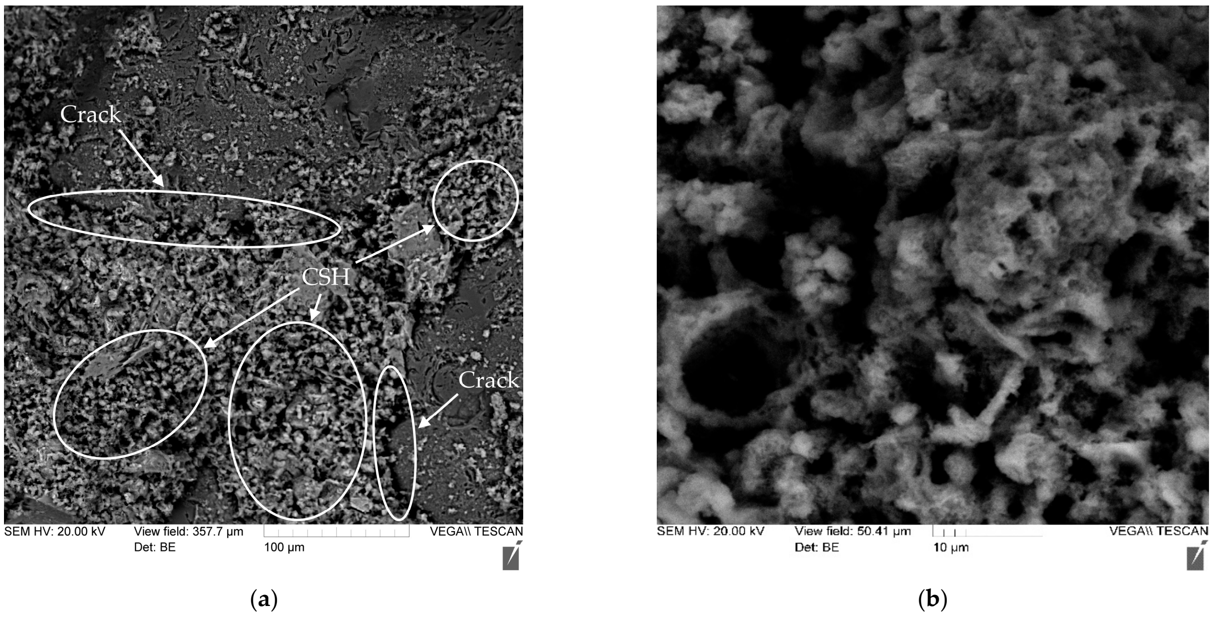
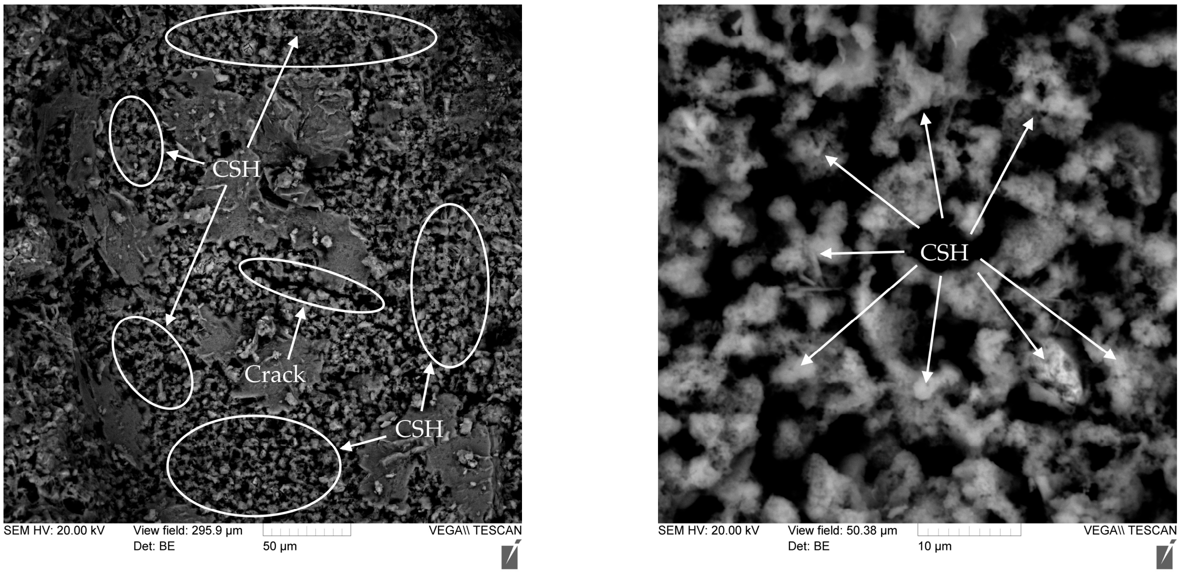
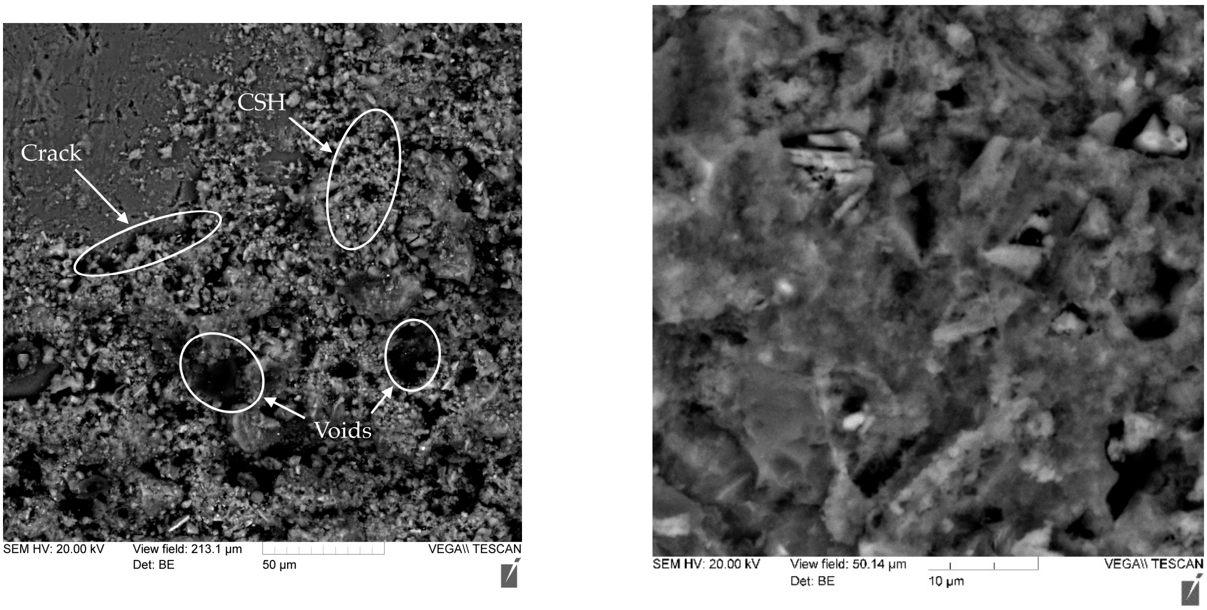


Figure 13. Photographs of the microstructure of concrete samples of the control composition: (**a**) with a magnification of 750×; (**b**) at 4500× magnification.



(**a**) (**b**)

Figure 14. Photographs of the microstructure of concrete samples with 6% BLA: (**a**) with a magnification of 750×; (**b**) at 4500× magnification.



(**a**) (**b**)

Figure 15. Photographs of the microstructure of concrete samples with 14% BLA: (**a**) with a magnification of 750×; (**b**) at 4500× magnification.

The photographs of concrete presented in Figures 13–15 show that the microstructure of concrete modified with 6% BLA (Figure 14) is the most ordered, homogeneous, with fewer pores and has a greater accumulation of zones of calcium hydrosilicates (CSH) in comparison with the structure control composition (Figure 13) and concrete structure with 14% BLA (Figure 15). Accordingly, microstructural analysis confirms that BLA in the concrete structure works as an active mineral pozzolanic admixture and as a microfiller [58,73].

The diagram shown in Figure 16 demonstrates the four main groups of factors influencing the final properties of concrete modified by BLA. Group 1 includes the properties of the materials from which concrete was made. Group 2 contains factors characterizing the parameters of concrete composition. Group 3 includes technological factors for concrete production. Group 4 consists of the properties of fresh concrete, from which it is already possible to predict the approximate characteristics of the finished composite. Compliance with the specified values of the presented factors and control of each of them in the process of design, production, and maintenance of concrete will allow us to extract maximum indicators of concrete quality.

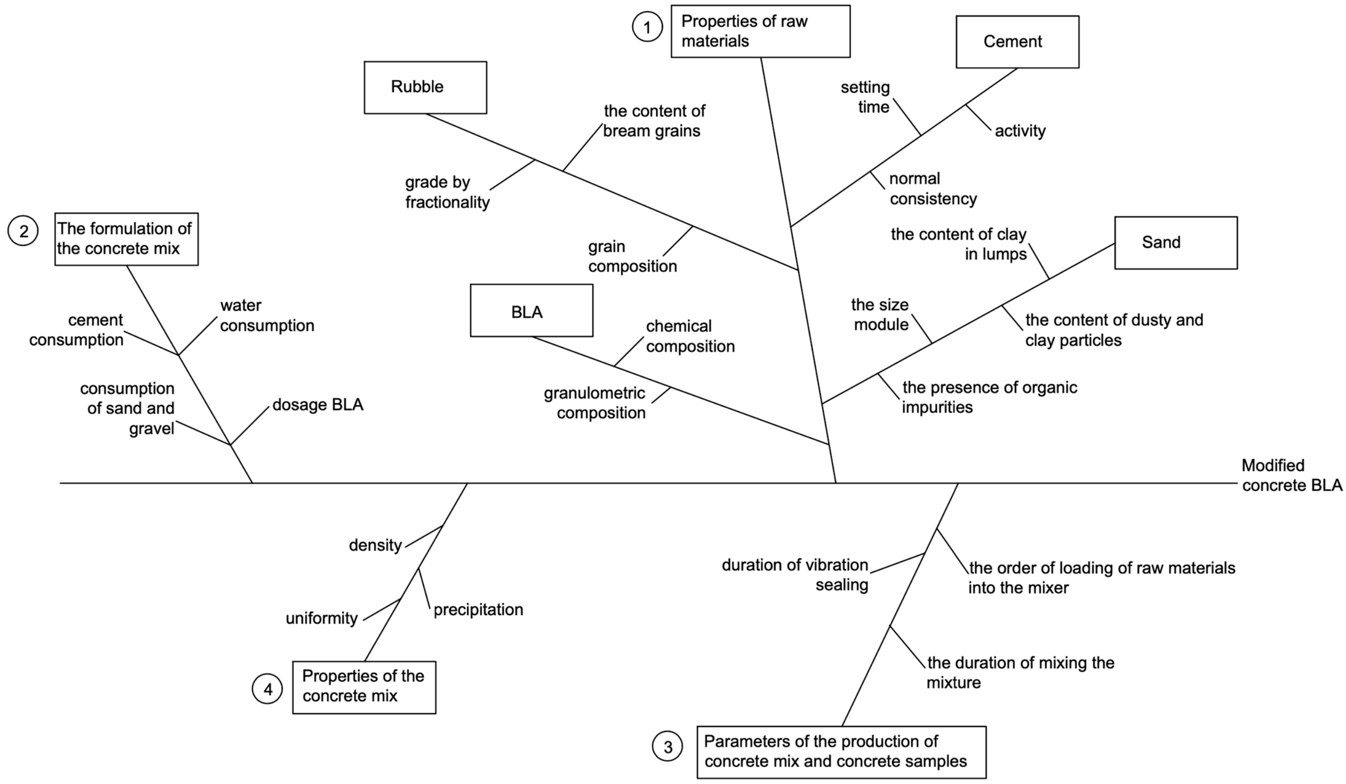


Figure 16. Factors affecting the properties of concrete with BLA.

The banana leaf ash produced in this study influences the nature of the formation of the properties of Portland cement-based composites and their practical significance in the manufacture of concrete and reinforced concrete products and structures [56]. If we consider BLA-modified concrete at the macro and micro levels, the following important points can be highlighted. At the macro level, the introduction of BLA, due to the highwater demand of the particles, worsens the settlement of the mixture and, as a result, somewhat complicates the process of forming and compacting concrete. At the micro level, additionally introduced silicon dioxide particles interact with calcium hydroxides and form cementitious compounds, which subsequently strengthens the structure of concrete [58,70].

The BLA additive has good prospects for its widespread use in the construction industry, especially in the manufacture of concrete and reinforced concrete products of a wide range. However, there are also a number of limitations. First, there is a need for more research into BLA concretes, particularly their resistance to sulfate and chloride ions and other durability properties. Secondly, there may be difficulties in establishing mass production of BLA related to the logistics of transporting banana leaves to processing and burning stations.

Overall, the results obtained in this study prove the promise and feasibility of using BLA admixture as a replacement for part of the binder in concrete. Note that in addition to the economic effect, BLA also has an environmental effect, as it solves the problem of recycling large volumes of plant waste. BLA is a fairly promising additive that can solve a number of problems, namely the environmental problem associated with reducing the carbon footprint and recycling of agricultural plant waste, and the economic problem, solved in part by saving cement in the mass production of concrete. The developed concrete is more environmentally friendly and is not inferior in its properties to traditional concrete.

After studying additional characteristics of the processes of structure formation and development of properties of concretes with BLA, as well as after clarifying the expediency of using these additives in concrete, it is important to mention the economic aspect of such a material. According to the conducted review and the expected cost analysis, based on similar productions, as well as the results of consultations with potential industrial partners, the economic effect of introducing BLA as an additive for cement composites is estimated at about 16–17% of savings per cubic meter of produced concrete mix. Cost savings arise due to the reduction of costs arising from defective products, as well as due to the use of a proven additive in the composition of concrete, which allows saving expensive components of the concrete mix, both cement and aggregates. Various options are possible, both with the use of lower grade cement and with some reduction in its consumption. In the case of aggregates, it is possible to use cheaper components.

4. Conclusions

The possibility of using banana leaf ash as a partial replacement for Portland cement in normal density concrete technology was investigated. The following conclusions are formulated.

(1) Replacing some of the Portland cement with BLA does not have a significant effect on the change in concrete density. The density of fresh concrete decreased slightly from 2437 kg/m^3 for the mixture without BLA to 2416 kg/m^3 for the mixture with 14% BLA. For hardened concrete, the maximum density value was 2416 kg/m^3 for the control composition and 2365 kg/m^3 for the composition with 14% BLA.
(2) The introduction of the BLA-modifying admixture reduced the slump of fresh concrete due to the high water demand of BLA particles. At 14% BLA, the slump reduction was 60.0%.
(3) The optimal amount of BLA replacing part of Portland cement is set to range up to 10% by weight of PC. When the amount of BLA increased to more than 10%, the strength properties of the composites decreased. Concrete with 6% BLA had the best properties.
(4) Increases in compressive and flexural strength of 7.42% and 7.01%, respectively, were recorded, water absorption decreased by 9.28%.
(5) Microscopic studies of the structure of concrete modified by BLA also confirmed the results of physical and mechanical tests and demonstrated the presence of a large number of CSH zones.

Limitations and further work include the need for additional research on BLA concretes, particularly their properties such as resistance to sulfate and chloride ion penetration and other durability properties, to clarify the scope of application of such concretes and the service life of structures made from them.

Author Contributions: Conceptualization, S.A.S., E.M.S., D.E. and A.C.; methodology, S.A.S., E.M.S. and D.E.; software, A.N.B., D.E. and A.C.; validation, A.C. and D.E.; formal analysis, A.N.B., S.A.S., E.M.S. and A.C.; investigation, D.E., S.A.S., E.M.S., A.N.B. and A.C.; resources, S.A.S., E.M.S. and A.N.B.; data curation, D.E. and A.C.; writing—original draft preparation, S.A.S., E.M.S. and A.N.B.; writing—review and editing, S.A.S., E.M.S. and A.N.B.; visualization, S.A.S., E.M.S. and A.N.B.; supervision, A.N.B.; project administration, A.N.B.; funding acquisition, S.A.S., E.M.S. and A.N.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The study did not report any data.

Acknowledgments: The authors would like to acknowledge the administration of Don State Technical University for their resources and financial support.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gaidzhurov, P.P.; Volodin, V.A. Strength Calculation of the Coupling of the Floor Slab and the Monolithic Reinforced Concrete Frame Column by the Finite Element Method. *Adv. Eng. Res.* **2022**, *22*, 306–314. [CrossRef]
2. Akerele, D.D.; Aguayo, F. Evaluating the Impact of CO_2 on Calcium SulphoAluminate (CSA) Concrete. *Buildings* **2024**, *14*, 2462. [CrossRef]
3. Moreno, S.; Rosales, M.; Rosales, J.; Agrela, F.; Díaz-López, J.L. Feasibility of Using New Sustainable Mineral Additions for the Manufacture of Eco-Cements. *Materials* **2024**, *17*, 777. [CrossRef]
4. Mailyan, L.R.; Stel'makh, S.A.; Shcherban', E.M.; Zherebtsov, Y.V.; Al-Tulaikhi, M.M. Researches of physicomechanical and design characteristics of vibrated, centrifuged and vibro-centrifuged concretes. *Adv. Eng. Res.* **2021**, *21*, 5–13. [CrossRef]
5. Fedchenko, E.A.; Gusarova, L.V.; Uskenbayeva, A.R. Green building in the ESG agenda for sustainable development of Russia: Conditions and trends. *Constr. Mater. Prod.* **2024**, *7*, 9. [CrossRef]
6. Paramonova, O.N.; Yydina, N.V. Construction Waste from Perspective of the Disperse Systems Stabilisation Theory. *Mod. Trends Constr. Urban Territ. Plan.* **2024**, *3*, 48–56. [CrossRef]
7. Guangcong, N.; Tiraturyan, A.N.; Uglova, E.V.; Vorobev, A.V. Study on Dynamic Response Characteristics of Different Asphalt Pavement Structures Based on ALF Test. *Adv. Eng. Res.* **2023**, *23*, 241–256. [CrossRef]
8. Youssf, O.; Mills, J.E.; Elchalakani, M.; Alanazi, F.; Yosri, A.M. Geopolymer Concrete with Lightweight Fine Aggregate: Material Performance and Structural Application. *Polymers* **2023**, *15*, 171. [CrossRef]
9. Chen, W.; Wu, M.; Liang, Y. Effect of SF and GGBS on Pore Structure and Transport Properties of Concrete. *Materials* **2024**, *17*, 1365. [CrossRef]
10. Liu, J.; Wu, Y.; Qu, F.; Zhao, H.; Su, Y. Assessment of CO_2 Capture in FA/GGBS-Blended Cement Systems: From Cement Paste to Commercial Products. *Buildings* **2024**, *14*, 154. [CrossRef]
11. Abdalla, J.A.; Hawileh, R.A.; Tariq, R.; Abdelkhalek, M.; Abbas, S.; Khartabil, A.; Khalil, H.T.; Thomas, B.S. Achieving concrete sustainability using crumb rubber and GGBS. *Mater Today Proc.* 2023, *in press*. [CrossRef]
12. Ganesh, P.; Ramachandra Murthy, A. Tensile behaviour and durability aspects of sustainable ultra-high performance concrete incorporated with GGBS as cementitious material. *Constr. Build. Mater.* **2019**, *197*, 667–680. [CrossRef]
13. Hu, P.; Li, X.; Zhang, Q.; Feng, F. Experimental Study on the Mechanical Properties of Steel Fiber Ferronickel Slag Powder Concrete. *Buildings* **2024**, *14*, 2471. [CrossRef]
14. Yang, J.; Wang, H.; Peng, L.; Zhao, F. The Properties of High-Performance Concrete with Manganese Slag under Salt Action. *Materials* **2024**, *17*, 1483. [CrossRef] [PubMed]
15. He, J.; Sun, C.; Wang, X. Study on the Effect of Fly Ash on Mechanical Properties and Seawater Freeze–Thaw Resistance of Seawater Sea Sand Concrete. *Buildings* **2024**, *14*, 2191. [CrossRef]
16. Velumani, S.K.; Venkatraman, S. Assessing the Impact of Fly Ash and Recycled Concrete Aggregates on Fibre-Reinforced Self-Compacting Concrete Strength and Durability. *Processes* **2024**, *12*, 1602. [CrossRef]
17. Akbulut, Z.F.; Yavuz, D.; Tawfik, T.A.; Smarzewski, P.; Guler, S. Examining the Workability, Mechanical, and Thermal Characteristics of Eco-Friendly, Structural Self-Compacting Lightweight Concrete Enhanced with Fly Ash and Silica Fume. *Materials* **2024**, *17*, 3504. [CrossRef]
18. Poranek, N.; Pizoń, J.; Łaźniewska-Piekarczyk, B.; Czajkowski, A.; Lagashkin, R. Recycle Option for Municipal Solid Waste Incineration Fly Ash (MSWIFA) as a Partial Replacement for Cement in Mortars Containing Calcium Sulfoaluminate Cement (CSA) and Portland Cement to Save the Environment and Natural Resources. *Materials* **2024**, *17*, 39. [CrossRef]
19. Beskopylny, A.N.; Shcherban', E.M.; Stel'makh, S.A.; Mailyan, L.R.; Meskhi, B.; Varavka, V.; Chernil'nik, A.; Pogrebnyak, A. Improved Fly Ash Based Structural Foam Concrete with Polypropylene Fiber. *J. Compos. Sci.* **2023**, *7*, 76. [CrossRef]
20. He, J.; Kawasaki, S.; Achal, V. The Utilization of Agricultural Waste as Agro-Cement in Concrete: A Review. *Sustainability* **2020**, *12*, 6971. [CrossRef]
21. Beskopylny, A.N.; Stel'makh, S.A.; Shcherban', E.M.; Mailyan, L.R.; Meskhi, B.; Smolyanichenko, A.S.; Beskopylny, N. High-Performance Concrete Nanomodified with Recycled Rice Straw Biochar. *Appl. Sci.* **2022**, *12*, 5480. [CrossRef]
22. Khalife, E.; Sabouri, M.; Kaveh, M.; Szymanek, M. Recent Advances in the Application of Agricultural Waste in Construction. *Appl. Sci.* **2024**, *14*, 2355. [CrossRef]
23. Maghfouri, M.; Alimohammadi, V.; Azarsa, P.; Asadi, I.; Doroudi, Y.; Balakrishnan, B. Impact of Fly Ash on Time-Dependent Properties of Agro-Waste Lightweight Aggregate Concrete. *J. Compos. Sci.* **2021**, *5*, 156. [CrossRef]
24. Prabhath, N.; Kumara, B.S.; Vithanage, V.; Samarathunga, A.I.; Sewwandi, N.; Maduwantha, K.; Madusanka, M.; Koswattage, K. A Review on the Optimization of the Mechanical Properties of Sugarcane-Bagasse-Ash-Integrated Concretes. *J. Compos. Sci.* **2022**, *6*, 283. [CrossRef]
25. Liu, B.; Wang, S.; Jia, W.; Ying, H.; Lu, Z.; Hong, Z. The Effect of RHA as a Supplementary Cementitious Material on the Performance of PCM Aggregate Concrete. *Buildings* **2024**, *14*, 2150. [CrossRef]
26. Muhammad, A.; Thienel, K.-C. Properties of Self-Compacting Concrete Produced with Optimized Volumes of Calcined Clay and Rice Husk Ash—Emphasis on Rheology, Flowability Retention and Durability. *Materials* **2023**, *16*, 5513. [CrossRef]
27. Xu, W.; Lo, T.Y.; Wang, W.; Ouyang, D.; Wang, P.; Xing, F. Pozzolanic Reactivity of Silica Fume and Ground Rice Husk Ash as Reactive Silica in a Cementitious System: A Comparative Study. *Materials* **2016**, *9*, 146. [CrossRef]

28. Zhang, W.; Liu, H.; Liu, C. Impact of Rice Husk Ash on the Mechanical Characteristics and Freeze–Thaw Resistance of Recycled Aggregate Concrete. *Appl. Sci.* **2022**, *12*, 12238. [CrossRef]
29. Su, Q.; Xu, J. Mechanical properties of rice husk ash and glass powder concrete: Experimental and mesoscopic studies. *J. Build. Eng.* **2024**, *95*, 110278. [CrossRef]
30. Nazari, A.; Toufigh, V. Effects of elevated temperatures and re-curing on concrete containing rice husk ash. *Constr. Build. Mater.* **2024**, *439*, 137277. [CrossRef]
31. Jing, Y.; Lee, J.C.; Moon, W.C.; Ng, J.L.; Yew, M.K.; Chu, M.Y. Mechanical properties, permeability and microstructural characterisation of rice husk ash sustainable concrete with the addition of carbon nanotubes. *Heliyon* **2024**, *10*, e32780. [CrossRef] [PubMed]
32. Barragán-Ramírez, R.; González-Hernández, A.; Bautista-Ruiz, J.; Ospina, M.; Aperador Chaparro, W. Enhancing Concrete Durability and Strength with Fly Ash, Steel Slag, and Rice Husk Ash for Marine Environments. *Materials* **2024**, *17*, 3001. [CrossRef] [PubMed]
33. Ordoñez, L.M.; Borrachero, M.V.; Monzó, J.; Soriano, L.; Payá, J. Binary and Ternary Blended Portland Cements Containing Different Types of Rice Husk Ash. *Materials* **2024**, *17*, 2923. [CrossRef] [PubMed]
34. Beskopylny, A.N.; Stel'makh, S.A.; Shcherban', E.M.; Mailyan, L.R.; Meskhi, B.; Smolyanichenko, A.S.; Varavka, V.; Beskopylny, N.; Dotsenko, N. Influence of Electromagnetic Activation of Cement Paste and Nano-Modification by Rice Straw Biochar on the Structure and Characteristics of Concrete. *J. Compos. Sci.* **2022**, *6*, 268. [CrossRef]
35. Lian, J.; Wang, Y.; Fu, T.; Easa, S.M.; Zhou, Y.; Li, H. Mechanical, Electrical, and Tensile Self-Sensing Properties of Ultra-High-Performance Concrete Enhanced with Sugarcane Bagasse Ash. *Materials* **2024**, *17*, 82. [CrossRef]
36. Memon, S.A.; Javed, U.; Shah, M.I.; Hanif, A. Use of Processed Sugarcane Bagasse Ash in Concrete as Partial Replacement of Cement: Mechanical and Durability Properties. *Buildings* **2022**, *12*, 1769. [CrossRef]
37. El-said, A.; Awad, A.; Ahmad, M.; Sabri, M.M.S.; Deifalla, A.F.; Tawfik, M. The Mechanical Behavior of Sustainable Concrete Using Raw and Processed Sugarcane Bagasse Ash. *Sustainability* **2022**, *14*, 11181. [CrossRef]
38. Farrant, W.E.; Babafemi, A.J.; Kolawole, J.T.; Panda, B. Influence of Sugarcane Bagasse Ash and Silica Fume on the Mechanical and Durability Properties of Concrete. *Materials* **2022**, *15*, 3018. [CrossRef]
39. Landa-Ruiz, L.; Landa-Gómez, A.; Mendoza-Rangel, J.M.; Landa-Sánchez, A.; Ariza-Figueroa, H.; Méndez-Ramírez, C.T.; Santiago-Hurtado, G.; Moreno-Landeros, V.M.; Croche, R.; Baltazar-Zamora, M.A. Physical, Mechanical and Durability Properties of Ecofriendly Ternary Concrete Made with Sugar Cane Bagasse Ash and Silica Fume. *Crystals* **2021**, *11*, 1012. [CrossRef]
40. Xu, Q.; Ji, T.; Gao, S.-J.; Yang, Z.; Wu, N. Characteristics and Applications of Sugar Cane Bagasse Ash Waste in Cementitious Materials. *Materials* **2019**, *12*, 39. [CrossRef]
41. Ramakrishnan, K.; Ganesh, V.; Vignesh, G.; Vignesh, M.; Shriram, V.; Suryaprakash, R. Mechanical and durability properties of concrete with partial replacement of fine aggregate by sugarcane bagasse ash (SCBA). *Mater. Today Proc.* **2021**, *42*, 1070–1076. [CrossRef]
42. Da Silva, S.R.; Andrade, J.J.d.O. A Review on the Effect of Mechanical Properties and Durability of Concrete with Construction and Demolition Waste (CDW) and Fly Ash in the Production of New Cement Concrete. *Sustainability* **2022**, *14*, 6740. [CrossRef]
43. Mohammadhosseini, H.; Alyousef, R.; Poi Ngian, S.; Tahir, M.M. Performance Evaluation of Sustainable Concrete Comprising Waste Polypropylene Food Tray Fibers and Palm Oil Fuel Ash Exposed to Sulfate and Acid Attacks. *Crystals* **2021**, *11*, 966. [CrossRef]
44. Alsubari, B.; Shafigh, P.; Jumaat, M.Z. Development of Self-Consolidating High Strength Concrete Incorporating Treated Palm Oil Fuel Ash. *Materials* **2015**, *8*, 2154–2173. [CrossRef]
45. Hasan, N.M.S.; Sobuz, M.H.R.; Shaurdho, N.M.N.; Meraz, M.M.; Datta, S.D.; Aditto, F.S.; Kabbo, M.K.I.; Miah, M.J. Eco-friendly concrete incorporating palm oil fuel ash: Fresh and mechanical properties with machine learning prediction, and sustainability assessment. *Heliyon* **2023**, *9*, e22296. [CrossRef]
46. Olivia, M.; Maulidi, M.A.; Wibisono, G. Characteristics of palm oil fuel ash concrete admixed with precipitated silica and silica fume. *Clean. Eng. Technol.* **2024**, *19*, 100738. [CrossRef]
47. Mhaya, A.M.; Shahidan, S.; Zuki, S.S.M.; Huseien, G.F.; Azmi, M.A.M.; Ismail, M.; Mirza, J. Durability and Acoustic Performance of Rubberized Concrete Containing POFA as Cement Replacement. *Sustainability* **2022**, *14*, 15510. [CrossRef]
48. Men, S.; Tangchirapat, W.; Jaturapitakkul, C.; Ban, C.C. Strength, fluid transport and microstructure of high-strength concrete incorporating high-volume ground palm oil fuel ash blended with fly ash and limestone powder. *J. Build. Eng.* **2022**, *56*, 104714. [CrossRef]
49. Amran, M.; Lee, Y.H.; Fediuk, R.; Murali, G.; Mosaberpanah, M.A.; Ozbakkaloglu, T.; Yong Lee, Y.; Vatin, N.; Klyuev, S.; Karelia, M. Palm Oil Fuel Ash-Based Eco-Friendly Concrete Composite: A Critical Review of the Long-Term Properties. *Materials* **2021**, *14*, 7074. [CrossRef]
50. Stel'makh, S.A.; Beskopylny, A.N.; Shcherban', E.M.; Mavzolevskii, D.V.; Drukarenko, S.P.; Chernil'nik, A.A.; Elshaeva, D.M.; Shilov, A.A. Influence of Corn Cob Ash Additive on the Structure and Properties of Cement Concrete. *Constr. Mater. Prod.* **2024**, *7*, 2. [CrossRef]
51. Shcherban', E.M.; Stel'makh, S.A.; Beskopylny, A.N.; Mailyan, L.R.; Meskhi, B.; Chernil'nik, A.; El'shaeva, D.; Pogrebnyak, A.; Yaschenko, R. Influence of Sunflower Seed Husks Ash on the Structure Formation and Properties of Cement Concrete. *Civ. Eng. J.* **2024**, *10*, 1475–1493. [CrossRef]

52. Șerbănoiu, A.A.; Grădinaru, C.M.; Muntean, R.; Cimpoeșu, N.; Șerbănoiu, B.V. Corn Cob Ash versus Sunflower Stalk Ash, Two Sustainable Raw Materials in an Analysis of Their Effects on the Concrete Properties. *Materials* **2022**, *15*, 868. [CrossRef] [PubMed]
53. Sai Vamsi Gangadhar, M.; Absar, W.; Siddharth, A.; Sofi, A. Comparative study on sugarcane bagasse ash and banana peel powder on concrete and its properties. *Mater. Today Proc.* 2023, *in press*. [CrossRef]
54. Beskopylny, A.N.; Stel'makh, S.A.; Shcherban', E.M.; Mailyan, L.R.; Meskhi, B.; Varavka, V.; Beskopylny, N.; El'shaeva, D. A Study on the Cement Gel Formation Process during the Creation of Nanomodified High-Performance Concrete Based on Nanosilica. *Gels* **2022**, *8*, 346. [CrossRef]
55. Sierra, O.M.; Payá, J.; Monzó, J.; Borrachero, M.V.; Soriano, L.; Quiñonez, J. Characterization and Reactivity of Natural Pozzolans from Guatemala. *Appl. Sci.* **2022**, *12*, 11145. [CrossRef]
56. Shah, M.; Ali, M. A Study on Mechanical Properties of Environmentally friendly Concrete Incorporating Banana Fiber and Banana Leaf Ash. *Eng. Proc.* **2023**, *53*, 56. [CrossRef]
57. Tavares, J.C.; Lucena, L.F.L.; Henriques, G.F.; Ferreira, R.L.S.; Dos Anjos, M.A.S. Use of banana leaf ash as partial replacement of Portland cement in eco-friendly concretes. *Constr. Build. Mater.* **2022**, *346*, 128467. [CrossRef]
58. Islam, M.H.; Law, D.W.; Gunasekara, C.; Sobuz, M.H.R.; Rahman, M.N.; Habib, M.A.; Sabbir, A.K. Assessing the Influence of Banana Leaf Ash as Pozzolanic Material for the Production of Green Concrete: A Mechanical and Microstructural Evaluation. *Materials* **2024**, *17*, 720. [CrossRef]
59. Hossain, M.M.; Karim, M.R.; Hasan, M.; Hossain, M.K.; Zain, M.F.M. Durability of mortar and concrete made up of pozzolans as a partial replacement of cement: A review. *Constr. Build. Mater.* **2016**, *116*, 128–140. [CrossRef]
60. *GOST R 57813-2017/EN 12350-6:2009*; Testing Fresh Concrete. Part 6. Density. Standartinform: Moscow, Russia, 2017. Available online: https://docs.cntd.ru/document/1200157335 (accessed on 15 August 2024).
61. *GOST R 57809-2017/EN 12350-2:2009*; Testing Fresh Concrete. Part 2. Slump Test. Standartinform: Moscow, Russia, 2017. Available online: https://docs.cntd.ru/document/1200157288 (accessed on 15 August 2024).
62. *EN 12390-7:2019*; Testing Hardened Concrete—Part 7: Density of Hardened Concrete. iTeh Standards: Etobicoke, ON, Canada, 2019. Available online: https://standards.iteh.ai/catalog/standards/cen/811a0cf3-55e3-495a-b06e-5c302d5f2806/en-12390-7-2019 (accessed on 15 August 2024).
63. *EN 12390-1:2021*; Testing Hardened Concrete—Part 1: Shape, Dimensions and Other Requirements of Specimens and Moulds. iTeh Standards: Etobicoke, ON, Canada, 2021. Available online: https://standards.iteh.ai/catalog/standards/cen/d1c9ccee-2e5a-425e-a964-961da95d2f99/en-12390-1-2021 (accessed on 15 August 2024).
64. *EN 12390-2:2019*; Testing Hardened Concrete—Part 2: Making and Curing Specimens for Strength Tests. iTeh Standards: Etobicoke, ON, Canada, 2019. Available online: https://standards.iteh.ai/catalog/standards/cen/ae7e6a86-1cbc-455e-8b2a-8964be9087f9/en-12390-2-2019 (accessed on 15 August 2024).
65. *EN 12390-3:2019*; Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. iTeh Standards: Etobicoke, ON, Canada, 2019. Available online: https://standards.iteh.ai/catalog/standards/cen/7eb738ef-44af-436c-ab8e-e6561571302c/en-12390-3-2019 (accessed on 15 August 2024).
66. *EN 12390-4:2019*; Testing Hardened Concrete—Part 4: Compressive Strength—Specification for Testing Machines. iTeh Standards: Etobicoke, ON, Canada, 2019. Available online: https://standards.iteh.ai/catalog/standards/cen/10b1c613-819b-42d7-8f94-480cd37a666a/en-12390-4-2019 (accessed on 15 August 2024).
67. *EN 12390-5:2019*; Testing Hardened Concrete—Part 5: Flexural Strength of Test Specimens. iTeh Standards: Etobicoke, ON, Canada, 2019. Available online: https://standards.iteh.ai/catalog/standards/cen/5653c2c7-55a9-4bcb-8e13-5b1dfb0e3baf/en-12390-5-2019 (accessed on 15 August 2024).
68. *GOST 12730.3*; Concretes. Method of Determination of Water Absorption. Gost Standard: Moscow, Russia, 2020. Available online: https://docs.cntd.ru/document/100177301 (accessed on 15 August 2024).
69. *BS 1881-122:2011+A1:2020*; Testing Concrete Method for Determination of Water Absorption. European Standards: Plzen, Czech Republic, 2020. Available online: https://www.en-standard.eu/bs-1881-122-2011-a1-2020-testing-concrete-method-for-determination-of-water-absorption/ (accessed on 15 August 2024).
70. Shcherban', E.M.; Stel'makh, S.A.; Beskopylny, A.N.; Mailyan, L.R.; Meskhi, B.; Elshaeva, D.; Chernil'nik, A.; Mailyan, A.L.; Ananova, O. Eco-Friendly Sustainable Concrete and Mortar Using Coal Dust Waste. *Materials* **2023**, *16*, 6604. [CrossRef]
71. Mim, N.J.; Meraz, M.M.; Islam, M.H.; Noroozinejad Farsangi, E.; Mehedi, M.T.; Arafin, S.A.K.; Shrestha, R.K. Eco-friendly and cost-effective self-compacting concrete using waste banana leaf ash. *J. Build. Eng.* **2023**, *64*, 105581. [CrossRef]
72. Kanning, R.C.; Portella, K.F.; Bragança, M.O.G.P.; Bonato, M.M.; dos Santos, J.C.M. Banana leaves ashes as pozzolan for concrete and mortar of Portland cement. *Constr. Build. Mater.* **2014**, *54*, 460–465. [CrossRef]
73. Shirgire, A.; Thenmozhi, S.; Praveen Jesuraj, V.; Shelar, A.; Chavhan, V.S.; Javanjal, V. Experimental study on high performance concrete using rice husk ash. *Mater. Today Proc.* 2023, *in press*. [CrossRef]
74. Gomes, C.L.; Valle Salles, P.; Bezerra, A.C.S.; Rodrigues, C.S.; Spitale Jacques Poggiali, F. Mechanical and durability properties of concrete produced with construction and demolition waste and rice husk ash. *Constr. Build. Mater.* **2023**, *406*, 133471. [CrossRef]
75. Trinh, H.T.M.K.; Fernando, P.H.H.U.; Tran, T.M.; Pham, T.M. Synergistic effect of rice husk ash and ceramic powder on mechanical properties of ultra-high-performance concrete. *Structures* **2024**, *67*, 106974. [CrossRef]

76. França, S.; Sousa, L.N.; Saraiva, S.L.C.; Ferreira, M.C.N.F.; Silva, M.V.d.M.S.; Gomes, R.C.; Rodrigues, C.d.S.; Aguilar, M.T.P.; Bezerra, A.C.d.S. Feasibility of Using Sugar Cane Bagasse Ash in Partial Replacement of Portland Cement Clinker. *Buildings* **2023**, *13*, 843. [CrossRef]
77. Jagadesh, P.; Ramachandramurthy, A.; Murugesan, R. Evaluation of mechanical properties of Sugar Cane Bagasse Ash concrete. *Constr. Build. Mater.* **2018**, *176*, 608–617. [CrossRef]
78. Marangu, J.M.; Sharma, M.; Scheinherrová, L.; Kafodya, I.; Mutai, V.K.; Latif, E.; Novelli, V.I.; Ashish, D.K.; Maddalena, R. Durability of Ternary Blended Concrete Incorporating Rice Husk Ash and Calcined Clay. *Buildings* **2024**, *14*, 1201. [CrossRef]
79. Endale, S.A.; Taffese, W.Z.; Vo, D.-H.; Yehualaw, M.D. Rice Husk Ash in Concrete. *Sustainability* **2023**, *15*, 137. [CrossRef]
80. Nduka, D.O.; Olawuyi, B.J.; Fagbenle, O.I.; Fonteboa, B.G. Assessment of the Durability Dynamics of High-Performance Concrete Blended with a Fibrous Rice Husk Ash. *Crystals* **2022**, *12*, 75. [CrossRef]