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Combined Effect of Coal Fly Ash (CFA) and Nanosilica (nS) on the Strength Parameters and Microstructural Properties of Eco-Friendly Concrete

Grzegorz Ludwik Golewski

Department of Structural Engineering, Faculty of Civil Engineering and Architecture, Lublin University of Technology, Nadbystrzycka 40 Str., 20-618 Lublin, Poland; g.golewski@pollub.pl; Tel.: +48-81-538-4394

Abstract: Disposal of the coal fly ash (CFA) generated from thermal power plants in huge quantities is one of the major concerns for the industry, as well as the natural environment. On the other hand, CFA can be used within a certain percentage range in the cement concrete mix as a replacement for cement. Nanomaterials can also be used to improve the properties of concrete. Therefore, this study investigated the effects of nanosilica (nS) on the mechanical parameters and microstructure of CFA cement concretes. This study utilized an nS content of 5%, along with three CFA contents, i.e., of 0, 15, and 25% by volume. Mechanical property tests and a thorough overview of changes in the structure of modified concrete were carried out to study the effect of the CFA content on the analyzed parameters of concrete containing nS. This study had the goal of elucidating the reinforcing mechanisms of CFA concrete by nS and providing design guidance for the practical engineering applications of CFA-nS composites. Based on the conducted studies, it was found that the combined usage of nS and CFA has synergistic and positive effects on improving mechanical parameters and microstructure in such concretes. The combined strengthening of a cement matrix by nS and CFA can fill the pores and microcracks in concrete composites and effectively improve the mechanical properties and microstructure of such materials. In this study, the optimal improvement was achieved when the concentration of additions was 5% nS and 15% CFA. The 28-day compressive strength and splitting tensile strength were increased by 37.68 and 36.21%, respectively, in comparison to control concrete. Tailored blended cements composed of nS and CFA content (up to 30% replacement level) can significantly improve the parameters of concrete composites, as well as reduce the carbon footprint of cement-based materials—constituting a step toward the production of eco-friendly concretes.

Keywords: coal fly ash (CFA); nanosilica (nS); eco-friendly concrete; SCMs; mechanical parameters; microstructure; C-S-H phase; microcracks; pores; synergistic effect

Citation: Golewski, G.L. Combined Effect of Coal Fly Ash (CFA) and Nanosilica (nS) on the Strength Parameters and Microstructural Properties of Eco-Friendly Concrete. *Energies* **2023**, *16*, 452. https://doi.org/10.3390/en16010452

Academic Editors: Izabela Hager, Krzysztof Adam Ostrowski and Katarzyna Mróz

Received: 15 November 2022
Revised: 26 December 2022
Accepted: 28 December 2022
Published: 31 December 2022

1. Introduction

The goal of producing environmentally sustainable concrete [1–5] is primarily to reduce the consumption of pure OPC in the technology of manufacturing these composites, by replacing it with other useful mineral-based materials [6–11]. In practice, such materials are referred to as Supplementary Cementitious Materials (SCMs), and their large group consists of various types of industrial, agricultural, and other waste [12–18].

However, for many years, the basic SCM used in eco-friendly concrete, e.g., [19], has been coal fly ash (CFA) [20–24]. This is due to the fact that 800 million tons of CFA are generated annually in the world [25], and it is also possible that in 2031–2032 it will be about 2100 million tons [26]. According to [27], India and China are the primary biggest nations for the generation of CFA worldwide with the production of 112 and 100 million tons, respectively.

Coal fly ash has a positive effect on the numerous properties of concretes made with its participation, and in addition, such action allows for the disposal of troublesome waste associated with residues from energy production from coal combustion in power plants [28,29].

The use of CFA in the amount of up to 20% improves, among others, the strength parameters of the composite, and has a positive effect on reducing the negative effects of impact and dynamic loads [30–35]. It also reduces the width of intra-material microcracks [36–42], which improves the durability of the material and its fracture toughness [43–47].

Unfortunately, the use of high amounts of CFA generates a loss of mechanical properties at short ages [26,48,49]. It can be explained, among others, by the slow progression of the pozzolanic reaction of CFA. For example, based on the earlier studies of composites including 30% CFA, it was found that after 12 months of curing, 50% of CFA particles did not enter into the pozzolanic reaction [50]. Therefore, among other things, because of this reason, the limit amount of CFA in the low-volume fly ash concrete (LVFA) is probably approx. 30% of cement mass [51].

Therefore, in order to eliminate this negative effect, attempts were made to combine the use of FA with other, more reactive SCMs [52–55]. Satisfactory research results, resulting from the synergy of both pozzolanic materials, were obtained, among others, in the case of the use of CFA in combination with silica fume (SF) [56–58]. Particularly favorable results were obtained in the case of concretes tested at an early age, because specifically in the initial period of CFA curing, they are characterized by the lowest activity, and SF is able to reduce the impact of this negative feature [59,60].

Another effective direction of the material modification of ash concretes in terms of improving their mechanical parameters and microstructure may be the use of nanotechnology achievements for this purpose. This is related to, among others, the fact that the current development in the engineering of building materials is evaluating in the direction of learning and improving the structure of concrete composites at the micro- and nano-scale levels [61–63]. The situation is certainly influenced by the increasing financial outlays for this branch of science (counted in millions of euros per year), hence more advanced research and its more and more spectacular results [64,65].

In the construction industry, one of the most important areas in which the application of nanotechnology is fairly clear is the production of concrete. Nanotechnology has a great potential to contribute to the understanding of the behavior of this material, in order to improve its mechanical properties and strengthen the structure of the skeleton forming the concrete composite, reduce production costs, and implement the concept of ecological materials on a larger scale [66,67].

For these reasons, over the past years, nanomaterials have been widely used as SCMs in cementitious composites. In recent years, researchers have investigated the effects of different nanomaterials on concrete, e.g., nano-SiO_2, nano-Al_2O_3, nano-TiO_2, nano-ZnO_2, nano-$CaCO_3$, nano-Fe_2O_3, carbon nanotubes, and C-S-H nanoseeds [68–73], as well as the combined effects of such SCMs on cementitious composites, e.g.:

- Ground granulated blast furnace slag (GGBFS) + rice husk ash (RHA) + CFA [74];
- nS + limestone powder (LS) + CFA [75];
- nS + CFA [76];
- Nano-sized calcite (NC) + CFA [77];
- Nano-Fe_2O_3 + nano-SiO_2 +CFA [78];
- GGBFS + nS + CFA [79];
- Silica fume (SF) + nS + CFA [80];
- SF + coconut fiber (CF) + CFA [81,82];
- SF + Ns + LS + CFA [83].

However, among the main group of nanomaterials, nano-SiO_2 (nS) is the most widely studied and used material [62,84]. Based on the previous studies, very positive results were observed on the influence of the addition of nS on the many different properties of cement composites. A few percent addition of nS to concrete improves, among other things, its parameters such as [85–90]:

- Compressive strength;
- Flexural strength;
- Flexural fatigue performance;

- Fracture toughness;
- Water anti-permeability;
- Chloride anti-permeability;
- Abrasion resistance;
- Frost resistance;
- Strength at elevated temperature;
- Decrease in water absorption capacity;
- Reduction in the porosity of the cement paste;
- The hydration of cement and generating a large amount of the C-S-H phase.

Although nS is a material that improves numerous parameters of concretes made with its addition, it still remains a relatively expensive SCM [88]. Economic reasons, i.e., the high price of nS, do not yet allow for widespread industrial use of this material [89,90]. Nevertheless, experimental work is still underway on the possibility of using nS as an addition "mitigating" the negative impact of CFA used as an SCM in an amount above 20%.

So far, the combined effect of nS and CFA on concrete has also been investigated among others in terms of evaluation:

- Hydration process, pozzolanic activity, and the pore size distribution and synergetic effect formation mechanism [91];
- Early-age mechanical parameters [92];
- Rheological parameters, setting time, and $Ca(OH)_2$ (CH) content [93];
- Impact resistance, chloride penetration resistance, and freezing–thawing resistance [76,94];
- The effects of nS on the properties of CFA-based geopolymers [95,96];
- The effects of nS on the properties of composites including CFA cenospheres [97];
- Physico-chemical behavior [98];
- Chloride ion penetration and effect of steel fiber [99];
- Improving impermeability [100];
- Enhancement mechanism in recycled aggregate concrete (RAC) [101,102];
- Durability properties [102];
- Workability and microstructure [103];
- Microstructure and properties of autoclaved aerated concrete [104];
- Water absorption [105];
- Exposure to high temperatures [106].

However, systematic investigations on the mechanical parameters and microstructure of concrete with the simultaneous additions of CFA (in various percentage ranges) and nS are still lacking, whereas the combined effect of nS and CFA on the mechanical parameters and microstructure of concrete composites still remains poorly understood. Therefore, this study utilized an nS content of 5%, along with three CFA contents, i.e., of 0, 15, and 25% by volume. Mechanical property tests and a thorough overview of changes in the structure of modified concrete were carried out to study the effect of the CFA content on the analyzed parameters of concrete containing nS.

This research had the following main objectives:

- Elucidating the reinforcing mechanisms of CFA concrete by nS;
- Providing design guidance for the practical engineering applications of CFA-nS composites.

Finally, the investigation presented was aimed at analyzing the properties of composites intended for the production of eco-friendly concretes [107,108].

2. Experimental Program

2.1. Materials

Cementitious materials include OPC (CEM I 32.5R) [109], low-calcium fly ash (CFA)—class F according to ASTM C618-03 [110], and nanosilica (nS). Tables 1–3 contain, respectively, the chemical components of cementitious materials, the physical properties of cement, and the physical properties of other cementitious materials.

Table 1. Chemical composition of binders.

Type	Component (wt %)											
	CaO	SiO_2	Al_2O_3	Fe_2O_3	K_2O	SO_3	MgO	P_2O_5	TiO_2	Ag_2O	Cl	LOI *
OPC	71.06	15.0	2.78	2.72	1.21	4.56	1.38	-	-	-	0.08	1.24
CFA	2.35	55.27	26.72	6.66	3.01	0.47	0.81	1.95	1.89	0.10	-	3.20
nS	-	>99.8	-	-	-	-	-	-	-	-	-	1.0

* Ignition loss.

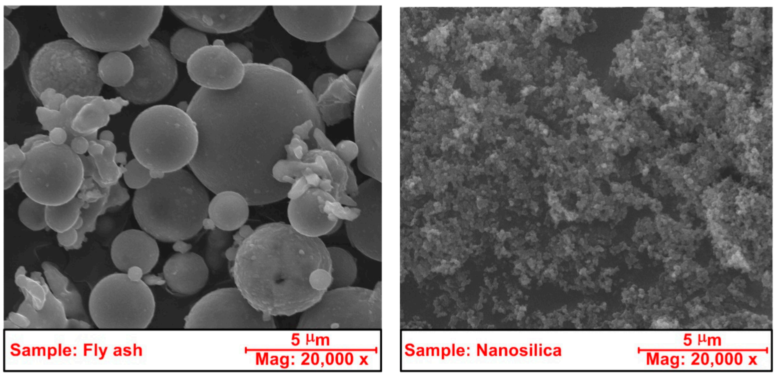
Table 2. Physical properties of OPC.

Analyzed Parameter						
Specific Gravity (g/cm^3)	Specific Surface Area (m^2/g)	Average Particle Diameter (μm)	Setting Time (min)		Compressive Strength (MPa)	
			Initial	Final	2 Days	28 Days
3.11	0.33	40.0	207	298	23.3	50.0

Table 3. Physical properties of mineral additions.

Type	Analyzed Parameter			
	Specific Gravity (g/cm^3)	Specific Surface Area (m^2/g)	Average Particle Diameter (μm)	Color (Visually)
CFA	2.14	0.36	30.0	Dark gray
nS	1.10	200	0.012	White

Additionally, in order to better visualize the differences in the size of the particles of the SCMs used, Figure 1 shows photos of the morphology of both materials, i.e., CFA and nS. The samples were selected in such a way as to present the particles of individual additions at the same scale and at the same high magnifications (Figure 1). The particle size analysis from Figure 1 confirms the data given in Table 3, which shows that the nS particle size distribution is much finer in comparison to CFA grains.



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

Figure 1. SEM micrographs of SCMs used: (**a**) coal fly ash, (**b**) nanosilica.

The specific density of the fine aggregate, i.e., pit sand (FA), used with a maximum diameter of 2 mm is 2.60 g/cm^3, and the compressive strength is 33 MPa. Natural gravel is used as the coarse aggregate (CA), with a maximum particle size of 8 mm. The specific density is 2.65 g/cm^3, and the compressive strength is 34 MPa. Water (W) represents laboratory pipeline water free from contamination.

Superplasticizer STACHEMENT 2750 (SP) is a polycarboxylic type (1.8% of binding material weight was used). The SP was used to improve the workability of mixtures with pozzolanic additions. It was related to the fact that, according to previous studies, the amount and specific surface area of the applied nS significantly affect the workability of cement composites [111]. The use of nS in the concrete mix leads to a significant decrease in its workability. It was found that the use of 2 and 4% nS in the concrete mix resulted in a decrease in flow by about 40 and 60% [112,113]. In general, along with an increase in the nS content, the workability of the mixtures decreases.

2.2. Mix Proportions and Specimen Preparations

The mixture proportions of the modified concretes are enumerated in Table 4, where REF and T1, T2, and T3 represent the reference concrete without CFA and nS (REF) and concretes made of ternary binders with an addition of 0% CFA and 5% nS by mass of cement (T1), additions of 15% CFA and 5% nS by mass of cement (T2), and additions of 25% CFA and 5% nS by mass of cement (T3), respectively.

Table 4. Mixture proportions of concretes (kg/m^3).

Mixture	Component							Water Binder Ratio
	OPC	CFA	nS	FA	CA	W	SP	
REF	352	0	0	676	1205	141	0	0.4
T1	334.4	0	17.6				6	
T2	281.6	52.8	17.6				6	
T3	246.4	88	17.6				6	

The manufacturing process of concrete specimens is illustrated in Figure 2. It contained the following steps:

- In the beginning, FA and CA are mixed for 120 s;
- Next, OPC and CFA are poured into the mixture and mixed for 3 min;
- Subsequently, 0.5 mixed water and SP in combination with nS are poured in and stirred for 120 s;
- In the last step, the remaining water is poured into the mixture and mixed for 2 min.

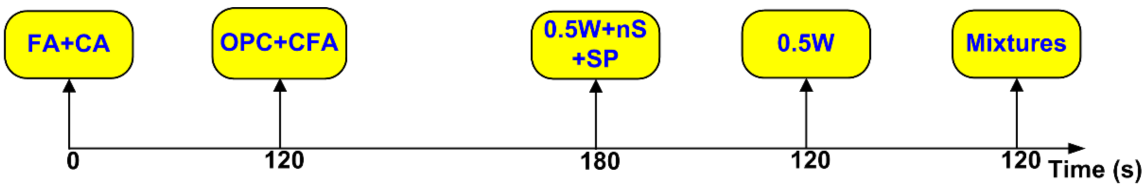


Figure 2. Mixing flowchart of concrete specimens.

Subsequently, the mixture was poured into the molds and vibrated intensively. The specimens were demolded after curing for 2 days under laboratory curing conditions (temperature 20 ± 2 °C; relative humidity >95%). Then, the curing process was continued for 28 days.

2.3. Experimental Methods

2.3.1. Mechanical Parameter Tests

Mechanical property tests were carried out according to the European Standards EN 12390-3: 2011 + AC: 2012 [114] and EN 12390-6: 2009 [115]. Compression strength f_{cm} and splitting tensile strength f_{ctm} were investigated during the studies. In order to ensure the repeatability of test results, 6 specimens for all composites and both mechanical tests were prepared and reported after 28 days of curing. Cube specimens (150 mm × 150 mm × 150 mm) were used for both types of tests, which were conducted in a hydraulic servo testing machine with a maximum bearing capability of 3000 kN. During the experiments, the specimens were loaded statically.

2.3.2. Microstructural Investigations

In order to elucidate the influence of combined effect of CFA and nS particles on the hydration mechanism for curing age of 28 days on analyzed concretes, microstructural analysis was conducted. The quality of the interaction of the additions used with the cement matrix was assessed with scanning electron microscope (SEM). The samples for the SEM analysis were collected from the failed specimens after the strength tests. In the course of the experiments, the following assumptions were made:

- The test specimens had rectangular shapes and approximate dimensions of 10 × 10 × 3 mm;
- The test was conducted using a QUANTA FEG 250, which was equipped with energy dispersive spectroscopy (EDS EDAX);
- For all specimens, the photos were taken at the same magnifications, i.e., 8000 and 16,000 times, and the same reference scales, i.e., 10 and 5 μm;
- For each type of composite, the photos were taken on 6 samples, and then 30 images were taken for each sample, from which representative photos were selected;
- The characteristic places observed in the structure of the modified cement matrixes were described in the photos.

In general, in the course of the conducted experiments, an effort was made to determine the effect of strengthening the cement matrix in CFA concretes by using active nS to see if it is possible to use such materials as eco-friendly concretes. The full scope of the research program for macroscopic and microstructural examinations, with specific parameters of specimens used in the studies, is given in Figure 3. In addition, Figure 3 contains photos of all test stands.

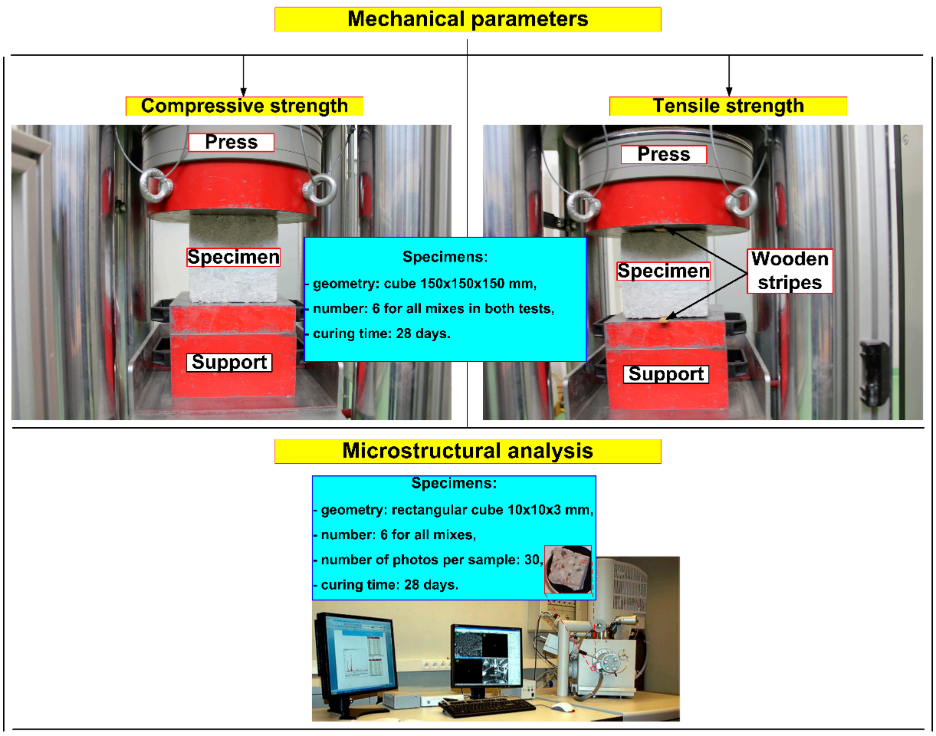
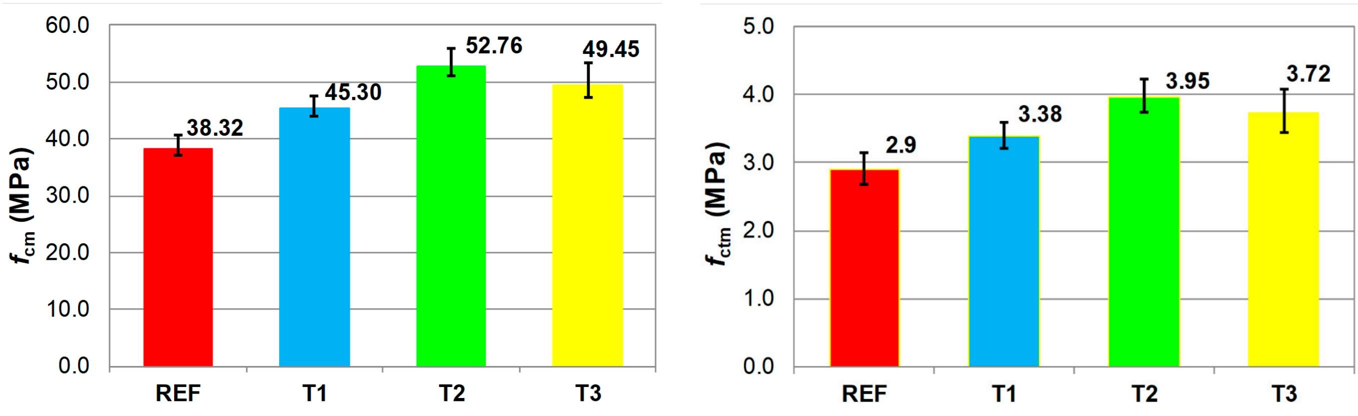


Figure 3. Flowchart of the study.

3. Results and Discussion

3.1. Mechanical Parameters

The compressive strength and splitting tensile strength of control concrete and modified concretes incorporating different contents of CFA and a constant content of nS, after 28 days of their curing, are depicted in Figure 4.



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

Figure 4. Results of compressive strength (**a**) and splitting tensile strength (**b**) of analyzed concretes.

Based on the obtained test results, it should be stated that the highest compressive and splitting tensile strength was obtained for concretes containing the addition of two different SCMs in the composition of the cement matrix, i.e., T2 and T3. The increases in both strength parameters were:

- In the case of T2, almost 40% higher when compared to the values obtained for the reference concrete (38% and 36% for f_{cm} and f_{ctm}, respectively);
- In the case of T3, almost 30% higher when compared to the values obtained for the reference concrete (29% and 28% for f_{cm} and f_{ctm}, respectively).

A slightly lower, although still clear, increase in the value of strength parameters was recorded for concrete containing only nS as a matrix modifier. For this composite, both parameters increased only by almost 20%. Nevertheless, these results also appear to be very advantageous in comparison to the values obtained for control concrete without any additives (Figure 3). In addition, this concrete, i.e., T1 was also characterized by the greatest convergence of the obtained test results (Figure 4). In order to clearly visualize the progress in the obtained results of strength parameters, resulting from a significant and complex modification of the cement matrix, Figure 5 shows the relative percentage increments of f_{cm} and f_{ctm} for all tested composites.

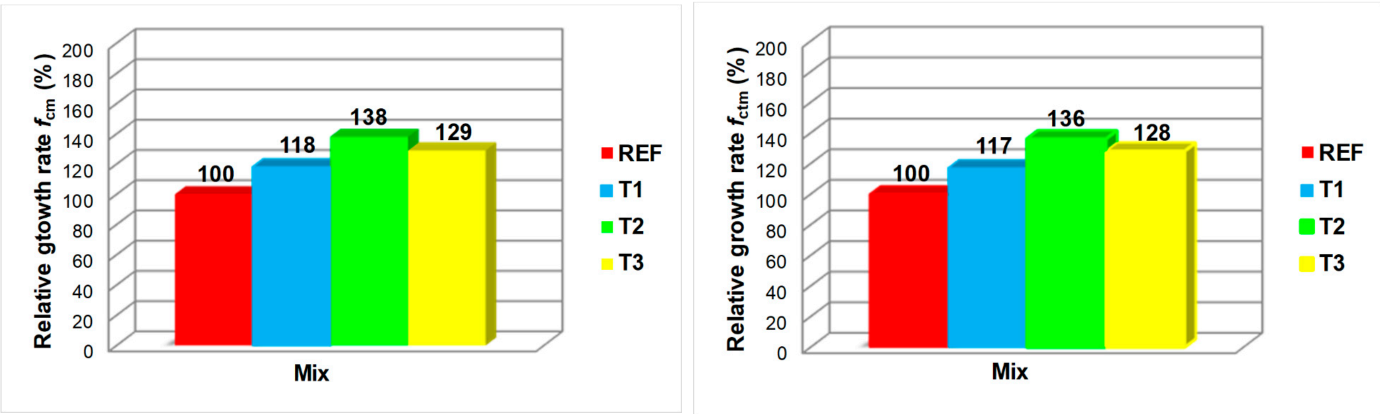
The favorable strength results of OPC + CFA + nS composites result mainly from the role of nS. In previous studies, it was observed that nS particles can activate CFA grains to activity in the formation of the structure of the cement matrix [116]. This is due to the fact that the CFA particles react only after a longer period of curing [117]. According to other reports, the use of nS can improve the strength of concrete with CFA in the curing period of 28 days and 91 days [118].

Therefore, in order to explain the obtained results of the research on the mechanical parameters of the analyzed composites, an in-depth analysis of their structure and morphology of the observed phases of the cement matrix were proposed. The results of these studies will be presented in the next section.

3.2. Morphology and Microstructure Analysis

SEM analysis was used to verify the microstructure of concretes investigated and to provide a better understanding of the obtained mechanical parameter results. This is due to the fact that the microstructure characteristics of modified concretes determine their macroscopic properties to a certain extent, thus affecting the mechanical properties of these composites [119].

The SEM microimages for the four types of analyzed concrete samples with two different types of magnification are shown in Figures 6–9. In order to better understand the changes in the structure of modified concretes, as a result of the application of CFA and nS particles, all important observed details were also marked on the selected representative photos.



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

Figure 5. Relative growth rate of compressive strength (**a**) and splitting tensile strength (**b**) of analyzed concretes.

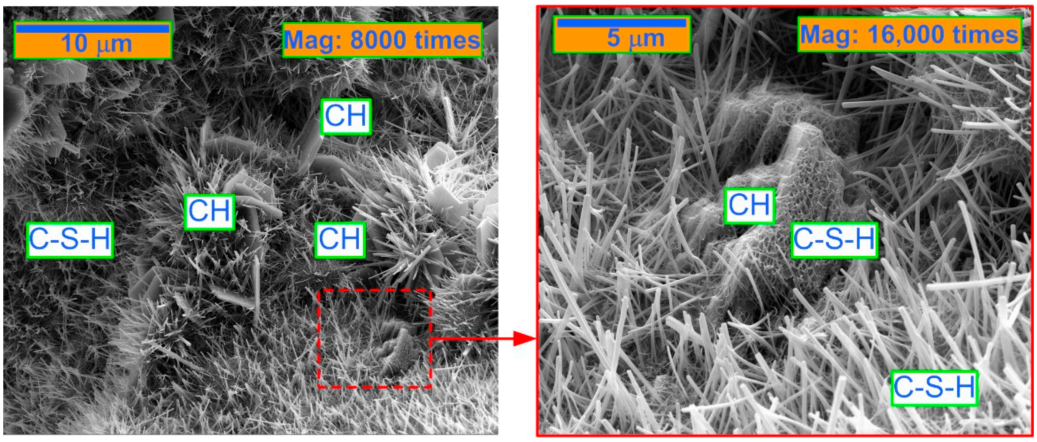


Figure 6. SEM microimages of analyzed REF concrete; descriptions in the text.

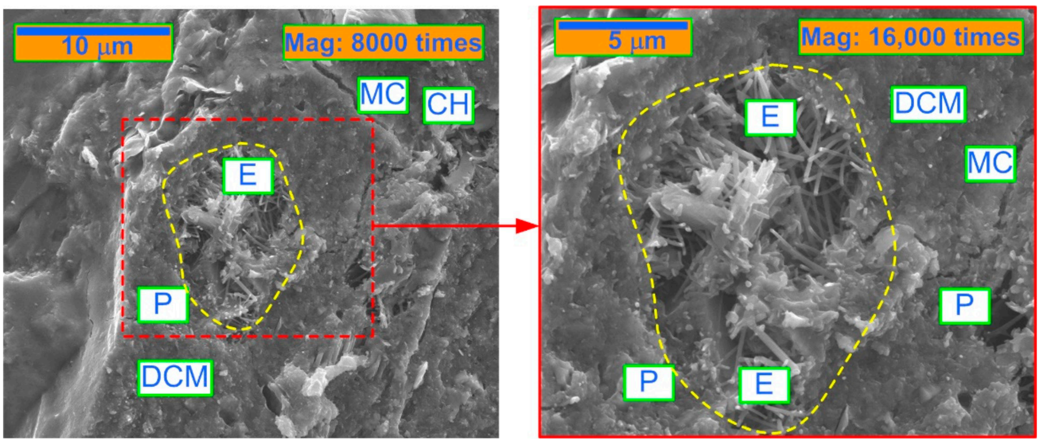


Figure 7. SEM microimages of analyzed T1 concrete; descriptions in the text.

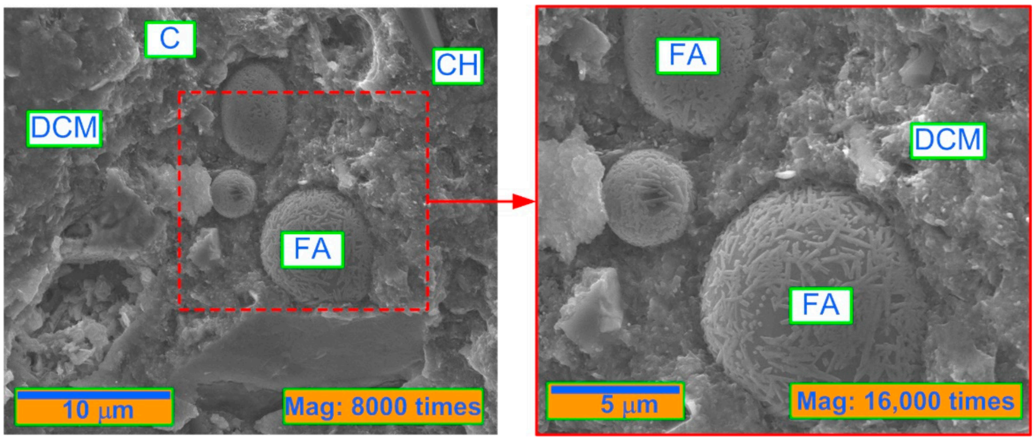


Figure 8. SEM microimages of analyzed T2 concrete; descriptions in the text.

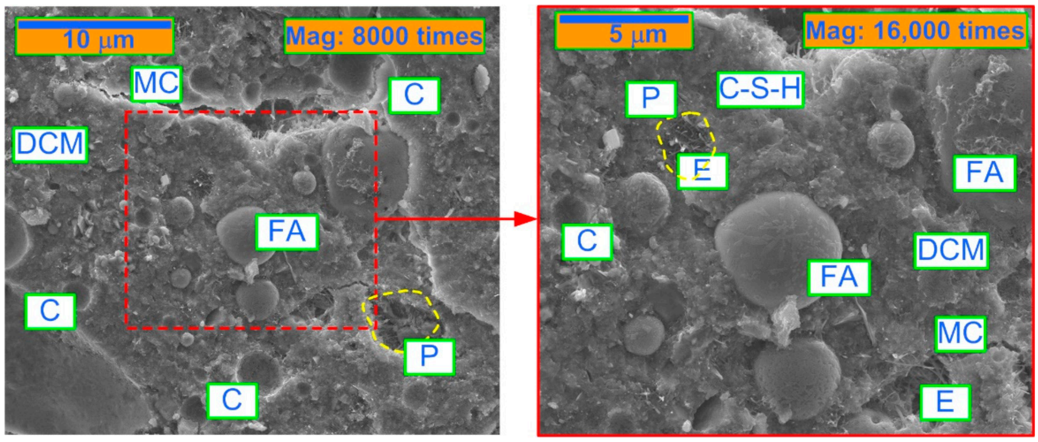


Figure 9. SEM microimages of analyzed T3 concrete; descriptions in the text.

Figure 6 shows the morphology of a typical reference concrete after 28 days of curing. The main phases in this composite were still in the development stage and presented a typical system containing the C-S-H phase, mainly in fibrous form and with a honeycomb structure. In the thicket of these structures, hexagonal plates of the CH phase, i.e., portlandite, were intensively distributed (Figure 6). At a larger magnification, i.e., 16,000 times, it was possible to observe the CH plate completely surrounded by the second morphological type of the C-S-H phase. The fragile CH phase in this concrete was visible both in large unreacted clusters and during transformation (Figure 6).

In the concretes modified with these SCMs, i.e., in the eco-friendly concretes of the T1 to T3 series, the structures of the cement matrixes differed significantly compared to the matrix of the reference concrete. First of all, in each of the concretes, reinforced by SCMs, significant areas of the cement matrix in a compact and homogeneous form (DCM) could be clearly observed (Figures 7–9).

In the case of the composite containing only the nS addition at the level of 5%, the effect of reinforcing the cement matrix, as a result of this material modification, was the least noticeable. The structure of this composite was slightly compact. In the concrete of the T1 series, numerous porous areas filled with the ettringite (E) phase, microcracks, and CH phase plates were visible. The matrix inhomogeneity area has been marked in Figure 7 with a yellow dotted frame.

Nevertheless, the CH phase was present in a much smaller amount than in the case of REF concrete (Figure 6). This was probably due to the consumption of this weak concrete phase, i.e., CH, by the reactive nS particles. It was found that the total exothermic heat of the samples containing nS increased significantly in comparison to the mixtures without this SCM [120].

In addition, in the representative images of this composite, DCM was visible in small areas (Figure 7). Similar results for 28-day concretes confirm the conclusions presented in the work [121]. Moreover, in concretes with the addition of silica fume (SF), a similar morphological system of phases in the cement matrix can be observed [122]. Such an image of the material structure resulted in an improvement in the strength parameters in this material, compared to the concrete of the REF series, only at the level of approx. 20% (Figure 4).

In the composite of the T2 series containing the combined addition of nS and CFA in the amount of 15%, a lot of DCM areas were visible (Figure 8). In this concrete, the structure of the cement matrix looked the most homogenized of all the analyzed materials, without clearly visible porous places. The reacting CFA grains, on the other hand, were well embedded in the paste. The occurrence of CFA grains in the form of a ferrosphere with stripline magnetite could be observed (Figure 8). The visible compacted and strongly homogeneous form of the cement matrix in this composite was probably the result of the synergy between two fine-grained and reactive materials, i.e., CFA and nS (Figure 8). The effect of the pozzolanic reaction and synergy between both mineral additives resulted in a clear strengthening of the material structure in T2 concrete, which in turn resulted in obtaining the best mechanical parameters in this composite (Figure 4).

Furthermore, the following factors could have contributed to obtaining such a favorable structure of concrete with two pozzolanic additives: the high pozzolanic activity of CFA, very high pozzolanic activity of nS, and filler effects of nS particles [123]. Similar results in the case of application to the concrete of the combined nS addition at the level of several percent and CFA in the amount of up to 20% were also observed in the work [103].

Unfortunately, the higher content of the SCM in the form of CFA, in the amount of 25%, partially delayed the processes of homogenization of the cement matrix. In previous studies, it has been proven that the optimal level of CFA in the structure of concrete, which can positively affect the parameters of composites with this addition, oscillates within 17% and should not exceed 20%. For this reason, small areas of porous zones (P—marked in yellow dotted frame), microcracks (MC), and cavities in the matrix after the separation of CFA (C) grains, which were in the form of a dendritic ferrosphere (Figure 9), were visible in the concrete structure of the T3 series.

Nevertheless, the synergy effect between additions, although slightly weakened, also caused a partial stiffening effect of the cement matrix (visible DCM areas), which resulted in an improvement in the mechanical parameters of this concrete compared to the results obtained for REF concrete (Figure 4). Such effects result from the acceleration of early reactions in this type of composite and the faster start of homogenization processes of the cement matrix structure including Ns and CFA. This phenomenon was noted, for example, in [55,124].

Additionally, apart from the benefits resulting from the effective reinforcement of the structure of composites containing the addition of CFA and nS in the composition of the cement matrix, such modification also brings measurable environmental benefits. It should also be noted that the solution, presented in this article, has a two-way dimension in this regard.

First of all, concrete can become more eco-friendly when the amount of CO_2 generated during the production of OPC is reduced as much as possible. With the progressing pollution of the environment and legal sanctions limiting the amount of CO_2 emitted into the atmosphere, this is the main way for the production of concrete to be burdened with less emission of this gas. The solution proposed in this article meets these requirements. It consists in the substitution of a part of the basic binder by active pozzolanic materials, i.e., CFA and nS.

At the same time, the use of CFA in the concrete industry causes limited landfills in the area of coal power plants. Therefore, the more CFA is utilized, the less it burdens the environment in open landfills or in sedimentation tanks.

On the other hand, the inclusion of nS in the cooperation in creating the structure of composites containing CFA significantly increases the possibilities of using this industrial waste to an even greater extent. Therefore, the solution proposed in the article meets the requirements for eco-friendly concrete in a wide range.

4. Conclusions

The current study assessed the influence of nS on concrete composites in three separate groups that contained 0%, 15%, and 25% CFA replacements, respectively. During the studies, the effect of a combined modification by nS and CFA of concrete composites on the main mechanical parameters and microstructure of such materials was analyzed. Based on the conducted studies, it was found that:

(1) OPC substitution by each proposed combination of active pozzolan SCMs in the form of CFA + nS brings clear benefits in the improvement of the main strength parameters and cement matrix morphology of modified eco-friendly concrete.
(2) With both nS and CFA added together, the main mechanical parameters as well as the microstructure of concrete composites could be further improved compared to those with only nS or without any SCMs added. It means that the combined usage of nS and CFA has synergistic and positive effects on improving mechanical parameters and microstructure in such concretes.
(3) Due to the activation of CFA grains by very fine and highly active nS particles, voids, pores, and initial microcracks in the structure of the cement matrix are filled. Homogenization of the cement matrix effectively improves the mechanical properties and microstructure arrangement of composites incorporating CFA and nS.
(4) The optimal improvement was achieved when the concentration of additions was 5% nS and 15% CFA. An increase in CFA content, i.e., when the concentration of additions was 5% nS and 25% CFA, showed lower strength development in this composite. This was probably due to the delayed pozzolanic reactivity of the larger amount of CFA.
(5) In the structure of the analyzed concretes incorporating nS and CFA, after 28 days of curing, the following could be observed:
    - In the case of T1—a slightly compact concrete skeleton with numerous porous areas filled with the ettringite (E) phase, as well as microcracks and CH phase plates;
    - In the case of T2—a compacted and strongly homogeneous cement matrix without clearly visible porous places and with visible reacting CFA grains, well embedded in the paste;
    - In the case of T3—small areas of porous zones and microcracks in the cement matrix and cavities in the paste after the separation of CFA grains.
(6) Tailored blended cements composed of nS and CFA content (up to 30% replacement level) can significantly improve the parameters of concrete composites after 28 days of their curing, as well as reduce the carbon footprint of cement-based materials—constituting a step toward the production of eco-friendly concretes.
(7) Due to the loss of mechanical properties of concrete composites containing CFA, mainly after a short period of curing, it is planned to conduct additional tests on the mechanical and microstructural parameters of the composites in question both at an early age, i.e., in the period up to 28 days, and after a long period of curing, i.e., from 28 days to a year. The results of these experiments will be the subject of subsequent publications.

Funding: The research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflict of interest.

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