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Performance Assessment of a Novel Green Concrete Using Coffee Grounds Biochar Waste

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Abstract: An actual scientific problem in current concrete science is poor knowledge of the problem of modifying concrete with plant waste. At the same time, plant waste benefits from other types of waste because it is a recycled raw material. A promising technological approach to modifying concrete with plant waste is the introduction of components based on the processing of coffee production waste into concrete. This study aims to investigate the use of biochar additives from spent coffee grounds (biochar spent coffee grounds—BSCG) in the technology of cement composites and to identify rational formulations. A biochar-modifying additive was produced from waste coffee grounds by heat treatment of these wastes and additional mechanical grinding after pyrolysis. The phase composition of the manufactured BSCG additive was determined, which is characterized by the presence of phases such as quartz, cristobalite, and amorphous carbon. The results showed that the use of BSCG increases the water demand for cement pastes and reduces the cone slump of concrete mixtures. Rational dosages of BSCG have been determined to improve the properties of cement pastes and concrete. As a result of the tests, it was determined that the ideal situation is for the BSCG ratio to be at a maximum of 8% in the concrete and not to exceed this rate. For cement pastes, the most effective BSCG content was 3% for concrete (3%–4%). The compressive and flexural strengths of the cement pastes were 6.06% and 6.32%, respectively. Concrete's compressive strength increased by 5.85%, and water absorption decreased by 6.58%. The obtained results prove the feasibility of using BSCG in cement composite technology to reduce cement consumption and solve the environmental problem of recycling plant waste.

Keywords: recycling waste; modified concrete; concrete additives; coffee ground biochar; green concrete

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1. Introduction

The current process of construction is dynamic and continually encourages the incorporation of innovative practices. The impact of innovation in construction extends to design solutions and technologies, and one particularly promising and knowledge-intensive field is construction materials science [1]. Construction materials science lies at the convergence of multiple scientific disciplines and serves as a compelling arena for exploring innovative materials, necessitating a preliminary examination from a fundamental standpoint. The creation of new materials is a key task in various aspects, including economic, environmental, and technological [2,3]. To solve any material science problem, it is important to consider the perspectives of ecology, economics, and manufacturing. Many studies have demonstrated the potential of introducing various types of waste into construction materials. This includes industrial waste such as slag, stone flour, and micro-silica [4–8]; waste from oil and fuel industrial complexes in the form of fly ash [9–11]; and many others.

However, one of the greatest interests in construction material science is the modification of concrete with plant waste [12]. Plant waste differs favorably from other types of waste because it is a renewable raw material. At the same time, a fundamental component of studying the issues of modifying artificial stone materials, such as concrete, with additives of organic plant origin is essential. It should be noted that heat treatment is used to produce modifying additives based on plant waste, resulting in ash or biochar. Rice husk and straw are widely utilized vegetable waste materials for the production of concrete additives. For example, in Ref. [13], the introduction of up to 10% RHA resulted in concrete with the best properties in comparison with concrete with a control composition. Rice husk ash increases the corrosion resistance of concrete [14]. Research [15–18] has also confirmed the effectiveness of using RHA and biochar in cement composites. The use of modification additives derived from plant wastes, such as sugarcane pulp, is also prevalent. A previous study [19] demonstrated the potential for utilizing sugarcane bagasse ash as a substitute for a portion of Portland cement in concrete mixtures, with an effective usage rate of up to 30%. Replacing up to 60% of Portland cement with sugarcane bagasse ash in ultra-high-performance concrete (UHPC) can increase its flexural and compressive strength by 18% and 12%, respectively. In Ref. [20], the authors developed effective concrete compositions with 10% sugarcane bagasse ash, replacing part of the cement. Similarly, in some studies [21–23], the authors proved the effectiveness of using additives based on ash and biochar from sugarcane bagasse in cement composites.

A promising and interesting technological approach to modifying concrete with plant waste is the introduction of additives made from coffee production waste into the concrete composition. Coffee is one of the most popular plant foods and beverages consumed worldwide. Many goods and food products are made from coffee [24]. Coffee is one of the most sought-after and cost-effective commodities across the world. Moreover, this product is characterized by the accumulation of various types of waste after its use at home, in public catering establishments, and in various factories and enterprises, as well as in places of social activity. In other words, society and the economy are faced with the question of the rational disposal of accumulated waste resulting from drinking coffee. Coffee grounds are the most significant waste of the coffee industry. They are obtained during the production of instant coffee, as well as after preparing the drink in a coffee shop or at home. From 1 g of ground coffee, about 0.91 g of spent grounds are formed, and from each kilogram of prepared instant coffee, about 2 kg of wet spent waste is obtained. According to Gunter Pauli, a researcher of sustainable development, about 7 million tons of coffee are produced annually in the world. Thus, about 14 million tons of wet spent coffee waste can be obtained from them. At the same time, spent coffee grounds emit harmful greenhouse gases in landfills, which negatively affects the environment and living organisms. One of the concepts of the "Waste Hierarchy", that is, the order of actions that must be taken to reduce the amount of garbage, is recycling. Waste is converted into raw materials from which a new item is made. In the context of a rapidly developing construction market worldwide, the demand for resource-intensive concrete is growing, which also creates a number of environmental problems. Thus, the question of modifying concrete with waste coffee products represents an important scientific and technological direction. In this discussion, we explore the major research conducted on the incorporation of coffee waste into concrete.

For example, in one study [25], the authors developed effective concrete compositions with 4% coffee husk ash content introduced instead of sand. Several studies [26–28] have also supported the rationality of incorporating waste coffee ground ash into cement composites.

Organic products such as coffee grounds cannot be added directly to concrete because they release chemicals that weaken the building material. Therefore, it is necessary to heat the coffee grounds to 400 °C to remove oxygen. This produces a porous, carbon-rich charcoal called biochar, which can form bonds and thus be effective in the cement matrix [25–28].

Summing up the literature review, the scientific deficit identified during its preparation should be noted. First, the fundamental dependence between the composition of ingredients, concrete structure, and properties of concrete modified with coffee waste has been poorly studied and has not been systematized. Second, the most promising waste of coffee origin is biochar from spent coffee grounds, that is, burned waste processed at high temperatures that remains after drinking coffee. The reasons for using biochar spent in coffee grounds as a green concrete modifier include technological, economic, and environmental aspects. From an environmental point of view, an important reason for searching for ways to use coffee grounds is the large accumulation of this waste at both the household level and the food and restaurant industries. From an economic perspective, this approach would be appropriate because waste can replace some of the expensive components of concrete in the form of coffee grounds. From a technological point of view, the reasons for conducting clarifying studies are data from the scientific literature, as well as an analysis of the technical properties of the grounds themselves with a working hypothesis about the good compatibility of biochar spent coffee grounds with other components of concrete. The technical advantages of using coffee grounds as a component of green concrete are summarized as follows:

- Ensuring good compatibility of the properties of these wastes and other concrete components;
- The possibility of effective integration of this additive into the composition and structure of concrete, subject to the choice of its rational dosage;
- To confirm the feasibility of using biochar spent coffee grounds in concrete by conducting experiments to determine the physical, mechanical, and structural characteristics of the resulting green concrete.

Thus, one of the objectives of this research was to test the working hypotheses based on our own analytical data, as well as to review the scientific and technical literature. The main goal of this work is to study the fundamental dependencies of the recipe components of the composition, the structure of concrete, and their influence on the properties of biochar concrete from coffee grounds waste, as well as the development of applied recommendations for real production using coffee ground waste as a modifier. The objectives of this study are to conduct experiments to determine the rational dosage of biochar-spread coffee grounds (BSCG) in concrete, analyze its microstructure and properties, and develop recommendations for actual concrete production.

2. Results and Discussion

The diffraction pattern of BSCG is shown in Figure 1. X-ray phase analysis was carried out using radiation from a copper anode on a DRON-7 diffractometer (NPP Burevestnik, St. Petersburg, Russia).

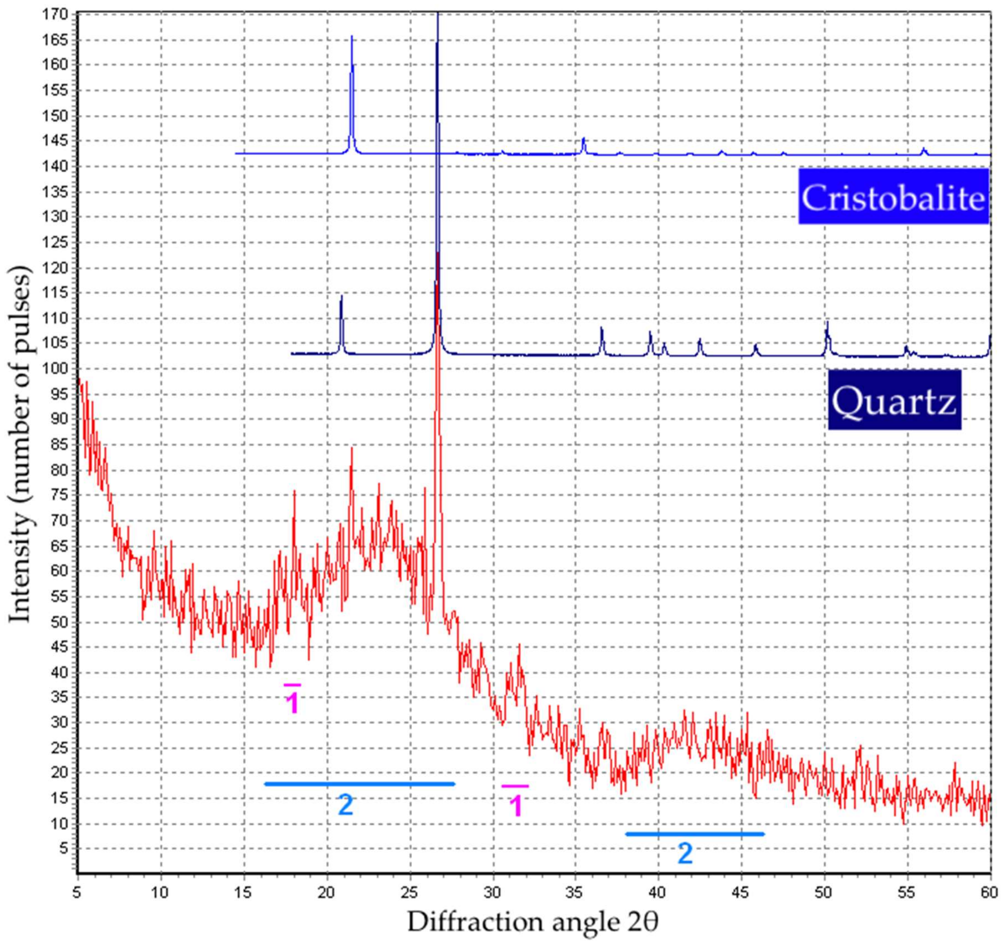

Figure 1. BSCG X-ray diffraction pattern.

Quartz and cristobalite phases were detected in the X-ray phase analysis of BSCG. Peaks 1 and 2 correspond to amorphous carbon.

Figures 2–4 show the test results for cement pastes with different BSCG contents. The graphical representation in Figure 2 illustrates how the normal consistency of cement paste varies with the BSCG used.

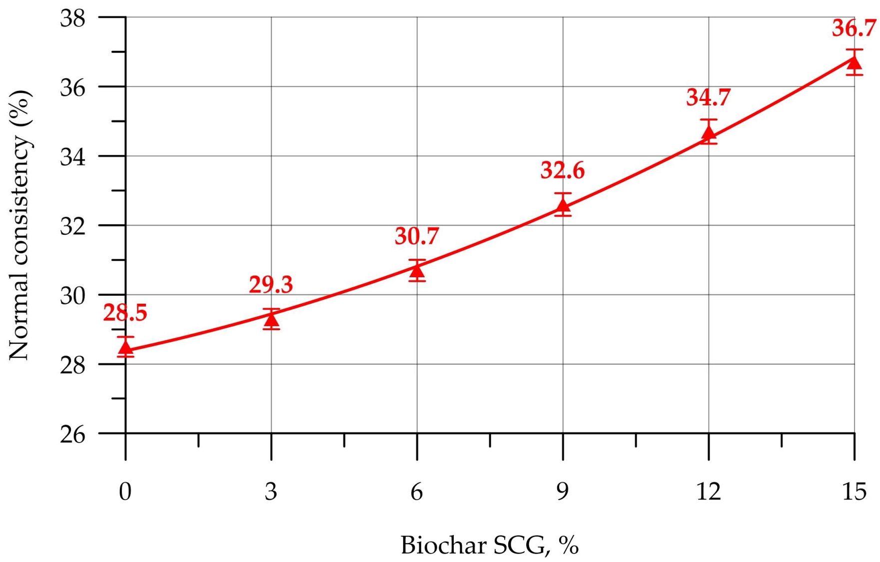

Figure 2. Normal consistency of cement pastes at different BSCG contents.

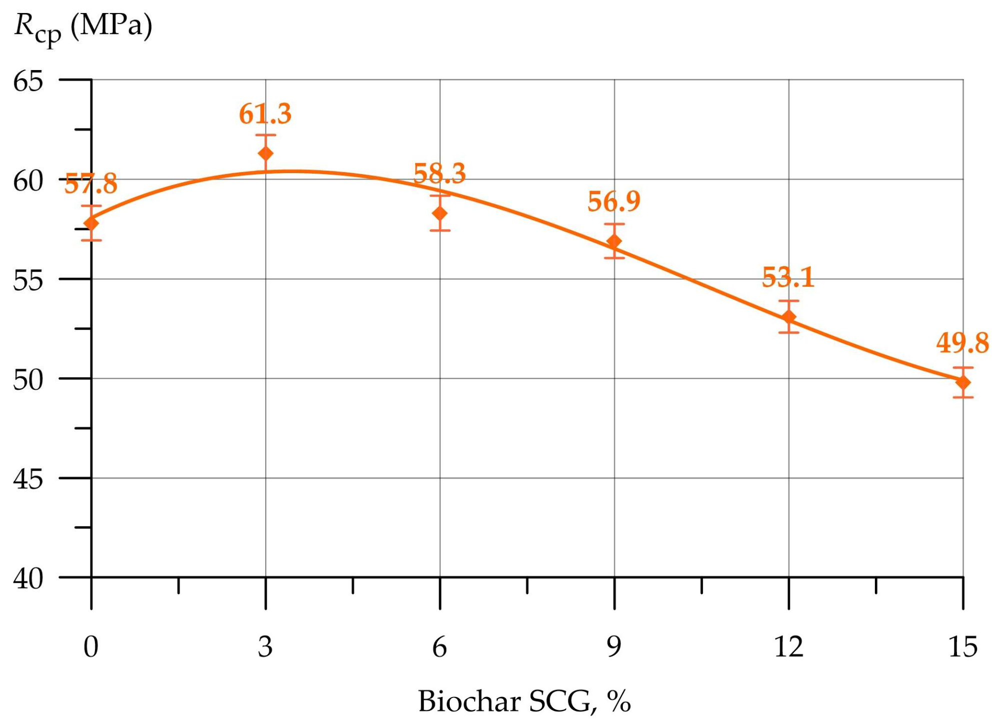

Figure 3. Compressive strength of cement paste (R_{cp}) at different BSCG contents.

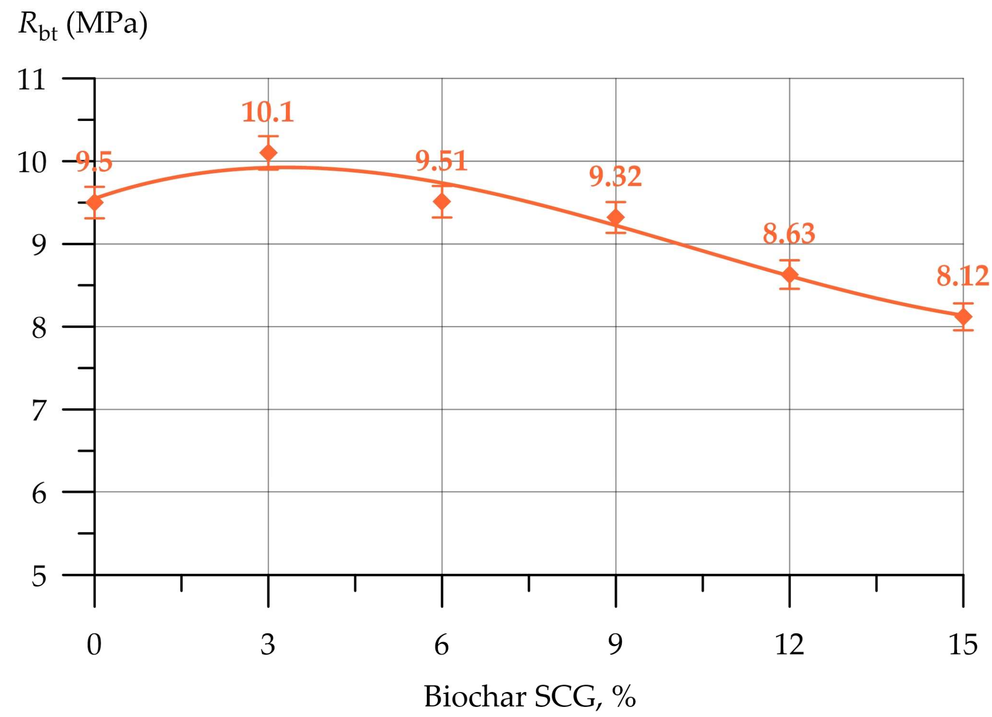

Figure 4. Flexural strength of cement paste (R_{bt}) at different BSCG contents.

The normal consistency of cement paste at different BSCG contents (x in the equation) relationship presented in Figure 2 is approximated by the following expression:

$$NC = 28.38 + 0.301\,x + 0.0174\,x^2, \qquad R^2 = 0.997 \quad (1)$$

where R^2 is the coefficient of determination.

Figure 2 shows that the use of BSCG instead of part of the cement in all considered ranges (0% to 15%) increases the water requirement of cement pastes. At 3% and 6% BSCG, the normal consistency of the cement pastes increased by 2.81% and 7.72%, respectively. The introduction of BSCG at concentrations exceeding 6% leads to a significant increase in the water demand for cement pastes. With a maximum BSCG content of 15%, the highest value of normal consistency of cement paste was recorded, which was 28.77% higher than that of the control. The primary reason for the increased water demand in cement pastes containing BSCG is the porous structure of the BSCG particles, which requires more water for effective wetting. We also note that the particles of the spent coffee grounds initially have a more dense and solid structure, and they acquire a porous structure during the thermal decomposition process. Studies by other authors [29,30] have validated an increase in the water consumption of cement pastes containing biochar-based additives.

In Figure 3, the amount of BSCG is plotted against the compressive strength of the cement paste. Figure 3 shows a curve of changes in the compressive strength of cement pastes with different BSCG contents, which can be characterized as follows: a slight increase in the compressive strength at a BSCG content of 3%; stabilization of the compressive strength at BSCG contents of 6% and 9%; and a sharp decrease in the strength at BSCG contents of 12% and 15%.

Equation (2) provides an approximation of the correlation between the compressive strength of the cement paste and the BSCG content, as depicted in Figure 3.

$$R_{cp} = 58.06 + 1.451x - 0.2512x^2 + 0.007887\,x^3, \quad R^2 = 0.971 \qquad (2)$$

The change in the flexural strength of the cement pastes with various BSCG contents showed a similar pattern to the change in the compressive strength. This dependence can be approximated by the following expression:

$$R_{bt} = 9.548 + 0.2430\,x - 0.0438\,x^2 + 0.00142\,x^3, \quad R^2 = 0.962 \qquad (3)$$

Table 1 presents the percentage changes in compressive and flexural strength as a function of BSCG content compared with the control composition.

Table 1. Changes (%) in compressive and flexural strength with increasing BSCG content.

BSCG (%)	ΔR_{cp} (%)	ΔR_{bt} (%)
0	0	0
3	6.06	6.32
6	0.87	0.11
9	−1.56	−1.89
12	−8.13	−9.16
15	−13.84	−14.53

The structures of the cement pastes modified with BSCG at dosages ranging from 0% to 15% are presented in Figure 5. An MBS-10 optical microscope (Measuring Technology, Moscow, Russia) with 6× magnification was used to obtain images. Cement paste samples were taken from prism samples after compression testing.

As shown in Figure 5, cement pastes with 3% BSCG content (Figure 5b) have the most integrity and uniform structure compared to cement pastes with an ordinary composition (Figure 5a) and those with 6% and 9% BSCG content (Figure 5c,d). Samples of cement pastes with 12% (Figure 5e) or 15% (Figure 5f) BSCG content have the worst structure, with numerous voids and cracks.

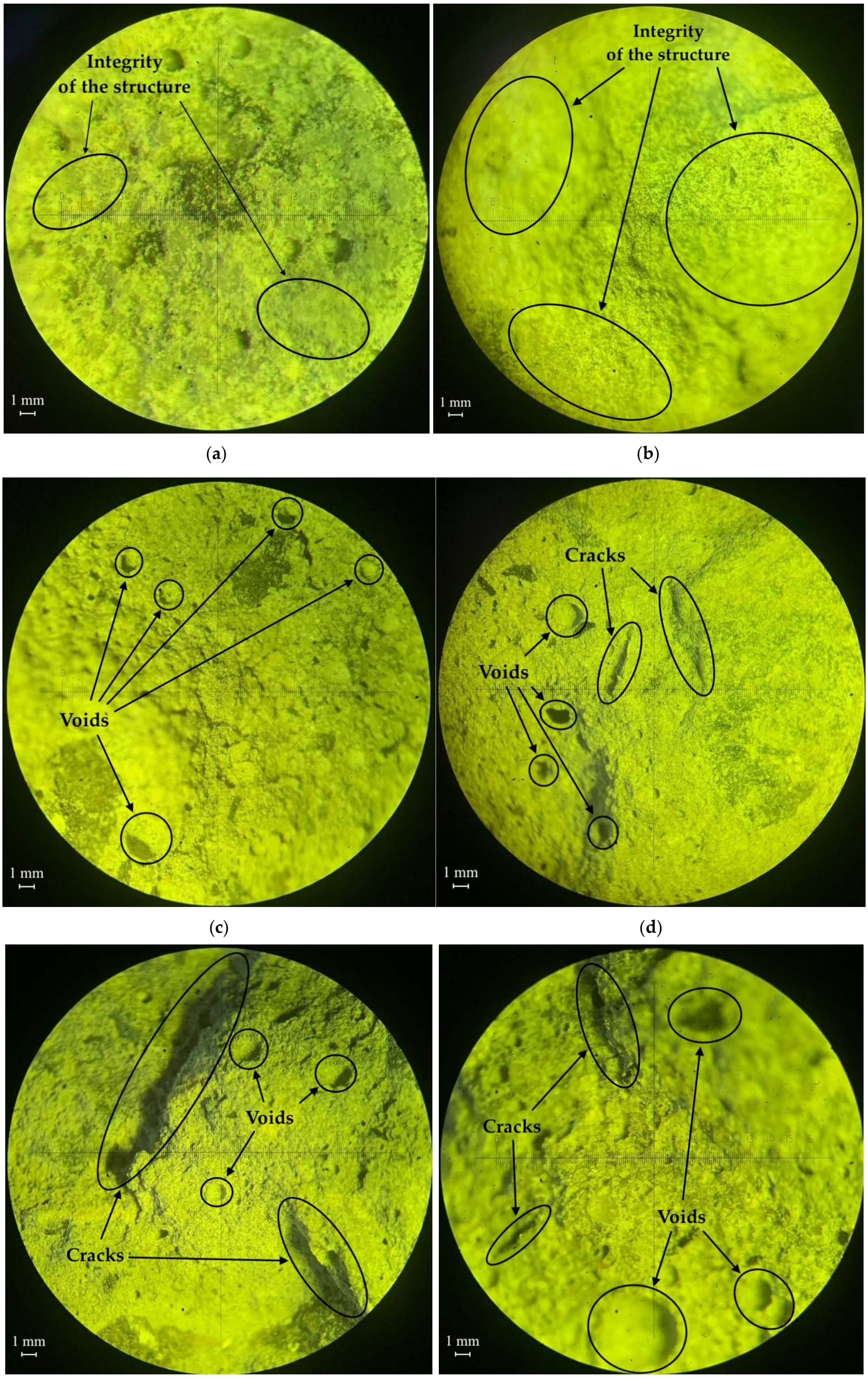

Figure 5. Structure of cement pastes: (**a**) control; (**b**) 3% BSCG; (**c**) 6% BSCG; (**d**) 9% BSCG; (**e**) 12% BSCG; and (**f**) 15% BSCG.

In general, after analyzing the obtained results regarding the changes in the strength characteristics of the cement pastes modified with BSCG, several conclusions can be drawn. First, the increase in compressive and flexural strength at a BSCG content of 3% can be explained because, at this dosage, BSCG particles act as mineral fillers. They fill voids and make the cement paste denser. Second, BSCG particles absorb some of the free water, which is released when the internal relative humidity of the cement matrix decreases, providing additional internal hardening [27]. In the presence of 6% and 9% BSCG, the strength of the cement pastes is at a level comparable to the control composition. In these quantities, BSCG particles also act as filler; however, the overall positive effect is offset by the reduction in the cement content. Further, when the amount of BSCG in the cement pastes increased to more than 9%, a significant decrease in their strength was obtained. This adverse impact is both logical and inherent and stems from a reduction in cement content, elevated water–cement ratio, and saturation of the cement paste structure with BSCG particles [26]. The positive effect of using biochar at optimal quantities in the composition of cement pastes was also confirmed in the works of other authors. For example, the use of two types of wood biochar instead of up to 5% of cement has a positive impact on the strength of cement pastes [31]. In Ref. [32], the use of 2.9% biochar instead of part of the binder yielded the best strength properties of the cement composite. Similarly, in previous studies [33,34], the use of biochar in the composition of cement pastes at a rational dosage improved their strength properties.

Figures 6–8 illustrate the properties of concrete mixtures and concretes modified with different quantities (0% to 10%) of BSCG. Figure 6 provides a visual representation of how the cone slump of the concrete is influenced by the BSCG content.

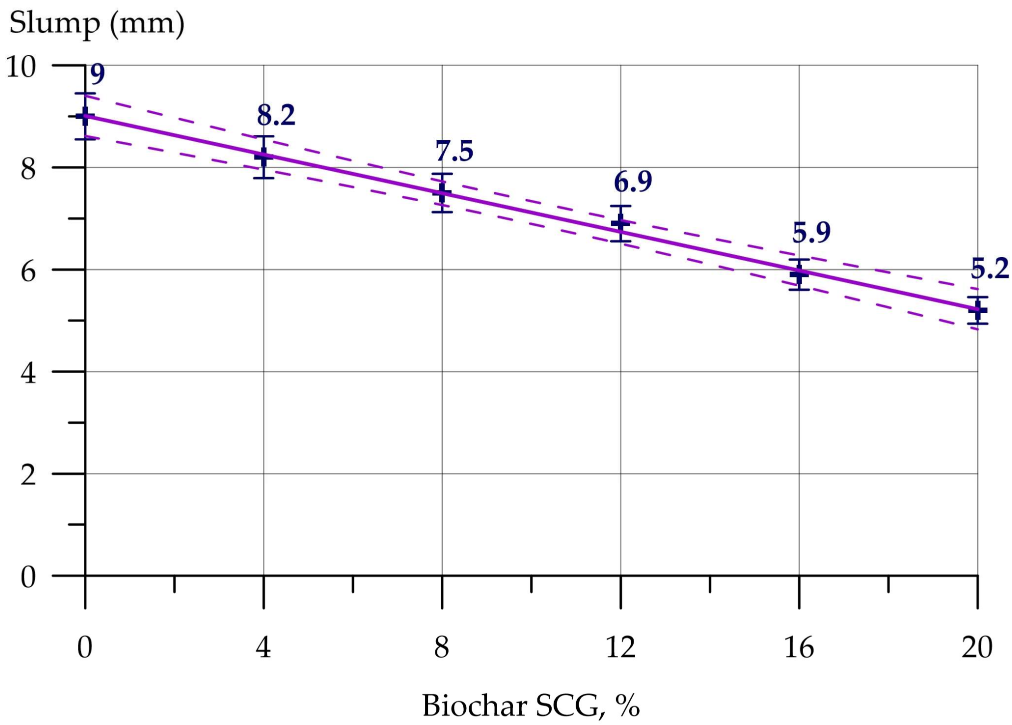

Figure 6. Cone slump of the concrete mixtures depending on the BSCG content.

The dependence of cone slump (Figure 6) on the BSCG content is expressed as follows:

$$Sl = 9.009 - 0.1892\,x, \quad R^2 = 0.996 \tag{4}$$

The dashed lines in Figure 6 show the confidence limits of the dependence (4) with a confidence probability of 0.95. The solid line shows the general regression line (4).

The workability of concrete mixtures is reduced by the application of BSCG, as depicted in Figure 6. The tendency for the cone slump of concrete mixtures to change depending on the amount of BSCG in their composition is such that the higher the content of BSCG, the lower the cone slump. As mentioned earlier, BSCG particles have a porous structure and a higher water requirement than cement particles. Hence, as the quantity of BSCG particles in the concrete mixture increases, a greater amount of water is required to saturate them, ultimately causing a decrease in the slump of the concrete mixture.

The impact of the BSCG content on the compressive strength of concrete is shown in Figure 7.

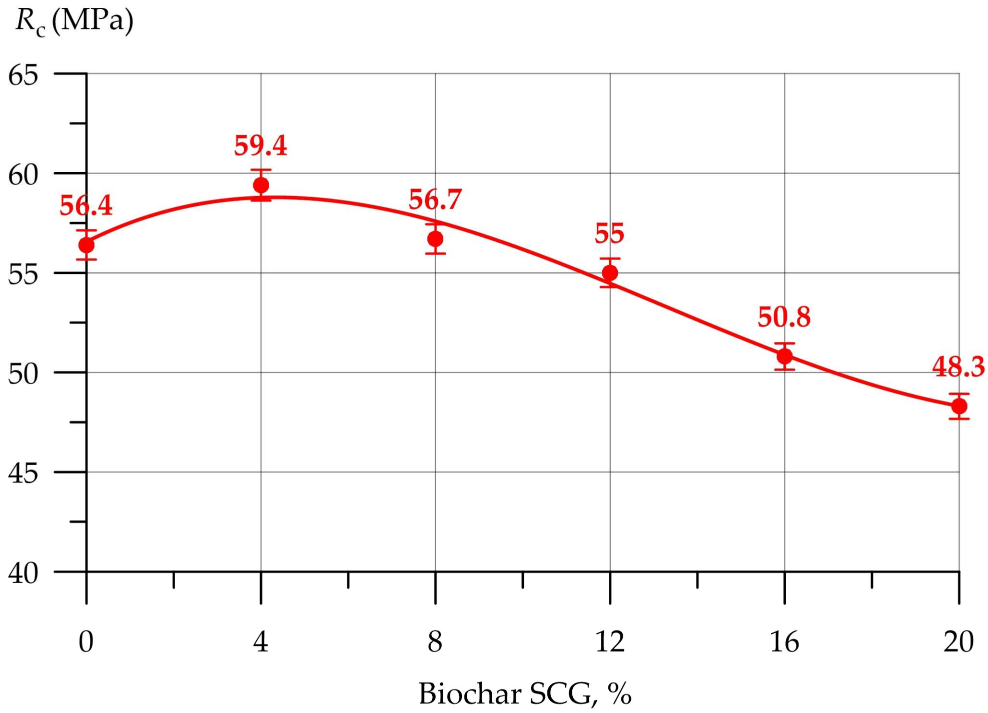

Figure 7. Compressive strength of concrete (R_c) versus BSCG content.

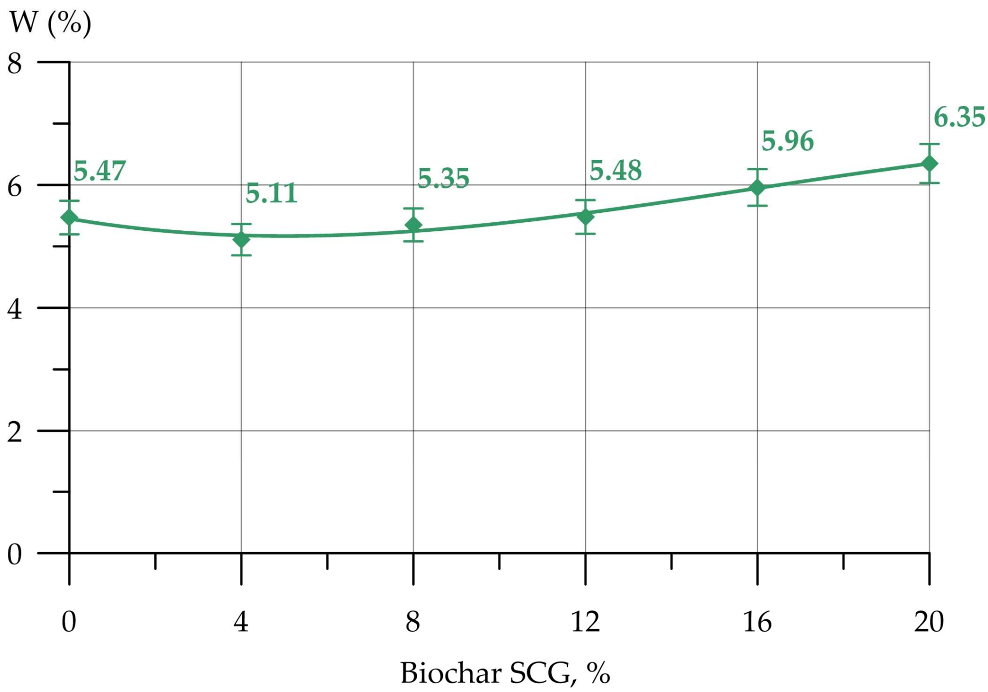

Figure 8. Water absorption (W) of concrete based on the BSCG content.

The expression of the correlation between the compressive strength of concrete (R_c) and the quantity of BSCG (Figure 7) was calculated as follows:

$$R_c = 56.56 + 1.102\,x - 0.1524\,x^2 + 0.003834\,x^3, \qquad R^2 = 0.982 \tag{5}$$

According to Figure 7, the introduction of 2% and 4% BSCG has a beneficial effect on compressive strength and promotes growth. Several factors contributed to the explanation of the increase in compressive strength. The role of BSCG particles is to act as a filler and to release excess water as the relative internal humidity of the concrete decreases. This restrains the establishment of a more compressed structure and the subsequent hydration reactions that occur with unreacted cement particles in subsequent phases. Additionally, the adhesion of biochar particles to the cement matrix was facilitated by the porous structure of the particles. This positive property of BSCG particles increases the adhesion strength at the cement–garbage interface [27]. Dosages of biochar at the 6% and 8% levels no longer have a positive effect on compressive strength; however, they allow biochar to be maintained at a level comparable to the control composition. This formulation is also considered effective because it saves the binder without compromising concrete strength. At 6% and 8% BSCG, all of its beneficial effects as a filler, identified at a dosage of 4%, were minimized due to a decrease in the amount of binder component. Regarding the higher BSCG content in the concrete composition (10%), it turned out to be irrational and led to a significant loss of compressive strength of up to 10.82%. Concrete supersaturated with BSCG particles exhibits the lowest cone settlement, which subsequently affects the compaction quality, density, and structural integrity of the concrete composite. Due to the excess content of BSCG in concrete, pores and voids are formed, and at the initial stage of hydration, a certain proportion of cement particles are not able to actively enter into the hydration reaction due to a lack of free water, which subsequently leads to deterioration of the strength of concrete [35].

Figure 8 shows a graphical illustration of the water absorption of concrete on the amount of BSCG added.

The amount of BSCG directly affects the water absorption (W) of concrete, as expressed by:

$$W = 5.45 - 0.1202\,x + 0.01424\,x^2 - 0.000299\,x^3, \quad R^2 = 0.980 \tag{6}$$

Figure 8 shows that concrete modified with 2% or 4% BSCG exhibited the lowest value of water absorption. At 6% and 8% BSCG, the water absorption of concrete remained approximately at the control composition. The positive impact of BSCG (up to 4%) is attributed to its ability to act as a filler and compact the structure of the concrete composite. However, when BSCG content increases by more than 4%, the binder content is reduced, and the addition of biochar no longer functions as a filler, which negatively affects the concrete properties.

In Table 2, the percentage change in the concrete properties with various BSCG contents is shown compared to the control composition.

Table 2. Changes in the concrete properties (Δ) depending on BSCG content.

BSCG (%)	ΔSlump (%)	ΔR_c (%)	ΔW (%)
2	−3.33	1.77	−4.75
4	−12.22	5.85	−6.58
6	−23.33	−2.48	0.18
8	−30.00	−4.61	2.93
10	−42.22	−10.82	9.32

In general, the use of BSCG and other types of biochar at a rational dosage can improve or maintain the properties of concrete at the required level. For example, in one study [36], the use of wood biochar at a concentration of 3% increased the mechanical strength of concrete and its resistance to the penetration of chloride ions. In Ref. [37], the introduction of biochar from vetiver roots up to 6% into the composition of concrete improved its strength and reduced shrinkage. The introduction of biochar into concrete with a large amount of iron ore waste in Ref. [38] increased its compressive strength and actively adsorbed particles of heavy metals such as Cu, Zn, Pb, and Cd. Research [39–42] has also confirmed the effectiveness of using biochar in small dosages (mainly up to 5%) instead of part of the binder in cement-concrete technology, which is in good agreement with the results of this study.

In general, based on the results of experimental investigations that were aimed at studying the properties of cement pastes and concretes modified with the BSCG additive, the following general scientific results can be emphasized.

The porous nature of the BSCG particle structure increases the water requirement of cement pastes and reduces the workability of concrete mixtures. With increasing BSCG content, a decline in the slump of the concrete mixtures was observed.

With rational dosages, BSCG acts as a mineral filler. The particles have good adhesion to the cement matrix, compact the concrete structure of the composite, and promote the occurrence of later hydration reactions.

The rational content of BSCG in concrete should not exceed 8%. Introducing 4% BSCG is the most effective approach. The compressive strength of the concrete increased to 5.85%, and water absorption decreased to 6.58%.

To confirm the distribution characteristics of BSCG in concrete, in addition to physical and mechanical tests, a structural analysis of the concrete was carried out using a special microscope. Microscope images indicate that the overall distribution of BSCG in the concrete appeared uniform. There is no concentration of foci or clusters that weaken or strengthen individual zones. A conditionally uniform distribution of BSCG in the concrete was established, as confirmed by the fairly uniform structure of the concrete over the entire area of the studied samples.

Let us analyze the experimental and theoretical results obtained from a scientific novelty perspective and compare them with the works of other authors. It should be noted that it seems methodologically correct to compare the addition of biochar from spent coffee grounds (BSCG) according to the effectiveness criterion with other types of biochar obtained from other plant wastes. Specifically, as previously stated in the literature review, one of the most prevalent forms of waste is recycling biochar derived from rice husks, straw, and other plant residues. These materials are renewable sources of raw materials [13–23,43,44]. Here, I would like to note the first criterion, which, in our opinion, is an advantage. This is the renewable nature of this resource, that is, an additive made from waste coffee grounds. In this regard, the BSCG additive compares favorably with additives, for example, that arise during other types of human activity, for example, with fly ash or granulated blast furnace slag. That is, plant waste is the most promising material in this regard, having a renewable nature [24,45]. The next advantage was the good compatibility of the characteristics of biochar from spent coffee grounds (BSCG) with other components of the concrete mixture. Analysis of the structure of concrete modified with BSCG showed a high efficiency of participation in the formation of the concrete structure. It was found that, in comparison with the control composition, a concrete sample modified with a rational amount of BSCG contained a high particle packing density and a high degree of homogeneity. The inclusion of biochar particles has proven valuable for crystallization centers in concrete [46]. That is, homogeneous, evenly distributed clusters are formed at the macro level, which looks like biochar particles from waste coffee grounds sticking to larger conglomerate particles. Moreover, this adhesion occurs fairly evenly, with high uniformity and good adhesion. Through its successful compatibility with other concrete components, BSCG contributed to the production of a high-quality structure with superior physical and mechanical properties, as evidenced by experimental tests [28,47]. The physical and mechanical characteristics determined during the experiments showed that the concrete samples modified with 4%

BSCG were superior to the control samples. It is important to mention the remarkable alignment between our findings and those of other researchers who also explored the use of waste coffee grounds as additives in concrete modification. Furthermore, our study aims to highlight the scientific novelty of our research, as evidenced by previous studies [25–28,47]. Our research confirms that, first and foremost, the incorporation of BSCG results in the robust formation of concrete, provided that appropriate technological conditions and recipes are followed. The clusters are uniformly formed throughout the structure of the concrete composite. In this case, BSCG particles act as additional auxiliary centers of crystallization and do not interfere with structure formation but rather promote this process [48–51].

Ultimately, we have determined the fundamental mechanism at the micro-level and macro-level for the formation of the structure of concrete modified by BSCG. Additionally, in the course of our research, we have determined the relationship between the composition of the concrete, the concrete structure, and the properties of concrete based on BSCG. Rational recipes and technological parameters for the production of concrete modified with BSCG have been identified. The dosage of each component was determined, and the compatibility of the components in the concrete mixture and the hardened concrete conglomerate was checked. The obtained scientific results determined the practical significance of this research. The feasibility of the industrial use of new concrete based on biochar from spent coffee grounds (BSCG) has been approved. The resulting concrete, which has high physical and mechanical characteristics and a high-quality structure, can be used in building structures for residential, civil, and social purposes. Consequently, we plan to continue and develop this research in the following directions. Subsequent studies will be devoted to the durability of BSCG concrete. Experimental studies will be conducted on frost resistance, water resistance, and resistance to cycles of alternating wetting and drying, as well as the effects of chloride and sulfate attack on such concrete. Ultimately, the goal of our large-scale research is to introduce new compositions into the regulatory and technical documents of modern construction. These concrete measures will play a special role in countries that are characterized by high coffee consumption and the accumulation of large amounts of waste. It is important to acknowledge, as previously stated, that coffee is a widely consumed beverage in many countries. Consequently, our suggested specific composition, technological parameters, and manufacturing approach can be successfully employed in actual construction production over virtually any geographical area [52,53].

According to Ref. [27], this method could be beneficial to the environment if it could reduce the amount of coffee waste sent to landfills, as well as the demand for natural sand used in the construction industry.

According to a feasibility study [27], in terms of a food waste strategy, food waste accounts for approximately 3% of annual greenhouse gas emissions, with a production capacity of 75,000 tons of coffee waste per year.

According to Ref. [27], creating biochar involves roasting coffee grounds without oxygen to prevent the formation of carbon dioxide and increase greenhouse gas emissions.

These findings justify the potential use of coffee waste.

3. Materials and Methods

3.1. Materials

To evaluate the feasibility of using biochar spent coffee grounds (BSCG) in cement composites, standard materials for the production of cement pastes and concrete were used. Portland cement CEM I 42.5N (PC) (CEMROS, Stary Oskol, Russia) with the following properties was used as a binder: compressive strength at the age of 28 days, 57.8 MPa; specific surface area, 346 m^2/kg; normal consistency, 27%. Polyfunctional sand (PS) (RostStroyMix, Rostov-on-Don, Russia) was used to produce cement paste samples. Concrete was prepared using coarse aggregates in the form of granite crushed stone (CrS) (RostMed, Kamensk, Russia) and quartz sand (QS) (RostStroyMix, Rostov-on-Don, Russia). Granite crushed stone (CrS) had the following characteristics: bulk density of 1467 kg/m^3; apparent density of 2651 kg/m^3; resistance to fragmentation of 11.5 wt%; and content of lamellar and acicular grains of 8.2 wt%. Characteristics of quartz sand (QS): bulk density, 1350 kg/m^3; apparent density, 2632 kg/m^3; content of dust and clay particles, 0.08%; content of clay in lumps, 0.04%.

BSCG was produced in a production process consisting of three sequential stages. In the initial phase, coffee grounds (Figure 9) were dried to a constant weight in a laboratory drying cabinet (ShS-80-01 SPU) (Smolensk SKTB SPU, Smolensk, Russia). Subsequently, a series of laboratory sieves were employed to separate any lumps and external impurities. During the second stage, the mass of the spent coffee grounds was transferred to an aluminum tray. The tray was then sealed with aluminum foil (Ural Aluminum Plant, Kamensk-Uralsky, Russia) containing micro-holes before pyrolysis. The pyrolysis temperature was 400 °C for 2 h in a SNOL 6.7/1300 oven (SNOL, Utena, Lithuania). In the third stage, BSCG was exposed to additional mechanical processing. The grinding of the BSCG was carried out in an Activator-4M planetary ball mill (Activator, Novosibirsk, Russia) for 5 h at a speed of 800 rpm.

Figure 9. Spent coffee grounds.

Granulometric curves of Portland cement (PC), BSCG, granite crushed stone (CrS), and quartz sand (QS) are presented in Figure 10.

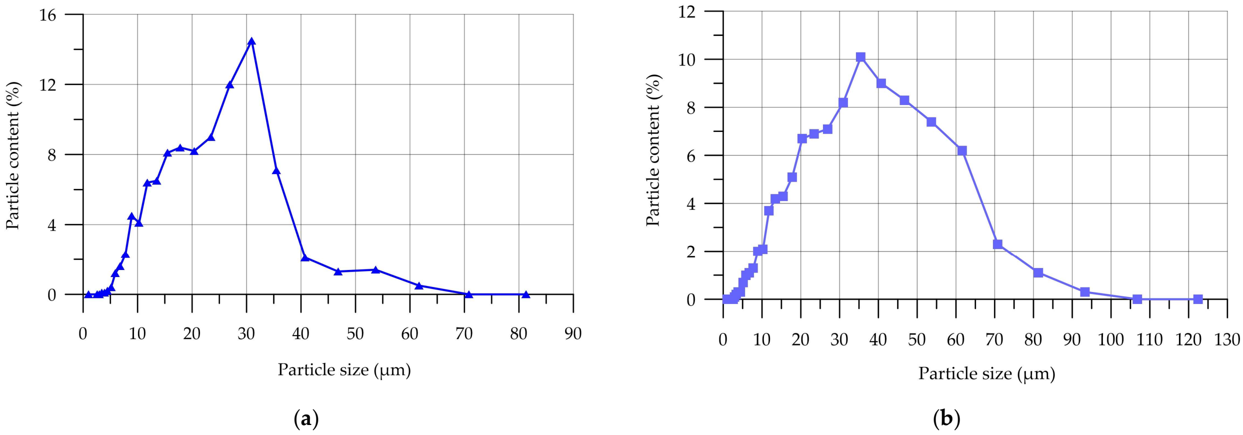

Figure 10. *Cont.*

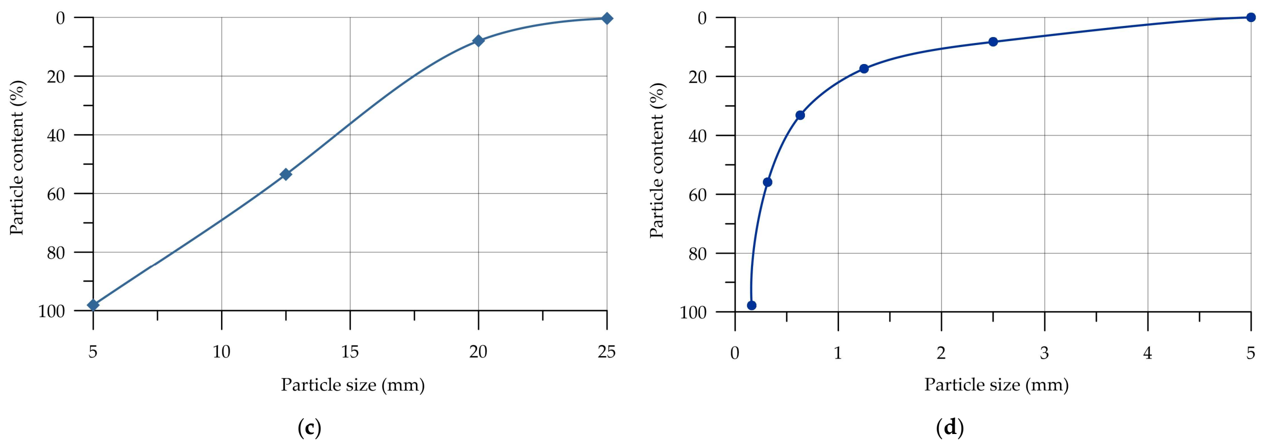

Figure 10. Particle size distribution: (**a**) Portland cement (PC); (**b**) BSCG; (**c**) granite crushed stone (CrS); (**d**) quartz sand (QS).

Based on Figure 10a, the majority (88.8%) of the cement particles fell within the 8 to 40 µm size range, with a peak distribution of 14.5% at 31 µm. The bulk of 83.5% (Figure 10b) of the BSCG particles after grinding ranged from 13 to 70 µm, and a distribution peak of 10.1% was recorded at 35 µm. Figure 10c shows that crushed stone (CrS) particles have sizes between 5 and 20 mm, while Figure 10d indicates a fineness modulus of 2.13 for quartz sand (QS).

3.2. Methods

The method of this study was selected individually for specific research. The use of BSCG involves the introduction of a fine micro-modifier into the concrete mixture. Therefore, a strict requirement for maintaining the purity of the experiment was to control the parameters of the concrete mixture. Of course, the workability of concrete mixtures changes because of the introduction of powder-type micro-modifiers, which certainly affects the water consumption of concrete mixtures. This factor cannot be ignored when conducting experiments. That is why it seems methodologically correct to first determine all the characteristics of the resulting fresh concrete to compare the characteristics of the concrete mixture with indicators of already hardened concrete conglomerates. Our research is focused on the methodological aspects of the relationship between the composition, properties, and structure of concrete, as well as its properties.

At the beginning of this study, the feasibility of BSCG as a cement composite was assessed using cement pastes. The properties of cement paste, including its normal consistency, compressive strength, and bending strength, were examined. The investigation of these characteristics of the cement pastes was conducted in compliance with the methodology outlined in Ref. [54].

The mixtures used to determine normal consistency are presented in Table 3. Cement pastes with different BSCG contents were prepared in a laboratory mixer Matest E093 Matest E093 (Matest, Treviolo (BG), Italy), and their normal consistency was determined using a Vika OGTS-1 device (RNPO "RusPribor", St. Petersburg, Russia). The normal consistency of cement pastes was recorded when the amount of water in the paste was such that the pestle did not reach the bottom of the plate (6 ± 1) mm.

The compressive and bending strengths of cement pastes were determined using prism samples 40 × 40 × 160 mm. The prism samples were prepared according to the recipe presented in Table 4.

Table 3. Mixture recipes for determining the normal consistency of cement pastes.

Mixture Type	PC (g)	BSCG (g)
BSCG0	500	0
BSCG3	485	15
BSCG6	470	30
BSCG9	455	45
BSCG12	440	60
BSCG15	425	75

Table 4. Cement paste formulations.

Mixture Type	PC (g)	PS (g)	Water (mL)	BSCG (g)
BSCG0	500	1350	225	0
BSCG3	485	1350	225	15
BSCG6	470	1350	225	30
BSCG9	455	1350	225	45
BSCG12	440	1350	225	60
BSCG15	425	1350	225	75

The manufacturing process included the following technological steps:

- Dosing of raw compotes;
- Making paste;
- Placing the finished paste into molds in three layers, in which each layer was compacted with 60 blows on a shaking table (VNIR, Moscow, Russia);
- Exposure of samples in a normal hardening chamber (KNT-1, RNPO "RusPribor", St. Petersburg, Russia) for 1 day and removal of formwork;
- Storing samples in a water bath for 27 days.

After 28 days of hardening, prism samples of cement pastes with different BSCG contents were removed from the bath, wiped with a damp cloth, and tested for bending and compressive strength. First, prism samples were installed on the supports of the press for bending testing so that the distance between the supports was 100 ± 0.2 mm and the rate of load increase was 50 ± 10 N/s. The flexural strength was determined by the following formula:

$$R_{bt} = \frac{1.5\,F\,l}{b^2} \tag{7}$$

where

F is the breaking load (N);
b is the size of the square section of the prism sample (mm);
l is the distance between the axes of the supports (mm).

The compressive strength was determined from six half-samples, which were obtained after determining the flexural strength. To determine compressive strength, half of the prism sample was fixed between two metal plates to transfer the load to the sample. The load increase rate during testing was 0.6 ± 0.4 MPa/s. The compressive strength was determined using the following formula:

$$R_{cp} = \frac{F}{S} \tag{8}$$

where

F is the breaking load (N);

S is the area of the working surface of the plate (mm^2).

To study the effect of BSCG on the properties of concrete, six experimental compositions were developed. The compositions of the concrete mixtures with different BSCG contents are listed in Table 5. The production of concrete samples with different BSCG contents included the following technological steps:

- Dosing of raw materials;
- Loading cement, sand, and BSCG in dry form into a concrete mixer BL-10 (ZZBO, Zlatoust, Russia) and mixing for 1 min;
- Introducing mixing water and stirring for 1 min;
- Introducing crushed stone (CrS) and mixing until a homogeneous consistency;
- Loading the mixture into molds and compaction on a vibrating platform;
- Keeping the samples for one day and removing them from the molds;
- Keeping the samples in a normal hardening chamber to acquire strength for another 27 days.

Table 5. Recipe for the production of concrete mixtures.

Mixture Type	PC (kg/m^3)	QS (kg/m^3)	CrS (kg/m^3)	Water (L/m^3)	BSCG (kg/m^3)
BSCG0	371	756	1013	205	0
BSCG2	363.58	756	1013	205	7.42
BSCG4	356.16	756	1013	205	14.84
BSCG6	348.74	756	1013	205	22.26
BSCG8	341.32	756	1013	205	29.68
BSCG10	333.9	756	1013	205	37.1

The workability of the concrete mixtures was determined based on the requirements of the methodology [55]. The prepared concrete mixture was loaded into a truncated metal cone with the following dimensions: base diameter 200 mm, top diameter 100 mm, and height 300 mm. Before loading the concrete mixture, the cone was wiped with a damp cloth, placed on a smooth metal sheet, and again wiped with a damp cloth. The mixture was loaded in 3 layers of equal height. Each layer was compacted using a metal bayonet with 25 blows. After compaction, the remaining concrete mixture was cut off flush with the edges of the cone, the surface of the mixture was smoothed, and the cone was raised in a strictly vertical position. The cone settlement was determined as the difference between the height of the form and the height of the highest point of the settled concrete mixture.

The compressive strength was determined in accordance with the requirements [56–59]. The concrete samples were tested on a Press P-50 laboratory installation (PKC ZIM, Armavir, Russia) at a constant load rate of 0.6 ± 0.2 MPa/s. The compressive strength of the concrete was calculated using the following formula:

$$R_c = \alpha \frac{F}{A} \tag{9}$$

where

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).

Figure 11 illustrates the procedure used to assess the compressive strength of concrete.

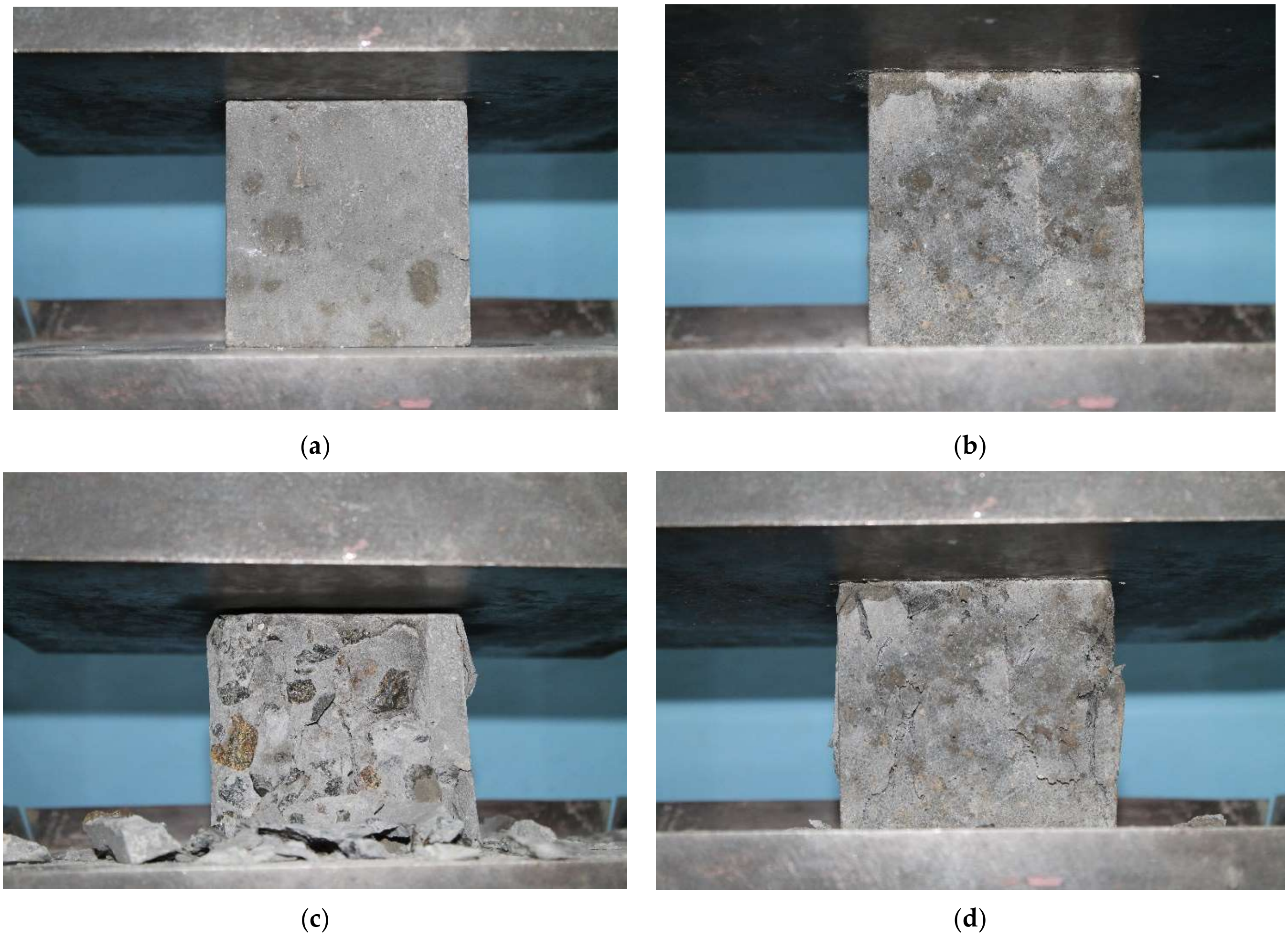

Figure 11. Determination of the compressive strength of concrete samples: (**a**,**c**) control composition before and after failure; (**b**,**d**) composition with 4% BSCG before and after destruction.

The water absorption measurements of the concrete specimens were conducted under the requirements of regulatory documents [60,61]. Concrete samples were placed in a container containing water for 24 h, saturated with water, and then weighed. Saturation was performed until the results of the last two tests differed by no more than 0.1%. The water absorption was calculated using the following formula:

$$W = \frac{m_w - m_d}{m_d} \times 100 \quad (10)$$

Here m_w is the mass of the sample saturated with water (g);

m_d is the mass of the dry sample (g).

The general experimental research program is presented in Figure 12.

A total of 18 prism samples of cement paste were fabricated to assess their compressive and flexural strength. Additionally, 18 cube samples of concrete were produced for the purpose of compressive strength evaluation, and an equal number of cube samples were fabricated to analyze water absorption.

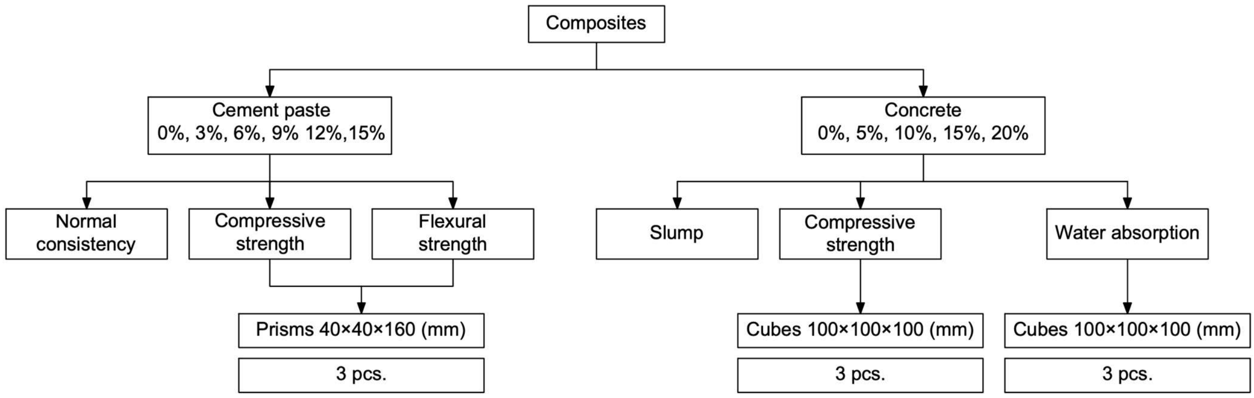

Figure 12. Experimental research program.

4. Conclusions

This study focused on understanding the influence of BSCG on the behavior of cement paste and concrete. An analysis was conducted to determine the properties of fresh and hardened cementitious composites, taking into account different BSCG concentrations.

(1) A biochar-modifying additive was produced from waste coffee grounds via thermal treatment of these wastes and additional mechanical grinding after pyrolysis. The phase composition of the manufactured BSCG additive was determined, which is characterized by the presence of phases such as quartz, cristobalite, and amorphous carbon.
(2) The introduction of BSCG into the composition of cement pastes and concrete mixtures increases the water demand for cement pastes and worsens the workability of concrete mixtures because BSCG particles have a porous structure and absorb more water.
(3) The rational content of BSCG, which maintains the properties of cement pastes at the level of the control composition, is fixed at up to 9%. The best strength properties of the cement pastes were obtained when the composition was modified with 3% BSCG. The compressive and flexural strength increases were 6.06% and 6.23%, respectively.
(4) For concrete, the optimal BSCG content should not exceed 8%. Concrete modified with 4% BSCG exhibits the best properties. The increase in strength was 5.85%, and water absorption decreased by 6.58% compared with the control samples.
(5) The addition of rational dosages of BSCG to the cement composite composition acts as a filler.

Thus, based on the results of experimental studies, the feasibility of using finely ground BSCG additives has been theoretically and practically proven. It was revealed that with a rational dosage of this additive, the strength of the new concrete not only decreased but also increased in relation to the control standard concrete composition.

Due to the plant origin of the proposed additive, as well as promoting the process of rational waste disposal, the resulting concrete can be classified as an environmentally friendly green building material. The proposed recipe, technological methods, and new theoretical knowledge obtained are thus proposed for implementation in the construction industry.

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