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Article

Complex additive for improving the strength properties of heavy concrete based on industrial waste

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Abstract. The article presents the results of using a complex modified additive to improve concrete's physical and mechanical properties. The complex additive includes industrial production wastes: metallurgical slag and alcohol production wastes (post-alcohol bard). To stabilize the hydrogen index the alkali KOH is included in the composition of the additive. A set of laboratory studies was carried out to measure the strength, absorption, and frost resistance of test specimens to assess the effect of the additive on the properties of concrete. A comparison of physical and mechanical properties was made for samples of different concentrations of slag. The ratio of slag components to cement was from 5 to 25% by the total mass of the binder, a multiple of 5%. The optimal composition of the mixture, with maximum strength values, corresponds to the percentage of slag 15%, post-alcohol bard 22.5 liters, and alkali 150 grams. In general, the results obtained from data points of the compared parameters showed consistent results with minimal variation in the data. The results obtained are of practical value related to the reduction of the cost of production of structural concrete with an increase in its strength indicators.
Keywords: concrete, production waste, slag, post-alcohol bard, strength, frost resistance, water absorption.

1. Introduction

Modern construction requires the development of materials that are strong, durable, and cost-effective. The use of additives in concrete mixtures made from industrial wastes such as metallurgical slag and chemical by-products is a successful trend to improve the performance of concrete. Studies show that such additives can significantly increase the strength properties of concrete, as well as improve its frost resistance and reduce water absorption. For example, metallurgical slag not only increases strength but also helps to improve the durability of concrete, as well as solving environmental problems related to waste disposal. Nevertheless, the effectiveness of different types of industrial additives in concrete mixtures continues to raise questions. Different admixtures may have different effects on the physical and mechanical properties of concrete, including strength, frost resistance, and water absorption. The aim of further research should be to develop a comprehensive admixture that best combines the benefits of different industrial wastes and allows for improved concrete performance, which will contribute to more sustainable construction.

The incorporation of additives to enhance the physical and mechanical properties of concrete is a prevalent practice in contemporary urban development [1]. Currently, there is significant market demand for specialized concrete additives utilized in both large-scale industrial production of concrete mixtures and individual construction projects [2]. A wide array of additives exists, ranging from those with complex effects to those that specifically target certain concrete properties [3].

Additives are used as follows depending on the construction conditions:

Antifreeze additives are used when the hydration temperature of concrete is between 5 and 250 °C to prevent the natural crystallization of water at sub-zero temperatures and to maintain the necessary hydration conditions [4], [5].

Additives to improve water permeability are used in hydraulic engineering and other types of construction to produce high-density concrete with a minimum number of micro and macro pores. [6]. Additives to improve water absorption are based on hydrophobizing concrete by reducing its wettability [7].

Additives to improve strength properties may include the addition of durable inert aggregates, fibrous materials, chemicals, plasticizers, and superplasticizers which together improve the properties of concrete [8].

The purpose of the research work was to develop a complex modifying additive based on the waste products of industrial production to improve the physical and mechanical properties of concrete. The additive based on metallurgical plant slags, and alcohol production wastes (post-alcoholic bard) with the addition of alkali is aimed at improving the strength properties, frost resistance, and water absorption capacity of concrete.

2. Methods

Tests were performed on samples with varying concentrations of slag (Table 1). Sample 1 represents the reference concrete composition, with no additives included. When selecting the composition, a superposition by mass was maintained: the cement content decreases directly proportional to the increase in slag, and water directly proportional to the content of after-alcohol bard with alkali (the density of after-alcohol bard is close to 1 g/ml).

Table 1 – Composition of the samples compared

Specimen type	Cement, kg	Slag, kg	Post-alcohol bard, l	KOH, g	Water, l
Type 1 (0%)	300	0	0	0	90.00
Type 2 (5%)	285	15	7.425	75	82.50
Type 3 (10%)	270	30	14.900	100	75.00
Type 4 (15%)	255	45	22.350	150	67.50
Type 5 (20%)	240	60	29.800	200	60.00
Type 6 (25%)	225	75	37.250	250	52.50

The mineralogical composition of blast furnace slag was obtained by X-ray diffractometric and X-ray phase analysis, presented in Table 2. The analysis was carried out on an automated diffractometer DRON-3 with CuKa-radiation, β-filter.

Table 2 – Mineralogical composition of slag

Akermanite	Fluorophosphate	Hematite	Spessartin	Jococuit	Quartz	Hollandite
$Ca_2Mg(Si_2O_7)$	$Ca_{9.3}Mn_{0.7}F_2(PO_4)_6$	Fe_2O_3	$Mn_3Al_2(SiO_4)_3$	$Mn(SO_4)(H_2O)_5$	SiO_2	$Mn_{6.95}Fe_{0.64}Al_{0.26}Si_{0.02}Ba_{0.47}K_{0.33}Pb_{0.11}Na_{0.11}O_{16}H_{1.41}$
36.0%	22.6%	11.7%	9.6%	8.4%	6.3%	5.4%

Laboratory tests to assess the physical and mechanical characteristics of the compared sample types include:

- Determination of cubic strength by destructive method in compression;
- Determination of water absorption capacity;
- Assessment of frost resistance by loss of strength and mass of samples after cyclic freezing.

Determination of cube strength was performed on automated press Pilot, controls. A total of 30 samples were made, 5 samples of each type. The use of five samples was accepted from the condition of the minimum number of samples in the case of mutually exclusive erroneous measurements (exceeding the coefficient of variation - 15%). Measurements of the samples were carried out after reaching the design age of 28 days.

Water absorption was determined by the standard method of specimen soaking followed by their weighing, after full water saturation and full drying. The criterion of complete water saturation was taken as the mass change of not more than 0.1% during the last hour of observation. Water absorption measurements were made for 30 samples, 5 samples of each type.

Assessment of frost resistance was performed on automated heat and cold equipment. Before the test, the samples were kept in water until completely soaked for 96 hours. The maximum number of freezing and thawing cycles was 350. Control measurements of the strength and mass of the samples were made in the following sequence of cycles: 100, 150, 200, 250, 300, 350. Each control measurement was matched with at least 3 specimens (for mutual exclusion in case of large deviation). Since the test method itself has a high variation, a total of 24 samples of each type were made, a network with a margin of 25% for random error. In any case, the remainder of the samples (in the case of the minimum number of errors) will give the best statistical values of the private values of the last cycle.

All tests were performed for 10x10x10 cm cube-shaped specimens.

3. Results and Discussion

Figure 1 shows the compared sample types of the results of cubic strength tests. According to the comparison results, the maximum strength value corresponds to samples of 15% slag concentration. Samples with a slag percentage of 25% showed very low strength values, 15% lower than the samples of traditional composition, without the inclusion of additives. The latter indicates that the use of slag over 20%, in order to improve the strength of concrete, is not recommended. In terms of saving the cost of concrete production, it is possible to use 25% concentration of slag, taking into account the reduction of strength characteristics.

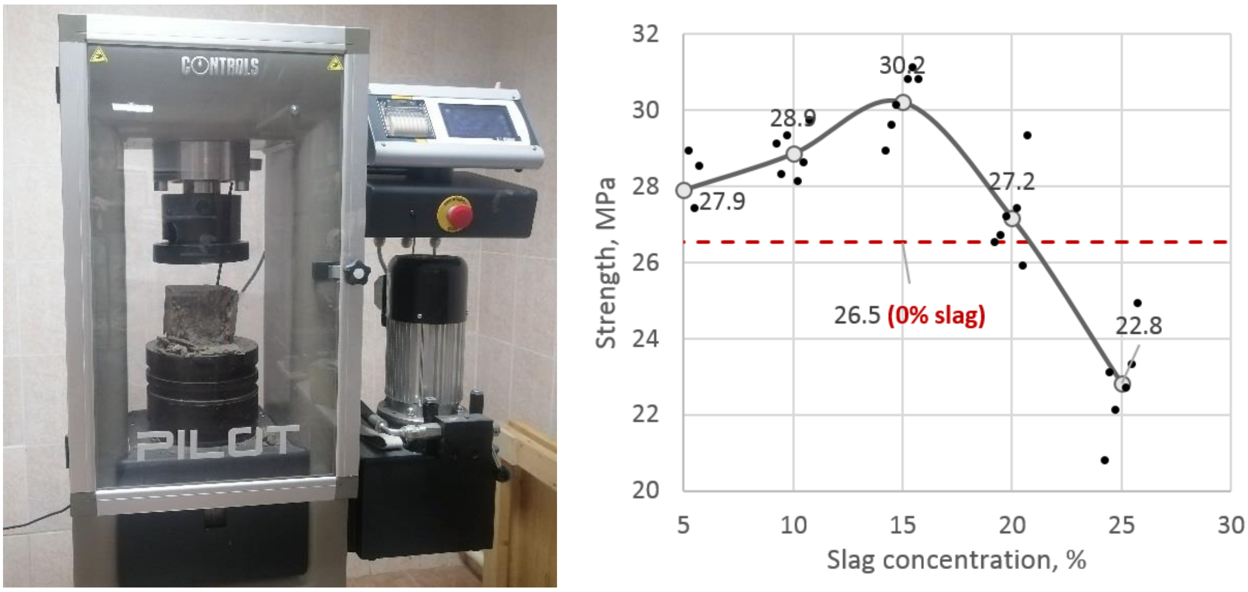

Figure 1 – Results of cube strength tests of specimens

The statistical data indicates that all measurements exhibit a high degree of consistency and strong correlation. Specifically:

For type 1, the standard deviation is no greater than 0.74, with an average value of 26.5 MPa and a coefficient of variation of 2.79%.

Type 2 has a standard deviation not exceeding 0.71, an average value of 27.9 MPa, and a coefficient of variation of 2.53%.

In type 3, the standard deviation reaches up to 0.62, the average value is 28.8 MPa, and the coefficient of variation is 2.14%.

Type 4 shows a standard deviation of no more than 0.84, an average value of 30.2 MPa, and a coefficient of variation of 2.80%.

For type 5, the standard deviation does not surpass 1.17, with an average value of 27.16 MPa and a coefficient of variation of 4.31%.

Lastly, type 6 exhibits a standard deviation of up to 1.36, an average value of 22.8 MPa, and a coefficient of variation of 5.96%. It will be noted that samples with a higher slag concentration have a greater scatter of individual values (higher coefficient of variation), which indicates the instability of strength indicators at high concentrations of slag. The correlation coefficient for the increase of strength characteristics as the percentage of additive increases has a direct proportional regularity in the range from 0 to 15% and is 0.997. The same coefficient in the range from 0 to 25% decreases to -0.408, indicating a violation of the pattern and the optimality of 15% concentration.

The results of water absorption tests are shown in Figure 2. According to the results, the minimum value of water absorption is observed in samples with maximum slag content, and the minimum in samples without additives. The obvious pattern can be explained by the presence of post-alcohol bard in the concrete composition, and the higher the concentration, the greater the hydrophobization of the material.

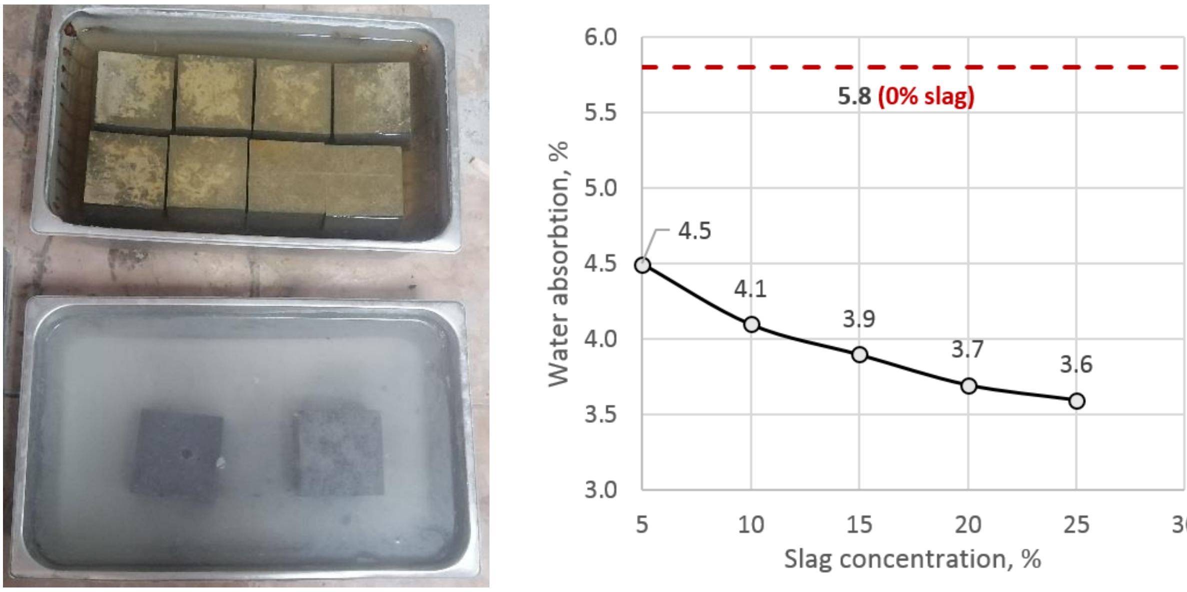

Figure 2 – Test results of cubic strength of specimens

According to statistical analysis, all particular values have a high degree of convergence, as evidenced by statistical indicators: coefficients of variation of all particular values lie in the range from 4.42 to 9.5%, for the average values shown in Figure 2 the standard deviations lie in the range from 0.108 to 0.336. The percentage decrease in water absorption with 5% of slag and 8.3% of post-alcohol bard with alkali is 22.4%; with 10% of slag and 16.7% of bard with alkali, the decrease in water absorption is - 29.3%; with 15% of slag and 25.0% of bard with alkali - 32.7%; with 20% of slag and 33.3% of bard with alkali - 36.2%; with 25% of slag and 41.7% of bard with alkali - 37.9%. Frost-resistance test results are shown in Figure 3 and Table 3. Figure 3 shows the dependences of the decrease in strength characteristics according to the increase in the cycles of freezing and thawing of the samples. Table 3 shows partial values of percentage strength reduction by control tests. According to the test results, the maximum resistance to cyclic icing is in type 4 specimens, with the percentage of slag - 15% and post-alcoholic bard with alkali - 25%.

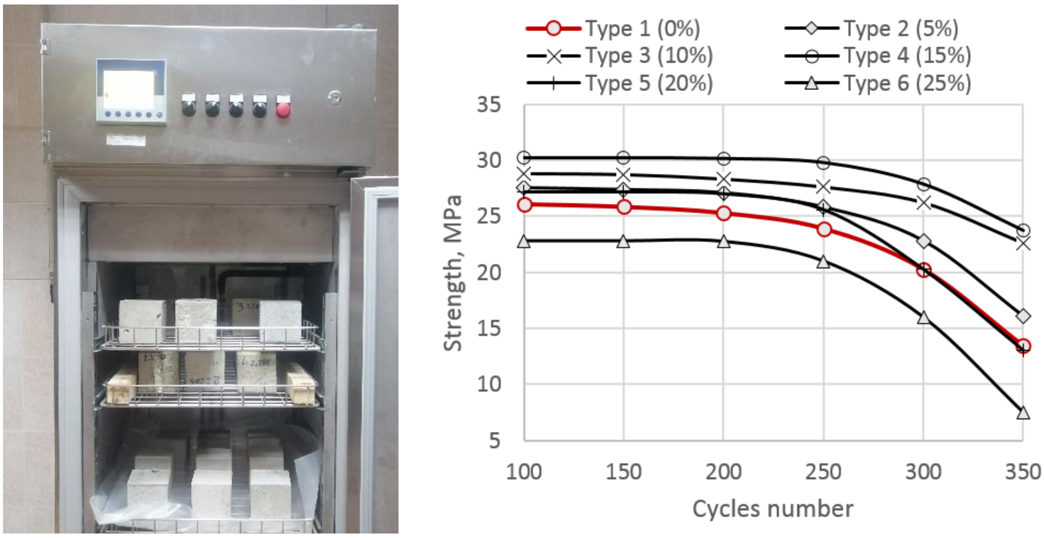

Figure 3 – Results of frost resistance of specimens

Table 3 – Results of the strength of control measurements

Type	Number of cycles					
	100	150	200	250	300	350
Type 1 (0%)	1.5	2.4	4.5	9.7	23.4	49.2
Type 2 (5%)	1.2	1.8	2.8	7.4	18.2	42.4
Type 3 (10%)	0	0.3	1.7	4.2	9.1	21.8
Type 4 (15%)	0	0	0.2	1.4	7.7	21.3
Type 5 (20%)	0	0	0.6	5.8	25.4	52.1
Type 6 (25%)	0	0	0.2	7.9	29.9	67.3

The statistical indices of the partial values of strength characteristics showed a medium to a high degree of convergence: the standard deviations are from 0.48 to 2.01 (at the average values presented in Table 3), which correspond to the coefficients of variation lying in the range from 1.87 to 13.32%. It should be noted that a greater scatter of particular strength values is observed for samples with a higher concentration of slag component (type 5 and 6), and the lowest for samples with a lower concentration (type 1 and 2). The latter characterizes the instability of samples with high slag content. The maximum reduction of strength characteristics was observed in specimens of types 1, 5, and 6, at 350 cycles a twofold reduction of strength was recorded. The obvious decrease in strength of specimens of type 1 is explained by the lower hydrophobicity of concrete in relation to specimens of another type. The decrease in type 5 and 6 specimens indicates the negative effect of less active slag in its excess in relation to cement content. Type 3 and 4 specimens showed relatively similar resistance to cyclic freezing. From the point of view of economic efficiency, the best option would be type 4 specimens with 15% slag component

4. Conclusions

– The research was carried out for concrete samples with different concentrations of slag components from 5 to 25%. Used as a substitute binder, slag from metallurgical production includes in its composition active elements, which in the process of electrolytic dissociation and hydrolysis take part in the process of concrete hydration.

– The optimal composition according to the results of laboratory research, which corresponds to the best values of comparable physical and mechanical parameters of concrete: slag content of 15%, content of post-alcohol bard, and alkali of 25%. The resulting composition can improve the design strength properties of concrete by 12-14%, reduce the water absorption of the material to 32%, as well as increase the frost resistance of concrete from grade F250 to grade F300.

– In the case of reducing the cost of concrete, it is possible to use a 20% concentration of slag with 32.7% of bard and alkali. In this case, the economic effect of the use of the additive will be achieved without compromising the design indicators of strength, water absorption, and frost resistance.

– Compared to other complex admixtures, metallurgical slag shows similar results in concrete strength and water resistance, while contributing to lower production costs. The use of metallurgical slag can achieve strength properties comparable to concrete containing traditional modifiers, making it a more cost-effective choice. This confirms its effectiveness in improving concrete properties without significantly increasing costs.

– In general, slag reduces water absorption but improves the frost resistance of concrete compared to mineral admixtures. Comparative studies show that concrete with slag addition exhibits stable strength properties under repeated freeze-thaw cycling, thus extending the service life of the material.

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