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ANALYSIS OF THE IMPACT OF SLUDGE AND SLAG WASTE ON THE BASIC PROPERTIES OF CEMENT MORTARS

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Abstract: The article examined the influence of two additives, which are post-production waste from metallurgical processes, on the basic properties of cement mortars. Sludge and slag waste were used for testing. Both wastes were examined in terms of their chemical composition using a spectrometer, their specific density and grain composition were determined. As part of the tests, a series of standard mortars were made and the results obtained for modified mortars were compared to them. The produced cement composites used waste in amounts of 5, 10, 15 and 20% of the cement mass, used as a substitute for standard sand. After preparing the standard mortar and mortars containing additives for each series, consistency tests were performed using the flow table method. After an appropriate maturing time, flexural and compression tests were performed for all mortar series after 7 and 28 days of maturing, as well as water absorption tests. The research shows that the addition of these two wastes thickens the fresh cement mortar (from 0.62 to 15 %). The use of such waste also results in a decrease in flexural strength after 7 and 28 days (for sludge from 5 to 21% and for slag from 2 to 11%). However, the compressive strength of mortars decreased by 11% in the case of the addition of 20% of sludge and was almost the same as that of the standard mortar after the addition of 20% of slag.
Keywords: cement mortar, post-production waste, sludge, blast furnace slag

1. INTRODUCTION

The development of industrial activities, characterized by an increase in production and the amount of waste generated, entails the need for effective waste management (Krynke, 2021). Effective management and utilization of generated waste materials becomes important in the context of sustainable development. Waste with a repeatable chemical composition, such as fly ash or slag generated in coal combustion processes, is used in various industries, in particular in the construction sector (Alterary, 2021; Yao et al., 2021). These waste materials are not only effectively used as backfill material for mine reclamation, but also play an important role as ingredients in the production of cement-based composite materials such as cement mortars and concretes (Fan et al., 2015; Huang and Zhao, 2019; Kurda et al., 2017; Yang et al., 2021; Yerramala et al., 2012;). In addition to fly ash and slag from the combustion of conventional fuels, laboratory tests also focus on determining the impact of waste such as biomass ashes (Jura, 2020; Jura, 2023; Jura and Ulewicz, 2021; Popławski, 2020; Popławski and Lelusz, 2023; Ulewicz and Jura, 2017; Ulewicz and Pietrzak, 2023) building ceramics (Gautam et al., 2021; Ray et al., 2021; Mohit and Sharifi, 2016; Nayana and Rakesh, 2021), sanitary ceramics

(Farinha et al., 2015; Pitarch et al., 2021; Ulewicz and Halbiniak, 2016), glass cullet (Adhikary et al., 2021*;* Dębska et al., 2020; Pietrzak, 2018) hemp shives (Šadzevičius et al., 2023), polymeric materials (Bassam et al., 2020; Pietrzak and Ulewicz, 2023; Saikia and de Brito, 2012; Ulewicz and Pietrzak, 2021. Ulewicz and Pietrzak, 2023), bio-silica (Muradyan et al., 2023), concrete and cement waste (Kalinowska-Wichrowska, 2022) as well as ash from the combustion of agricultural and municipal waste and sewage sludge (Kalak et al., 2023; Pietrzak, 2019) on the properties of composites with a cement matrix. The literature also contains reports on the use of waste from the iron, aluminum and copper metallurgy for the production of cement-based composite materials (Ahmad et al., 2022; Bae et al., 2021; Brachaczek et al., 2023; Cardoso et al., 2022; Faraone et al., 2009; Lee et al., 2019; Lehner et al., 2022; Lis and Nowacki, 2022; Mohit, 2014; Nazer et al., 2021; Pizoń et al., 2020; Rashad, 2014; Rashad, 2022; Rooholamini et al., 2019; Santamaría et al., 2020; Santamaría-Vicario et al., 2016; Yee Leng Ng et al., 2022;). Waste from the steel industry has been of interest to scientists for many years, because the majority of it is still deposited in landfills. According to work (Lis and Nowacki, 2022) metallurgical waste meets environmental protection requirements and can be safely used in construction. In Europe, only 40% of steel slag is effectively processed, of which 69.9% is used for road construction (Rashad, 2022). This material, like other waste from the steel industry (blast furnace slag, sludge or ash from electric arc furnaces), is used in laboratory tests as a substitute for cement or aggregate in concrete (Ahmad et al., 2022; Lee et al., 2019; Lehner et al., 2022; Rashad, 2022) and cement mortars (Bae et al., 2021; Brachaczek et al., 2023; Cardoso et al., 2022; Lehner et al., 2022; Rashad, 2014; Santamaría et al., 2020; Santamaría-Vicario et al., 2016). Despite numerous studies, it is not possible to clearly determine their impact on the basic properties of the materials produced, as the review work (Rashad, 2022) shows, because the chemical composition of waste generated by the metallurgical industry is very diverse and these materials were used to a different extent. Due to their characteristics (presence of various metals) and the potential effects of their use on the environment, the processes of management and recycling of waste such as slag and sludge are crucial for the sustainable development of both the metallurgical and construction industries. Determining the economically effective and safe direction of their use is still an important problem to consider. Therefore, in this study, an attempt was made to determine the basic properties of cement mortars, i.e. one of the basic building materials containing post-production waste from the metallurgical industry.

2. METHODOLOGY OF RESEARCH AND MATERIALS

All tests of mortar properties were carried out on laboratory-prepared samples of cement mortars made in accordance with the PN EN 196-1 standard in the form of cuboid beams with dimensions of 40×40×160 mm. The beams were made by pouring 225 g of water into the bowl of a laboratory mixer and adding 450 g of cement. The mixer was then started in automatic mode at low speed. After 30 seconds, 1350 g of standard sand (for standard mortar) was poured into the bowl and mixing was continued at high speed for another 30 seconds. The mixer was stopped for 1 minute and 30 seconds: during the first 15 seconds, the mortar that stuck to the walls and bottom of the bowl was collected and transferred to the center of the bowl, and then the mortar was continued to be mixed for another 60 seconds at high mixing speed.

The detailed methodology for testing the properties of cement mortars has been described in previous works (Jura, 2021; Jura and Ulewicz, 2021). The consistency test of cement mortars was carried out in accordance with PN-EN 1015-3:2000 regarding the determination of the consistency of standard cement mortar using a flow table for mortars prepared in accordance with the procedure of the PN-EN 196 standard. Flexural strength tests (i.e. tensile strength when flexural) were performed on the basis of the PN-EN 1015-11 standard, and compressive strength tests according to the PN-EN 1015-11 standard. In addition, the water absorption of cement mortars was determined according to the PN-B-04500 standard.

Research materials

Cement mortars were made using Portland cement CEM I 42.5R from CEMEX, standard sand (CEN PN-EN 196-1), tap water in accordance with the requirements of the PN-EN 1008:2004 standard "Mixing water for concrete" and two types of post-production metallurgical waste. The first one is waste sludge (SS) and the second one is slag (SL) shown in Figure 1.

(a) (b)

Fig. 1. Waste sludge (a), waste slag (b) before drying

Source: own study

Due to the fact that the sludge waste was moist (humidity about 5%), it was dried to a constant weight before being used for research. X-ray spectrometry tests were performed for the tested waste materials (Spectro XEPOS D) allowing for learning about the chemical composition (Table 1). The research shows that the waste tested showed significant differences in chemical composition. In the case of waste sludge (SS), over 55% is Fe_2O_3, over 13% CaO, and the next largest content in the sample are SiO_2, Al_2O_3, MgO and MnO. The remaining elements and compounds occur in amounts below 1%. In the case of slag waste (SL), almost 40% is CaO, Fe_2O_3 19%, followed by SiO_2, Al_2O_3, MgO and Na_2O. The remaining elements and compounds occur in amounts below 1%.

The waste used in the tests with a grain size ranging from 0.063 to 2 mm was used as a substitute for natural aggregate in the cement mortar mixture in the amount of 5, 10, 15 and 20% of the cement mass. The amount of waste used and aggregate reduction was done in a volumetric manner. Obtaining data on waste made it possible to calculate the content of individual materials in the cement mortar mixture. The composition of the standard mortar to which the obtained results were compared and the compositions of the modified concrete mixtures are presented in Table 1. The control series is described as

CS, while the series with the addition of sludge waste in amounts of 5, 10, 15 and 20% are described as SS, and similarly in the SL series containing the additive of post-production slag waste.

Table 1
Chemical composition of waste

Oxide / Element	SS	SL	Oxide / Element	SS	SL
SiO_2	5.43	9.56	BaO	<0.01	0.02
CaO	13.09	38.54	Cr_2O_3	0.01	0.08
K_2O	0.32	0.04	SrO	0.01	0.02
Al_2O_3	3.89	5.83	ZrO_2	<0.01	0.01
MgO	1.72	2.30	CuO	0.03	0.01
Fe_2O_3	55.66	18.70	Rb_2O	<0.01	0.01
P_2O_5	0.01	0.01	NiO	<0.01	0.10
Na_2O	<0,01	1.07	PbO	0.49	0.01
MnO	0.67	0.97	SO_3	1.68	0.42
TiO_2	0.06	0.09	Cl^-	0.70	0.03
Zn	2.47	0.01	Other	13.71	22.17

Source: own study

Table 2
Compositions of cement mortar mixtures

Series	Cement	Water	Standard sand	Sludge - SS	Slag -SL
CS	450	225	1350.0	-	-
SS-5	450	225	1329.0	22.5	-
SS-10	450	225	1307.9	45.0	-
SS-15	450	225	1287.9	67.5	-
SS-20	450	225	1265.8	90.0	-
SL-5	450	225	1328.9	-	22.5
SL-10	450	225	1307.7	-	45.0
SL-15	450	225	1286.6	-	67.5
SL-20	450	225	1265.5	-	90.0

Source: own study

3. RESULTS

Consistency tests were performed for the fresh cement mortar mixture. The flow of the standard mortar was 15.9 cm, which allowed the mortar to be classified as plastic. As shown in Figure 2, both additives used thickened the mixture and it became thicker with the increasing amount of the additive. Despite the density of the mortar mixtures, all series except SL-20 could be classified as plastic mortars. However, due to the fact that the flow of the SL-20 mortar was less than 14 cm (13.7 cm), this mortar should be classified as dense plastic. Also, Santamaría et al., 2020 observed a reduction in cone slump (by 2.56%) for mortars where fine natural aggregate was replaced by 60% with electric arc furnace (EAF) slag, and Santarmaría-Vicario et al., 2016 showed lower workability (from 21.61% to 72.26%) of mortar mixtures as a result of replacing fine aggregate with EAF in the range from 25% to 100%. On the contrary, Lee et al., 2019 obtained the opposite results showing 14.29% greater fluidity of the mortar after replacing natural silica sand with steel dust.

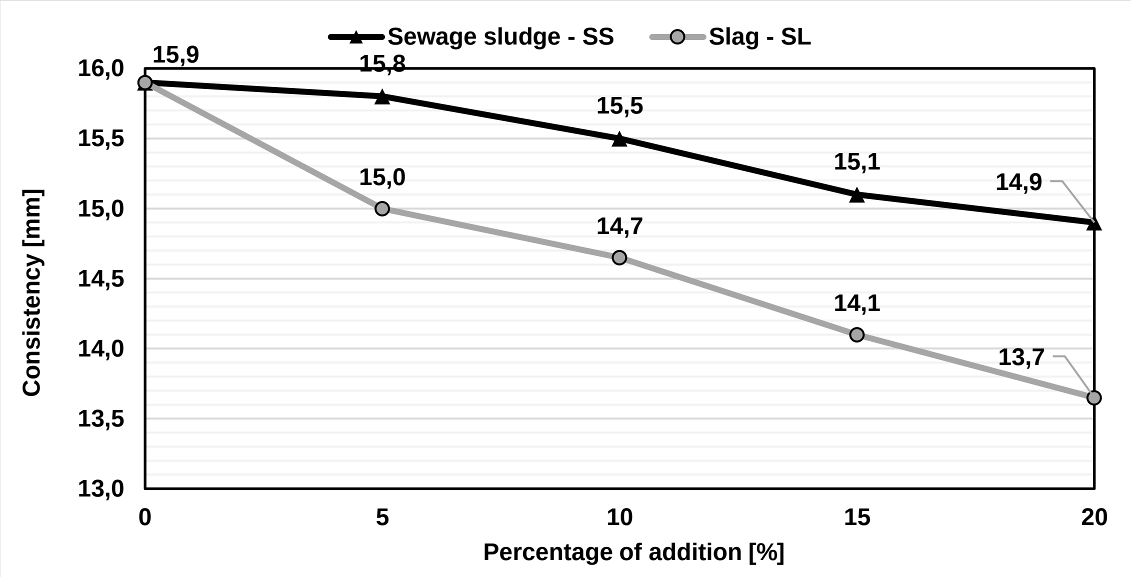

Fig. 2. Consistency of cement mixtures

Source: own study

In the next stage of the research, cuboidal beams made of mortar mixtures were tested for their flexural strength. After 7 days of maturing, the beams of the standard CS mortar achieved a strength of 7.8 MPa (Fig. 3). The addition of sludge waste caused a decrease in the flexural strength of the mortars by 9, 11.1, 12.2 and 13.1% for 5, 10, 15 and 20% of the addition, respectively, so with the increase in the amount of the addition, the mortar gained lower flexural strength. A similar tendency is noticeable in the case of the addition of post-production slag, but in this case the strength drops up to 15% of the addition amounted to a maximum of 5.5% and 10.5 for 20% of the addition.

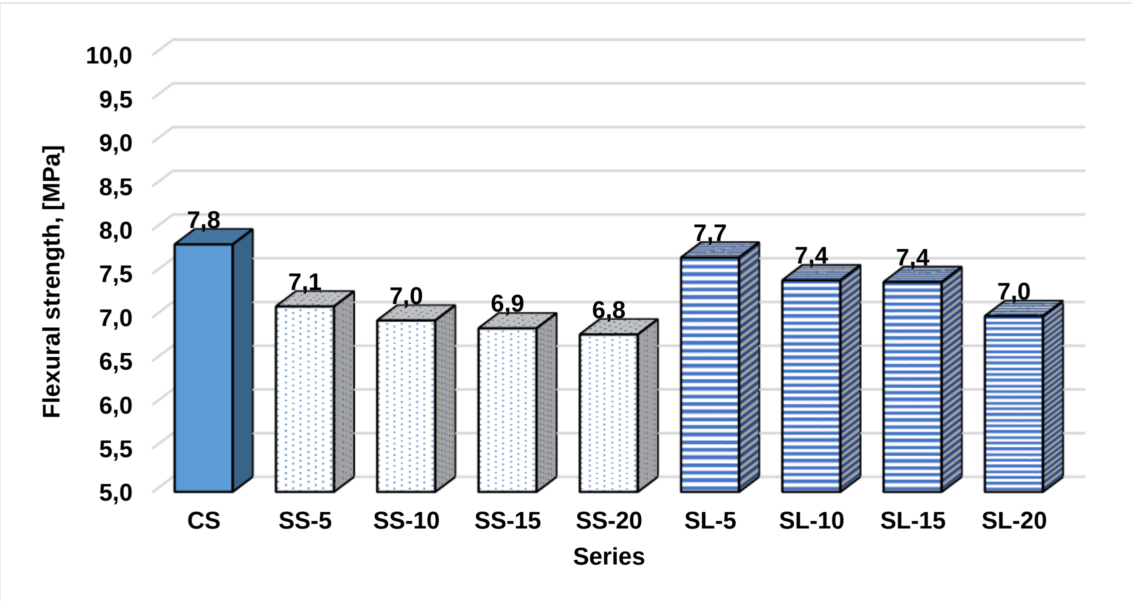

Fig. 3. Flexural strength after 7 days of sample maturation

Source: own study

Analyzing the effect of additives on the flexural strength after 28 days (Fig. 4) of maturation, it can be noticed that one of the additives had a positive effect on the mortar. The addition of sludge, as in the case of tests after 7 days, resulted in a decrease in flexural strength. The control sample achieved a strength of 8.7 MPa, while the sample with 20% of sludge added 6.9 MPa, which results in a decrease of approximately 21%. In contrast to this waste, the slag waste resulted in an increase in flexural strength when smaller amounts were used (up to 10%), a slight decrease for 15% and a greater decrease in strength for the addition of 20%. Mortar modified with 5% post-production slag resulted in an increase in strength by almost 5% (9.1 MPa), while 10% of the addition allowed for an increase in this property by over 2.5%. 15% of the addition resulted in a decrease in strength by less than 1%, while 20% of the slag addition resulted in a decrease of over 11% (7.8 MPa).

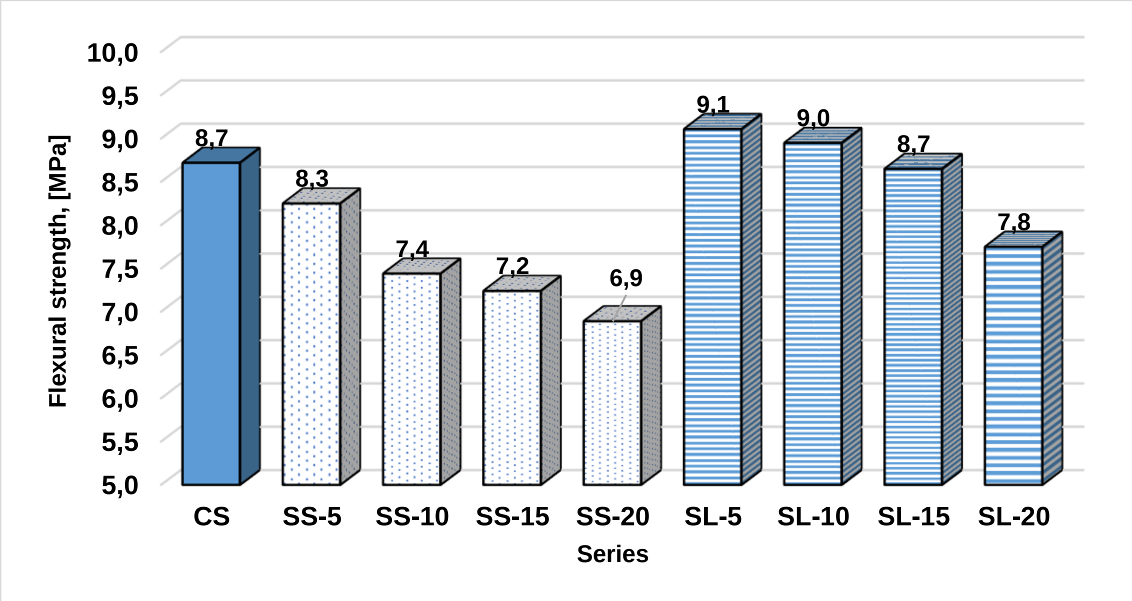

Fig. 4. Flexural strength after 28 days of sample maturation

Source: own study

The study also analyzed the effect of two additives on compressive strength after 7 and 28 days of maturation. The control sample, after 7 days of maturation, achieved an early strength of 37.8 MPa (Fig. 5). All samples with the addition of sludge had lower strength than the standard mortar and for 20% of the addition the decrease was over 8%. The addition of slag had a positive effect on the obtained values. The sample containing 5% slag obtained a value very similar to the control series. A larger amount of the additive resulted in an increase in compressive strength and for 20% of the addition, the strength increased by over 7%.

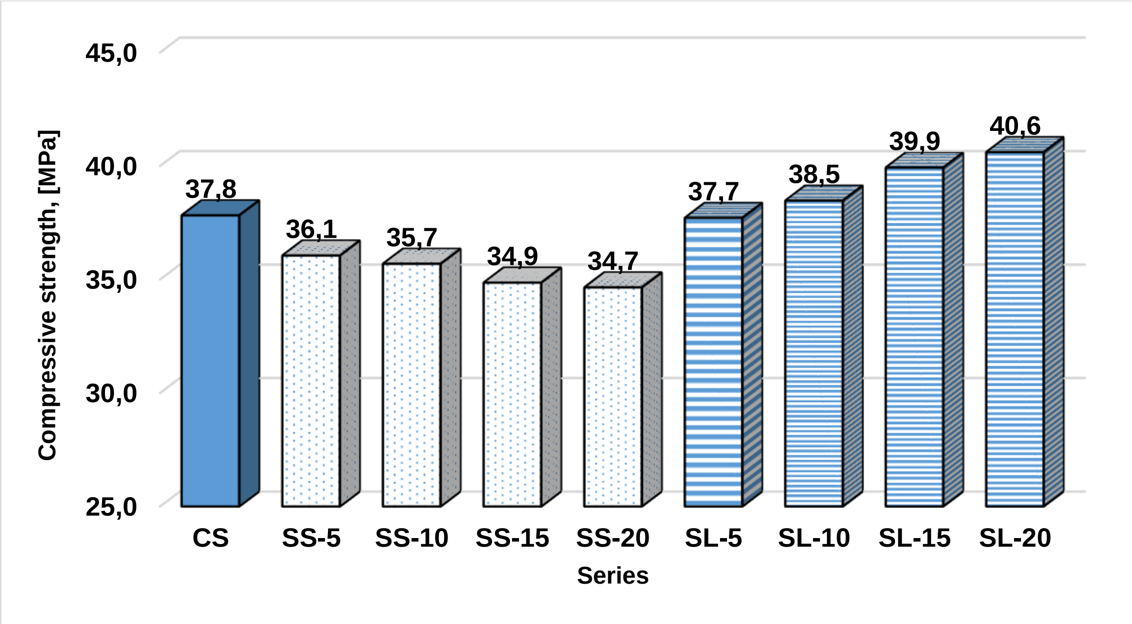

Fig. 5. Compressive strength after 7 days of sample maturation
Source: own study

Compressive strength tests were also carried out after 28 days of sample maturation. Standard mortar samples obtained an average compressive strength of 50.6 MPa (Fig. 6). Similarly to the compressive strength after 7 days, all samples containing the addition of waste sludge obtained lower compressive strength values. As the amount of the additive increased, the compressive strength of the samples also decreased. In the case of slag waste, the use of 5 and 10% of the additive increased the strength up to 3%. The use of 15 and 20% of the additive resulted in a slight reduction in strength compared to the control series samples. Comparing the compressive strength results after 7 and 28 days, it can be seen that the use of a larger amount of slag waste accelerates the increase in early strength (the highest strength of samples with 20% of the addition). However, a longer maturation time allows samples with less additive to obtain higher compressive strength after 28 days of maturation (the highest strength for samples with 5% additive). Sludge waste (SS) caused a decrease in compressive strength at each stage of maturation. The compressive strength parameter, as well as the flexural strength parameter, depend on the type and amount of metallurgical waste used. For concretes, numerous publications have shown both its increase and decrease (Rashad, 2022). Also in the case of cement mortars, a few studies observed its increase (Santamaría, 2020) and decrease (Santamaría-Vicario, 2016). Santamaría et al., 2020 observed an increase in compressive strength by 18.83% and 20% after 7 and 28 days of maturation by partial (60%) replacement of fine natural limestone aggregate with EAF slag and an increase in flexural strength by 16.28% and 5.35% after 7 and 180 days of maturation. However, Santarmaría-Vicario et al., 2016 observed a decrease in compressive strength (in the range of 0.79-6.35%) after 7 days of maturation for mortars when the natural fine aggregate was replaced with EAF slag in the amount of 25, 50 and 75%. Only after 28 days of mortar maturation, an increase in this parameter was recorded in the range of 16.45-17.22%.

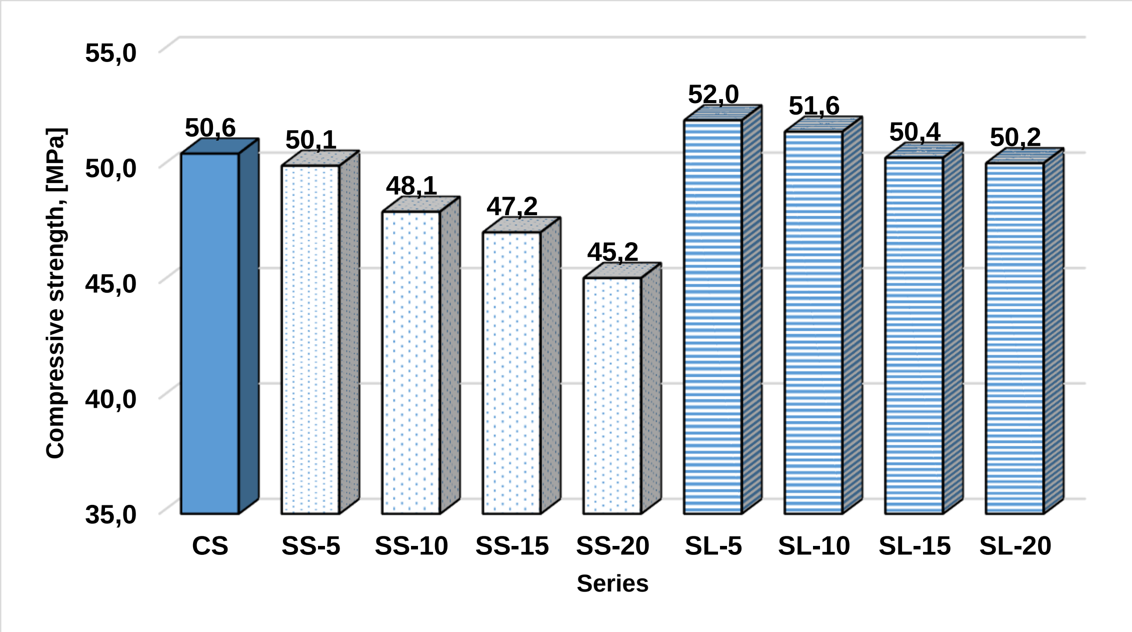

Fig. 6. Compressive strength after 28 days of sample maturation

Source: own study

The prepared mortars were also subjected to water absorption tests (Fig. 7). The standard mortar samples had an absorbability of 8.72%. Post-production sludge waste increased the absorbability of samples by 7.2, 8.9, 14.3 and 16.5% for the addition of 5, 10, 15 and 20%, respectively. Modification of cement mortars with post-production slag waste resulted in the samples reaching absorbability similar to the standard mortar series. Depending on the amount of additive, the samples reached a lower water absorption by 1-4% (for waste content of 5-15%) or higher by less than 1% when using 20% slag.

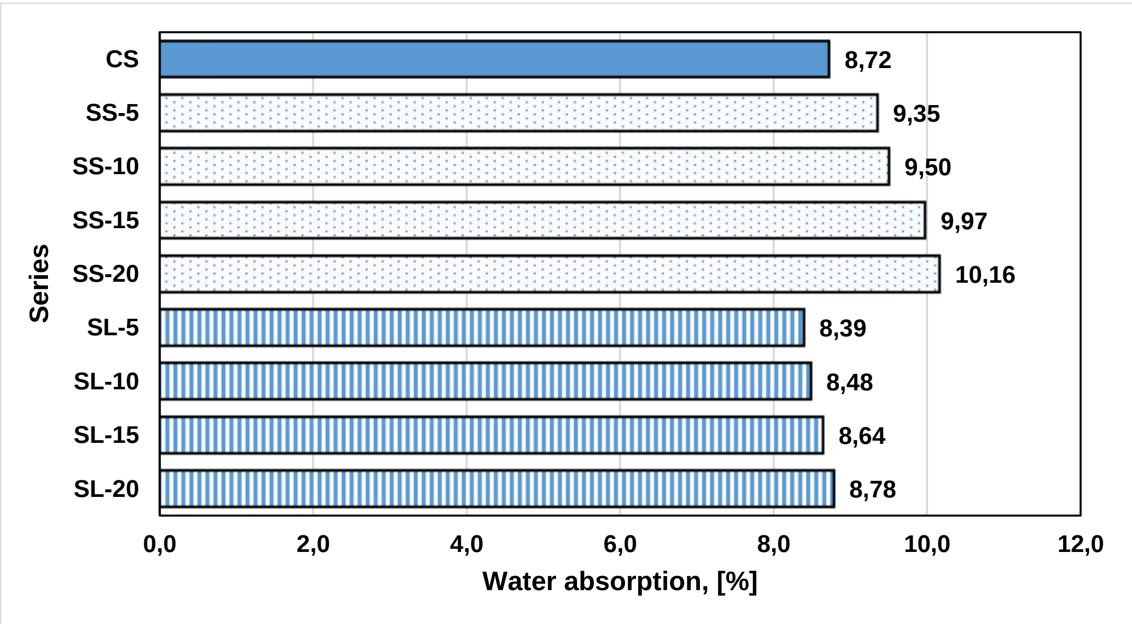

Fig. 7. Absorption of samples

Source: own study

3. CONCLUSION

The research carried out to assess the impact of additives, such as sludge and post-production slag from metallurgical processes, on the properties of the cement mortar mixture provided significant information regarding the consistency, mechanical strength and absorbability of this material. In the context of consistency, it was found that additives influence the mixture thickening process, although most of the tested mortars obtained a plastic consistency, except for one, which was classified as dense plastic. The addition of sludge significantly reduced the flexural properties of mortars (from 5 to 21%), and the effect of the addition of slag varied, depending on the amount of the addition. In the case of compressive strength, the addition of sludge led to an overall decrease in strength (up to 10%), while the addition of slag had a positive effect, especially for lower addition amounts (from a decrease of 3% to an increase of 1%). It is worth noting that the analysis of compressive strength after 7 and 28 days indicated an accelerated increase in early strength in the case of larger amounts of slag added, although a longer maturation time contributed to obtaining higher strength for samples with a smaller amount of slag added. The absorbability of mortars with the addition of sludge is higher and that of slag is slightly higher compared to the control mortar.

When comparing the influence of the addition of sludge and slag on the individual properties of the cement mortar mixture, significant differences can be noticed. The addition of sludge generally leads to a decrease in mechanical properties and an increase in water absorption, while the addition of slag shows more variable effects depending on the amount of addition and the property being tested. The impact of this additive can be considered neutral on the basic properties of cement mortars and using it in mortars could be one of the ways to utilize this waste. Slag recycling can help reduce waste and is safe for the environment.

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