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Influence of Sunflower Seed Husks Ash on the Structure Formation and Properties of Cement Concrete

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Abstract

The limitation of the application of non-renewable materials is one of the solutions to the problem of the sustainable evolution of civilization in the 21st century. Using additional binders in concrete obtained from plant waste will be economically and environmentally beneficial and will also allow us to move closer to achieving sustainable development goals. This study searches for rational composition components and a methodological approach regarding the technological characteristics to get the highest quality elements and prime concrete properties on the basis of sunflower seed husk ash (SSHA). Experimental concrete specimens were manufactured with partial Portland cement substitution with SSHA amounts ranging from 2% to 16% by weight in increments of 2%. This study focuses on investigating the density and workability of the concrete mixture, along with the compressive strength, concrete density, and water absorption. This article used granulometric, microscopic, and X-ray phase analysis methods. Including SSHA in all considered ranges reduces the slump in concrete mixtures. The optimal SSHA content in concrete is up to 12%. An 8% SSHA content has been found to deliver the most favorable mechanical characteristics of the concrete studied. The compressive strength of the investigated concrete has increased by 14.89%, and water absorption has decreased by 15.78%.

Keywords: Agricultural Waste; Sunflower Seed Husk Ash; Concrete Mixture; Concrete; Compressive Strength.

1. Introduction

Many sectors of the economy, like construction, industrial production, and agriculture, are facing ever-new and more stringent requirements. First, the tightening of requirements for various areas of manufacturing industries is because of the existing environmental agenda and the need to achieve sustainable development goals [1]. Let's take a closer look at agriculture and, in particular, processing industries, which are accompanied by a large amount of plant waste [2, 3]. Solving the problem of recycling plant waste in many regions of the world is currently an urgent environmental problem. And the existing environmental problem poses various tasks for process engineers to find ways of using this waste [4].

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One of the most interesting and promising methods for recycling plant waste is its combustion in muffle furnaces and the further use of the resulting ash in cement concrete technology [5, 6]. The most popular plant wastes are rice husks and rice straw because of the large volumes of rice cultivation worldwide [7, 8].

The issue of using ash from these wastes in cement concrete technology and its effectiveness has been quite well studied, which is confirmed by various studies [9–23]. For example, in Salas Montoya et al. (2023) [9] study, "the application of rice husk ash as a substitution of a part of the Portland cement" provided a fairly significant rise in strength properties, namely over 20% compared to the reference prototype. In Joel (2020) [10] study, including rice husk ash in an amount from 5 to 15% helped improve the characteristics of the composite, and much better characteristics were presented at a 10% rate. In general, "it has been demonstrated that the rice husk ash (RHA) application can replace up to 20%" of the binder without significantly degrading the characteristics of concrete like strength, durability, and workability. The enhanced strength and long-term properties of concrete are primarily because of "the high pozzolanic activity of ash", which promotes the organization of additional CSH gels, compacting, and strengthening the composite structure [11–13]. RHA was also used as a fine aggregate. In Stratoura et al. (2023) [14] study, including RHA in concrete technology made it possible to get lightweight concrete with increased resistance to the effects of chlorides. In Rani & Jaya Krishna (2022) [15] study, the use of rice straw ash in an amount of 10% also improved "the compressive strength by 23.21% and tensile strength by 28.25% compared to the control composition". Studies [16–20] have confirmed the positive impact of rice husk and straw ash on the quality characteristics of composites in concrete technology.

Sugarcane pulp is commonly used as a replacement for binder ash. For example, in Landa-Ruiz et al. (2021) [21] study, the authors developed concrete compositions containing sugarcane bagasse ash up to 50% instead of part of the cement and also found that the most effective waste dosages were 20% and 30%, at which a rise in compressive strength of 5.58% and 7.13% was recorded. Using sugarcane bagasse ash in the reactive powder concrete [22] made it possible to get composites with a compressive strength of over 200 MPa. By optimizing the packaging of dry fine powders, this effect was achieved in many ways. In França et al. (2023) [23] study, the use of sugarcane bagasse ash up to 30% in conventional concrete allowed for an environmentally friendly composite with improved strength properties. The effectiveness of this type of ash as a binder in building materials has been confirmed by several other studies [24–28]. Also, in various works, the authors proposed the simultaneous use of several types of ashes of both plant and industrial origin as a cement replacement. In Marzouk et al. (2023) [29] study, compositions of extra-strong self-compacting concrete comprising four kinds of ash were developed. The best composites were obtained using 3% sugarcane bagasse ash, 10% rice husk ash, 5% rice straw ash, and 10% Phragmites ash. In Lertwattanaruk & Makul (2021) [30] study, the introduction of rice husk ash and bagasse ash substituting a portion of cement allowed to get self-compacting concrete mixtures with optimal rheological characteristics and acceptable strength characteristics. The effectiveness of using such complex additives from several types of ash has also been confirmed by research [31–34].

In many regions of the world, there is a problem of rational utilization of waste as sunflower seed husk ash (SSHA). The existing environmental problem poses various challenges for process engineers to find ways to use these wastes. In this regard, various works by world scientists propose various methods for recycling waste, such as sunflower seed husks [35–37]. By using ash from sunflower and pumpkin seeds as a partial replacement of binder up to 15% in Shahbazpanahi & Faraj (2020) [35] study, concrete with enhanced compressive strength characteristics was achieved. Using SSHA in the technology of ceramic products [36] up to 50% made it possible to obtain products with the required engineering characteristics. In Zhu et al. (2023) [37] study, the authors examined the possibility of using straw ash in the technology of geopolymer concrete and substantiated the prospects for using this waste. Concrete technology offers a fascinating and promising way to recycle waste, particularly through the use of sunflower seed husks [35, 37]. As is known, concrete, being a heterogeneous conglomerate material, involves the use of several components in its composition that determine its physical nature. It is assumed that sunflower seed husks, when burned, form biochar, which turns into ash at a certain degree of crushing. Sunflower seed husk ash often turns out to be useful in terms of chemical and physical interactions with concrete components to get a dense, cohesive, and high-quality structure for a stone composite.

Analyzing recent research on the application of sunflower seed husk ash [38–41], it is possible to identify some gaps consisting in a more thorough analysis and systematic scientific justification for the effective use of SSHA as one of the components of concrete in the context of the fundamental principle "composition - structure - properties". Thus, the novel component of this investigation is to find a rational recipe, technological parameters, and the correct dosages of sunflower seed husk ash so that this additive brings maximum effect. The research's scientific novelty lies in establishing the fundamental connections between recipe and technological parameters in a concrete modification with sunflower seed husk ash and the resulting structure formation and concrete performance.

The primary aim of this article is to find a rational recipe and technological parameters for achieving superior concrete quality and properties using sunflower seed husk ash. The aim of the study is the rational choice and justification of the initial recipe and technological parameters for modifying concrete with the ash of sunflower seed husks. This should be completed by reviewing and analyzing the literature on using plant waste ash to modify concrete. The next aim of the investigation is to provide large-scale experiments to study the impact of different dosages of sunflower seed husk ash on the properties and formation of concrete structures. And finally, the last task of the study is to analyze the results obtained by issuing specific recommendations for the development of the study and the prospects for applying the obtained data in the practice of agriculture, production, and construction.

The structure of the article is as follows: In Section 2, the study's materials and methods are discussed. In Section 3, the research results are presented and discussed, along with a comparison of previous achievements. The research results are summarized in Section 4. Section 5 Declarations provide information about author contributions, data availability statements, funding, acknowledgments, and conflicts of interest. Section 6 References contains a list of previously published studies necessary to identify gaps, articulate scientific novelty, and conduct a comparative analysis of this investigation.

2. Materials and methods

2.1. Materials

The materials used for the study were selected as follows: When selecting materials for the study, the authors proceeded from the following postulates: the traditional components for manufacturing concrete are binder, filler, mixer, and additives. It should be noted and understood that the additive proposed for conducting new research in order to investigate structure formation and new concrete properties is an atypical, non-standard component, largely based on working hypotheses and an analysis of the world scientific literature. In this regard, an important aspect was the selection of the basic components for conducting research.

Traditional materials were accepted in quantities that were well studied and had known specified characteristics: Portland cement, crushed stone, sand, and water with a known composition, in order to ensure the purity of the experimental study. When conducting experimental studies, the authors adhered to the principles of invariance and repeatability so that the comparison of the results obtained was as correct as possible. The authors used exclusively materials that had undergone a preliminary quality assessment at manufacturing plants, accompanied by passports and quality certificates, thereby preparing the basis for consolidating the obtained data at the level of regulatory and technical constant parameters. Methods were applied in accordance with GOST for relevant materials and methods, and data processing was used as enshrined in regulatory and technical documents.

Thus, by using tools that are properly validated and reliable in use, the authors ensured maximum efficiency in terms of outcome assessment.

The following precursors were used to prepare concrete specimens:

- Portland cement CEM I 52.5N (C);
- Crushed sandstone (CS);
- Quartz sand (S);
- Microsilica MK-85 (MS);
- Sunflower seed husk ash (SSHA);
- Plasticizer Poliplast PC (P).

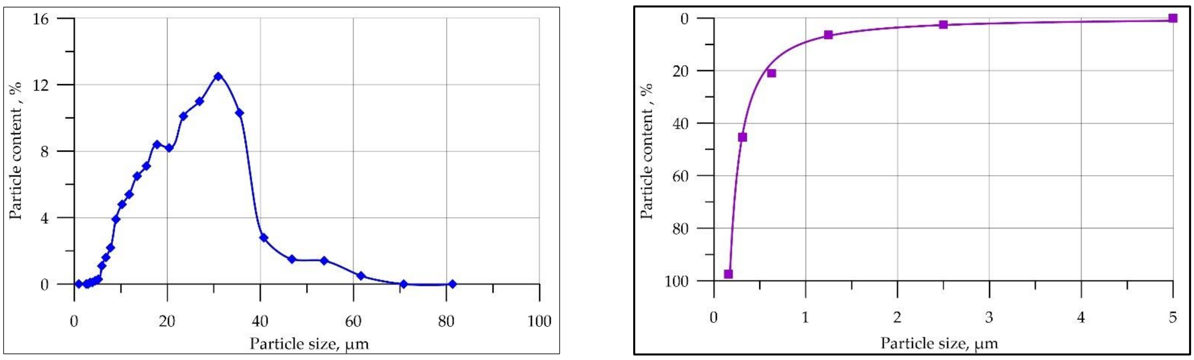
Table 1 presents the attributes of the raw materials.

Table 1. Properties of raw materials

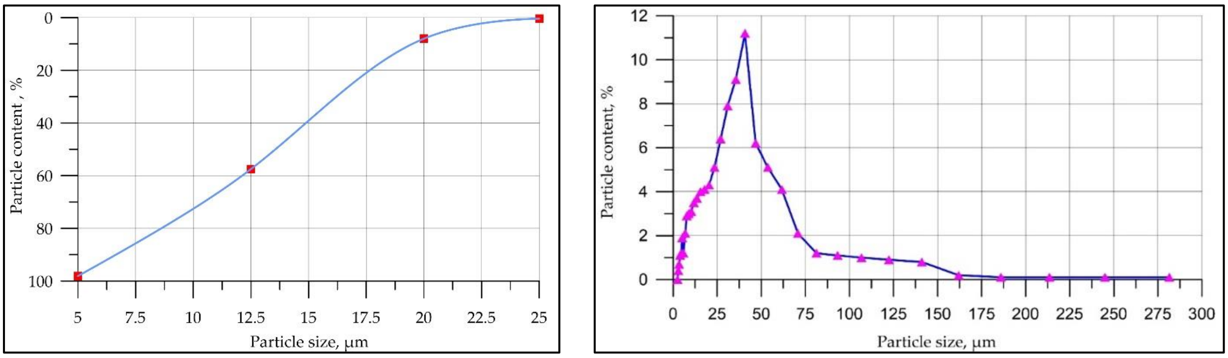
Property	Value
Portland Cement CEM I 52.5N	
Specific surface area (m^2/kg)	338
Soundness (mm)	0.3
Fineness, passage through a sieve No 008 (%)	95.9
Setting times (min)	
- Start	180
- End	250
Compressive strength (MPa):	
- 2 days	27.3
- 28 days	57.1
Crushed Sandstone	
Resistance to fragmentation (wt %)	11.1
Apparent density (kg/m^3)	2561
Bulk density (kg/m^3)	1378
Particle size (mm)	5…20
The content of lamellar and acicular grains (wt %)	8.2

Quartz Sand						
Sieve Diameter (mm) Partial residues on sieves (%) Total residues on sieves (%)					Content (% by weight) of grains with a particle size of less than 0.16 mm	Fineness modulus
2.5	*1.25*	*0.63*	*0.315*	*0.16*		
1.6	4.3	7.9	39.7	43.7	2.8	1.72
1.6	5.9	13.8	53.5	97.2		
Bulk density (kg/m^3)					1341	
Content of clay in lumps (%)					0.12	
The content of dust and clay particles (%)					0.09	
Contaminant and organic content (%)					No	
***Sunflower Seed Husk Ash* [42, 43]**						
CaO (%)					26.6	
K_2O (%)					9.93	
SiO_2 (%)					12.4	
MgO (%)					4.38	
P_2O_5 (%)					3.56	
Fe_2O_3 (%)					1.12	
Al_2O_3 (%)					0.25	
Na_2O (%)					2.12	
MnO (%)					0.019	
ZnO (%)					0.067	
CuO (%)					0.048	
Cr_2O_3 (%)					0.004	
Ni_2O (%)					0.002	
Loss on ignition (%)					39.5	
Bulk density (kg/m^3)					402	
Microsilica MK-85						
SiO_2 (%)					93.0	
Al_2O_3 (%)					1.68	
Fe_2O_3 (%)					0.65	
CaO (%)					2.17	
MgO (%)					1.01	
K_2O (%)					1.23	
S					0.26	
Plasticizer Polyplast PC						
Chemical basis					polycarboxylate	
Appearance/color					clear liquid	
Density (g/cm^3)					1.130	
pH value					6.7	

The granulation curves of used materials are presented in Figure 1.



(a) (b)



(c) (d)

Figure 1. Particle granulation curves of used composite elements: (a) Portland cement, (b) quartz sand, (c) crushed sandstone, (d) sunflower seed husk ash

From Figure 1, the results show that most of the ash particles of sunflower seed husks 76.9%, subjected to additional mechanical activation, fall within the range from 2 to 40 µm. SSHA particles larger than 40 microns contained 23.1%. The appearance of sunflower seed husks used to make concrete is shown in Figure 2.

Figure 2. Sunflower seed husks

2.2. Methods

Sunflower seed husks were supplied from a sunflower oil production plant in Rostov-on-Don, Russia. The preparation of ash from sunflower seed husks was conducted as follows. Sunflower seed husks were pre-dried in a laboratory oven for one day at a temperature of 80 °C, and then calcined in a muffle furnace at a temperature of 450 °C for 3 hours. Afterwards, the resulting SSHA was cooled to room temperature and subjected to additional mechanical activation by grinding using a laboratory planetary mill Activator-4M. SSHA was milled for 3 hours at 600 rpm. Table 2 contains the presented concrete mix designs.

Table 2. Concrete mix compositions

Mixture type	Mortar mixture proportion per 1 м^3						
	C (kg/m^3)	W (L/m^3)	S (kg/m^3)	CS (kg/m^3)	SSHA (kg/m^3)	MS (% by weight of binder)	P (% by weight of binder)
0/SSHA	347	195	713	978	0	4	1.5
2/SSHA	340	195	713	978	7	4	1.5
4/SSHA	333	195	713	978	14	4	1.5
6/SSHA	326	195	713	978	21	4	1.5
8/SSHA	319	195	713	978	28	4	1.5
10/SSHA	312	195	713	978	35	4	1.5
12/SSHA	305	195	713	978	42	4	1.5
14/SSHA	298	195	713	978	49	4	1.5
16/SSHA	291	195	713	978	56	4	1.5

The main stages of manufacturing concrete samples with different SSHA contents are shown in Table 3. Figure 3 displays the experimental program.

Table 3. Stages of manufacturing concrete samples with different SSHA contents

Stage description	Technological equipment
Dosing of raw materials under the recipe: • Cement; • Ash from Sunflower Seed Husks; • Sand; • Crushed Stone; • Water; • Microsilica; • Plasticizer Additive.	Scales VLTE-5100S (Gosmeter, St. Petersburg, Russia)
The following sequence is used to prepare the concrete mixture: • Mixing cement, sunflower seed husk ash, microsilica and sand in dry form for 60 seconds; • Introducing mixing water with a plasticizer pre-diluted in it into the mixture of dry components and stirring for 60 seconds; • Introducing crushed stone into the mortar mixture and mixing until smooth	Laboratory mixer BL-10
The molding of the samples was conducted by placing the mixture into a mold in 3 stages with intermediate vibration for 20 seconds	Molds 2FK-100; platform for vibration
Samples were removed from molds 1 day after production.	–
Hardening chamber was used for 27 days at a temperature of 20±2 °C and an air humidity of 95%	Curing chamber KNT-1

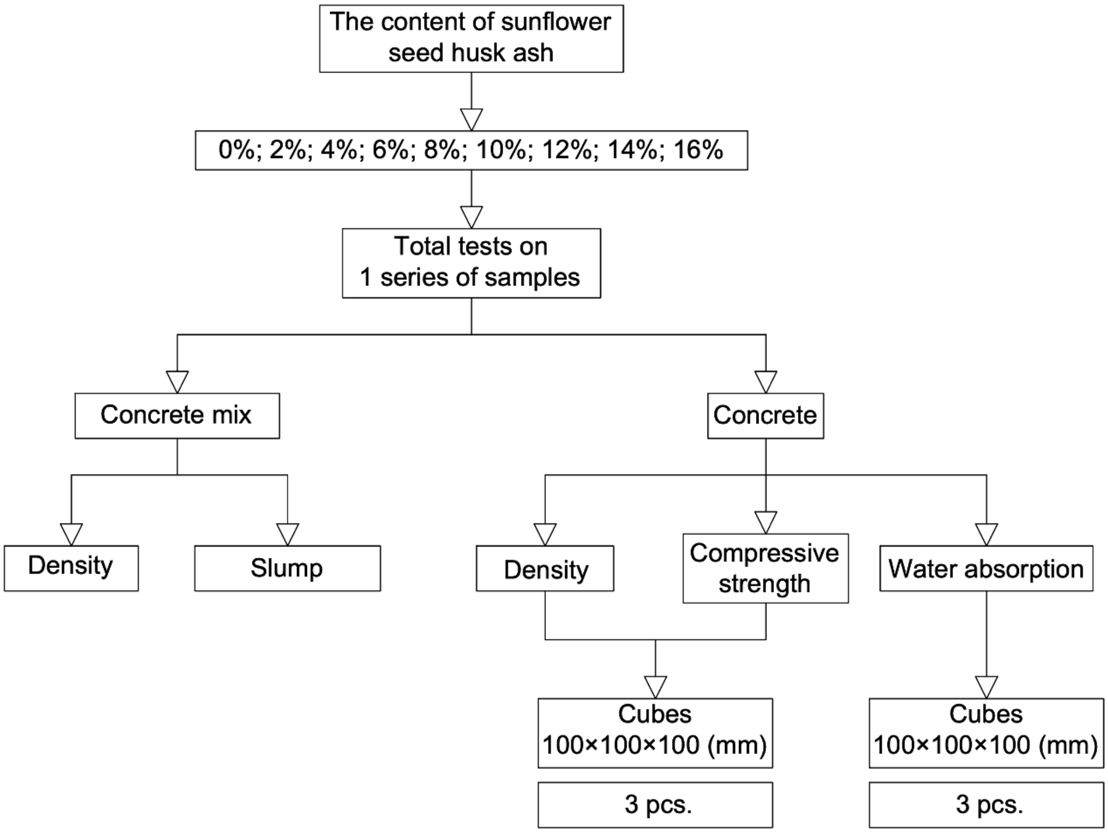


Figure 3. Experimental program

The fresh concrete mixture's average density [44, 45] was assessed by dividing the mixture mass by its volume. The determination of the concrete mixture density was provided by pre-weighing the measuring vessel, filling it with the mixture, and compacting it. After compaction, the excess concrete mixture was cut off with a metal ruler and the surface was carefully leveled at the level of the edges. The container with the concrete mixture was weighed with an error of only 5 g. The Equation 1 was used to calculate the concrete's average density.

$$\rho = \frac{m - m_1}{V} \times 1000 \tag{1}$$

where m and m_1 are the mass of the form with and without the concrete mixture (g); V – capacity of the form (cm^3).

The fresh concrete workability was estimated by measuring the settlement of a cone formed from the mixture. Before testing, the cone and all devices in contact with the concrete mixture were moistened. Next, the cone was positioned on a flat surface and filled with a concrete mixture. The compaction process involved bayoneting a metal rod into each layer 25 times. Once the concrete mixture was compacted, the excess mixture was trimmed flush with the cone's upper edges using a trowel, and the surface was smoothed. Time from the beginning of filling the cone to its removal did not exceed 3 minutes. The cone rose smoothly in a strictly vertical direction from the molded concrete mixture and was placed beside it. The time spent raising the cone was 5-7 s.

The compressive strength of concrete was estimated using prescribed methods [46-49] with a Press P-50 equipment. In compression testing, the cube samples were placed on the lower support part of the press. To align the cube samples centrally, marked indications on the press plate were utilized. After installation, a force increase speed of (0.6 ± 0.2) MPa/s is consistently applied until failure. The calculation of compressive strength is determined by utilizing the following equation:

$$R = \alpha \frac{F}{A} \tag{2}$$

here F is the collapse force, N; A − the cross-sectional area of the sample, mm^2; α is the scale factor, α is 0.95.

Method [50] was applied to estimate the density of hardened concrete. To evaluate water absorption [51, 52], concrete specimens were placed in a water-filled container, where the water level kept around 50 mm above the sample surface. The saturated specimens were subjected to weighing every 24 hours, with the experiment concluding when the discrepancy between two consecutive weights surpassed 0.1%. The formula used to calculate water absorption was as follows:

$$W = \frac{m_d - m_s}{m_s} \times 100 \tag{3}$$

here m_d is the drying sample mass (g); m_s is dry sample mass (g).

A microscope with the stereoscopic aperture MBS-10 was used to assess the structure of the samples at a 10x magnification. The Microsizer model 201C device was used to evaluate the granulometric composition of mechanically activated ash from sunflower seed husks.

The concrete composites with SSHA were analyzed using X-ray diffraction on an "ARLX'TRA" diffractometer.

3. Results and Discussion

Findings of a study on concrete mixtures with varying amounts of SSHA as a cement replacement are presented in Figures 4 and 5. The change in the mixture's density is presented in Figure 4.

The relationship between concrete density D_{CM} and SSHA content, shown in Figure 4, can be approximated by a parabola equation (R^2 is coefficient of determination):

$$D_{CM} = 2217 - 1.504x - 0.0487x^2, \qquad R^2 = 0.997 \tag{4}$$

Equation 4 shows that the concrete density decreases as the portion of SSHA substituting part of the cement increases, as shown in Figure 4. So, when replacing 2%, 4%, 6%, 8%, 10%, 12%, 14% and 16%, the density of the mixtures in accordance with the control composition decreased by 0.14%, 0.36%, 0.50%, 0.72%, 0.86%, 1.13%, 1.40% and 1.67% respectively. As seen, in percentage terms, the decrease in density is insignificant, and this is primarily because SSHA has a lower density than cement. Accordingly, the tendency for the density of the concrete composite to decrease when the percentage of SSHA replacement is natural and logical.

Figure 5 focuses on the dependence of the mixture slump on the amount of SSHA.

The slump of the concrete mixture is expressed by Equation 5, which relates to the SSHA content (x in equation) as shown in Figure 5. This relationship is well approximated by a parabola

$$S_l = 8.48 + 0.00303x - 0.01477x^2, \qquad R^2 = 0.997 \tag{5}$$

According to the data, an increase in SSHA content correlates with a decrease in concrete mixture workability, as determined by cone slump. The workability of the concrete mixture gradually decreases when the SSHA cement portion is increased from 2% to 8%. The reduction in cone settlement when replacing part of the cement with 2%, 4%, 6% and 8% SSHA compared to the control specimen was 1.18%, 3.53%, 5.88% and 9.41%, respectively. Further, with an increase in the SSHA dosage at around 10%, a sharper decrease in the workability of the concrete mixture is observed. At dosages of 10%, 12%, 14% and 16%, the drops in cone settlement were 17.65%, 25.88%, 34.12% and 43.53%, respectively. Note that at SSHA dosages from 2% to 14% inclusive, the workability value of concrete mixtures according to GOST 7473-2010 [53] remains within the same grade P2. When the amount of SSHA is 16%, the workability goes beyond the P2 grade and reaches the P1 grade [53]. The main reason for the decline in workability of concrete mixtures as SSHA content increases is the high-water demand and particle dispersion of SSHA. As the SSHA content rises, the water demand of concrete mixtures increases, resulting in decreased workability due to constant water and plasticizer content. The influence of ash particles of plant origin on the rheological characteristics of concrete mixtures has been quite well studied and is confirmed by a number of the following works [54, 55].

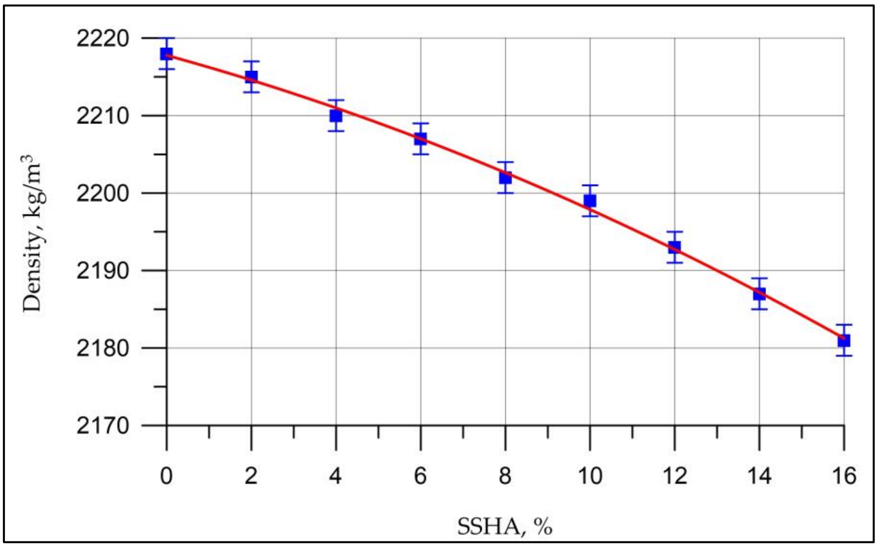


Figure 4. The impact of SSHA content on changes in density of the concrete mixture

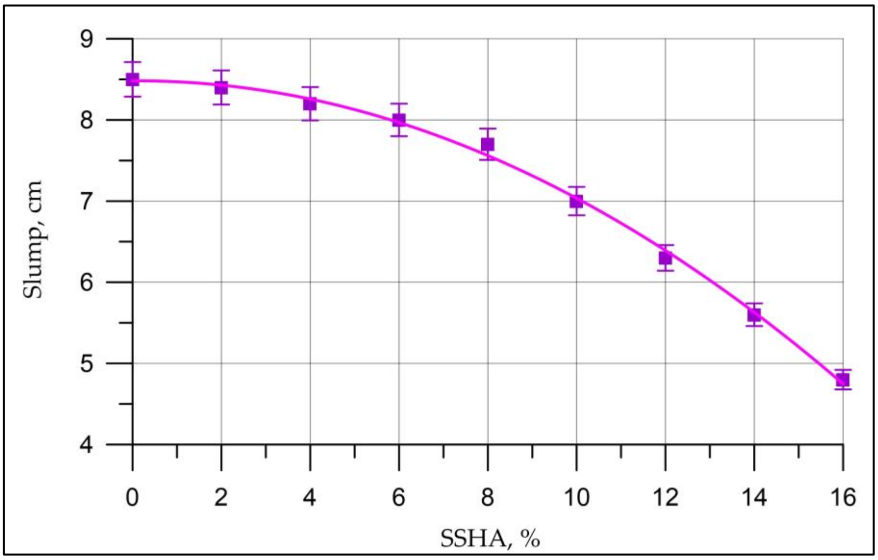


Figure 5. The impact of SSHA content on the slump of a concrete mixture

The analysis of concrete samples with different SSHA concentrations yielded the following results regarding their physical and mechanical properties. The relationship between concrete density and SSHA content is depicted in Figure 6.

The regression model of concrete density and SSHA content (x in equation), as shown in Figure 6, can be accurately expressed using a 3rd degree polynomial:

$$D_C = 2278 - 0.3042x - 0.5762x + 0.0251x^3, \qquad R^2 = 0.996 \tag{6}$$

Figure 6 shows that substituting SSHA for part of the cement, same as in the case of the density of concrete mixtures, leads to a slight reduction in composite density due to the lower density of SSHA. However, in percentage terms, the drop in density is not so significant and does not have any significant effect on other characteristics [56]. At dosages of 2%, 4%, 6%, 8%, 10%, 12%, 14% and 16%, the reduction in concrete density compared to the control composition was 0.13%, 0.40%, 0.75%, 1.10%, 1.67%, 1.89%, 2.06% and 2.19% respectively.

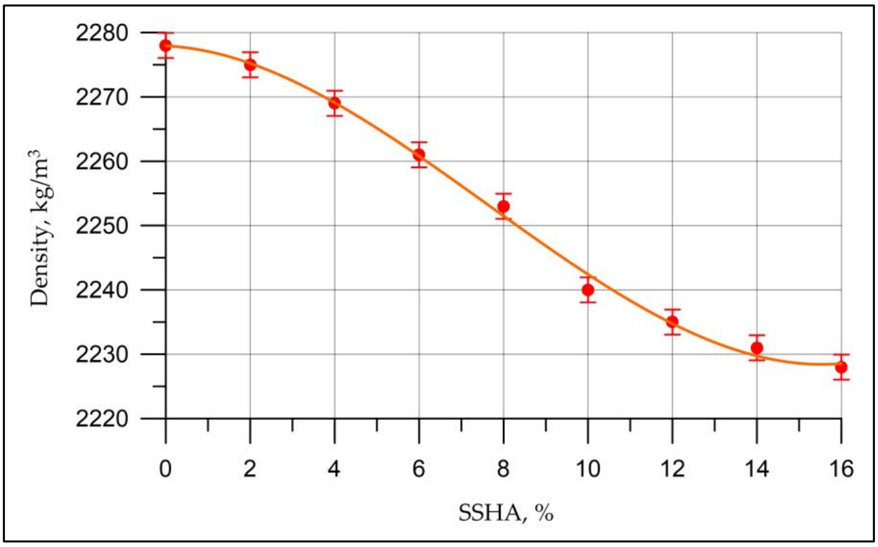


Figure 6. The impact of SSHA content on concrete density

Figures 7 and 8 show the process of testing of the specimens for the compressive strength determination of concrete samples of the control composition and the composition containing SSHA, respectively.

(a) (b)

Figure 7. Assessment of the compressive strength of a control concrete sample: (a) pre-testing sample; (b) specimens after collapse

(a) (b)

Figure 8. Determination of compressive strength of concrete sample with SSHA: (a) sample before testing; (b) sample after test

The figure depicted in Figure 9 demonstrates the correlation between the increase in SSHA content and the alteration of the compressive strength of concrete.

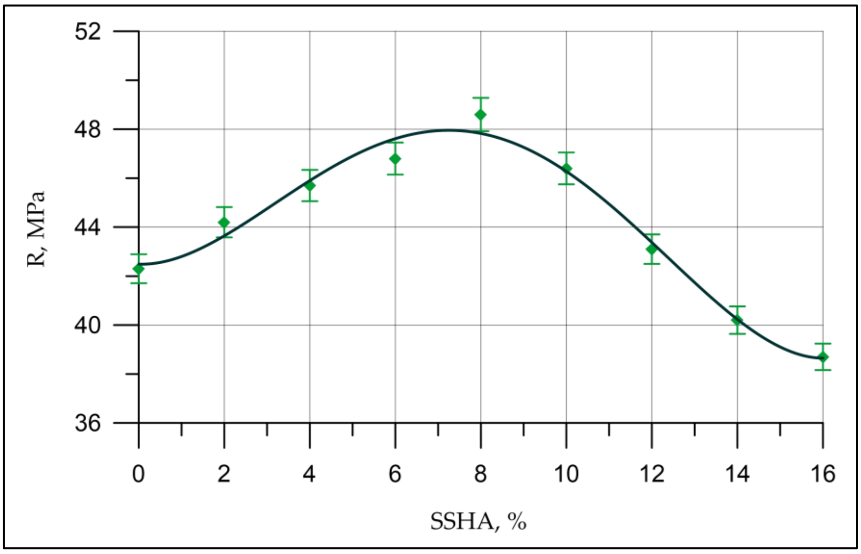


Figure 9. Compressive strength of concrete as a function of SSHA content

The regression model of the compressive strength of concrete R and the SSHA, as presented in Figure 9, can be accurately represented by a fourth-degree polynomial expression:

$$R = 42.5 - 0.0577x + 0.422x^2 - 0.05576x^3 + 0.00179x^4, \qquad R^2 = 0.979 \tag{7}$$

According to the data of the concrete compressive strength tests with different SSHA content, presented in Figure 9, the results show that SSHA, applied to substitute a part of the cement, in a range from 2% to 12% has an advantageous impact on the compressive strength of the concrete composite. The maximum in compressive strength was recorded at 8% SSHA. Compared to the control composition, the increases in compressive strength at SSHA dosages of 2%, 4%, 6%, 8%, 10% and 12% were 4.49%, 8.04%, 10.6%, 14.89%, 9.69% and 1.89%, respectively. At SSHA dosages of more than 12%, a negative effect was observed, and the drop in strength values at SSHA amounts of 14% and 16% were 4.96% and 8.51%, respectively. As is known, the complex use of organic and inorganic compounds as additives in concrete technology with rationally selected dosages can have a significant impact on the processes of formation of the structure of hardened cement paste and, as a result, lead to an improvement in physical and mechanical properties [18, 57]. In general, an increase in the compressive strength of concrete modified with a complex organomineral modifier, namely: SSHA in an amount from 2% to 12% instead of part of the cement, microsilica in an amount of 4% by weight of the binder and a poly carboxylate-based plasticizer in an amount of 1.5% by weight of the binder, can be explained by the following two factors.

The first factor is physical interactions. Particles of microsilica and mechanically activated ash of sunflower seed husks, having a smaller or comparable size compared to cement particles, act as a filler and fill the volume and voids between cement particles, thereby forming numerous coagulation contacts and reducing the volume of free water. As is known, a reduction in free water will directly contribute to a reduction in capillary porosity [57]. The second factor is chemical interactions. Micro silica and ash from sunflower seed husks, containing reactive oxides SiO2 and CaO, contribute to the formation of additional low-basic calcium hydrosilicates such as CSH, the presence of which helps to increase the strength of the concrete composite and the density of its structure. The negative effect at a higher SSHA content (more than 12%) is because the concrete composite is over-saturated with SSHA particles, as a result of which water consumption increases. An increase in W/C will negatively affect the performance of the composite. Also, in addition to the increased water requirement of concrete mixtures, the hydration process also begins to proceed somewhat differently. The concentration of CaO in the liquid phase of the concrete system becomes too high, and this already has a negative effect on the emerging structure of the concrete composite. The amount of low-basic calcium hydrosilicates of the CSH(I) type decreases, and the amount of CSH(II), on the contrary, increases [18, 26, 57].

The water absorption of concrete is depicted in Figure 10, showcasing the impact of introducing SSHA in place of part of the cement. The correlation between water absorption W of concrete and SSHA content (x in equation) content, as shown in Figure 10, can be accurately estimated using a fourth-degree polynomial equation:

$$W = 5.81 + 0.114x - 0.084x^2 + 0.00981x^3 - 0.0003083x^4, \qquad R^2 = 0.935 \tag{8}$$

Analyzing the data of the water absorption of concrete samples enhanced with SSHA, it is evident that SSHA has a beneficial impact and aids in reducing water absorption within the range of 2% to 12%. The alteration in water absorption of concrete on the SSHA, shown in Figure 10 and Equation 8, has several characteristic sections. From 2% to 6%, a smooth, stable decrease in water absorption is observed, and the decrease in water absorption values at 2%, 4% and 6% SSHA compared to the control composition was 2.06%, 5.15% and 9.43%, respectively. At 8% SSHA, a sharper decrease in water absorption is observed, which is 15.78% less compared to the control composition. Further, with an increase in the SSHA dosage starting from 10%, a negative effect is observed, expressed in an increase in water absorption. At 10% and 12% SSHA, water absorption is less than the control value by 8.40% and 1.89%, respectively. Concrete containing 14% and 16% SSHA has higher water absorption values, which are 1.72% and 4.97% higher than the water absorption values of the control composition.

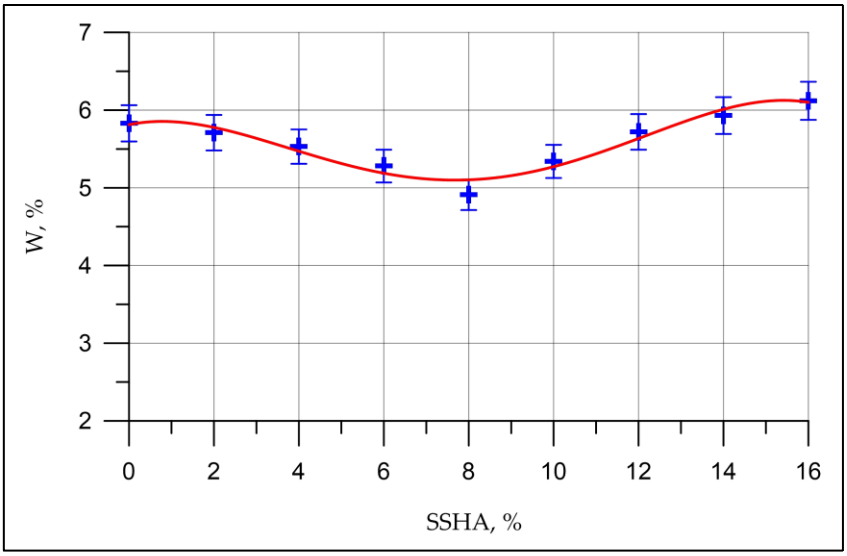
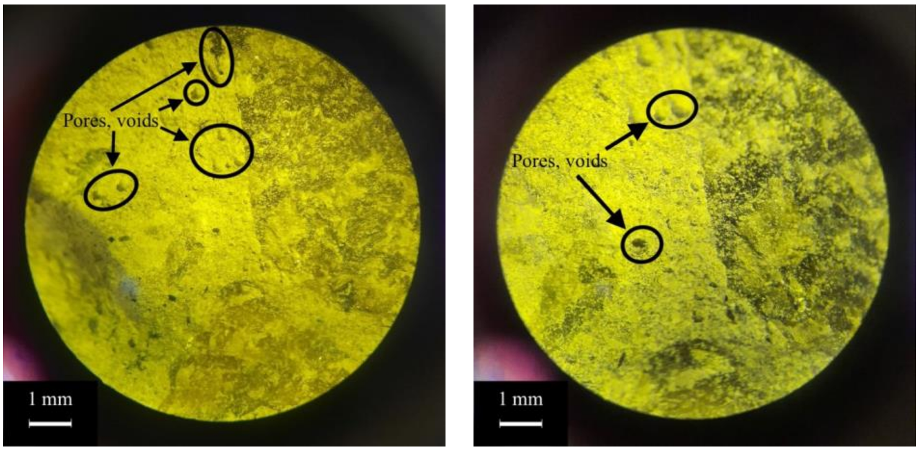


Figure 10. The impact of SSHA content on the water absorption of concrete

The introduction of the SSHA additive to replace part of the cement in an amount from 2% to 12%, as well as microsilica and a plasticizer, helps improve the structure of the concrete composite by changing its phase composition and reducing capillary porosity. The content of oxides such as SiO_2, Al_2O_3, CaO in the composition of SSHA and microsilica and the degree of their dispersion determine the structure quality of the concrete composite and its final physical and mechanical properties, including water absorption [18,57]. The main factor influencing capillary porosity is effectiveness in the interaction of the plasticizer with the SSHA particles. Polycarboxylate super plasticizer particles are adsorbed on the surface of cement grains and SSHA, giving them a negative charge. As a result, all particles of the system begin to repel each other mutually, setting the entire system in motion. Thus, the optimal combination of SSHA additives, microsilica and super plasticizer makes it possible to reduce the cohesion between the components of the concrete mixture, which subsequently helps to create a more uniform and dense composite structure [58-61].

Figure 11 displays photographs showcasing the structure of the examined samples of both the control composition and the composition containing 8% SSHA.



(a) (b)

Figure 11. Photographs of the concrete structure: (a) control composition; (b) formulation with 8% SSHA

The findings from estimating the physical and mechanical properties align well with the structural analysis of the examined samples. Compared to the concrete sample with 8% SSHA content, the control sample has a higher number of inter-grown pores and voids. As noted earlier, the processes and chemical interactions occurring during the formation of the structure of a concrete composite modified with the addition of SSHA, microsilica, and a poly carboxylate-based plasticizer provide an improvement in the phase composition of concrete, making the structure more homogeneous and with fewer capillary pores [55, 62, 63].

The results of the X-ray phase analysis of concrete of the control composition and composition with 8% SSHA are presented in Figures 12 and 13.

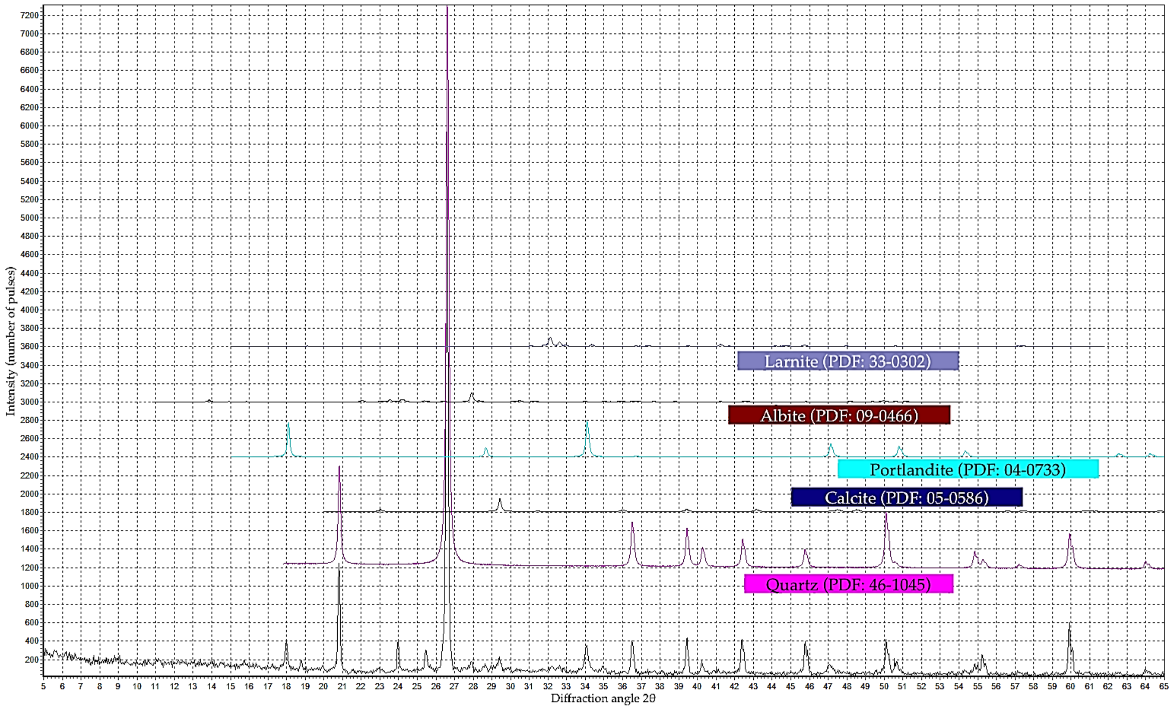


Figure 12. X-ray diffraction pattern of concrete of the control composition

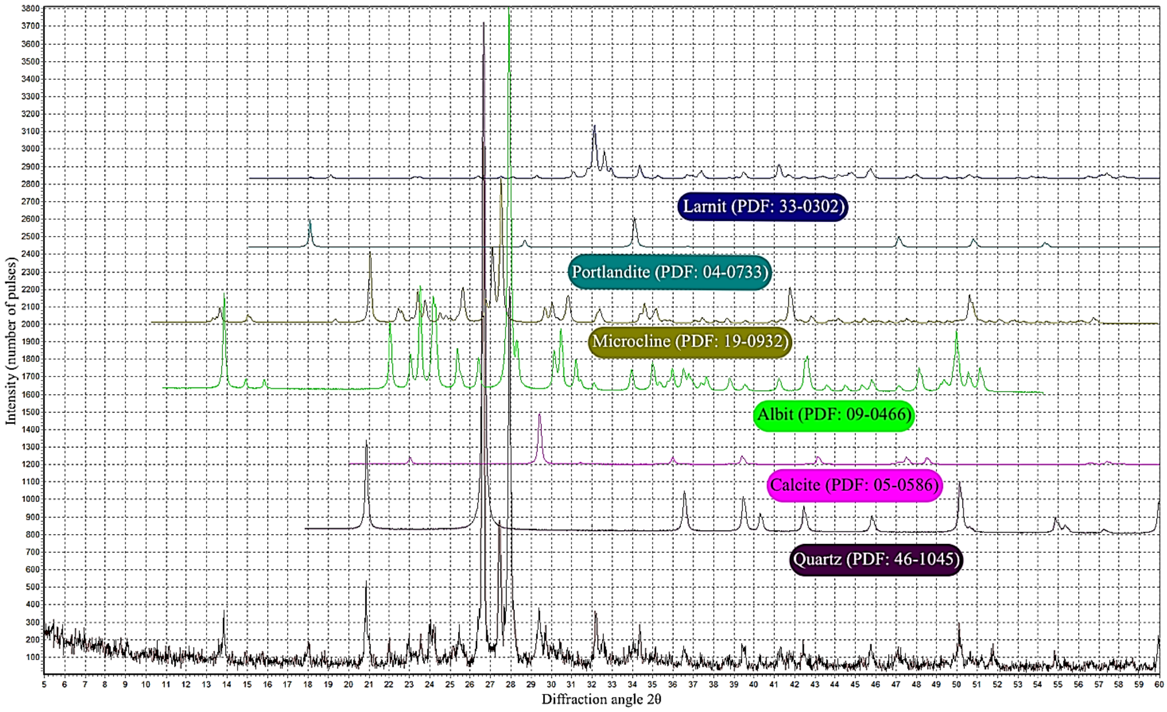


Figure 13. The concrete's X-ray diffraction pattern, which includes 8% SSHA

The XRD analysis results of the control composition concrete and the concrete with 8% SSHA content are provided in Table 4.

Table 4. Results of XRD analysis

Name of phase (mineral)	Composition	
	0/SSHA	8/SSHA
Quartz	+	+
Calcite	+	+
Anorite	+	-
Illit	+	-
Portlandite	+	+
Larnit	-	+
Albid	-	+
Microcline	-	+

As seen from Table 4, the phase compositions of concrete in the control composition and the composition with 8% SSHA are different. The absence of the illite phase and larite, albide, and microline phases in concrete with SSHA indicates this composite has better strength characteristics compared to the control composition.

In a general sense, the conducted experimental studies enabled a comparison of the obtained results with those previously attained by other authors. In particular, it is important to compare the results obtained in this article with the results of other studies of concrete, where part of the cement was replaced with rice husk ash, neem seed ash, sugarcane bagasse ash, palm oil fuel ash, and an ash mixture of sunflower and pumpkin seed husks. The results of this study regarding the use of sunflower seed husk ash are in good agreement with previous studies on the use of agricultural waste in concrete production. For example, as a comparative technology, we can consider the production of concrete based on agricultural waste in the form of rice husk ash and rice straw ash [11–20]. Another interesting direction is to compare concrete based on the ash of sunflower seed husks with concrete based on the ash of corn cobs [64]. It should be noted that the strength indicators are approximately comparable and the efficiency indicators of all the methods mentioned are high. For example, in the works [11–15], the use of rice husk ash instead of part of the cement up to 10% contributed to the improvement of the strength and physical characteristics of concrete, and the values of the increase in compressive strength varied from 9% to 20%.

Replacing part of the binder from 10% to 30% with rationally selected compositions makes it possible to obtain a composite with characteristics no worse than those of control concrete made only with cement. In studies [65, 66], the use of mine seed ash up to 10% contributed to an increase in compressive strength. Substituting part of the cement with sugarcane bagasse ash (up to 10%) positively impacts the physical and mechanical properties of concrete, but the range from 20% to 30% is also acceptable and does not lead to significant losses in strength [23, 26]. Palm oil fuel ash, when replacing part of the cement up to 10% [67–70], contributed to an increase in the strength characteristics and durability of concrete. The addition of ashes from sunflower and pumpkin seed husks [35] improved the compressive strength by 27.3% when used as a partial replacement of the binder, up to 15%. In this study, the optimal replacement of part of the cement with the ash of sunflower seed husks was up to 12%. Concrete, with up to 12% replacement of cement with SSHA, exhibits improved compressive strength and water absorption properties. The most effective dosage is 8% SSHA, where the increase in compressive strength was 14.89% and water absorption decreased by 15.78%. Replacing the binder with SSHA by more than 12% is irrational and has a negative effect, expressed in the deterioration of the physical and mechanical characteristics of concrete. Thus, the use of sunflower seed husk ash as a modifier for concrete is a worthy successor to the options for modifying concrete with various agricultural wastes and has prospects for practical application.

The comparative criterion for determining the effectiveness and efficiency of the study is the constructed graphical dependencies for the indicators “compressive strength” and “water absorption”. Analyzing the results obtained in the study, it should be noted that if the rational recipe identified during the work is followed, it is possible to obtain concrete with a high-quality structure. The obtained effect can be explained using the following theses: Firstly, the modifying additive in the form of sunflower seed husk ash acts effectively in the process of structure formation and the formation of concrete properties and allows the creation of additional crystallization centers around which the concrete structure is formed, thereby manifesting the homogeneity of the distribution of properties in the mass of cement conglomerate [18, 26, 71–74]. The increase in strength characteristics is determined by an increase in the mechanical properties of concrete, obtaining a structure with a denser packing of particles, a high degree of homogeneity, and the possibility of qualitative improvement of all properties and characteristics of concrete, subject to compliance with rational recipes and technological parameters [53, 75, 76]. Thus, by obtaining a rationally created concrete composite based on sunflower seed husk ash, we can talk about its use in the construction of buildings and structures that have additional requirements for the strength and quality of the concrete structure. The observed improvement in compressive strength and water absorption of SSHA also has positive consequences for improving the load-bearing capacity and durability of concrete structures based on this concrete. This is explained by the fact that the structural quality of concrete and its durability make it possible to create an additional protection factor for structures, which will reliably protect the structure and potential reinforcement inside it from external aggressive influences. As for the load-bearing capacity of concrete structures using SSHA, it also increases due to an increase in an important parameter: the compressive strength of concrete.

The results of this study contribute to the broader discussion about sustainability practices and the use of alternative materials in the construction industry. This is due to the fact that during the research and implementation of the proposed technology, the disposal of waste that accumulates in the fields is implied. This improves the environment and contributes to sustainable development goals. This also makes it possible to reduce the carbon footprint by reducing the amount of cement used, which, on a large scale, will somewhat reduce the harmful burden on the environment. All this contributes to the greening of the construction industry and the achievement of sustainable development goals.

Additional research in the future development plan of what has already been carried out is seen in the study of the long-term properties of the resulting environmentally friendly concrete based on sunflower seed husks. In particular, large-scale studies of the structure and properties of concrete subjected to alternating cycles of freezing and thawing will be carried out, as well as water resistance and other properties that will characterize the special operating conditions of new environmentally friendly concrete based on sunflower seed husk ash [35, 53, 76–78].

Based on the findings, a set of recommendations can be developed and proposed for policymakers, engineers, and stakeholders regarding the inclusion of SSHA in concrete production to achieve the goal of sustainable development. From the point of view of political processes, it is important to develop a unified approach to the greening of agricultural areas where waste accumulates in the form of ash from sunflower seed husks. To do this, it is necessary to develop a uniform document that will be applicable to the agricultural areas of various countries where sunflower grows, and there is such a problem. From an engineering point of view, the applicability of the proposed technology should be clarified and verified at each stage of changing process parameters that differ from those proposed by us or when changing recipe factors associated with replacing components. All this is important in order to contribute to the final result—the standardization of new technology introduced into real production. At the same time, interested parties, namely manufacturers of building materials and construction organizations, are recommended from the point of view of the professional community to also promote the maximum implementation of this technology and standardization of these methods by including in the regulatory and technical documents of the relevant countries where agricultural waste in the form of ash from sunflower seed husks grows.

The discussion of the results also made it possible to analyze and understand the range of applicability of the proposed method and composition, as well as to identify limitations that may be present when using ash from sunflower seed husks in concrete technology. In particular, these restrictions and ranges are expressed by a reasonable limit on the applicability of ash as a modifying component. This is due to the laws of nature of the formation of the structure and properties of a concrete composite and is based on the following postulates. There is a small range in which a certain percentage of adding ash from sunflower seed husks will not have a significant effect on the processes of formation of the structure and properties of the concrete composite. As the dosage of sunflower seed husk ash approaches the optimal values, the properties of concrete, other things being equal, will grow in a certain way, reaching their peak in the area of the optimal value of such a modifying additive. At the same time, after overcoming the peak of maximum efficiency of the ash content of sunflower seed husks, a certain drop in properties occurs, which at first is gradual, and as it grows, it goes down significantly and sharply. The nature of this dependence can be explained by the fact that, like many other modifying additives, the first section with an insufficient amount of ash is a characteristic section and comparable to concrete with normal properties.

The area with close to optimal values of husk ash is the area of greatest efficiency, in which the process of structure formation is intensified and modifier particles become certain centers of crystallization during the formation of the structure; the packing density of particles increases, the uniformity parameter of concrete increases, and thereby its characteristics improve, including mechanical. When the dosage of seed husk ash in concrete is slightly exceeded, the efficiency begins to decrease gradually at first and then drops sharply due to the fact that the concrete is oversaturated with a finely dispersed component, which no longer serves as a crystallization center but is an excessive destructuring component, which increases water demand and reduces the homogeneity of the concrete structure, thereby worsening its structure and reducing the importance of its quality characteristics. With all the benefits associated with the large-scale implementation of sunflower seed husk ash in concrete production, there are still some potential challenges. Firstly, it is a search for the appropriate type of waste, which must be uniform in its composition and properties and regularly checked for quality indicators. The second potential problem is the need for additional processing of sunflower seed husks to burn them into ash. This entails some additional technological difficulties and energy costs. In addition to energy costs, there are some resource and labor costs that are not present in the production of conventional standard concrete. However, at a large-scale level, with well-established production technology, the use of sunflower seed husk ash as a modifier for concrete makes it possible to reduce the percentage of defective products, achieve high-quality concrete, and thereby eliminate all the necessary additional costs that were present at the initial stages.

Thus, the nature of the introduction of sunflower seed husk ash and the limitations of these new methods are comparable to previously known ones and obey the general laws of modifying additives in cement concrete. Speaking about the practical applicability of the obtained result and the value of the data obtained for science and production, the following can be noted. The proposed methodology will be most useful at enterprises and construction sites in those regions where there are a large number of fields with sunflower cultivation. This will solve a complex environmental and economic problem, since the accumulation of sunflower seed husk waste is a significant environmental and economic problem. At the same time, the use of such renewable waste in concrete will increase its economic efficiency and profitability in production.

4. Conclusions

- Concrete mixtures and hardened concrete containing SSHA exhibit a reduced density compared to those without the admixture. The relationship between changes in concrete density and the portion of replacement is represented by a descending curve, wherein the density gradually decreases as the replacement percentage increases from 2% to 16%. Compared to conventional concrete, the decrease in durability is relatively insignificant. Moreover, with an SSHA content of 16%, the density of the concrete mixture decreased by 1.67%, while the density of the concrete decreased by 2.19%. The slight decline in density is a result of the lower bulk density exhibited by SSHA in contrast to cement.
- The introduction of SSHA into a concrete mixture negatively affects its workability, which is characterized by cone slump. At 2%–8%, the effect of SSHA on the cone settlement is insignificant, and the reduction in cone settlement does not exceed 9.41%. As SSHA dosage increases above 8%, the reduction in workability becomes more significant. SSHA primarily influences the slump of concrete mixtures because its particles have a high dispersion and water requirement.
- The substitution of cement with SSHA, ranging from 2% to 12%, enhances the physical and mechanical properties of concrete. The greatest effect is seen at 8%, with a 14.89% increase in compressive strength and a 15.78% decrease in water absorption compared to the control mixture. This positive effect is due to the fact that the reactive oxides SiO2 and CaO in the composition of the applied microsilica and SSHA additives contribute to the formation of additional crystallization centers of CSH(I), the presence of which subsequently ensures the creation of a more dense and durable structure. SSHA content of more than 12% is irrational and leads to the deterioration of concrete characteristics.
- Compared to the conventional composition, the phase composition of concrete with SSHA shows distinct features. It lacks anorite and illite, but has larnite, albide, and microlin, which improve the durability and cohesiveness of the concrete structure.
- Concrete with ash from sunflower seed husks can be used in construction that has additional requirements for the durability and quality of the concrete structure. The continuation of the study of such concrete is planned toward studying the durability of the resulting environmentally friendly concrete based on sunflower seed husks. It is planned to conduct a study of the structure and properties of concrete after freezing and thawing cycles, as well as its water resistance and other properties that will characterize the special operating conditions of new environmentally friendly concrete based on sunflower seed husk ash.

5. Declarations

5.1. Author Contributions

Conceptualization, S.A.S., E.M.S., A.C., D.E., R.Y., and L.R.M.; methodology, S.A.S., E.M.S., and A.N.B.; software, R.Y., A.P., and D.E.; validation, R.Y., A.C., S.A.S., E.M.S., and A.N.B.; formal analysis, A.P., A.C., and A.N.B.; investigation, L.R.M., S.A.S., E.M.S., A.N.B., B.M., A.C., D.E., A.P., and R.Y.; resources, B.M.; data curation, S.A.S., E.M.S., A.C., D.E., R.Y., and A.P.; 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, L.R.M. and B.M.; project administration, L.R.M. and B.M.; funding acquisition B.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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