



Article

Investigation of the Possibility of Utilizing Man-Made Waste to Produce Composite Binders

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Abstract

In this article, composite binders based on industrial waste—phosphogypsum, granular phosphoric slag, and burnt barium carbonate tailings—are investigated. It was found that the optimal composition (65% slag, 20% phosphogypsum, 15% tailings) provides compressive strength up to 31.1 MPa after steaming, which corresponds to grade M300 cement. Replacing natural gypsum with phosphogypsum increases strength by 5–10%, and using waste reduces cost by 20–25% compared to traditional binders. This technology eliminates the need for high-temperature firing, reducing energy consumption by 40–50%. Neutralization of harmful impurities of phosphogypsum with oxides of MgO and CaO reduces the ecotoxicity of the material by 70–80%. It is shown that hydrothermal treatment accelerates hardening, providing 90% of brand strength in 28 days. The developed binders are promising for the production of building blocks, road surfaces, and land reclamation.

Keywords: composite binders; phosphogypsum; phosphoric slag; barium carbonate tailings; hydrothermal hardening; eco-friendly construction; environmental engineering



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1. Introduction

Thousands of millions of tons of industrial waste accumulate annually all over the world and, in particular, in Kazakhstan. Industries such as mining [1–5], chemical [6–10], metallurgical [11–15], construction [16–19], oil and gas [20–23], and a number of others produce waste products which, because of their chemical and mineralogical composition, are capable of acting as secondary mineral raw materials, replacing natural raw materials.

In our cutting-edge world, ecological concerns, rational use of sources, and strength saving have become increasingly relevant. The continuously developing need for binders from diverse origins calls for greater in-depth use of all feasible assets, including uncooked mineral substances conventionally treated as commercial waste.

Despite the fact that using diverse varieties of technogenic uncooked mineral substances to manufacture composite binders could be very promising, this problem nevertheless remains unsolved because of the particular physicochemical traits of such substances and the presence of unwanted impurities in them. This necessitates extra studies and improvement of theoretical and technological factors regarding the complicated processing of uncooked technogenic and herbal mineral substances to obtain powerful composite binders.

Currently, many studies are aimed toward analyzing the problem of acquiring gypsum binders from gypsum-containing waste generated by numerous manufacturing processes. One of those forms of waste is phosphogypsum, a large-scale byproduct of the manufacturing of extraction phosphoric acid [24].

Phosphogypsum is a gypsous raw material that can serve as a secondary raw material in the production of gypsum binders. The content of phosphogypsum generated by different enterprises is approximately equal, except for a small amount of mixtures.

The impurity content is regulated by normative acts. Non-compliance of the content of phosphoric acid and phosphates with normative acts can lead to the appearance of an acid phase with the formation of phosphogypsum, which can decrease the rate of its reuse. Complications with storage, packing, and transportation can be caused by moisture absorption, the presence of free acids, adfreezing, and a tendency toward adhesion. Currently, the quantity of phosphogypsum in dumps is more than 250 million tons, and this value will increase annually [25,26].

In southern Kazakhstan, there is one plant that produces phosphogypsum: NDPP “Phosphorus Plant.” The waste situation at this enterprise remains the same, despite a great number of studies devoted to utilization of such waste. The NDPP “Phosphorus Plant” dumps contain more than 16–17 million tons of phosphogypsum, and its storage and transportation are associated with great expenses.

1. These costs are proportionate to 11.9% of the cost of building of a phosphoric acid plant.
2. The cost of exploiting dumps with phosphogypsum is rather high, and is equal to approximately 20% of the expense of phosphogypsum processing.
3. The areas of land occupied by dumps can successfully be used for agriculture.
4. The negative impacts of these dumps on the environment cannot be evaluated.

Many undesirable impurities contained in phosphate ores can remain in the waste (phosphogypsum) during processing, complicating its further reuse [25].

The issue of phosphogypsum utilization has become very relevant. Enormous contributions to investigating phosphogypsum and improving technology for generating Portland cement and sulfuric acid, ammonium sulfate, blended hydraulic substances, and similar construction substances primarily based on them have been made by S. M. Royak, P. P. Budnikov, E. Z. Ognyanova, P. F. Gordashevsky, T. A. Atakuziev, P. V. Klassen, F. M. Mirzaev, M. A. Akhmedov, and others [24–28]. The application of this substance as a mineralizer in clinker burning is reasonable.

A group of scientists from Japan have analyzed the characteristics and properties of phosphogypsum and devoted their research to the problem of reusing it [29]. As a result of their study, as well as studies by other scientists, it becomes clear that the main spheres of phosphogypsum use are

1. Binder production;
2. Cement production;
3. Calcium carbonate and acid production;
4. Soil remediation.

Studies on phosphogypsum processing can be divided into three groups:

- Alpha and beta modifications of gypsum binders;
- Construction material production;
- Application as an additive or filler substance

The application area of gypsum binders is rather wide. Even if the energy of gypsum binders reaches grade 300 or more (along with waste), this does not assure their sturdiness in load-bearing systems below running conditions, given that irreversible creep deformations can occur when they are moistened [30].

Because of the good solubility of gypsum in water, gypsum products have low water resistance. In the process of wetting gypsum samples, microcracks on the internal surface absorb water, increasing the stability of samples [30].

Thus, is the aim of this study was to create composite gypsum binders that offer improved electrical and water resistance, as well as to improve products primarily based on them that do not require heat treatment, in order to decrease energy consumption, cost, and steel consumption; to recycle man-made industrial waste; and to decrease anthropogenic effects on the environment.

2. Materials and Methods

Based on the objectives of this study, natural phosphogypsum and gypsum dihydrate modified by chemical and mineral agents were used as active components of the system. Waste from the enrichment process of polymetallic ores (Ca and Mg oxides, BaSO_4 , CaCO_3), together with electrothermophosphorus slag, were used as modifiers of the system components.

The objects of study: $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ —the waste of NDPP “Phosphorus Plant” (17 million accumulated tons, with an annual production of 1.5 million tons/year), tailings from the enrichment process of polymetallic ores from JSC “Yuzhpolimetal” in Khantagi, Russia (7 million accumulated tons, with an annual production of 0.3 million tons/year), and electrothermophosphorus slag, which is produced during the manufacturing of phosphorus using the sublimation approach in electric-powered furnaces and transformed into a fine-grained shape with the aid of rapid cooling within the furnace granulating unit of the Novo-Dzhambul phosphorus plant in Taraz, Kazakhstan (10 million accumulated tons, with an annual production of 0.7 million tons/year).

Samples of technogenic raw materials were preliminarily selected. Manual sampling was carried out in accordance with a generally accepted sampling methodology [31]. Six point samples were taken along the perimeter of tailings, phosphogypsum, and slag dumps, which were subsequently combined into single samples for each of the technogenic wastes. Each pooled sample, consisting of a specified number of spot samples, was labeled according to a standard accounting system and sent to the sample preparation laboratory, where it was further processed.

The remainder of the pooled sample (after part of the sample was taken to determine the water content) was prepared for physicochemical analysis. This sample was subjected to averaging until a mass of at least 200 g was obtained. Averaging was carried out manually by reduction and quartering [32].

After reduction to a mass of at least 0.2 kg, the sample was subjected to further grinding for physicochemical research. It was ground in a porcelain mortar to the state required for this study, and then sifted through a sieve with a mesh size of 0.08 mm [32].

Several samples taken from this crushed mass were used for physicochemical analysis of selected samples of technogenic raw materials.

Then, the selected samples of technogenic waste underwent physical-chemical and physical-mechanical studies and tests. In particular, they were dried in an oven at 105 °C for 6 h until a constant weight was achieved, in accordance with GOST R 57758-2017 “Resource conservation. Waste management. Preparation of analytical portions from a laboratory sample.”

In particular, the industrial waste used in the study showed no loss of volatile components at 105 °C. The samples were spread on drying trays in a thin layer and dried in an oven. This process was not accelerated by ventilation, as this may lead to the loss of fine particles from the test samples. Humidity was then determined by weighing; that is, by the difference in mass before and after drying. Next, the samples of natural and technogenic raw materials were subjected to quantitative chemical analysis. In particular, the gravimetric method was used, which is a classical method of quantitative chemical analysis and one of the first chemistry methods developed. Gravimetric methods, as has already been noted by many researchers, are simple to implement and have good repeatability and high accuracy. However, they can be labor-intensive and time-consuming.

The samples were also subjected to X-ray segment evaluation sequentially and in parallel using an ARL 9900 Intel Work Station X-ray fluorescence wave-dispersive spectrometer from Thermo Fisher (Switzerland, Bern). The chemical composition and X-ray structure were evaluated using an ARL X'TRA X-ray diffractometer (Thermo Fisher Scientific, Basel, Switzerland) at the “Department of Cement Technologies and Composite Materials” at Belgorod State Technological University, named after V. G. Shukhova (Russia, Belgorod). Differential thermal evaluation was carried out to detect changes in the materials that accompanied temperature changes. Most structural and chemical changes were observed via discharge or absorption of heat, and those changes may be reversible or irreversible.

Reversible processes, such as melting, crystallization, entiotropic polymorphic transformation, and others, are seen during heating and cooling. Irreversible processes, for example, the transition of a metastable segment to a solid one, decomposition of a strong solution, and so on, are seen best while heating.

Classical thermal analysis (TA) involves constantly monitoring thermal results by measuring the temperature of the material at regular intervals while altering the temperature consistently. The recording is executed using the “pattern temperature—time” coordinates. If any transformation takes place within the material, it is detected by discharge or absorption of heat.

If no variations arise in the discharge or absorption of heat during heating (or cooling), the thermogram is a simple line. If an endothermic or exothermic transformation takes place, the material heats up more slowly or more quickly than the surrounding environment. On a thermogram, this is manifested by deviation of the graphed line toward the abscissa (endothermic effect) or ordinate (exothermic effect).

Recording thermal changes on a temperature–time coordinate system, while easy, is not sensitive. This is particularly true of silicate systems, in which segment transitions are observed with small thermal effects (for example, in the course of the transition from melting to crystallization).

Therefore, to increase sensitivity, the differential thermal evaluation (DTA) technique was created. This technique has an extensive variety of capabilities and may be used to remedy the following problems:

1. Identifying the character of chemical substances with the aid of melting points, transitions among polymorphic features, and thermal decomposition;

2. Carrying out qualitative and, in a few cases, quantitative evaluation of mechanical combinations of numerous materials;
3. Measuring temperatures of segment transitions in character materials and systems, in addition to generating melting diagrams based on them;
4. Determining the kinetic and thermodynamic traits of segment and chemical transitions;
5. Determining the thermophysical traits of materials.

During differential thermal analysis, the temperature distinction among the actual sample and the reference sample is recorded. A substance that does not go through section transitions in response to temperature changes is used as a reference pattern. Usually, whilst reading non-metal materials, magnesium oxide or aluminum oxide calcined at a temperature of 1300 °C is used as a standard. For low-temperature studies, NaCl and KCl are used as standards. The actual sample and the reference sample are located concurrently within the same oven to ensure a uniform temperature for each sample. The differential thermal analysis studies of the samples were carried out on a Q-1500D derivatograph (Hungarian Optical Plant, Hungary, Budapest) at the experimental regional laboratory of the engineering direction “Structural and Biochemical Materials” of JSC “M. Auezov South Kazakhstan University.”

The particle size distribution of the enrichment waste was also determined via manual sieving through a set of special laboratory sieves [33,34]. Concentration tailings are already crushed, homogeneous, and fractionated raw materials.

The main stages of the experiment were as follows: joint grinding of components in various ratios; forming of samples (beams $4 \times 4 \times 16$ cm) at $w/v = 0.4$; and hardening in two modes: hydrothermal treatment (steaming at 95 °C for 2–9–2 h) and water hardening (28 days). They were also subjected to radiological examination, firing in a high-temperature oven, hardening and steaming in a climate chamber, and determination of the bending and compressive strength of the resulting samples on a laboratory press, according to a well-known method [35–47].

3. Results and Discussion

In this study, fine dispersed phosphogypsum with a particle size of 20–200 µm was used. The pH of the studied sample is 2.7–3.5. Its density is 2.3–2.56 g/cm³, and the specific surface is 336 m²/kg. The chemical composition of the samples is represented through the subsequent oxides in mass percent: SiO₂—6.69; CaO—31.25; Al₂O₃—0.38; SO₃—42.29; H₂O—18.21; Fe₂O₃—0.09; F—0.09; P₂O₅—1.09. The ratio of SO₃ to CaO is 1.343.

From X-ray section evaluation and IR spectroscopy of phosphogypsum (Figures 1 and 2), it was concluded that the principle and dominant section is gypsum dihydrate. The presence of this section was shown using feature alerts within the diffraction pattern ($d = 1.62$; 1.67; 2.08; 2.87; 3.06; 3.77; 4.29; 7.63 Å) and absorption bands within the IR spectrum (675–670 and 618 cm^{−1}; 1160–1130; 1720–1640; 3270; 3440; 3558; 3600).

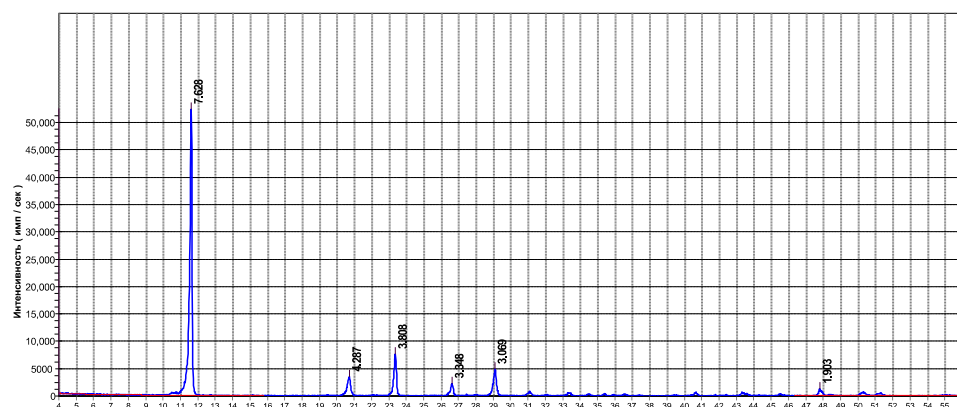


Figure 1. X-ray image of phosphogypsum.

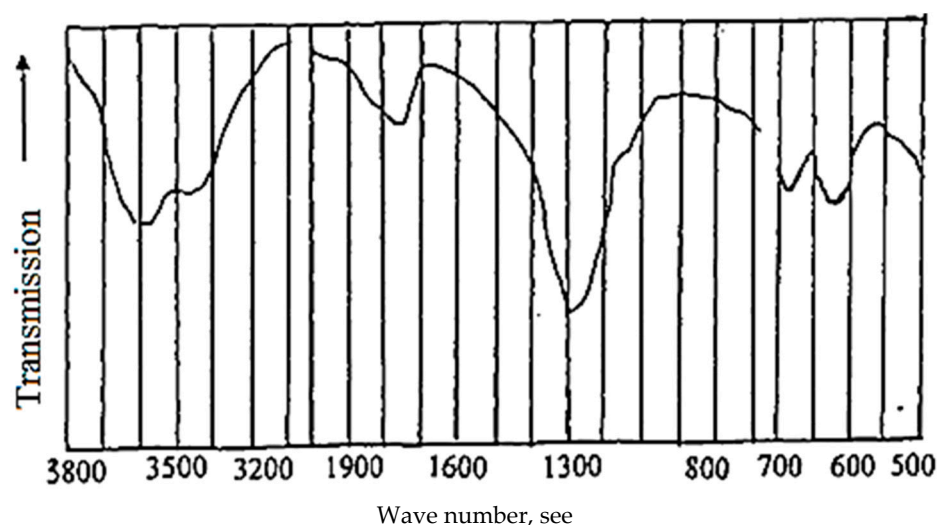


Figure 2. IR spectrogram of a selected phosphogypsum sample.

Based on the granulometric composition of tailings from the enrichment of non-ferrous metals of ores from the Khantaginsky waste facility by sieve analysis, the minimal and maximal sizes of waste and tailings debris were established. The waste particle size distribution was as follows: particles with the size 84–86 μm , 24–31%; particles with the size 24–84 μm , 54–66%; particles with the size 190 μm and more, 9–14%. Limestone, barite, clay substances, and ore minerals were the tailings minerals.

A diffractogram of the differential thermal analysis of phosphogypsum is shown in

To study the polymetallic ore enrichment process, X-ray phase analysis was used. In Figure 4, the results of the analysis are presented.

X-ray diffraction analysis of polymetallic ore enrichment tailings indicates reflections similar to the following minerals: dolomite $\text{CaMg}(\text{CO}_3)_2$ ($d/n = 1.807; 2.02; 2.199; 2.730; 2.898$), calcite CaCO_3 ($d/n = 1.873; 1.912; 2.021; 3.033$), barite BaSO_4 ($d/n = 2.021; 2.033; 2.033; 2.033; 2.033$ and 3.56), and quartz SiO_2 ($d/n = 1.671; 2.284; 2.467; 3.357$ and 4.281).

The studied waste from polymetallic ore from JSC Yuzhpoly metal is quite stable and has the following chemical composition (in%): SiO_2 (4.35–6.1); Al_2O_3 (0.97–1.1); Fe_2O_3 (2.87–3.9); CaO (27.78–28.9); MgO (14.44–16.2); BaSO_4 (12.8–14.1); FeS_2 (1.38–1.4); PbSO_4 (0.03–0.05); PbCO_3 (0.09–1.1); PbS (0.14–0.1); ppp (35.24–36.9). Furthermore, the catalytic and modifying elements present in the wastes of polymetallic ores are (in wt.%): Cu—0.002–0.004; Cd 0.002–0.003; Zn—0.01–0.05; and Ti—0.03–0.05. Figure 3.

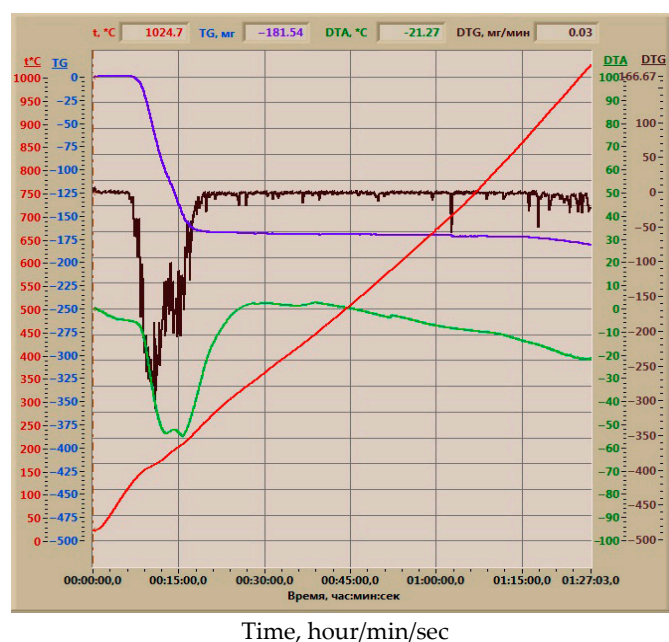


Figure 3. Derivatogram of differential thermal analysis of a selected phosphogypsum sample.

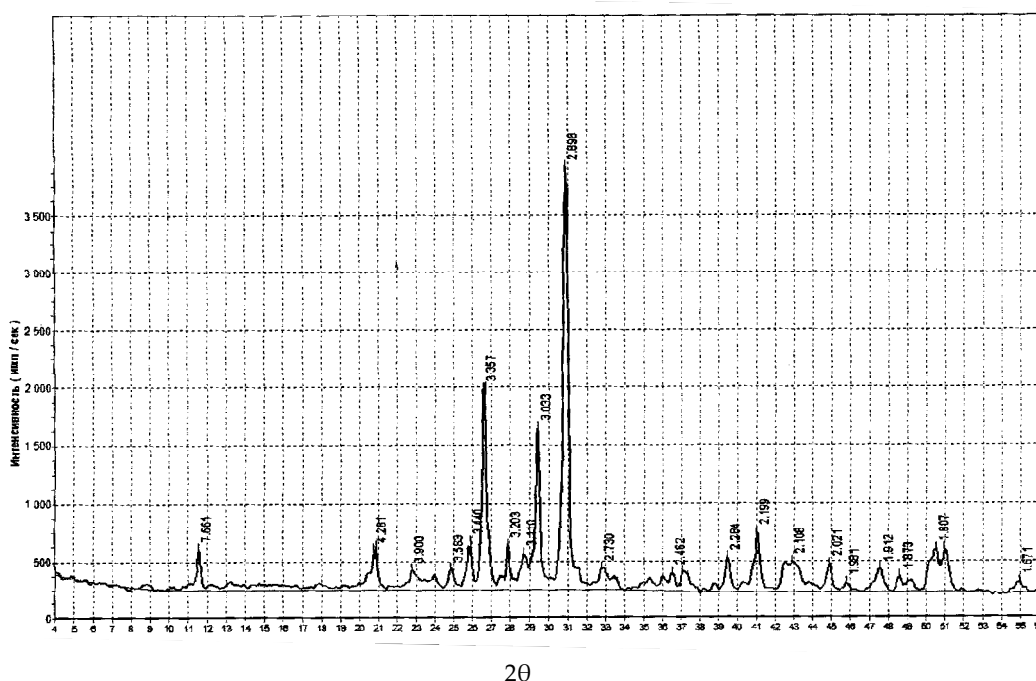


Figure 4. X-ray phase analysis of carbonate-barium tailings of polymetallic ores from "Yuzhpolymetal" JSC.

The radiative ecological safety of the wastes is proved by the low activity of radionuclides of the wastes (53–55 Bq/kg), the absence of toxic emissions from the wastes, and the low volatility of heavy metals of the wastes.

Granulated electrothermophosphorus slag includes 95–98% glass. Its crystalline component consists of calcite, quartz, and wollastonite. The chemical composition of those slags is fairly solid and consists of the subsequent mass fractions of components: 42–43% CaO; 40–43% SiO₂; 0.9–1.0% Fe₂O₃; 1–3% Al₂O₃; 3.0–4.0% MgO; 2.0–3.0% F; 0.2–1.4% SO₃; and 0.9–3.0% P₂O₅.

To assess the chemical and mineral composition of the electrothermophosphorus slag, X-ray evaluation was carried out. The slag includes quartz ($d/n = 1.813; 2.458; 3.343$), pseudowollastonite ($d/n = 1.471; 3.30; 3.88$), and calcite ($d/n = 3.03$).

After studying the physicochemical properties of the waste, it was found that these wastes, based on their chemical and mineral properties, can replace natural mineral raw materials. Binders from the production waste were prepared as follows: granulated electrothermal phosphorus slag, calcined barium carbonate tailings, and phosphogypsum were subjected to joint grinding and grinding at various proportions. Then, certain samples were made from the resulting binder at a water–binder ratio of 0.4. The samples were subjected to hardening in water for 28 days and steaming at 95 °C, in line with the 2–9–2 h regime [48]. The components and properties of the phosphogypsum-containing composite binders after hydrothermal hardening are presented in Table 1.

Table 1. Composition and properties of phosphogypsum-containing composite binders after hydrothermal hardening.

Compound	Components, wt.%			Binder Activity, MPa			
	Phosphogypsum Dihydrate	Granular Phosphorus Slag	Burnt “Tails” $t_{obzh} = 900\text{ °C}$	Steaming		Water Curing	
				R_{com}	R_{meas}	$R_{com.}$	R_{meas}
1	20	50	30	5.29	27.88	5.57	28.48
2	15	60	25	5.48	29.87	5.08	24.29
3	20	65	15	5.58	31.08	4.49	24.12

The composite binder samples, containing granulated phosphorous slag, dehydrated gypsum, and calcinated carbon barium tailings, were obtained in the same way. Table 2 shows the components and properties of the gypsum composite binders.

Table 2. The gypsum-containing composite binder structures and properties.

Compound	Components, wt.%			Binder Activity, MPa					
	Phosphogypsum Dihydrate	Granular Phosphorus Slag	Burnt “Tails” $t_{obzh} = 900\text{ °C}$	$R_{com.}$			R_{meas}		
				28 Days	3 Months	6 Months	28 Days	3 Months	6 Months
1	55	25	20	6.11	6.77	7.18	23.18	25.08	26.68
2	55	15	30	5.77	6.58	6.79	19.68	21.48	23.11
3	35	30	35	5.19	6.12	6.28	19.79	21.27	22.12
4	35	35	10	4.18	4.89	5.77	18.69	19.08	21.17

Table 3 details the outcomes of structural and mechanical examinations of samples fabricated from a composite binder produced from gypsum derived from phosphogypsum [49].

Hardening of gypsum binders without firing happens because gypsum can recrystallize via supersaturated solutions. The finer the gypsum is crushed, the more likely it is to recrystallize.

Clinker cement containing calcium sulfate and calcinated dolomite, obtained by joint grinding of wastes, was proposed by Budnikov P.P. [50]. The most intensive hardening of such cement occurs at a content of CaO (0.4–0.5 g/liter). Increased calcium oxide content in the hardening cement phase can cause “gypsum swelling” due to the delayed formation of $\text{Ca}(\text{HSO}_4)_2$. $\text{CaMg}(\text{CO}_3)_2$ fired at 790–910 °C until partial decomposition of calcium

carbonate is used as the alkaline catalyst for the basic slag in slag cement. $\text{CaMg}(\text{CO}_3)_2$ fired at 990–1110 °C until complete dissociation of calcium carbonate is used in acid slags.

Based on Table 1, the best strength indicators of a phosphogypsum-containing binder during hydrothermal hardening are represented by compound 3 (65% slag, 20% phosphogypsum, 15% tailings): $R_{cj} = 31.1$ MPa (steaming) and $R_{cj} = 24.0$ MPa (water hardening). At the same time, with an increase in the proportion of slag, the strength increases, but an excess of phosphogypsum can reduce water resistance.

Based on Table 2, the maximum strength of the gypsum-containing binder is obvious after 6 months, when it reaches a value of $R_{sf} = 26.7$ MPa (composition 1: 25% slag, 55% gypsum, 20% tailings), while prolonged hardening increases strength due to recrystallization of gypsum.

When compared with the phosphogypsum analog (Table 3), it can be seen that phosphogypsum demonstrates higher strength than natural gypsum, especially compound 1, where the R_h index = 28.3 MPa (6 months) versus 26.7 MPa for gypsum binder. This is due to additional structure formation through the interaction of phosphate impurities with slag oxides and enrichment tailings.

Based on the advantages over traditional binders, the present method has:

1. Environmental and economic benefits. Phosphogypsum, phosphorous slags, and enrichment tailings, which would conventionally be disposed of as waste, can be used to replace natural raw materials (gypsum, cement). Energy consumption is reduced due to no need for high-temperature firing (unlike Portland cement, which requires 1450 °C).
2. Technological advantages. Hydrothermal treatment accelerates hardening (steaming gives a strength of 30 MPa in 28 days). Alkaline components (MgO , CaO from tailings) neutralize the acidic impurities of phosphogypsum, increasing durability. Mechanical activation (grinding) enhances recrystallization, improving the structure of the material.
3. Improved physical and mechanical properties. Due to the high early strength (5–7 MPa for bending, 20–30 MPa for compression), strength increases over time through the hydration of slag and formation of hydrosilicates. Water resistance is increased due to the formation of insoluble compounds (calcium fluoride, hydroxylapatite).

Table 3. Composition and properties of phosphogypsum-containing composite binders.

Compound	Components, wt. %			Binder Activity, MPa					
	Phosphogypsum Dihydrate	Granular Phosphorus Slag	Burnt “Tails” $t_{obzh} = 900$ °C	$R_{com.}$			R_{meas}		
				28 Days	3 Months	6 Months	28 Days	3 Months	6 Months
1	55	25	20	6.58	7.29	7.49	24.08	25.87	28.28
2	55	15	30	6.12	6.78	7.02	21.48	23.88	25.58
3	35	30	35	5.69	6.18	6.58	21.87	22.49	23.19
4	35	35	10	5.11	5.58	6.18	19.48	21.29	22.37

According to [51], the calcium and magnesium oxides present in the wastes of polymetallic ores that are burned at 950 °C act as additives, increasing the pH of the medium in the course of binder hydration, thereby neutralizing acid impurities. Other studies [51–53] have proven the practicability of combining caustic magnesite and calcium sulfate.

The simultaneous presence of caustic magnesite and phosphogypsum within the binder will increase the energy and water resistance of the ensuing composition. It is

essential to notice that the strength of the samples ($R_{com.}$ and $R_{meas.}$) will increase with increasing solidification time.

Obtaining long-lasting systems from finely ground herbal gypsum stone and phosphogypsum is viable because of its potential to recrystallize after mechanical processing.

Next, we summarize the data for comparing the proposed binder with its analogs in Table 4.

Table 4. Comparison of the proposed binder with analogs [54–58].

Parameter	Proposed Binder	Portland Cement	Classic Gypsum Cement
Raw material base	Waste products (phosphogypsum, slags)	Limestone, clay	Natural gypsum
Energy consumption	Low (grinding + firing at 900 °C)	High (firing at 1450 °C)	Moderate (grinding)
Strength (R_{sl} , MPa)	24–31 (28 days)	30–50 (28 days)	10–20 (28 days)
Water resistance	Increased (by neutralizing impurities)	High	Low
Environmental friendliness	Waste recycling	High carbon footprint	Depends on the extraction of gypsum

From Table 4, the advantage of the proposed binder is obvious, compared with its analogs. The studies carried out and the results obtained have confirmed the effectiveness of using composite binders based on industrial waste (phosphogypsum, granular phosphoric slag, and burnt barium carbonate tailings) as an alternative to traditional building materials.

According to EN 197-1, the developed gypsum binder (31.1 MPa) corresponds to class 32.5N, which is close to ordinary Portland cement (CEM I 32.5N) and in alignment with concrete classes (EN 206). The resulting gypsum binder covers the range C20/25–C25/30, which allows it to be used in unloaded structures (partitions, screeds) and low-grade concretes (road foundations, blocks).

It is advisable to focus further research on optimizing the composition for special operating conditions (high humidity, chemically aggressive environments).

The developed composite binder demonstrates advantages in terms of strength, cost-effectiveness, and environmental friendliness over traditional materials, which makes it promising for large-scale implementation in the environmentally friendly construction industry.

4. Conclusions

The main conclusions of this work are as follows:

- the optimal composition (65% phosphorous slag, 20% phosphogypsum, 15% burnt tailings) provides compressive strength up to 31.1 MPa after steaming, which is comparable to cement grade M300;
- when replacing natural gypsum with phosphogypsum, the strength increases by 5–10% (from 26.7 to 28.3 MPa after 6 months of hardening);
- the technology eliminates the need for high-temperature firing (unlike Portland cement), reducing energy consumption by 40–50%;
- the use of waste reduces the cost of raw materials by 30–35% compared to the production of traditional binders;
- utilization of phosphogypsum and slags reduces the load on landfills and prevents environmental pollution;

- neutralization of acidic impurities of phosphogypsum with oxides of MgO and CaO from tailings reduces leaching of toxins by 70–80%;
- hydrothermal treatment (steaming) accelerates strength gain, up to 90% of the grade in 28 days against 60–70% for cement systems;
- mechanical activation of the components increases the reactivity of the binder by 15–20% by increasing the degree of recrystallization of gypsum;
- the technology is applicable in the production of building blocks, road foundations, and reclamation materials with a cost 20–25% lower than analogs.

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