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Article

Utilizing granulated blast furnace slag as an alternative cement binder

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Abstract. This study addresses the challenges associated with the accumulation of technogenic waste in the production of ferrous and non-ferrous metals. We present the findings of global research on the utilization of blast furnace slag as a sustainable alternative to traditional cement binders. Our scientific investigation focuses on the laboratory exploration of replacing cement binders with a highly efficient clinkerless alternative based on blast furnace slag. The fundamentals of formulating clinkerless binders from slag were thoroughly examined for binder design. Through an extensive review, we conducted tests to identify an optimal composition, constrained within the ranges of 70-90% blast-furnace granulated slag, 14% lime, 1.5-2% gypsum, 1.5-2% C-3, and 2-25% microsilica. The outcome of these tests resulted in the development of a novel binder that combines the characteristics and properties of a lime-slag binder with the advantages of a low water consumption binder. This clinker-free binder presents a sustainable solution for construction, serving as a viable substitute for traditional cement. Our findings contribute to the ongoing efforts in adopting environmentally friendly practices in the construction industry.
Keywords: clinkerless binder, concrete, slag, waste, microsilica, superplasticizer, gypsum.

1. Introduction

Kazakhstan is one of the world leaders in the production of mining industry, strongly developed ferrous, non-ferrous metallurgy, oil and gas extraction industry. The total volume of production of solid minerals has brought the Republic of Kazakhstan to the 13th place in the world among 70 mining countries [1]. In the technological process of production of steel, pig iron, rolled steel and other non-ferrous metals, a large amount of solid waste is generated, which is a source of environmental pollution [2]. Over the last twenty years, the world production of pig iron, steel has increased almost 2-fold, which has led to an increase in the amount of slag recycled [3].

The construction industry directly depends on the quality and cost of building materials. Resource saving is an urgent problem facing research teams in the field of production of building materials, products and structures. To save and reduce the cost of building materials, to protect and protect the environment, the use of recycled slag as a binder or partial replacement of cement binder with technogenic waste is an urgent issue at present [3–10]. Iron and steel slags can be reused in bituminous mixtures, concrete and cement production, metallurgy, hydraulic engineering, internal recycling in iron and steel production processes, and for fertilizer and soil stabilization due to their unique characteristics [3].

The article [4] presents the results of research on the replacement of cement binder in the concrete mixture with finely dispersed blast-furnace granulated ground slag. The authors of [5] considered the possibility of using slag concrete in underground construction. To increase the use of slag in the mining industry, [6] presented a new slag binder (SB) consisting of 91% slag powder and 9% activator (3% clinker, 5% desulfurized gypsum and 1% mirabilite. The paper [11] considers the results of experimental studies on the production of high-performance clinkerless binders in order to ensure the possibility of obtaining high-strength composites on their basis. The authors of [3] presented a review of the production of iron and steel slags and their reuse in concrete as a replacement for cement, fine or coarse aggregates. Due to their physical and chemical properties, blast-furnace slags are widely used for partial replacement of cement in concrete production and allow significant cement savings from 20 to 70% [3].

Regarding the treatability of concrete with blast furnace slag as a partial replacement of cement, an improvement has been observed [9-10-12-13]. The use of ground granulated blast furnace slag (GGBFS) as SCM (supplementary cement materials) or partial replacement of binder components in concrete offers advantages both in terms of economy and performance improvement. It has been found that GGBFS can replace cement up to 50 %, with compressive strength comparable to conventional concrete [12]. In [13], cement was replaced by 30 % and 40 % with fly ash, GGBS and metakaolin for M30 and M35 grade concrete. According to [14] it is found that blast furnace slag is very suitable as a cement substitute, providing properties superior to those of the reference concrete.

The research is aimed at studying the properties of granulated blast furnace slag of JSC «ArcelorMittal» (Temirtau) in order to establish the possibility of its use for the production of economically beneficial binders.

The purpose of the work is the development of binders from waste metallurgical production of Karaganda region (granulated blast furnace slag of JSC «ArcelorMittal») and obtaining on their basis the optimal compositions of concrete.

To achieve the objectives of the study the following tasks were set:

- Analytical review of the state and theoretical basis for the use of secondary industrial raw materials;
- Analytical review of receipt, characteristics, properties and ways of application of granulated blast furnace slag of JSC «ArcelorMittal» (Temirtau, Kazakhstan);
- Consideration of the requirements for the developed binder using granulated blast furnace slag;
- Study of properties and characteristics of initial materials, selection of research methods and experimental study of properties of the developed binder;
- Conducting research on selection of raw material mixture composition;
- Analytical review and experimental study of the process of hardening and strength gain of the developed binder.

The subject of the study is the production of binder using industrial wastes of Karaganda region. The object of the study is a binding agent obtained by joint grinding of granulated blast furnace slag, lime, gypsum, microsilica and addition of superplasticizer C-3.

Microsilica (MC), generated during ferrosilicon and alloy smelting, is a finely condensed product with spherical particles rich in amorphous silica. It finds extensive application in cement, dry building mixtures, concrete, and foam concrete production [15].

2. Methods

The research work was carried out to study the binder obtained by joint grinding of lime, gypsum, blast furnace slag of JSC «ArcelorMittal» (Temirtau, Kazakhstan), microsilica and superplasticizer C-3.

Table 1 shows the requirements for the chemical composition of the used powdered hydraulic lime that meets the requirements of [16] (Table 1). Gypsum used in the preparation of the raw material mixture meets the requirements of [17].

Table 1 – Chemical composition of hydraulic lime [16]

Chemical composition	Norm for lime, %, by weight	
	Semi-hydraulic	Electro-hydraulic
Active CaO + MgO:		
- not more	65	40
- at least	40	5
Active MgO: not more than	6	6
CO_2: not more than	6	5

According to [16] strength of samples, MPa (kgf/cm^2), after 28 days of hardening in bending not less than 0.4 (4.0) for weak hydraulic lime; 1.0 (10) for strong hydraulic lime; in compression not less than 1.7 (17) for weak hydraulic lime; 5.0 (50) for strong hydraulic lime. The degree of dispersibility of powdered hydraulic lime when sieving a sample of lime through a sieve with mesh №02 and №008 was at least 98.5 and 85% of the mass of the sieved sample, respectively [16].

The blast-furnace granulated slag used in the manufacture of the binder meets the requirements of [18]. According to the results of studies of chemical composition of blast furnace granulated slag (Table 2) from the plant «ArcelorMittal» (Temirtau, Kazakhstan) the following indicators (%) were determined [19]: the basicity modulus of the studied granulated slag is equal to 0.75, therefore, this slag is considered acidic. Quality coefficient of blast furnace granulated slag K is equal to 1.56, in accordance with the classification by grades, this slag belongs to the second grade.

Table 2 – Chemical composition of granulated slag [19]

Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	MgO	K_2O	CaO	SO_3	Na_2O	P_2O_5	Impurities
I	33.86	15.90	1.97	0.67	0.02	7.16	0.93	29.94	0.25	0.95	0.06	7.56

Superplasticizer C-3 met the requirements of [20] and [21].

Table 3 shows the chemical composition of microsilica.

Table 3 – Chemical composition of microsilica [22]

Name	Grade	Batch no.	Mass fraction, %								
			SiO_2	Stv	moisture	Fe_2O_3	Al_2O_3	CaO	pH	*p*, *g*/cm^3	Impurities
Condensed microsilica	MKU-95	27	96.85	1.31	1.07	0.07	0.24	0.46	7.89	0.44	1.68

Water and sand used in the laboratory experiments met the requirements of [23] and [24].

The fineness of grinding was determined in accordance with [25]. Sieving was carried out using a sieve with sieve №008 according to [26]. Control sieving was performed manually with the bottom removed on paper for 1 minute. The fineness of cement grinding was determined as the residue on the sieve with mesh No. 008 as a percentage of the initial mass of the sieved sample with an accuracy of 0.1%. Normal density, setting time and uniformity of volume change were determined in accordance with [27]. All these properties of the binder were determined on the verified instruments and equipment of the accredited laboratory of «KaragandaTechnoService» LLP (Karaganda, Kazakhstan). The cone blur and tensile and compressive strength were determined in accordance with [28].

Strength properties were determined on specimen beams of size 40×40×160 mm at the age of 28 days of curing in water. The bending and compressive strength at steaming was determined on beam specimens after curing in a steaming chamber at the age of 24 hours from the moment of manufacture. The steaming chamber of the construction laboratory of the Faculty of Architecture and Civil Engineering of Abylkas Saginov Karaganda Technical University was used for testing.

3. Results and Discussion

During the period of research work, laboratory tests were conducted to study the properties of the prepared binders (Table 4).

Table 4 – Mass fraction of components in the composition of binders prepared, %

No.	C-3 additive	Hydraulic lime	Bi-hydro gypsum	Granulated blast furnace slag	Condensed microsilica
1	2	14	2	72	10
2	2	14	2	82	-
3	1.5	14	1.5	68	15
4	1.5	14	1.5	83	-
5	1.5	14	1.5	63	20
6	1.5	14	1.5	78	5
7	1.5	14	1.5	78	25
8	1.5	14	1.5	80	2

The tests were carried out to determine the fineness of grinding, normal density, setting time, cone blurring, uniform volume change, and tensile and compressive strength. Also, the samples of the tested binder were subjected to treatment in a steaming chamber.

Table 5 – Test results of clinkerless binder bar samples

No.	Grinding fineness, %	Normal density, %	Setting time (Start / End), min	W/C	Steaming mode, hours	Tensile / Compressive strength after 2 days of steaming, kgf/cm^2	Tensile / Compressive strength after 28 days of steaming, kgf/cm^2	Uniformity of volume change
1	90.20	0.14	25.00 / 50.00	0,22	2+12+2	98.30 / 374.25	67.00 / 346.00	Uniform
2	90.00	0.16	34.53 / 39.05	0,24	2+12+2	67.70 / 265.13	71.00 / 310.00	Uniform
3	91.76	0.14	20.39 / 26.36	0,24	2+12+2	88.00 / 384.34	68.00 / 322.20	Uniform
4	94.48	0.16	45.20 / 53.20	0,24	2+12+2	71.50 / 287.78	66.00 / 327.70	Uniform
5	88.00	0.14	18.35 / 48.50	0,24	2+12+2	93.70 / 450.00	72.00 / 401.10	Uniform
6	96.00	0.15	28.43 / 59.39	0,24	2+12+2	90.00 / 401.60	62.00 / 435.11	Uniform
7	95.00	0.14	15.15 / 17.35	0,24	2+12+2	84.00 / 542.00	70.15 / 397.27	Uniform
8	99.00	0.16	18.00 / 28.00	0,25	2+12+2	73.10 / 316.93	74.60 / 386.70	Uniform

Selection of quantitative ratios between the starting materials was carried out by analytical review of literature and theoretical bases of the use of blast furnace granulated slag, lime, gypsum, superplasticizer and microsilica in the production of binders, fine grinding of composite raw material mixtures, as well as through experimental determinations of the properties of the manufactured binder, different composition in laboratory conditions.

In the design of binder were considered the basics of the manufacture of slag clinkerless binders, in particular lime-slag, sulfate-slag substances and theoretical aspects of the use of superplasticizer C-3, the impact of fine grinding, and therefore the production of binders of low water consumption.

The components of the raw material mixture of the studied binder are a base of blast-furnace granulated slag and raw material additives to improve hydration, strength set and increase strength characteristics. So, lime is an alkaline activator of potential hydraulic properties of blast furnace slag constituents, gypsum acts on slag as a sulfate activator. Superplasticizer is a complex modifier of binder.

As a result of the review, tests were conducted to select the composition within the following limits: blast-furnace granulated slag – 70-90 %, lime – 14 %, gypsum – 1.5-2 %, C-3 – 1.5-2 %. microsilica – 2-25 %.

In the course of research work was obtained binder using blast furnace granulated slag of JSC «ArcelorMittal» two experimental compositions. Binder of the first composition was obtained by joint grinding of the given blast furnace granulated slag, lime, gypsum and superplasticizer C-3. The binder of the second composition was obtained by joint fine grinding of the same raw materials, but with the addition of microsilica.

Thus, a new binder was obtained, including the characteristics and properties of lime-slag binder and low water consumption binder [7].

Joint grinding of raw material components was carried out in a ball mill of the construction laboratory of the architectural and construction faculty of the Abylkas Saginov Karaganda Technical University. The duration of grinding was 8 hours, and grinding balls of different diameters were used in the experimental production of binder samples.

During the production of experimental samples of binders were also taken into account research data that at fine grinding in a ball mill, the content in the raw mix of additive C-3 at the same duration of the process increases the fineness of grinding of the finished product [29]. Figure 1 shows the dependence of specific surface area on the content of C-3.

The fineness of grinding of the studied binder was in the range of 88-99 %. When determining the uniformity of fracture volume change, radial cracks and distortions were not found in the samples. The normal density of the binder with gypsum corresponded to a water-cement ratio of 0.22-0.24. The beginning and end of setting corresponded to quick-setting cement, so it is desirable to use this binder not directly in production.

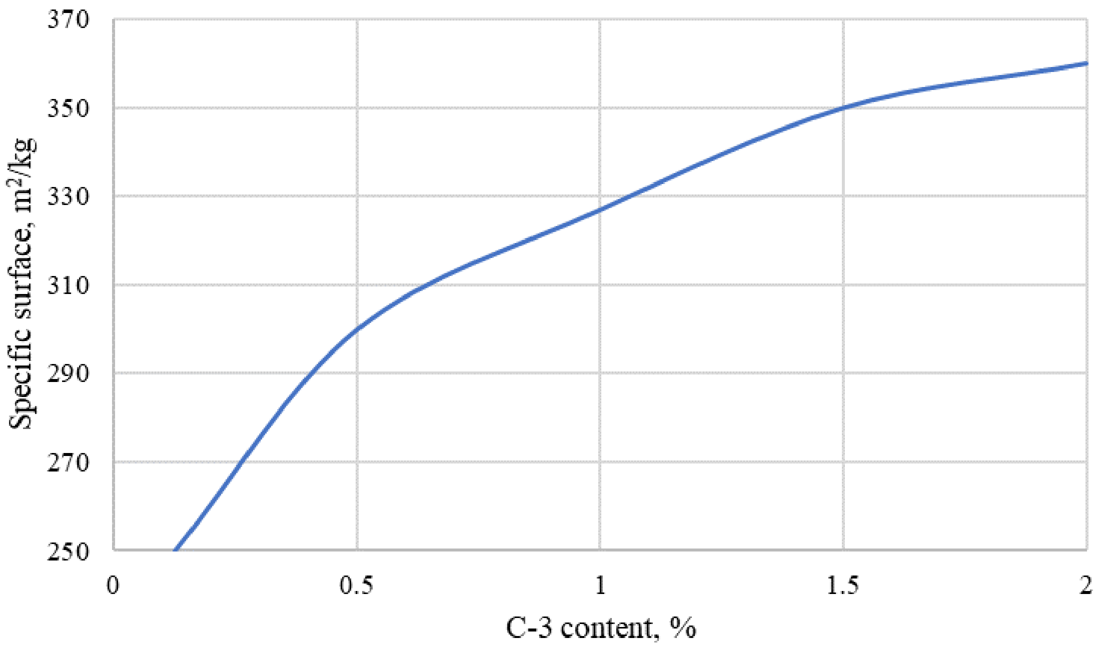

Figure 1 – Graph of dependence of specific surface after grinding on the content of C-3 in the composition of the raw material mixture

To determine the activity of the investigated binders, samples of beams with the size of 40x40x160 mm were prepared. The samples were made using Volsk sand of composition 1/3. After manufacturing the samples in molds were stored (24±1) h in a bath with a hydraulic seal, then the samples were carefully unformed and placed in a bath with water in a horizontal position. Samples for determining the strength of cement during steaming were placed in the steaming chamber. Steaming took place according to the following regime: 2 hours of holding the samples in the chamber at a temperature of 20°C, 3 hours for a uniform rise in temperature to 90°C, isothermal heating at the temperature was held for 12 hours, the process of cooling the samples 2 hours. Further in accordance with [28] the strength characteristics of the considered binders were tested under steaming conditions and after 28 days.

The obtained results of laboratory studies of the properties of the developed binder showed that the binder made by joint grinding of lime, gypsum, blast furnace granulated slag, microsilica and superplasticizer C-3 has higher compressive flexural strength. Also, the flexural and compressive strength of this binder increases significantly after treatment in a steaming chamber (Figures 2, 3, 4).

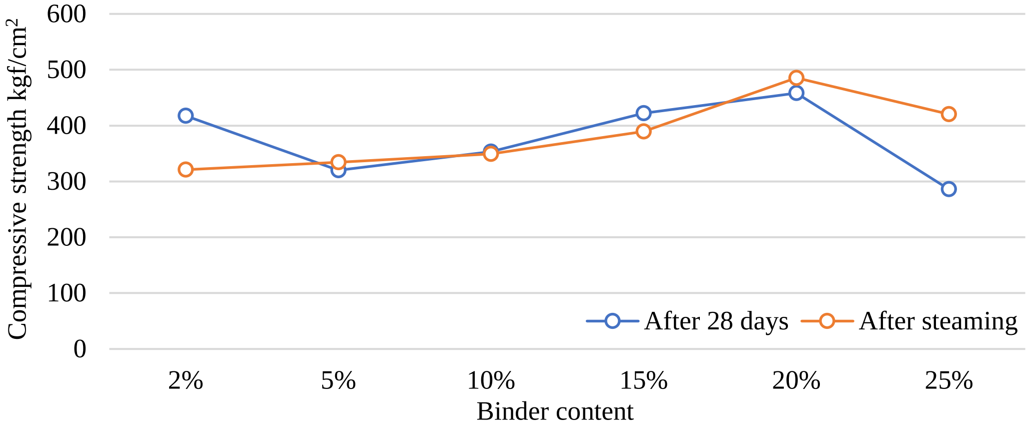

Figure 2 – Dependence of compressive strength on binder composition

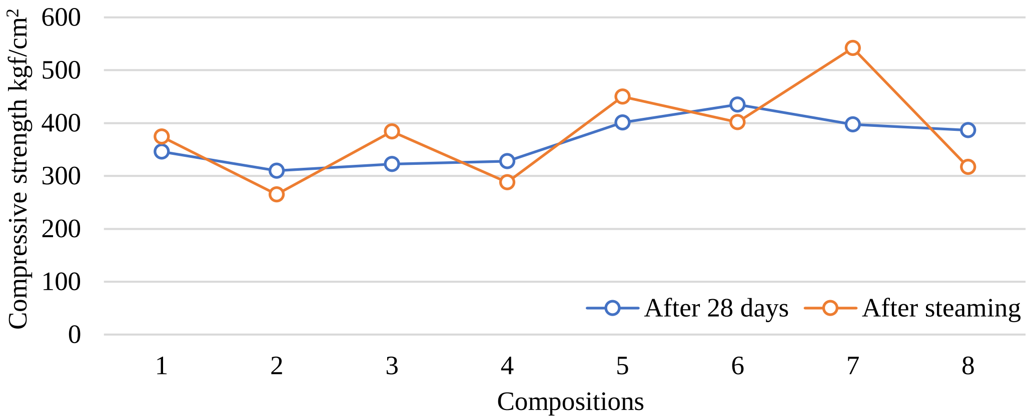

Figure 3 – Compressive strength of clinkerless compositions

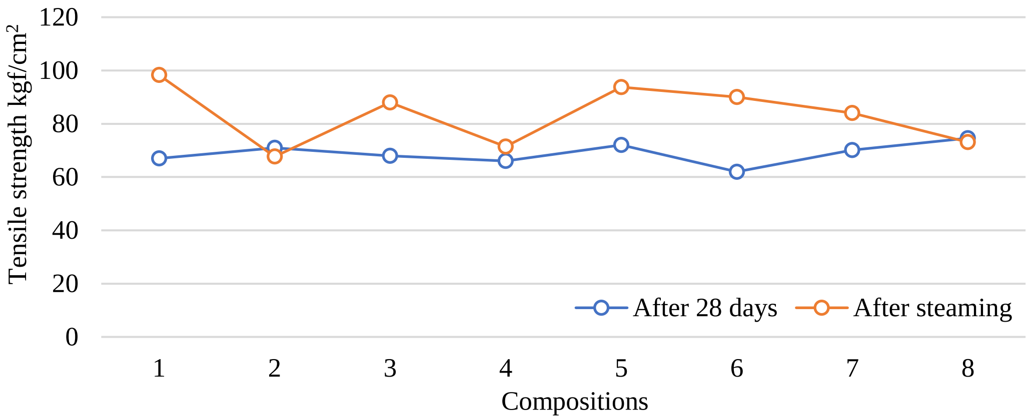

Figure 4 – Tensile strength of clinkerless compositions

Also, the presence of superplasticiser C-3 reduced the water requirements during mixing. It also draws attention to the fact that the water-cement ratio of the studied binders decreases in the presence of gypsum additive in the raw mix. Gypsum content also increases the fineness of grinding.

The content of C-3 additive in binders increases the setting time, while the content of gypsum in the raw mix does not affect the beginning and end of setting of the studied binders.

Technological scheme of binder production using industrial wastes consists of the following main operations: dosing of raw material components, joint fine grinding, packaging and warehousing of finished products.

4. Conclusions

In the course of laboratory tests, raw materials meeting all requirements of state standards were used.

Laboratory research work was carried out in accordance with the requirements of state standards.

Two binder compositions were selected: 1) 14% lime, 2% gypsum, 1.5-2% C-3 additive, 82% blast furnace granulated slag; 2) 14% lime, 1.5% C-3 additive, 2-25% microsilica, 63-80% blast furnace granulated slag.

The tensile and compressive strengths of the specimens were 62-74 kgf/cm^2 and 310-435 kgf/cm^2 for the first and second compositions, respectively.

The production process involves sulphate-alkali activation of potential hydraulic properties, binder modification as well as mechanical activation through fine grinding.

The obtained binders in the research work need further study of the properties of frost resistance, water resistance.

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