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WASTE SULFUR AS A PARTIAL FILLER REPLACEMENT IN SELF-PLACING CONCRETE

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ABSTRACT

The effect of partial replacement of natural filler by ground waste sulfur originated from the oil refining process on fresh and hardened properties of self-compacting concrete was investigated. Properties investigated were slump flow, V-funnel, L-box, and sieve segregation of fresh concrete mixes; and compressive, flexural, and bond (pull off) strengths, dynamic modulus of elasticity, ultrasonic pulse velocity, dynamic Poisson's ratio, specific electrical resistance, density, and microstructure of hardened concrete. Results showed a slight decline in compressive, flexural, and bond strengths and dynamic elasticity modulus with increased addition of sulfur. Specific electrical resistance and density were higher for samples containing sulfur. Also, scanning electron microscopy indicated a slight porosity increase of the samples containing sulfur. Having in mind that, in the case of waste valorization in concrete, all properties of self-placing concrete should remain within acceptable levels or improve, this study proved that mixtures containing ground sulfur as a partial replacement for filler can be used for structural applications.

Keywords: self-placing concrete (SPC); waste sulfur; fresh concrete properties; hardened concrete properties

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1. INTRODUCTION

Self-placing concrete (SPC) presents one of the biggest achievements in the field of concrete technology, because of plentiful benefits that offer such are reduction in construction time, maximum freedom of design work, improvement in product quality, and working environment, etc.

Modern trends in building materials include several approaches such are: acceptable physical and mechanical properties for specific applications, economic effects, durability, and ecological impact [1-3]. Conventional concrete (CC) is usually placed by vibration to reduce the entrained air content and eliminate cavities in contact with reinforcement and formwork. Very fine powders-admixtures are added to CC as fillers, densifiers, or to reduce water content. The development of super-plasticizers allowed easier installing of stiffer consistency concrete without vibrations leading to the concept of SPC that spreads into place, easily fills framework and seals, encapsulates or wraps even the most congested reinforcement without segregation.

During the eighties of the last century, the problem of concrete constructions lifespan was very prominent and outstanding. The solution to this problem led to the development of SPC. Introducing the term SPC and initial investigations were originated from Japan in 1986 and 1988, respectively [4,5].

The most important advantage of SPC is the ability to flow into and fill spaces within the formwork under its weight while maintaining homogeneity during placement and compaction without vibration [1,6-8]. Its high flowability can be attributed to careful mix design, usually replacing much of the coarse aggregate with fines and cement, and adding admixtures. By excluding the vibration, segregation between solid and liquid phases is avoided, thus resulting in a less porous transition zone between the paste and aggregates and also higher compressive strength and durability, compared to CC. Installation without any vibration into the formwork of highly reinforced structures causes many benefits such are reduction in construction time, maximizing freedom of design work, improvement in product quality, and working environment.

Some disadvantages of SPC are higher content of powdered components (< 0.125 µm) and cement, and usage of chemical additives that increase cost and can lead to more pronounced sensitivity of SPC, meaning reduced robustness that demands more frequent quality control [9,10]. To overcome disadvantages, it is suitable to use inert or non-pozzolanic and hydraulic or pozzolanic materials in the form of waste and recycling materials as a replacement for binder, filler, and/or chemical admixtures which also provides huge environmental benefits [6,11-13].

The amount of available sulfur in the world has considerably grown during the last decades mainly due to the actual strict environmental regulations regarding the petroleum and gas refining processes, which limit the maximum content of sulfur present in combustibles. Extremely large quantities of sulfur are thus obtained as a by-product of these processes and stored leading to its more or less controlled disposal. The production of sulfur will continue to increase, thus assuring its continuous abundant supply and availability.

Therefore, the development of new applications of sulfur becomes of global relevance. It is necessary to consider alternative ways of sulfur valorization in the real process (large scale).

Construction and building materials undoubtedly represent media that should be examined as potential acceptors for large quantities of wastes from various sources. The fact is that a wide range of hazardous waste can be inerted by their incorporating into usable construction and building materials. These materials come into the focus of interest when waste, industrial or municipal, gains increasing importance as a potential raw material. Modification of conventional building and construction materials is commonly realized using some of the secondary raw materials from various industrial processes. Generally, these materials and their products are important recipients of waste as long as they can provide complete immobilization without degradation of their basic properties [14].

Application of the principles of sustainable development in the construction industry is the motive for the adopted research concept in this study. The intention is to evaluate the usage of an industrial by-product, sulfur, as a mineral supplement- filler, in terms of its influence on the properties of SPC in the fresh and hardened state.

An increase in the quantity of secondary sulfur for manufacturing SPC with a positive impact on the environment by reducing the amount of this waste material in landfills presents a desirable effect that should arise from this research.

To the best of the knowledge of the authors, no information is available in the literature on the use of waste sulfur in the production of SPC.

Considering the experience of the authors in the production of sulfur polymer concrete, the idea of this study is to synthesize and characterize SPC with sulfur from oil production as a partial replacement of usual filler, limestone, for application in certain construction parts [15-17]. Keeping in view the structural applications of SPC, this investigation has been planned to evaluate the properties of the samples made with different proportions of sulfur as partial replacement of limestone in comparison with the reference sample. The main goal is the consumption of waste sulfur, whereby it is not important to obtain a material with superior properties compared to the reference one, but to meet standards for its use as a construction material.

2. EXPERIMENTAL

This study compares properties of SPC mixtures with limestone as a filler (reference) and with waste sulfur which partially replaced limestone in various portions.

2.1. Materials

2.1.1. Aggregate

Natural aggregate originated from the river Danube was separated and the following fractions were used for the synthesis of SPC: I (0/4), II (4/8), and III (8/16). Contents of small grains in fractions II and III were 1.84 % and 0.94 %, respectively, while the contents of coarser grains in fractions I, II, and III were 1.96 %, 5.81 %, and 0 %, respectively. Fineness modulus (granularity modulus) for the fraction I was 2.92 (being within the limits of 2.30-3.60, according to [18]). The fineness moduli (granularity moduli) for fractions II and III were 6.04 and 6.99, respectively.

Content of fine particles in fraction I, determined according to the standard procedure [19], was 0.59 % (grains smaller than 0.063 mm) and 1.68 % (grains smaller than 0.09 mm) and content of coarse grains (larger than 4 mm) in fraction I was close to zero. Content of harmful and potentially hazardous materials in coarse and fine aggregate, investigated according to the related standard [20], was 3.8% of cherts (chalcedony) in fraction III.

A mass ratio of fractions II and III was determined on a laboratory test that included the highest value of density for the mixture of these fractions in a dry compacted state. Consequently, the mass ratio of these fractions was adopted to be 1:1. Content of fraction I in the aggregate mixture was determined based on the pilot mixtures and it was 31.8 % of SPC total volume. The particle size distribution of used aggregate is displayed in Figure 1.

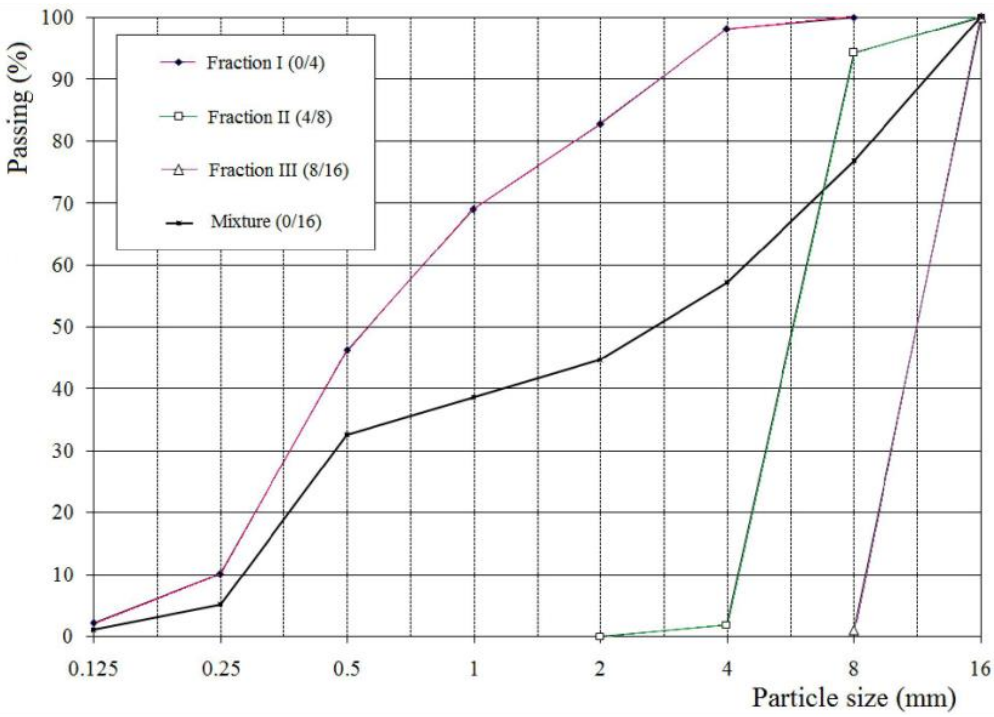

Figure 1. Particle size distribution of aggregate

2.1.2 Cement

Cement without additives (*CEM I 42.5R, Lafarge, Serbia*) was used for the SPC synthesis. The chemical composition of the cement, tested by energy-dispersive X-ray spectroscopy (EDS) analysis, is shown in Table 1. The physical and mechanical properties of the cement are given in Table 2.

Table 1. Chemical composition of cement (%)

CaO	SiO_2	SO_3	Al_2O_3	MgO	Fe_2O_3	K_2O	Na_2O	TiO_2
61.64	21.21	6.37	4.81	2.22	2.13	1.11	0.33	0.18

Table 2. Physical and mechanical properties of cement

Property	Value
Sieve 0.09 mm residue (%)	0.5
Specific area–Blaine (cm^2/g)	4240
True density (kg/m^3)	3040
Loose density (kg/m^3)	890
Compacted density (kg/m^3)	1440
Standard consistency (%)	27.8
Setting time - start (min)	170
Setting time – end (min)	270
Soundness – cookie	Sound
Soundness - Le-Chatelier (mm)	1.0

2.1.3 Limestone

Limestone powder (*Granit Pescar, Ljig*) was used as the filler. This is carbonate filler with a medium grain size of 25 µm and a specific surface area of 3800 cm^2/g. The chemical composition of limestone is given in Table 3.

Table 3. Chemical composition of limestone powder

Component	Content (%)
CaO	54.86
MgO	1.10
Al_2O_3	0.5
P_2O_5	0.5
Fe_2O_3	0.09
K_2O	0.05
MnO	0.005
SO_2	Traces
S	0
Loss on ignition	43.64

2.1.4 Sulfur

Sulfur used as the mineral filler originates from the oil refining process by Claus's procedure in the Oil Refinery Pancevo and its purity was 99.9 %. The density of used sulfur was 2050 kg/m^3 and specific surface area 2600 cm^2/g.

2.1.5 Superplasticizer

Glenium Sky 690 (*BASF Construction Chemicals, Italy*) was used as the superplasticizer. This is a poly-carboxylate-based superplasticizer.

2.2. Mixture design

SPC mixtures were designed based on the preliminary screening experiments that included variations of composition and obtained properties of fresh and hardened concrete. Compositions of five SPC mixtures are given in Table 4- the reference (REF) with limestone as filler, and S2, S5, S10, and S20, with 2%, 5%, 10%, and 20% of sulfur, respectively, as partial replacement of limestone. The content of water and superplasticizer were kept constant for all mixes.

The laboratory mixer with a capacity of 60 l, fixed drum, and paddles at the vertical axel was used for the concrete preparation. To provide flowability and homogeneity of mixes and uniformity of concrete properties, the following mixing procedure was applied: mixing of coarse (II and III fractions) and fine (I fraction) aggregates for 60 s, addition of cement, and mixing for another 30 s, and then the dosage of water and superplasticizer with additional mixing of 270 s. SPC series was made at the ambient temperature of 20-22 °C. The fresh concrete was poured into the molds, demoulded after 24 hours, and cured. For various testing, cubes (10 cm), prisms (12x12x36 cm), and plates (50x50x8 cm) were prepared.

Table 4. Compositions of SPC mixtures

Property	Sample				
	REF	S2	S5	S10	S20
Aggregate fine fraction (0/4 mm) (kg/m^3)	840	840	840	840	840
Aggregate coarse fraction (4/8 mm) (kg/m^3)	430	430	430	430	430
Aggregate coarse fraction (8/16 mm) (kg/m^3)	430	430	430	430	430
Cement (kg/m^3)	380	380	380	380	380
Water (kg/m^3)	183	183	183	183	183
Limestone powder (kg/m^3)	220	215.6	209	198	176
Sulfur (kg/m^3)	0	4.4	11	22	44
Superplasticizer (kg/m^3)	7.6	7.6	7.6	7.6	7.6
Water to cement ratio (w/c)	0.482	0.482	0.482	0.482	0.482
Fluid* to powder ratio (f/p)	0.318	0.318	0.318	0.318	0.318

Fluid-sum of water and superplasticizer; Powder- a sum of cement, limestone, and ground sulfur

2.3. Test procedure

The performed tests were standard procedures for testing fresh and hardened concrete. The testing of fresh concrete included the following: slump-flow (SRPS EN 206-1:2011), V-funnel (SRPS EN 206-1:2011), L-box (SRPS EN 12350-10:2012), and segregation resistance (SRPS EN 12350-11:2012).

The testing of hardened concrete included the following: compressive strength (SRPS EN 12390-3:2010), flexural strength (SRPS EN 12390-5:2010), bond strength (SRPS EN 1542:2010), ultrasonic pulse velocity (SRPS U.M1.042:1998), dynamic Poisson's ratio (SRPS U.M1.026:1993), specific electrical resistance (IEEE 81-2012), and microstructure by SEM.

3. RESULTS AND DISCUSSION

3.1. Fresh concrete properties

3.1.1. Slump-flow

The flowability of SPC with added sulfur, determined by the slump-flow test, was higher than in the referent sample. The slump-flow values were from 76.1 cm for the REF sample to 82.0, 82.0, 78.0, and 77.5 cm for S2, S5, S10, and S20, respectively, thus classifying all the series to the SF3 class based on [7]. The slump-flow increase of the samples with sulfur compared to the reference sample is displayed in Figure 2.

The positive impact of sulfur on the slump-flow value can be attributed to the hydrophobicity and lower density of powder sulfur compared to the limestone. The highest slump-flow values of S2 and S5 suggest an optimal sulfur fraction for partial limestone substitution.

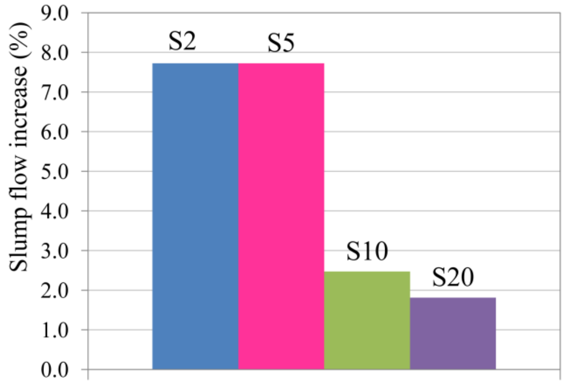

Figure 2. Slump-flow variation of SPC with sulfur compared to the reference sample

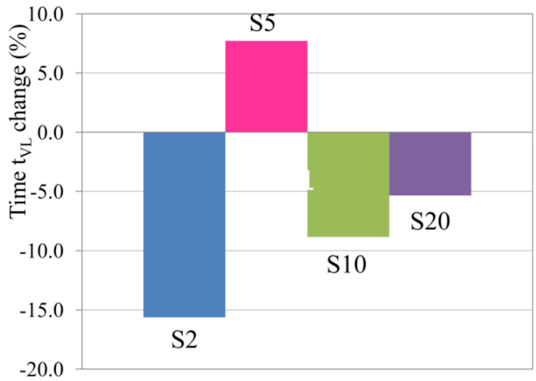

Figure 3. V-funnel time variation of SPC with sulfur compared to the reference sample

3.1.2. V-funnel

The obtained V-funnel time values for the samples REF, S2, S5, and S10 were 9.73, 8.21, 10.48, 8.87, and 9.21 s, respectively, whereby it can be concluded that they mutually differ below 2,5 s, which is in the range of repeatability. The V-funnel time variation of

the samples with sulfur compared to the reference sample is given in Figure 3.
As seen in Figure 3, the increment is positive only for the S5. Anyhow, all samples satisfy the SPC viscosity criteria and belong to the VF2 category according to [7].

3.1.3. L-box
Based on the criteria for determination of passing ability specified in the standard with three smooth steel bars of 12±0.2 mm in the L-box test, all concretes achieved class PL2 (H2/H1> 0.8). The obtained H2/H1 value for the reference sample was 0.97, and for the samples with sulfur S2, S5, and S10, the ratio values were 0.98, 0.98, 0.96, and 0.96, respectively. It can be concluded that there are no significant changes in H2/H1 depending on sulfur content since all results are in the range of ± 0.01, indicating a similar behavior of tested samples.
Figure 4 shows the changes in passing ability expressed by ratio H2/H1 of SPC mixtures with sulfur compared with the reference mixture.

Figure 4. Heights ratio (H2/H1) variation of SPC with sulfur compared to the reference sample

Compared with the H2/H1 value of the reference sample, it is evident that the mixtures with lower sulfur content (S2 and S5) exhibit an increase in passing ability ratio for 1 %, while the mixtures S10 and S20 show a decrease of H2/H1 for 1 %. This indicates a slight workability enhancement of the samples with lower sulfur content and a slight workability reduction of the samples with higher sulfur content.

3.1.4. Segregation resistance
The portion of segregated particles, i.e. segregation ratio values, obtained by the sieve segregation test, for the samples REF, S2, S5, and S10 were 3.5, 4.3, 3.8, 4.2, and 3.6, respectively. Figure 5 presents the segregation resistance variation, expressed as a change in the portion of segregated particles of the samples containing sulfur compared to the reference sample.

Figure 5. Segregation resistance variation of SPC mixtures with sulfur compared to the reference sample

It is obvious that the segregation resistance of the samples with a sulfur decline in relation to the reference sample. There is a certain increase in the segregated portion due to the presence of sulfur, but this value was decreasing with the sulfur content increase.
Regarding fresh concrete properties, higher values of slump-flow diameters of the SPC samples with sulfur in relation to the reference sample indicate a noticeable positive effect of sulfur on flowability. Sulfur addition in SPC did not have a significant influence on the V-funnel time. Since the L-box test results are in the range of ± 0.01, all samples have a similar passing ability. The addition of sulfur resulted in a certain increase in the portion of segregated particles.

3.2. Hardened concrete properties
3.2.1. Compressive strength
Compressive strength measurements were performed on three samples (cubes of 10 cm edge length) for each composition and curing age, and the average values are shown in Figure 6a).

Namely, increasing of added sulfur content would induce declining of compressive strength value per day of aging, while these values are increasing during the aging per each tested series. This behavior is probably because sulfur is more brittle than limestone.

A negative increment in compressive strength given in Figure 6b) shows the percentage of compressive strength loss of SPC with sulfur in relation to the reference SPC sample. Compressive strength decreases with the increase of added sulfur amount compared to the compressive strength of the reference SPC without sulfur, so that after 28 days of aging decrement of compressive strengths ratio increases from 0.3 (S5) to 11.9 % (S20). Also, the drop in compressive strength during the aging was lower for the SPC with lower sulfur content having in mind that this drop was not related to the increase of ground sulfur content linearly. In addition, the drop of compressive strength for the SPC with 10 % and 20 % of ground sulfur was almost similar at all ages. More precisely, differences of compressive strength drop between S10 and S20 are becoming smaller and smaller with increasing aging time.

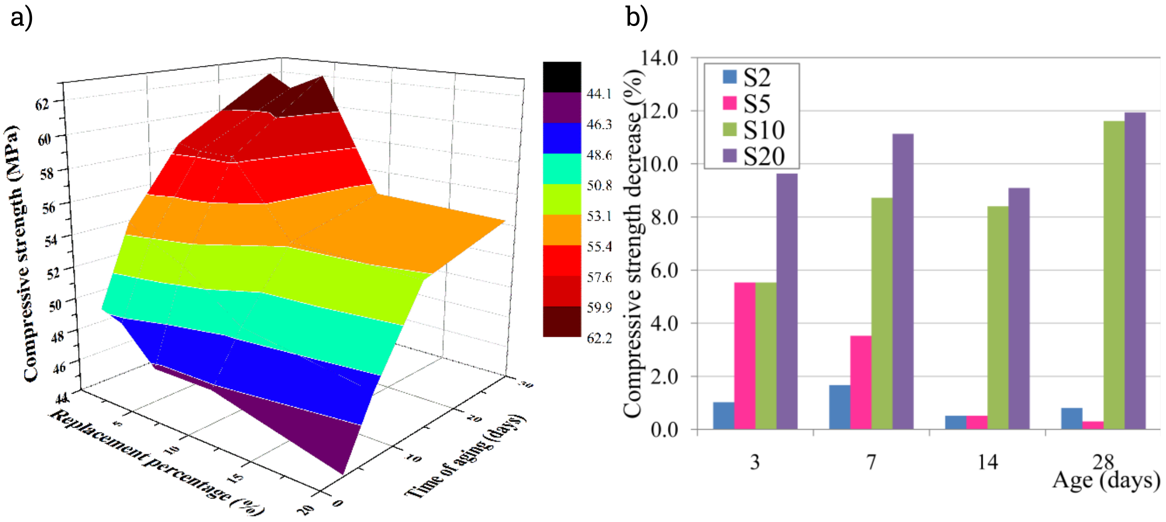

Figure 6. a) Compressive strength values of SPC samples during the aging; b) Compressive strength variation of SPC with sulfur compared to the reference sample during the aging

3.2.2. Flexural and bond strength

Flexural strength measurements, according to the three-point loading test in the middle of the span, at the age of 180 days, were carried out on three 12x12x36 cm samples, while the average values are shown in this study.

The bond strength determined by the pull-off strength test is often used for the evaluation of concrete resistance and verification of the adhesion strength of the concrete repairing structures. The quality of SPC was determined at the age of 180 days, on the 50x50x8 cm plates. Test dollies of two different diameters, Ø20 mm and Ø50 mm, were applied. Five measurements were conducted for each series and both dolly diameters, while the average values are presented in this study. Diagrams presented in Figure 7 show the decrease of flexural and bond strength of SPC with sulfur in relation to the reference SPC.

Flexural strength values were in the range of 6.9 (S20) and 10.5 MPa (REF), while the bond strength values were within 5.53 MPa (REF) and 7.50 MPa (S10) in the case of Ø20 dolly and within 5.77 MPa (REF) and 6.28 MPa (S10) for the Ø50 dolly.

Flexural strength decreases for samples with sulfur in comparison to the reference sample from 18.1 % (S2) to 34.3 % (S20), Figure 7a). This decrease is almost linearly proportional to the increase of limestone replacement by sulfur. Similar to compressive strength, flexural strength decrement of SPC with sulfur compared to the reference SPC can be explained by higher water to cement ratio and lower sulfur hardness.

Figure 7b) shows the change in bond strength of SPC with sulfur compared to the reference sample. Results of the pull-off test show that the decrement of bond strength decreases with the quantity of replacing limestone with sulfur for both dolly diameters. In the case of Ø20 dolly diameter, decrement of bond strength increases compared to the reference sample in the range from 15.0 % (S20) to 35.7 % (S10). For the test of Ø50 dolly diameter, the decrement of bond strength increases slightly from 0.8 % (S20) to 8.8 % (S10). It can be concluded that the use of sulfur has no negative influence on the bond strength regardless of the used dolly diameter. In addition, bond strength decrement is more pronounced for the dolly diameter of Ø20 compared to Ø50.

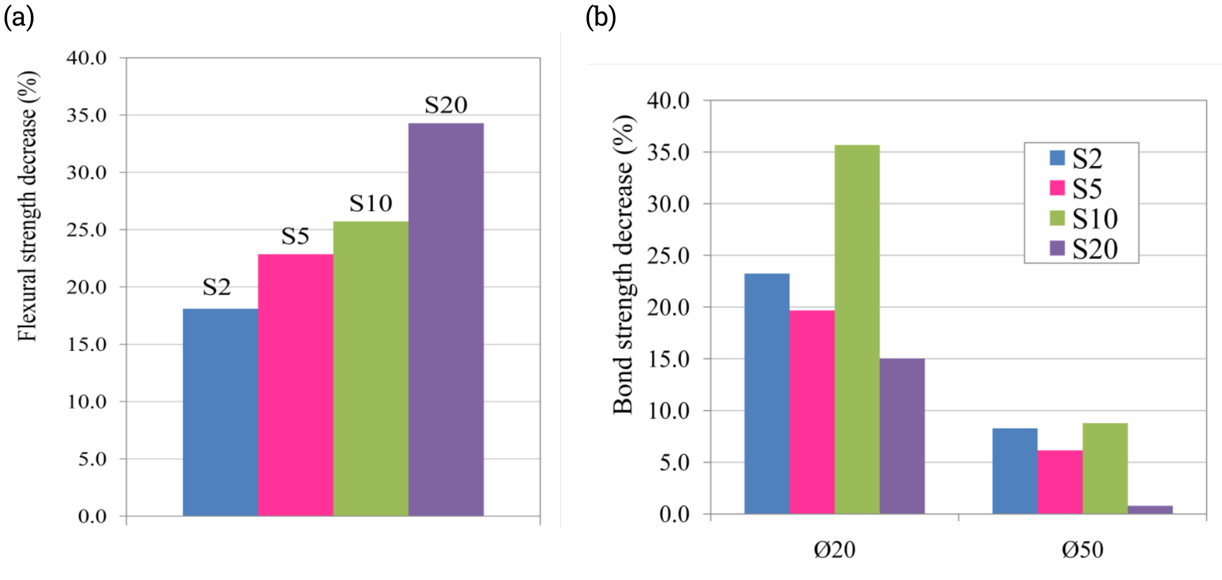

Figure 7. Strength variation of SPC with sulfur compared to the reference sample: a) flexural, b) bond

3.2.3. Ultrasonic pulse velocity testing (UPVT)

Ultrasonic pulse velocity measurements provide important information about the mechanical, anisotropic, and elastic properties of the medium it passes through. Since the theory proves that ultrasonic pulse travels with lower velocity through the material of higher porosity and lower density [21-23], methods of measuring ultrasonic velocity can be used for monitoring the changes in the structure of the material with increasing content of added sulfur.

Measuring both ultrasonic pulse velocities started at the age of 7 days and lasted until the age of 28 days, with one additional measurement at the age of 180 days being done. Results are given in Figure 8.

An overall analysis of the ultrasonic measurements, shown in Figure 8a), indicates that the ultrasonic pulse velocity is decreasing with the increase of sulfur content in the SPC while it is increasing during the aging for each series.

Changes in relations between ultrasonic pulse velocities of SPC with sulfur and reference sample REF are illustrated in Figure 8b). UPV in almost all examined samples decreased with aging. The largest decrease (1.7 %) was at the age of 14 days, for the S10 sample. Also, mutual deviations of UPV per examined series of SPC with sulfur are small and within the relatively narrow range (-0.15 % - 1.7 %) compared to the UPV of the reference sample.

The dynamic Poisson ratio values, calculated for all ages, are given in Table 5.

The values are ranging from 0.239 for the reference sample at the age of 7 days up to 0.257 for sample S20 at the age of 180 days. In other words, the values of the dynamic Poisson coefficient for the SPC with sulfur were very close to the calculated values of the reference sample REF

(a) (b)

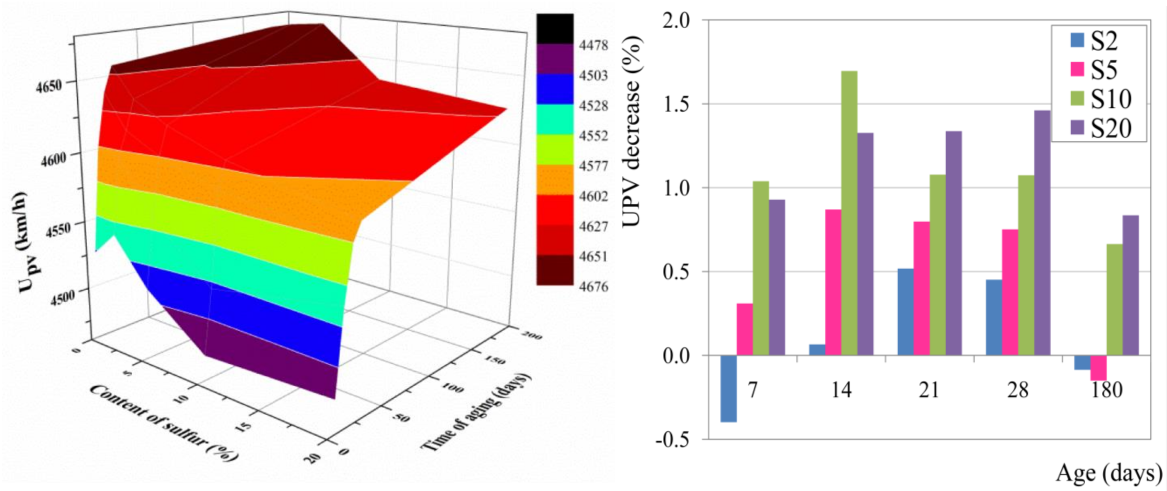

Figure 8. a) UPV values of SPC samples during the aging; b) UPV variation of SPC with sulfur compared to the reference sample

Table 5. Dynamic Poisson ratio values during the aging of SPC samples

	Age (days)	REF	S2	S5	S10	S20
Dynamic Poisson's ratio, μ_d	7	0.239	0.254	0.253	0.250	0.245
	14	0.250	0.252	0.248	0.243	0.250
	21	0.252	0.250	0.253	0.256	0.254
	28	0.248	0.245	0.250	0.254	0.255
	180	0.239	0.244	0.252	0.251	0.257

3.2.4. Specific electrical resistance

Specific electrical resistance was tested to estimate the influence of sulfur on the corrosion probability of self-placing concrete. Namely, since corrosion is an electrochemical process where the electrons flow through the material occurs, the ability of concrete to withstand the motion of ions through it can be described based on electrical resistance.

The obtained values of specific electrical resistance for all self-placing concrete samples are given in Table 6. Compared with the reference sample, the specific electrical resistance of the self-placing concrete samples containing sulfur is higher. The higher specific electrical resistance of SPC samples containing sulfur reduces the possibility and rate of corrosion in this material in relation to the reference one.

Table 6. The specific electrical resistance of SPC samples

Property	Sample				
	REF	S2	S5	S10	S20
Specific electrical resistance (MΩm)	0.216	0.743	0.373	0.532	0.411

3.2.5. Microstructure

The microstructure of the SPC specimens was monitored using a scanning electron microscope (SEM) JEOL JSM-6610LV. The samples were cleaned immediately before the SEM analysis using petroleum ether and then left in an ultrasonic cleaning bath for a few minutes. After drying, thin layers of gold were applied to the samples. Microstructure analysis was performed on the surfaces of the reference and S20 samples. SEM images of the reference and S20 samples are given in Figure 9.

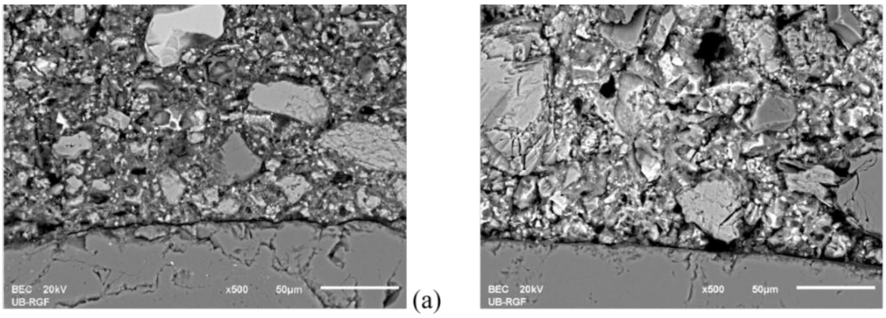
(a) (b)

Figure 9. SEM images of SPC samples: a) REF, b) S20

According to the presented micrographs and application of image analysis, the surface porosity of the S20 sample is slightly higher than of the reference one. However, the reference sample has a larger amount of smaller pores while the S20 sample possesses a lower amount of bigger pores.

To characterize the phase distribution in the matrix, EDS analysis was done at a few spots of the S20 sample surface. The obtained EDS analysis results are given in Table 7.

Table 7. EDS analysis of the matrix of the sample S20

Spot	Content (weight %)									
	O	Mg	Al	Si	S	Cl	K	Ca	Fe	Total
1	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	100.00
2	57.20	0.00	0.69	5.19	8.78	0.75	0.49	26.90	0.00	100.00
3	55.30	0.64	1.55	5.30	3.14	0.17	0.54	32.48	0.88	100.00
4	54.40	1.64	3.05	8.20	3.50	0.00	0.00	27.51	1.70	100.00
5	54.31	0.00	0.00	45.69	0.00	0.00	0.00	0.00	0.00	100.00

The chosen spots for the analysis were: 1- sulfur, 2- contact between sulfur and the surrounding matrix, 3- matrix, 4- contact between aggregate and matrix, and 5- aggregate. It can be seen that the matrix has similar composition regardless of the selected spot on the sample surface and distance from the coarse aggregate. The matrix consists mainly of the hydrated cement phases, CSH phase, and, to a lesser extent, CH phase. The higher concentration of the CH phase was not recorded in the interfacial zone, which proves the good compactness of the material. The content of sulfur in the contact zone between the grains of sulfur and the surrounding matrix is insignificantly higher and with similar constituents compared to the other parts of the matrix thus indicating that this zone practically didn't undergo chemical change. Mapping by elements S, Ca, and Si (qualitative analysis) was performed at several places on the matrix surface, Figure 10.

The main particles of the matrix are uniformly distributed showing the good homogeneity of components inside the matrix. Regarding the dispersion of limestone powder and sulfur grains performed at several places of the matrix surface, a grouping of ground particles was not observed and good distribution of all matrix components is evident. Therefore, the negative impact of ground sulfur application in SPC was not noticed. Based on the obtained mapping results, there was a good distribution of the components, and clustering of the grains was not noticed.

Concerning hardened concrete properties, the compressive strength of the samples with sulfur was lower than that of the reference sample. After 28 days of aging, this drop is noticeable only for the samples with higher sulfur content. Sulfur addition also resulted in flexural and bond strength reduction. Propagation velocity of ultrasonic pulses decreased with increasing the sulfur content in the SPC samples compared with the reference sample for all ages. SEM analysis pointed out similar porosities of all samples. EDS confirmed the existence of cement matrix without changes in chemical composition, while mapping indicated the absence of segregation.

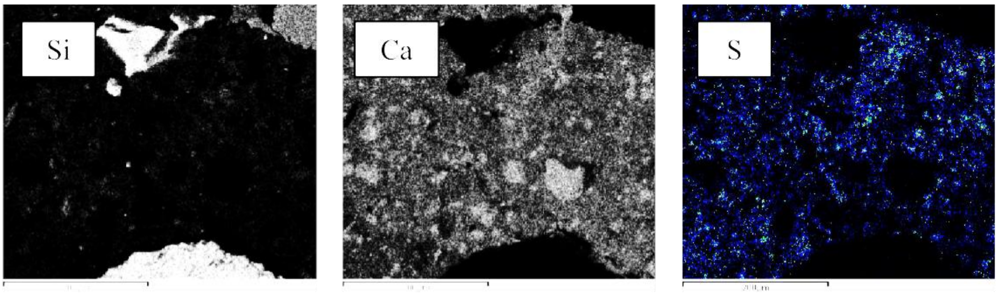

Figure 10. Mapping result of SPC sample S20

4. CONCLUSION

The influence of waste sulfur on properties of self-placing concrete was done by comparing five series with different compositions. The conclusions are as follows:

The compressive strength of SPC with ground sulfur was lower compared with the reference sample, at all ages. Also, a non-linear decrease of compressive strength was noticed with increasing sulfur content. Based on the compressive strength results after 28 days of aging, all series can be used in common structural applications.

There is approximately linear flexural strength decrease with increasing the ground sulfur content. Also, bond strength decline at the age of 180 days was noticed.

The addition of ground sulfur in SPC resulted in an ultrasonic pulse velocity decrease (up to 1.7 %), regardless of both sulfur content and age.

The specific electrical resistance of the self-placing concrete samples containing sulfur is higher compared with the reference sample. Increased specific electrical resistance indicates inhibited chances of corrosion as well as the slowing down the corrosion process of the samples containing sulfur compared with the reference one.

The SEM analysis points out slightly higher porosity of the S20 sample compared with the reference one which is by the compressive strength results (decrease). The mapping reveals a good distribution of the components without clustering the grains.

It can be concluded that the addition of sulfur did not negatively affect the properties of SPC and that all prepared compositions satisfy requirements for structural applications. Accordingly, with respecting principles of sustainable development in the construction industry, the possibility of valorization of waste sulfur as a mineral filer for producing a material having use value was proved.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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