Master thesis

Comprehensive utilization of iron ore tailings

JSC "Stoilensky Mining and Beneficiation Plant"

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Preface, Dedication, Acknowledgement

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Abstract

The master's thesis is devoted to the comprehensive utilization of iron ore tailings of JSC "Stoilensky Mining and Beneficiation Plant" by producing iron-containing coagulants and using the residues after iron recovery in the construction industry.

The state of knowledge of the experience of using alternative methods of iron ore tailings reuse has been considered in detail on the basis of the scientific papers of Russian and foreign scientists. The technological part contains a description of Stoilensky Mining and Beneficiation Plant, an analysis of its impact on environmental components, as well as a description of the tailings damp. The research part contains a description of the conducted experiments to obtain and verify the effectiveness of the iron - containing coagulant, as well as a theoretical study of usage of the residues after iron recovery from iron ore tailings. The calculations were carried out on economic efficiency to prove the feasibility of the proposed project. The results showed that the implementation of the project in the enterprise pays off, and allows to reduce the negative impact on the components of the environment.

Zusammenfassung

Die Masterarbeit befasst sich mit der umfassenden Verwertung von Eisenerzabfällen der AG "Stoilenskij Bergbau- und Aufbereitungswerk" durch die Herstellung eisenhaltiger Koagulationsmittel und die Verwendung der technologischen Rückstände in der Bauindustrie.

Auf der Grundlage der Arbeiten russischer und ausländischer Wissenschaftler wurde der Kenntnisstand über die Erfahrungen bei der Anwendung alternativer Methoden der Wiederverwendung von Eisenerz-Tailings eingehend betrachtet. Der technologische Teil enthält eine Beschreibung des ausgewählten Objekts, eine Analyse seiner Auswirkungen auf die Umweltkomponenten sowie eine Beschreibung der Haldenfeuchtigkeit. Der Forschungsteil enthält eine Beschreibung der Experimente, die zur Gewinnung und Überprüfung der Wirksamkeit des gewonnenen Koagulationsmittels durchgeführt wurden, sowie eine theoretische Studie über die Verwendung der technologischen Rückstände. Der wirtschaftliche Teil enthält die Berechnung und Bewertung der wirtschaftlichen Effizienz des vorgeschlagenen Projekts.

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1. Introduction

According to the state report " Mineral resources of the Russian Federation in 2021" for the last three years in Russia an average of 358 million tons of iron ore per year is extracted. At the same time, as a result of enrichment, a large volume of "tailings" is formed, which may contain particles of iron-containing minerals in addition to waste rock. In fact, tailings dumps are technogenic mineral deposits, which can be used in various industries. The storage of iron ore tailings (IOT) in tailings facilities is not only a heavy financial burden for management companies, but also causes a number of environmental problems, such as soil, water, and air pollution. For this reason, the development of environmentally and economically efficient technologies in the field of recycling iron ore tailings is gaining popularity.

Table 1 presents data on the amount of Iron ore tailings in the Russian Federation in 2021, it shows that the percentage of recycling from the annually generated waste is currently quite low (34%).

Type of Iron ore tailings	**The amount of IOT at the beginning of the reporting year [tons]**	**IOT generation during the reporting year [tons]**	**Disposed IOT [tons]**	**The amount of IOT at the end of the reporting year [tons]**
IOT from wet magnetic separation of iron ores	2 299 640 217	174 340 872	56 895 639	2 353 218 509
IOT from dry magnetic separation of iron ores	27 142 856	5 000 508	3 044 780	27 290 354

Table 1: Amount of Iron ore tailings in Russia, 2021 (*Rosprirodnadzor | Information on the formation, processing, disposal, neutralization, disposal of production and consumption waste*, no date).

The main reason why recycling of IOT has not found mass application on an industrial scale in the Russian Federation is the lack of innovative, cost-effective technologies. According to the Forecast of Scientific and Technological Development of the Russian Federation for the period until 2030, one of the leading directions of the current state policy is the integrated development of mineral resources as well as technogenic raw materials on an industrial scale. The expected result of this policy is the rational use of the mineral resource base.

In order to create the necessary conditions, the Government of the Russian Federation issued a "Strategy for the development of industry for the treatment, utilization and neutralization of production waste for the period up to 2030," in which ferrous metallurgy enterprises are listed as the main types of industrial facilities that generate waste and use processed secondary raw materials from waste in production, on the basis of which an updated system was created, focused on the involvement of industrial waste in economic turnover.

The current situation of tailings storage at Stoilensky is as follows: the annual generation of tailings is 20 million tons, 15 million tons of which are accumulated in the tailings storage facility, and 5 million tons are used for dam formation. Regarding planned production growth, the formation of tailings will increase to 27 million tons, 20 million tons of which will go to the accumulation and 7 million tons - to the formation of the dam. At the beginning of 2020, the amount of accumulated IOT amounted to 381 million tons with the useful capacity of the tailings dump of 490 million tons (*Information concerning NLMK's tailings dam management*, 2020). Thus, the priority task of Stoilensky GOK is the maximum processing and application of the generated tailings to prolong the lifetime of the existing tailings storage facility, because the construction of an additional tailings storage facility will require impressive costs from Stoilensky GOK, and will also entail increased risks of environmental pollution.

Stoilensky is developing the Stoilenskoye deposit, which is the third largest deposit in the Russian Federation in terms of its share of balance reserves and is represented by the hematite-magnetite in ferruginous quartzite type of ore with a Fe content of $Fe_{\text{общ}}$ of 30 percent. At the same time, the geological and industrial type of ores of this deposit is identical to the Mikhailovskoye deposit, which is the largest in scale of mineralization in Russia. Both of these deposits along with Lebedinsky constitute the main part (about 60%) of the reserves of the Kursk Magnetic Anomaly, which in turn forms the basis of Russia's iron ore base (more than 63% of the country's reserves are concentrated in the KMA). It is important to note that the main source of iron ore raw materials in Russia are the deposits of ferruginous quartzites, which are also mostly of medium quality (their $Fe_{\text{общ.}}$ varies from 16 to 40%) (Ministry of Natural Resources and Ecology of the Russian Federation Federal Agency for Subsoil Use (Rosnedra)., 2021). The solution of the problem of iron ore tailings recycling at Stoilensky GOK can make a significant contribution to solving the problem of tailings recycling for most of the Russian enterprises due to the typicality of the host rock and the quality of ores.

The goal of the work is the scientific justification and development of technical solutions for obtaining iron coagulant on the basis of iron ore tailings, providing an effective treatment of industrial wastewater.

In order to achieve this goal, the following tasks were formulated:

1. Conducting analyses to determine the chemical, mineralogical, granulometric composition, as well as identifying the morphology of IOT particles in order to assess the suitability raw material for a new commercial product - ferric coagulant.

2. Selection of parameters of the process to obtain a coagulant based on iron ore tailings. Evaluation of the effectiveness of the obtained coagulant.

4. Conducting analyses to determine the chemical and particle size distribution composition of residues after iron recovery from iron ore tailings as raw materials for the construction industry.

5. Environmental and economic justification of the effectiveness of the proposed engineering and technical solutions.

Scientific Significance:

Method for the preparation of coagulant on the basis of iron ore tailings was developed.

The composition of coagulant and residues after acid leaching depending on the acid used in the preparation process, the method of contacting, contact time, heating and the ratio solid: liquid was established.

For the first time a comprehensive approach to the utilization of iron ore tailings on the example of Stoilensky GOK by creating on its basis a coagulant for wastewater treatment and raw materials for the construction industry is considered.

Practical Significance:

On the basis of the research the flow chart of utilization of iron ore tailings with obtaining a highly effective coagulant has been developed. The results indicate that the production of coagulants may be considered to extend the productive chain of iron ore exploration. The benefits may include the improving of iron recovery in the iron ore sector, production of a chemical reagent that could be used in sanitary operations, and the reduction of the environmental pressure for siliceous sand.

The main defended provisions:

1. Obtaining a complex coagulant with Fe in form of sulfates (III), - 11% and Al in the form of sulfates - 2 % is achieved by modifying the iron ore tailings of Stoilensky GOK with 40% sulfuric acid solution in the ratio solid: liquid 1:1 at temperature 100^{0}C for 60 minutes.

2. Processing of iron ore tailings of Stoilensky GOK with obtaining coagulant is achieved by using the following chain of apparatuses: acid feed tank, acid leaching reactor, waste feeder and hopper, gas trap, sedimentation tank, with the formation of primary processing waste, which is a sand-like mixture with quartz content of 77 - 79% and particle size range 2 - 1000 microns, which can potentially be used as a raw material for the construction industry.

2. Company description

1.1 General information

Stoilensky develops one of the largest deposits of the Kursk Magnetic Anomaly: the Stoilensky deposit. The main consumer of Stoilensky's products, namely iron ore sinter, pellets and concentrate, is Novolipetsk Iron and Steel Plant. Stoilensky is one of the top three producers of iron ore. The company is a part of NLMK Group.

1.1.1 Orohydrography

Relief, landscape and geological characteristics. In geomorphological terms, the area occupies part of the southern slope of the Sredne-Russkaya Upland, located within the sublatitudinal Timskoye uplift. The construction and operation of Stoilensky GOK facilities has led to the formation of technogenic landforms: dumps, tailings pits, and various production sites, which are mostly located on the western and northeastern part of the quarry. The natural forms of relief include ridges with plateau-like tops with separating them with a gully system. In the northern part there is an area of arable land, in the western part there is an oak and maple forest.

Speaking of the deposit developed by SGOK, it is located within the Stoilo-Lebedinsky ore cluster. The deposit is characterized as large and complexly folded, with the presence of a complexly dislocated complex of Archean and Precambrian metamorphic formations. They are also overlain by a cover of horizontally deposited Phanerozoic sedimentary rocks.

The ores at Stoilensky are both unoxidized and oxidized ferruginous quartzites. The main rock-forming minerals of the Stoilensky deposit include: martite, magnetite, limonite, iron mica and quartz.

Climatic characteristics of the territory. The type of climate of the territory of Stoilensky is moderately continental. Climatic characteristics are given in Tables 2-4.

I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII	annual average
-7,5	-16,8	-1,6	7,8	14,7	18,3	20,1	18,7	12,8	6,4	-0,4	-5,2	6,5
- average maximum temperature of the hottest month (July),° C												+25,9
- average temperature of the coldest month (February), ° C												10,6

Table 2: Average air temperatures by month and by year [ºC]

Monthly average wind speed [m/s]

I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII	annual average
3.5	3.6	3.4	3.3	3.0	2.7	2.6	2.5	2.6	3.2	3.4	3.6	3.1

Frequency of wind direction and doldrums, %

N	NE	E	SE	S	SW	W	NW	Calm
17	8	12	10	17	12	14	10	7

Table 3: Wind conditions

Fogs. The greatest duration of fog during the year, days - 61. Stratification coefficient - 180.

I	II	III	IV	V	VI	VII	VII	IX	X	XI	XII	annual average
9	32	30	38	49	68	74	55	51	43	49	44	572
number of days per year with precipitation												154

Table 4: Sum of precipitation by months and year [mm]

Hydrogeological conditions. The sediments above the albsenomanian deposits were drained, as Stoilenskoye field is located in the zone of disturbed hydrogeological regime. At the same time, three aquifers are developed in the immediate vicinity of the dried part: the albsenomanian aquifer, the aquifer of Middle-Upper Jurassic sediments and the aquifer of fractured Archean-Proterozoic rocks. The first one is the main source of domestic and drinking water supply for the SGOK. Water-bearing rocks are represented by fine- and medium-grained sands. According to the chemical composition, the waters of the horizon are calcium-hydrocarbonate. The second one has a small thickness: 4-14m within the boundaries of the deposit. Water-bearing rocks are represented by rare small interlayers and lenses of clayey sands and siltstones among sandy clays. The third of the above-mentioned rocks is confined to a weathered and fractured zone with a thickness of 10-50. Rich iron ores and fractured oxidized quartzites are the most watered. The hydrodynamic regime of groundwater is characterized by the presence of regional depression sinkholes from Lebedinsky and Stoilensky open pits with conditional radii of 10-15 km. The greatest decrease in the groundwater level is not more than 250 m.

Properties and composition of the main types of soils, characteristics of flora and fauna of SGOK. Black earth soils in combination with dark gray forest-steppe soils predominate in the soil cover on the territory of SGOK. Soil-forming rocks are loess-like loams. Soil cover of undisturbed land plots consists of podzolized, leached, typical, typical carbonate and dark gray forest soils. In chernozem soils the content of humus in the upper horizon is from 2,5 to 5 %. The thickness of the humus profile is 20-70 cm. The soils are characterized as soils suitable for biological land reclamation. Such soils can be used without restrictions.

In the area of quarry site the natural vegetation has been significantly affected, which manifests itself in the reduction of typical meadow and steppe species and the strengthening of weed vegetation. There are also plantings of acacia, aspen, common ash, pine, birch, poplar, with the occasional inclusion of apple and pear trees throughout the dump area. The entire area adjacent to the quarry and not exposed to mining has natural greenery. In the area of the southwestern part of the quarry, local areas of forest land and arable agricultural land adjoin.

The number of many animal species in the area of Stary Oskol is much lower than optimal; in the territory of the industrial enterprise and the settlements of Kotenevka and Verkhnechufichevo the animal world is extremely impoverished. As for the fauna, the inhabiting animals are adapted to anthropogenic factors. The most pronounced are soil fauna and small mammals. Birds: pigeon, sparrow, gray crow, magpie, reptiles: jumping lizard, among amphibians - grass frog. Among terrestrial invertebrates stiff-winged, two-winged hymenopterous insects dominate. Animals and plants included in the Red Book were not found.

1.2 Description of the main technological processes of SGOK

1.2.1 Process flowsheet of beneficiation

The Process flowsheet of rich ores processing includes three crushing stages and two screening stages with separation of agglomerated ore, and enrichment of ferruginous quartzite (magnetite) - three crushing stages with a closed cycle in the last stage, three-stage crushing, wet magnetic separation, desliming, concentrate dehydration on vacuum filters. Hydrotransport of tailings is pressure-suction. Recycled water supply is used.

Ore from the quarry is transported by rail first to an intermediate storage facility and then to the crushing and sorting section. Two types of ore are received from the quarry - hematite-siderite-martite iron ore and unoxidized ferruginous quartzites. After the CSS coarse lumps of rock with a fraction up to 20 mm are sent to the coarse crushing unit (CCU), then the crushed ferruginous quartzite is sent to the medium and fine crushing unit (MFCU). There are 40 mills in the MFCU, which grind the ore and bring it to a fraction of 5.8 mm.

The ferruginous quartzite of the required fraction is sent by conveyor method to the beneficiation plant, divided into 4 sections, where the ore is upgraded to particle size of 45 microns and the useful component is separated from the waste rock by means of wet magnetic separation. The enriched iron in the 45 μm fraction goes to the pelletizing plant, whose main objective is to increase the share of own prepared iron ore in NLMK Group's total consumption in order to achieve the maximum economic effect in the production of commercial products. After the pelletizing process is completed, raw materials are sent by rail to the main customer, Novolipetsk Steel.

1.2.2 Process flowsheet of the tailings storage area

Waste rock or pulp from the concentrator flows by gravity to the main pulp tray and through the switch chambers to the thickening unit, and is also distributed to the switch chambers. The tailings management facility (TMF) includes two sections: the slurry and rock systems section (SDS) and the tailings pond section. The thickening unit is located at the slurry system section at an altitude of about 200 meters above sea level and includes three radial thickeners connected by water lines to the water recycling pumping station and by slurry lines to the slurry pumping station.

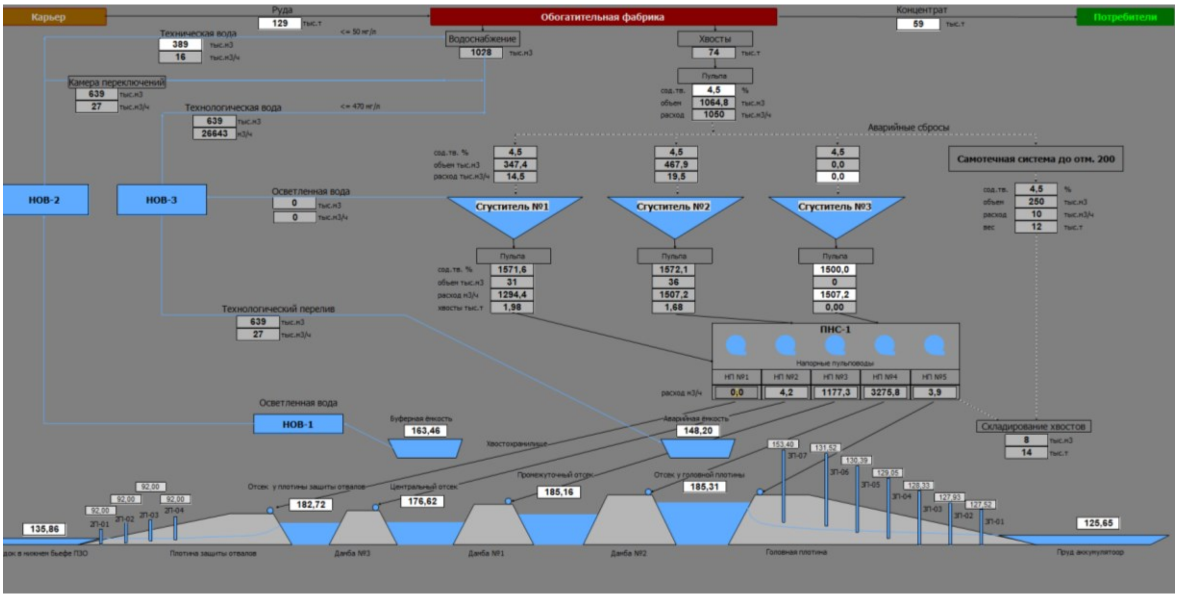


Figure 1:Schematic diagram of the hydrotransport and water recycling system of the tailings management facility

Thickeners are designed to separate solid and liquid phases of slurry and supply thickened slurry to slurry pumping station №1 (PPS-1), clarified water to pumping station of recycled water supply №3 (NOV-3) (figure 1).

The scheme of the thickeners operation is as follows: through the underground main pulp tray the pulp comes from the concentrator and is distributed by switching chambers to the feeding wells of radial thickeners 1,2,3, where through the feeding device (figure 1) the flocculant is supplied and the pulp is mixed with the reagent and the solid phase and clarified water are separated. The reagent used is Nalco 9901, the main component of which is urea or carbonic acid diamide derived from ammonia and carbon dioxide. The quality data sheet for the product is shown in Table 5.

Indicator name	Normative value	Analysis result

Content of active substance, %	88-100	91,6
Content of active acrylamide, %	0,499	0,120
pH 0.5 of the solution	5,5-7,5	7,5
Solution appearance	Slightly cloudy, viscous solution	Corresponds

Table 5: Product quality passport.

In the thickener vat the solid phase gradually settles and separates into a "mass" and a "bed" (a slurry layer between the sludge and clarified water in the thickener vat). Inside the thickener vat there are rakes - two long and two short - which are driven by the power plant and mix the slurry, while the cone-shaped design helps the slurry (also called "mass") to collect at the bottom of the thickener in the discharge cone - from where the thickened slurry flows to the slurry pipes and then to the NPS.

In-situ pressure slurry pipelines of the plant are built into the subchannel space of the thickeners - they start from the pump units of the thickener and are intended for transportation of the thickened slurry to PNS-1.

The water supply system of the processing plant includes a complex of structures and equipment to ensure uninterrupted water supply to the processing plant. Structurally, the water supply system for the processing plant consists of a number of structures, including pumping stations NOV-1, NOV-2, NOV-3, as well as technical and technological water lines from the pumping stations to the processing plant. Water supply to the processing plant is carried out in three ways.

The first one is technical water supply to the processing plant in two lifts, from the buffer tank NOV-1 to the water intake sump NOV-2, from NOV-2 through water pipelines to the processing plant. The requirements to the technical water supply: solid content should not exceed 50 mg/l, this parameter is controlled by the personnel of the laboratory for environmental protection and chemical and bacteriological analysis.

Second - process water supply to the processing plant is carried out by the pumping station NOV-3 in one lift through the process water pipelines to the processing plant. The requirements to the process water supply: solid content must not exceed 470 mg/l, it is controlled by the personnel of the Central Sewage and Disposal Department according to the readings of turbidity sensors installed on the water pipelines of NOV-3.

The third one is a combined water supply to the processing plant. In the water pipe switching chamber, by opening gate valves No.1-1 and No.4-1, process water is supplied to the process water pipelines.

Before thickening, the slurry contains about 4.5 to 7 percent solids, whereas after passing through the radial thickeners, the thickened slurry contains 54 percent suspended solids.

The process of technical water clarification takes place in the compartments of the tailings pond. After slurry release to the beach, large particles of solids are deposited on the beach, and smaller ones are carried to the pond zone of the compartment, where they settle to the bottom along the flow path. Partially clarified process water from the tailings pond compartments flows by gravity to the central pond compartment, where it is additionally clarified (solid content 10 to 12 mg/l). From the central pond section the clarified process water flows through the bypass structure to the buffer tank in Sychev Log headrace. On the left slope of Sychev Log, there is a stationary pumping station. On the left slope of Sychev Log is a stationary pumping station of water recycling supply of the first lift (NOV-1) of coastal type with a water-receiving bucket. WWS-1 supplies service water through water pipes to the receiving chamber of WWS-2, which in turn supplies service water through water pipes to the processing plant and for its own needs of the thickening unit (US). Excess water is discharged to the buffer tank through the system of technological overflow. Technical water pipelines from NOV-2 to OPF and from OPF to NOV-3 operate continuously. Full stops of water pipelines coincide with the shutdown of OPF for repairs. Technical water is also intended for filling the bowl of thickeners 1,2, receiving sump of No.3 and process water pipelines during each start-up of RS.

Reagent facilities. Reagent facilities include a flocculant storage facility and the reagent preparation and dosing area itself. Water for preparation of flocculant solution comes from the tailings storage facility through HOB-1 and HOB-2 and is of technical quality - less than 50 mg/l of solid particles.

Flocculant preparation and dosing systems POLY-35 and POLY-75 (35 and 75 kg of reagent per hour), which are part of the reagent preparation section, are designed to prepare and feed the solution automatically. The working solution of flocculant has a concentration of 0.05% of the reagent in accordance with the manufacturer's instructions, although experimental production tests (OPI) with concentrations of 0.03% and 0.08% were conducted, but the effect of changing the concentration was negligible. An emergency solution of 0.5% concentration is provided. The flocculant storage warehouse is designed for long-term and short-term storage of flocculant and its supply to the preparation place. The flocculant aid in dry form is stored in the warehouse in big bags (750 kg) - one such package is enough for about a day of operation of two thickeners.

Nalco (PULV) 9901 is used as a flocculant. This type of reagent as a result of OPI and comparison with other brands, for example, Superflok A137, Praestol 2540, proved to be cheaper and has a lower specific consumption.

All operations in the thickeners are automatic, the controllers control water consumption, reagent amount, discharge turbidity, bed level, pulp density, specific power consumption of power units, pumps, rake torque, feeding pressure. All data is summarized in electronic tables, strict control is carried out.

The dispatcher also corrects reagent supply, if necessary, contacts the operating plant, workers from the LOV-1 and LOV-2, where the digitalization of the processes has not yet been carried out, collects the data necessary for reporting. Provides for suspension of thickener operation in case of repair/maintenance, weather conditions (thunderstorm), emergencies, etc. Repair/maintenance works are performed for 5 days per year on each thickener in accordance with the annual planning.

From the thickeners the slurry is delivered to the slurry pumping station No.1 (PPS-1), then it is conveyed to the tailings pond section by the pressure tailings impoundment pipelines No.1, 2, 3, 4, 5. The pressure slurry line 1 is designed to transport the tailings for reclamation of the tailings protection dam and the right board of the central compartment, slurry line 2 - for reclamation of dam 3 and the right board of the central compartment, slurry line 3 - for reclamation of dam 1, slurry line 4 - for reclamation of dam 2, slurry line 5 - for reclamation of the head dam.

Tailings Management Facility site. Table 6 shows the main characteristics of the tailings storage facility.

Name of characteristic	Value of characteristics
Class	1
Type by relief	Girder
By method of filling	Flush
Scope:	
Useful	
Million tons.	470.461
General	
Mil. tonnes	472.630
Capacity	
Mil. tonnes	489.259
Area, thousand m^2	
Useful	9829
general	14927
Maximum height of dam [m]	67.5

Number of dams	7
Number of compartments	4
The number of sedimentation ponds	2

Table 6: Characteristics of the tailings storage facility

The tailings storage facility includes the following systems: tailings hydrotransportation, tailings hydraulic stacking, water recycling system, hydraulic protection and drainage water return system, thickening, recycling water supply and tailings transportation unit, local warning system, irrigation and dust suppression system.

The tailings hydrotransport system includes:

– trunk pipeline (underground) with switching chambers №1, 3, 5, 6, 7 and installation opening;

– slurry outlet from the enrichment plant in the headwaters of c. Rubizhny Log (underground) with switching chambers No. 5a, 8 and installation opening;

– distribution tray-pulp 1 (underground) with switching chamber 2;

– open tail chute paddle 2;

– pressure slurry pipeline №1 with slurry outlets;

– pressure slurry pipeline №2 with slurry outlets;

– pressure slurry pipeline №3 with slurry outlets;

– pressure slurry pipeline №4 with slurry outlets;

– pressure slurry pipeline №5 with slurry outlets.

The entire tailings impoundment is divided by dams into four compartments: the head dam compartment, the intermediate compartment, the central pond compartment and the compartment at the tailings dam (Figure 2). The slurry flowing between the tailings pond compartments is directed from the central compartment to the buffer tank. From the buffer tank, the pumping station of the first lift of the recycling water supply with the water receiving bucket (NOV-1) takes the clarified water and delivers it to the pumping station of the second lift (two zones of water lifting exist due to the height difference and head loss). The pumping station of the second lift of the recycled water supply (NOV-2) is designed to supply water to the concentrator and the post-treatment section.

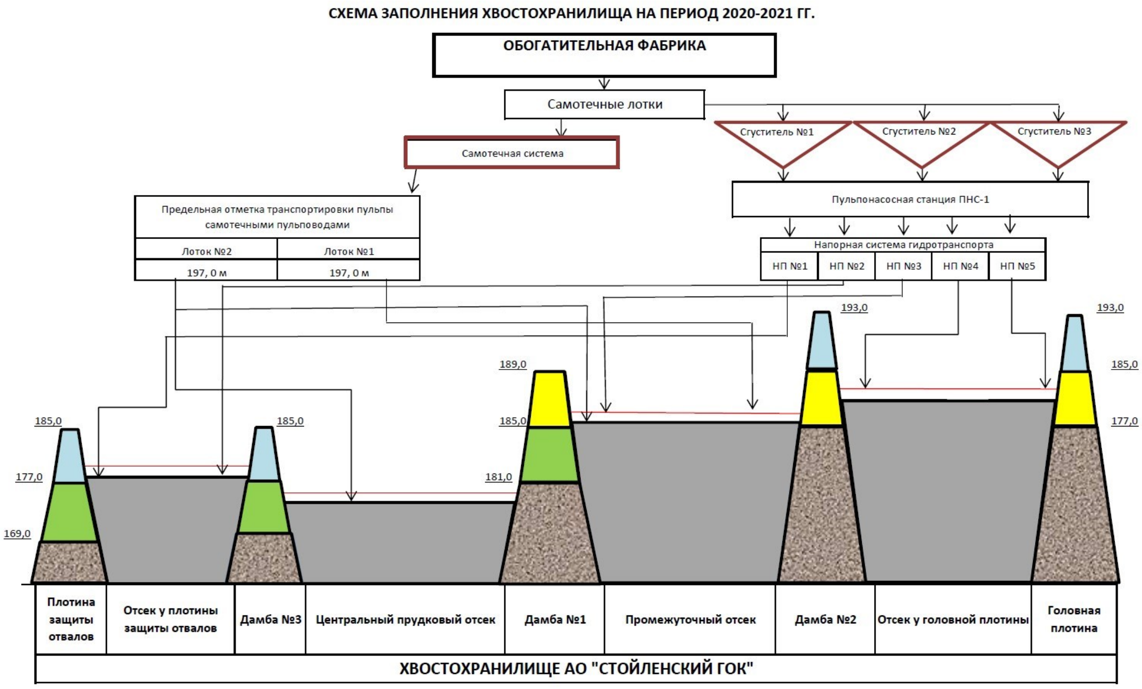


Figure 2: Location of the tailings storage facility compartments

The head dam compartment is bounded by the head dam, dam No.2, and the dam in the Rubizhny Log gully, with crest marks of 193.0 m. The total volume of the section is 99.529 million m3. On the side of the dams and dikes, the bases of the next tiers are being reclaimed, and on the side of the bank reaches - the impervious blanket is being reclaimed.

The intermediate section is bounded by dam No.2 with crest marks - 193.0 m, dam No.1, head dam, with crest marks - 189.0 m. Total volume of the section is 93.328 mln m 3 . From the side of the dam and dikes, the bases of the next tiers are being reclaimed, and from the side of the bank reaches the impervious blanket is being reclaimed.

The compartment at the tailings protection dam is limited by the dam No.3 and the tailings protection dam with crest marks of 185.00 m, total volume of the compartment - 48.409 mln m 3. The bases of the next tiers are being reclaimed on the side of the BFZ and dyke No.3, and the impervious blanket is being reclaimed on the side of the onshore reaches.

The central pond section is bounded by dike No. 1 with a crest mark of 189.0 m, dike No. 3 with a crest mark of 185.0 m and a spoil protection dam with a crest mark of 185.0 m. The total volume of the compartment is 60.186 million m^3 . The base of the next tier is being reclaimed on the side of the Dump Protection Dam, and the impervious blanket is being reclaimed on the side of the dikes bank reaches.

The buffer storage capacity of NOV-1 is limited by a road access dam with a crest elevation of 166.0 m and a spoil protection dam, the total volume is 2.023 million m^3.

Head dam (hereinafter referred to as HS) is the downstream dam enclosing the tailings dam in the Chufichev gully. It has an embankment dam, filled with tailings at the height of 193.0 m. The width along the crest is 15.0 m. The upstream slope is secured with rock to prevent scour, the ridge is secured with sediment. Lower slope is secured with loam and chernozem. Along the ridge the pressure pulp line №5 with outlets for reclamation of the base of the next layer of the build-up, as well as water line of irrigation and dust suppression system were installed.

Dump Protection Dam (hereinafter referred to as DPS) is the upstream dam enclosing the tailings storage facility in B. Chuficheva and Sychev Log. Sychev Log. It has an embankment dam, filled with tailings at 185.0 m height. The width along the ridge is 15 m. The upstream slope is fixed with rock, the downstream slope is covered with loam and chernozem, the ridge is fixed with sediment. Along the ridge the pressure pulp line #1 was installed with outlets for reclamation of the base of the next build-up tier, and in the section in Sychev Log, also with outlets for reclamation of the base of the next build-up tier. In the Sychev Log area, the pressure slurry pipeline 2 with outlets for reclamation of the base of the next build-up tier was installed as well (Sychev Log). At the height of 173.00, the water conduit of the DIS was installed. In 2022 it is planned to build up the dam to the elevation of 189.0 m.

Dam No.1 is a separating dam with crest mark of 189.0 m. It is made of tailings with rock fixing of upstream and downstream slopes, the dam crest is fixed with sediment. The width along the crest is 15.0 m. To pass clarified water from the intermediate compartment to the central pond compartment, a shaft-type outlet structure with a receiving well of 2 pipes Ø1020 mm and a spillway collector of 2 pipes Ø820 mm is made in the dam body. The capacity of the outlet structure is regulated by installing control rings on the well. At the height of 189.0 m there is a slurry pipeline with slurry outlets to the intermediate and central compartments of the tailings pond, designed for beach reclamation in the upstream and downstream embankments.

Dam No.2 is a separating dam with crest mark of 193.0 m. It is made of tailings with rock fixing of upstream and downstream slopes, the dam crest is fixed with crushed stone. The width along the crest is 15.0 m. To pass clarified water from the head dam compartment to the intermediate compartment, a shaft-type outlet structure with a receiving well of 2 pipes Ø1020 and a spillway collector of 2 pipes Ø530 mm is made in the dam body. The capacity of the outlet structure is regulated by installing control rings on the well. At the height of 193.0 m, a slurry pipeline with slurry outlets to the head dam compartment and intermediate tailings pond compartment, designed for beach reclamation in the upstream and downstream embankments, was installed.

Dam #3 is a separating dam with a crest elevation of 185.00 m. The dam is made of tailings with rock fixing of the upstream and downstream slopes, the dam crest is fixed with sediment. The width along the crest is 15,0 m. The dam body is equipped with a shaft-type culvert to pass clarified water from the compartment at the tailings protection dam to the central compartment. Along the crest the pressure slurry pipeline No. 2 with slurry outlets was installed for reclamation of the base of the next tier of the dam and downstream reclamation of the tailrace dam. In 2022, it is planned to build up the dam to elevation 189.0 m.

Dam in Rubizhny Log gully - is an enclosing structure. It has an embankment dam, piled with tails at 193.0m height. The dam crest is secured with crushed stone, the upstream slope is secured with rock. The downstream slope is fixed with loam and chernozem. The width along the crest is 15.0 meters. Along the crest there were installed: pressure slurry pipeline No.5 for reclamation of the base of the next build-up tier, pressure slurry pipeline No.4 - reclamation at the intermediate section, transit of slurry pipeline to the dam No.2, and also water line of irrigation and dust suppression system.

Dike-roadway in Sychev Log gully - is a cut-off dike. It is filled with loam at a height of 166.0 m. The slopes and crest of the dam are secured with rock. It is designed to create a buffer capacity and road crossing through Sychev Log gully.

1.3 Environmental impact

The development of a mineral deposit and the operation of an enrichment plant are accompanied by a disturbance of the natural geological structure

Reclamation of disturbed lands. The currently explored reserves of the deposit will provide the SGOK with mineral raw materials for more than 100 years. In this regard, reclamation of disturbed lands may be considered only at the later stages of design taking into account measures for liquidation of the mining and processing facilities, but during the operation of the tailing facility territory it is necessary to perform reclamation of the tailing dump dam. Also, at this stage of the operation of the SGOC, measures for preservation of the soil layer as well as measures for operational reclamation of individual tiers are implemented.

Reclamation of the tailings dam is carried out in the following way: firstly, two tiers of the tailings dam are reclaimed (each tier is 3 meters high), then the fixing materials in 4 layers are dumped directly on the slopes: waste rock, loam, sand and fertile soil layer. The surface of the slope is leveled by bulldozers and thus, the top of the lower slope and the top of the upper slope are connected, resulting in a stable recultivated slope. The berm is left for greater stability of the slopes and is also used as roads for transport.

Impact on atmospheric air. The total number of production emission sources is 649. The number of pollutants discharged into the atmospheric air is 101 substances. According to the Information and Technical Handbook on the Best Available Technologies, the characteristic (marker) substances for mining and concentration of iron ores are pollutants: - dust; - nitrogen oxides; - sulfur dioxide. The main pollutants (in terms of gross emission) are: sulfur dioxide (64.4%), nitrogen dioxide (17.4%), inorganic dust containing 20-70% SiO2 (5.5%), sulfur dioxide (2.3%). 20-70% SiO2 (5,7%), inorganic dust containing less than 20% SiO2 (5,0%), carbon oxide (4,2%), and nitrogen monoxide (2,8%). The contribution of each of the other pollutants does not exceed 1.0%.

According to the data of the environmental impact assessment of the enterprise, it is established that the emissions by all pollutants and summation groups in all control points do not exceed the permissible standards. The volume of pollutant emissions is presented in Table 7.

Pollutant code	Contaminants	Emission of pollutants into the atmosphere [tons]	
		From fuel combustion (for electricity and heat generation)	From technological and other processes
2	Solid substances	0.006	3684.506
330	Sulfur dioxide	-	3684.506
337	Carbon monoxide	58.735	1330.573
12	Nitrogen oxide (in terms of NO2)	27.061	5234.295
7	Hydrocarbons including VOCs (excluding methane)	-	410.75

Table 7: Volume of pollutant emissions

Impact on surface and ground waters. The sewerage system of SGOK is centralized, separate by type of waste water with connection to the existing networks of the enterprise.

Since the company operates a recycling water supply system, water from the quarry is used to recover losses at the concentration plant associated with evaporation of water from the tailings pond. Thus, the mine operations do not have a negative impact on the condition of surface and ground waters.

Environmental impact of production and consumption waste management. In the course of production activity of OJSC Stoilensky GOK a wide range of production and consumption wastes is generated. According to the document on approval of waste generation standards and waste disposal limits, 155 types of wastes of hazard classes I to V are generated with an annual volume of 105.215.696.175 tons.

As a result of the increase in the productivity of the open pit for ore, an increase in waste of ore mining and processing is expected. At the same time, compliance with the currently established requirements and rules in the field of waste management established at the enterprise will not lead to additional hazards to the environment.

Activities to reduce the environmental impact caused by dried up beach areas are based on a multitude of activities. First of all, it is the use of waste for the construction of hydraulic structures, as well as the reclamation and reinforcement of the slopes of dams and dikes. An important role is played by the care of a forest belt 7 km long and the treatment of beaches with reagent.

In 2010, an irrigation system was installed in the tailings ponds to keep the beaches moist. This led to a significant reduction in the amount of dust. In 2015, a stationary irrigation system was built, which proved to be very effective, despite the fact that it does not work during the build-up period of the compartment.

In addition, experiments have been conducted on dust suppression using binder mortars and various techniques. However, these methods have encountered problems associated with the need to create an emulsion base, high operating costs and low efficiency.

In October 2020, pilot tests were conducted on an area of 6 hectares, where treatment with the reagent was carried out with an agricultural irrigation unit. This method proved to be effective, especially in windy weather.

Plans for 2021 include building up a compartment at the head dam, constructing an irrigation system, and providing dust suppression with fixing reagents on 106 hectares before the irrigation system is launched. The expected total costs will be about 14 million rubles.

The irrigation system introduced in 2021 is an improved version of the former 2015 system. A distinctive feature of the new system is the possibility of dismantling the main elements for further operation when the dam is expanded. It works thanks to irrigation plants operating within a radius of 50 meters and maintaining the wet condition of the near-dammed areas of the beaches.

As part of air protection, the company actively combats various environmental problems, including exhaust emissions, dust and other pollutants. These measures include transport diagnostics, reclamation of slopes, planting of vegetation, irrigation of ore extraction areas and replacement of filters. Other measures include technical upgrading of the dust suppression system.

Protecting water bodies is another important area of the company's activities. Numerous environmental protection measures, including construction of sewage systems, interception of drainage shafts and reduction of pollutants in wastewater, help reduce the impact on the environment. Of particular note is the construction of a heavy vehicle washing station, which helps reduce pollution in adjacent areas.

3. Research part

1.4 Literature review

Problem statement. At the present in the Russian Federation is an unfavorable situation associated with the formation and storage of IOT. It is well known that the accumulation of IOT, consequently, their distribution in the environment can cause a serious environmental hazard, which, in turn, has attracted considerable attention to the possibility of iron ore tailings processing and their further use as raw materials for the production of other materials.

The current situation of tailings accumulation at Stoilensky is as follows: the annual formation of tailings is 20 million tons, of which 15 million tons are accumulated in the tailings storage facility, and 5 million tons are used for dam formation. In connection with the planned production growth, the formation of tailings will increase to 27 million tons, of which 20 million tons will go to the accumulation and 7 million tons - to the formation of the dam. At the beginning of 2020, the amount of accumulated wastes amounted to 381 million tons with the useful capacity of the tailings dump of 470.461 million tons (*Information concerning NLMK's tailings dam management*, 2020). Proceeding from this, the priority task of the enterprise is the maximum processing and application of the generated tailings to prolong the lifetime of the existing tailings storage facility, because the construction of an additional tailings storage facility will require impressive costs from Stoilensky GOK, and will also entail increased risks of environmental pollution.

Stoilensky is developing the Stoilenskoye deposit, which is the third largest deposit in the Russian Federation in terms of its share of balance reserves and is represented by the hematite-magnetite in ferruginous quartzite type of ore with a Fe content of$_{\text{общ}}$ of 30 percent. At the same time, the geological and industrial type of ores of this deposit is identical to the Mikhailovskoye deposit, which is the largest in scale of mineralization in Russia. Both of these deposits, along with Lebedinsky, account for the bulk (about 60%) of the reserves of the Kursk Magnetic Anomaly, which in turn forms the basis of Russia's iron ore base (more than 63% of the country's reserves are concentrated in the KMA). It is important to note that the main source of iron ore raw materials in Russia are deposits of ferruginous quartzite, which in most cases are also of medium quality (their F content$_{\text{еобщ}}$. varies from 16 to 40%) (Ministry of Natural Resources and Ecology of the Russian Federation Federal Agency for Subsoil Use (Rosnedra)., 2021). In fact, the solution of the problem of utilization of iron ore tailings of Stoilensky SGOK can make a significant contribution to the problem of tailings utilization for most of the Russian enterprises due to the typicality of the enclosed rock and the quality of ores.

The main reason why recycling of Iron ore tailings has not found mass application on an industrial scale in the Russian Federation is the lack of innovative, cost-effective technologies. According to the Forecast of Scientific and Technological Development of the Russian Federation for the period until 2030, one of the leading directions of the current state policy is the integrated development of mineral resources as well as technogenic raw materials on an industrial scale. The expected result of this policy is the rational use of the mineral resource base.

In order to create the necessary conditions, the Government of the Russian Federation issued a "Strategy for the development of industry for the treatment, utilization and neutralization of production and consumption waste for the period up to 2030," in which ferrous metallurgy enterprises are listed as the main types of industrial facilities that generate waste and use processed secondary raw materials from waste in production, based on which an updated system focused on the involvement of industrial waste in economic turnover.

In order to solve these problems, numerous research works have been focused on the utilization of iron ore tailings and their multipurpose use. Since the chemical composition and, accordingly, the physical properties of iron ore tailings vary significantly depending on the deposit and the method of concentration, the choice of a particular disposal technology in each case requires special attention.

The aim of the work is to analyze and summarize the current information about the existing modern technologies for processing of iron ore tailings. The analysis of technologies is based on a review of recent studies aimed at the description and experimental confirmation of the compliance of the materials obtained from iron ore tailings to the required standards.

Research objectives - search, analysis and synthesis of literary sources on the topic of utilization (processing) of iron ore tailings.

The object of the study is the iron ore tailings of Stoilensky GOK.

The subject of the research is the methods of utilization of iron ore tailings.

1.5 Analysis of IOT processing technologies

Iron ore tailings (IOT) is the result of the ore enrichment process, which is a combination of methods to separate metals and minerals due to differences in their chemical or physical properties.

Waste Origins. According to a rough estimate by Global Tailings Review (D. Franks, no date), based on information provided by public companies, there are currently 1,743 unique sites containing 44.54 billion m^3 tails. At the same time, the authors suggest that the actual number of tailings facilities is much higher, namely: there are about 3,250 active tailings facilities around the world, and the total number of active and closed facilities is about 8,500. It is estimated that in 2016, more than 8 billion tons of tailings were produced in mining worldwide. Meanwhile, iron ore tailings account for nine percent of total waste (*Global Tailings Review. Chapter II. Mine Tailings Facilities: Overview and Industry Trends*, no date). Despite the fact that the authors refer to a rather large possibility of data inaccuracy due to non-disclosure of information by mining companies, the reported volume of waste indicates the criticality of the problem.

According to the state report "On the State and Use of Mineral Resources of the Russian Federation in 2020" (Ministry of Natural Resources and Ecology of the Russian Federation Federal Agency for Subsoil Use (Rosnedra)., 2021), the leading countries in the production of iron ore products are Australia, Brazil, China, India and Russia (Table 8).

Country	Stocks, category	Reserves [billion tons]	Share in world reserves [%]	Production in 2020 [million tons]	Share in world production [%]
Australia	Proven + probable reserves	23.1	9.4	917.2	38.4
Brazil	Stocks	34	13.8	389.5	16.3
China	Installed reserves	85.3	34.6	340	14.2
India	Proven + probable reserves	5.4	2.2	203.1	8.5
Russia	Category A+B+C reserves$_1$	29.4	12	110.8	4.6

Table 8: Iron Ore Reserves and Commercial Iron Ore Production in the World.

Accordingly, in these countries the issue of recycling and utilization of Iron ore tailings is the most acute. Table 9 presents data on the amount of Iron ore tailings in the

Russian Federation as of 2021, from which we can conclude that the percentage of waste recycling at the moment is quite low.

Type Iron ore tailings	Iron ore tailings the beginning of the reporting year [tons]	Iron ore tailings generation during the reporting year [tons]	Disposed Iron ore tailings [tons]	Iron ore tailings at the end of the reporting year [tons]
Iron ore tailings of wet magnetic separation of iron ores	2 299 640 217	174 340 872	56 895 639	2 353 218 509
Iron ore tailings of dry magnetic separation of iron ores	27 142 856	5 000 508	3 044 780	27 290 354

Table 9: Amount of Iron ore tailings in Russia, 2022 (*Rosprirodnadzor | Information on the formation, processing, disposal, neutralization, disposal of production and consumption waste*, no date)

Iron ore tailings characterization. For the most complete assessment of the properties of IOT were considered tailings from various enterprises in Eurasia, which are among the top five countries in iron ore mining (Ministry of Natural Resources and Ecology of the Russian Federation Federal Agency for Subsoil Use (Rosnedra)., 2021). The results of studies on the chemical composition of iron ore tailings obtained in numerous studies are presented in Table 10. Although the chemical composition varies depending on the type of mine, there is often a higher content of SiO_2 , Al_2O_3, CaO and Fe_2O_3 .

	Lebedinskoye field, KMA, Russia (Bessmertniy- *et al.*, 2016)	Kovdorskii GOK, Russia (Shcherbina and Kochetkova, 2016a)	Abagur enrichment plant, Russia (Bessmertny V.S., 2017)	Jindal steels in Bellary, Karnataka, India (George, 2023)	BMM ISPAT mines, India (Thejas and Hossiney, 2022)	Nanjing Iron and Steel Group, China (Young and Yang, 2019)	Panzhihua Iron and Steel Group, China (Lv *et al.*, 2021)	Jungar, Inner Mongolia, China (Duan *et al.*, 2016)
SiO_2	66.19	24.06	41.2	34.65	30.37	29.14	38.8	34.72
Al_2O_3	9.51	3.12	12.14	28.65	12.43	5.01	15.2	16.22
Fe_2O_3	9.06	5.99	11.0	0.12	46.33	17.01	15.8	12.31

FeO	6.44	-	8.0	-	-	-	-	
CaO	3.70	21.76	8.6	28.42	3.88	13.20	14.8	7.63
MgO	4.08	24.83	5.8	5.7	1.68	16.27	5.9	8.92
Na_2O	0.51	0.45	-	0.441	-	0.41	2.5	0.54
K_2O	0.69	0.25	2.17	0.249	0.25	1.10	0.1	1.52
SO_3	0.16	0.09	2.8	-	-	1.74	0.5	-
Cl^-	-	-	-	-	-	-	0.02	-
TiO_2	-	-	0.28	-	3.96	-	4.9	0.30
MnO_2	-	-	-	-	-	-	-	-
MnO	-	-	0.45	-	-	-	0.31	0.13
ZnO	-	-	-	-	-	-	0.42	-
P_2O_5	0.11	3.40	-	-	-	-	-	-
Loss on drying	-	-	-	-	-	-	0.98	-
LOI	5.19	12.93	7.56	8.47	1.10	16.04	0.092	13.18

Table 10: Chemical composition of Iron ore tailings

Having analyzed the results of X-ray diffraction in (Duan *et al.*, 2016; Finih P. et al., 2019; Lv *et al.*, 2021), we can conclude that the main crystalline waste phases are quartz, anorthite, and hematite with the presence of other minerals. In the study (Zhao *et al.*, 2021a), the author concludes that, in addition to quartz and hematite, the main phases also include gibbsite.

Physical properties. Particle size. In most previous studies, iron ore beneficiation wastes are mainly classified into three categories: particle size > 4.75 mm, 0.16 mm to 4.75 mm, and <0.16 mm (Zhao *et al.*, 2021a). With the development of iron ore beneficiation technologies, the particle size of tailings is getting smaller and smaller. For this reason, in recent studies, the particle size of tailings grains is in the range of tens of micrometers to hundreds of micrometers (Sarkar, Sarkar and Biswas, 2017; Finih P. et al., 2019; Almeida and Schneider, 2020; Cheng *et al.*, 2020; Zhang *et al.*, 2020). Table 11 shows the physical properties of Iron ore tailings.

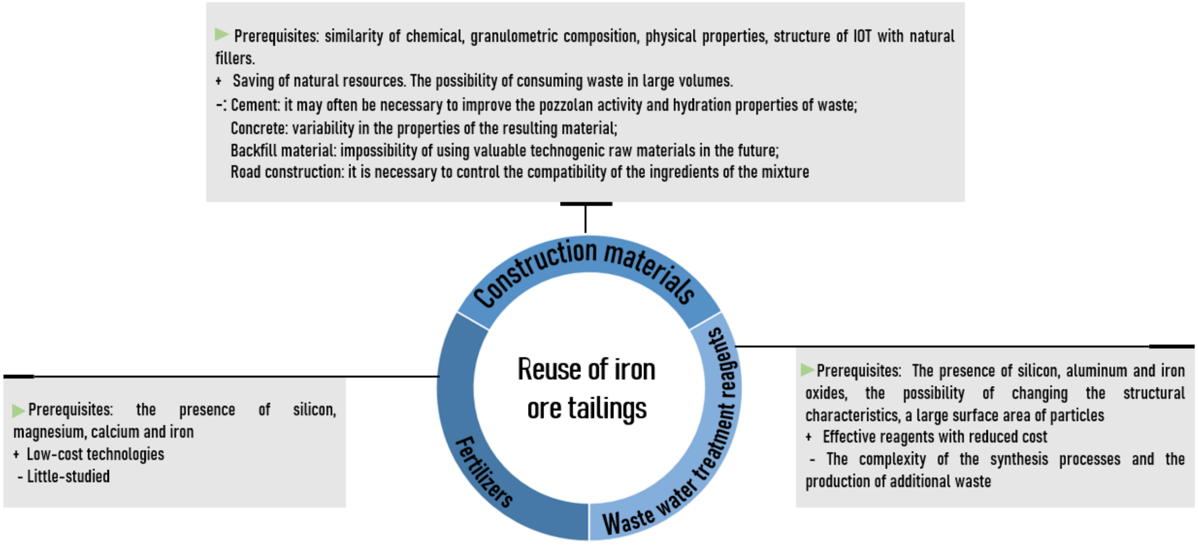
Region	Modulus of grain size	Apparent density, kg/m^3	Water adsorption capacity, %	Specific weight	Source
India	2.54-3.78	3310	0.96-15.87	2.27-2.67	(Narasimhaiah *et al.*, 2021), (Zhao *et al.*, 2021b), (Shwetha R. A., 2017)

China	0.07 – 1.58	2580-3426	1.22	-	(Finih P. et al., 2019; Zhang *et al.*, 2020; Lv *et al.*, 2021; Gong *et al.*, 2022)
Malaysia	1.05	-	7.0	1.27	(Shettima *et al.*, 2016; Umara Shettima *et al.*, 2018)

Table 11: Physical properties of Iron ore tailings

Speaking about the appearance of iron ore tailings particles, it should be noted that, according to the images obtained by emission scanning electron microscopy, as a rule, they have an angular, irregular shape, as well as a rough surface (Duan *et al.*, 2016; Umara Shettima *et al.*, 2018; Zhang *et al.*, 2020; Han *et al.*, 2021)

Iron ore tailings recycling directions. There are the following directions for iron ore tailings recycling: use as a raw material for production of fertilizers (Hu *et al.*, 2018; Lei *et al.*, 2019; Pendyurin E. A., 2019; Rao *et al.*, 2019), for production of wastewater treatment chemicals (Duan et al., 2016; Sarkar, Sarkar and Biswas, 2017; Xu and Deng, 2018; Zhang and Li, 2018; Almeida and Schneider, 2020; Bai et al., 2020; Deng et al., 2020; Dong et al., 2020; Han et al., 2021; Puiatti et al., 2021), construction materials (cement (Ranade *et al.*, 2013; Luo *et al.*, 2016; Xiong *et al.*, 2017; Fontes *et al.*, 2018; Yao *et al.*, 2020), concrete (Tian et al., 2016; Han et al., 2019; Lv et al., 2019; Mendes Protasio et al., 2021; Sushmitha and Dhanabal, 2021; Chen et al., 2022), as a backfill material (Lu *et al.*, 2018; Rybnikova L. S., 2018; Shchekina, 2020; Deng, Cao and Zhang, 2021; Krishna *et al.*, 2021), for road construction (J *et al.*, 2017; Barati *et al.*, 2020; Apaza Apaza *et al.*, 2021; Wei *et al.*, 2022). Figure 3 shows in general terms the prerequisites of the possibility of implementation, as well as the advantages and disadvantages of these directions.



▶ Prerequisites: similarity of chemical, granulometric composition, physical properties, structure of IOT with natural fillers.
+ Saving of natural resources. The possibility of consuming waste in large volumes.
-: Cement: it may often be necessary to improve the pozzolan activity and hydration properties of waste;
Concrete: variability in the properties of the resulting material;
Backfill material: impossibility of using valuable technogenic raw materials in the future;
Road construction: it is necessary to control the compatibility of the ingredients of the mixture

▶ Prerequisites: the presence of silicon, magnesium, calcium and iron
+ Low-cost technologies
- Little-studied

▶ Prerequisites: The presence of silicon, aluminum and iron oxides, the possibility of changing the structural characteristics, a large surface area of particles
+ Effective reagents with reduced cost
- The complexity of the synthesis processes and the production of additional waste

Figure 3: Figure 3 - Prerequisites, advantages and disadvantages of using tailings in different disposal directions

The use of Iron ore tailings in the production of fertilizers. The problem associated with the need to preserve and increase soil fertility has always been topical, respectively, the search for new fertilizers is a current task for researchers. The use of alternative sources of raw materials to create reagents to solve the problem of soil fertility preservation and including the cheapening of the existing technologies of production of currently known fertilizers is of great interest for the agricultural industry.

One of the components of such fertilizers can be Iron ore tailings. To date, relatively few studies have been conducted on the use of source materials as fertilizers and soil additives. Iron ore wastes can be included in silicon and organomineral fertilizers.

Speaking of silicon fertilizers, it is important to mention that silicon promotes crop growth and development, improves crop quality and increases crop resistance to pests and diseases, drought and extreme temperatures. Silicon can also effectively prevent pollution by heavy metals (Cd, Mn, Cr, Pb, Cu and Zn). This is achieved by passivation of active heavy metal ions in the soil, preventing the transfer of heavy metals to the buds and fruits, stimulating the production of various antioxidants and regulating the expression of metal carrier genes and structural changes in plants. The silica gel layer formed by silica accumulation on the leaf surface can effectively prevent pathogen invasion and insect invasion. Silica can also improve the ability of plants to absorb light, thereby promoting photosynthesis. Silicon has been recognized by international soil academies as the fourth major plant nutrient after nitrogen, phosphorus and potassium (Hu *et al.*, 2018).

Silicon in the soil is formed through natural processes such as weathering, which is a rather lengthy process. Therefore, plant silicon supply provided exclusively by natural processes cannot meet the silicon requirements of modern agriculture, which implies high production capacity.

Soluble silicates such as Na_2SiO_3 and K_2SiO_3 , are common industrial chemicals, but their use in agriculture is limited due to their high cost. Accordingly, industrial wastes containing SiO_2 , are often used as raw materials for the production of silicon fertilizers, which may include iron ore beneficiation wastes, due to the fact that they contain silicon, magnesium, calcium and iron (Table 12) and are potential raw fertilizers. The difficulty is that all of these elements are in the form of undissolved silicate minerals and cannot be easily absorbed by plants directly. By transforming SiO_2 , CaO and MgO in iron tails into soluble substances, it is possible to provide plants with nutrients. For this reason, slow-release silica fertilizers have been created on the basis of iron tailings. In this case, increasing the availability of silicon for plants is achieved by adding alkaline substances at a certain temperature to convert them into soluble silicates [16].

Chemical composition [mass %]	China (Hu *et al.*, 2018)	China (Rao *et al.*, 2019)	Russia (Pendyurin E. A., 2019)
Fe общ	-	-	10.30
SiO_2	39.21	95.96	69.35
CaO	16.73	0.038	2.93
MgO	12.98	0.018	4.95
Fe_2O_3	11.2	0.066	-
Al_2O_3	11.11	0.12	2.13
TiO_2	3.97	0.56	0.168
P_2O_2	3.97	-	-
Na_2O	3.97	-	0.785
K_2O	0.535	0.02	0.54
SPT	1.46	-	4.64
Sc_2O_3	-	7.5	-
CO_2	-	-	3.602
S	-	0.53	0.204
P	-	-	0.163
Other	-	2.68	-

Table 12: Chemical composition of iron ore enrichment waste

The content of heavy metals in solid wastes is an important practical indicator to assess the applicability of such fertilizers and requires monitoring the value of their transfer into the soil to prevent a reduction in crop quality.

Obtaining silica fertilizers using crystalline silica from waste rock after ore processing can also provide plant nutrition with silicon. In (Deng *et al.*, 2020), after extracting metallic elements from a large anatase waste deposit, such as scandium and titanium, tailings with silica as the main component were obtained (Table 12). The silica in the sample is microcrystalline quartz, which is a common form of silicon in the ore, and which is subsequently transformed into plant-available silicon by roasting and the addition of calcium-containing raw materials and sodium hydroxide, as they contribute to the conversion of silica into substances such as $CaSiO_3$, Ca2SiO4 , and Ca_3 SiO_5 , which are major sources of silicon in silicon fertilizers.

Organomineral fertilizers are fertilizers that include organic matter and related chemical or adsorption-mineral compounds. It is possible to obtain such fertilizers on the basis of secondary raw materials (Pendyurin E. A., 2019). Secondary raw materials for such fertilizers, for example, can be a mixture of kiln dust from electric filters, cement dust, compost, citrogyps, organic part, which is represented by animal wastes and plant residues. The composition of by-products of iron ore enrichment by wet magnetic separation is used as an additional component to improve the physical properties of the soil. The important components of iron ore waste in this case are SiO2, $Fe_{общ.}$, Mg and Ca oxides.

In the production of fertilizers based on secondary raw materials, of course, it is necessary to assess the toxicity of the fertilizer components and, accordingly, clearly comply with their dosage (Pendyurin E. A., 2019). It is also necessary to assess the basic agrochemical indicators of the obtained organomineral fertilizers and phytotoxicity to fully evaluate the possibility of using the obtained materials.

In addition to the above, Iron ore tailings can improve the growing conditions of agricultural structures in other ways. For example Iron ore tailings can be used to clean the soil of arsenic, which is a toxic element that can be absorbed by plants. To date, many methods have been proposed to reduce As uptake from soil by plants, some of which are based on the fact that iron oxide surfaces are involved in the adsorption of arsenic from soils, the source of which can be iron ore dressing waste (Lei *et al.*, 2019).

At the moment, the production of fertilizers based on waste iron ore processing has not found mass application, since research on this topic is rather small, indicating the slow development of such technologies, however, this direction is promising and in the future due to the cheapness of secondary resources and their effectiveness may attract public attention.

The introduction of iron ore enrichment waste in the production of reagents, the use of which is possible in wastewater treatment. Currently, there are quite a large number of ways to treat wastewater from various pollutants, however, the production of reagents with sufficient efficiency and acceptable cost - is still a pressing problem that requires modern technology to solve it.

At the moment there is a need to develop new cost-effective adsorbing materials with high heavy metal removal efficiency, aimed at protecting water resources and ensuring wide access to clean water. Also due to the widespread use of synthetic dyes in the textile, paper, rubber, tanning and other industries, there is a need to develop modern methods to reduce the concentration of dyes before discharging wastewater.

As we know, iron can be present in the environment as several phases with different oxidation degrees and structures, such as FeO (wustite), Fe O_{34} (magnetite), γ-Fe O_{23} (maghemite), α-Fe2O3 (hematite) and FeOOH (oxyhydroxides). All these phases have unique physical and chemical properties that can be used in processes of removal of pollutants from the environment, including wastewater treatment. Other attractive characteristics of these iron phases, given this goal, are their low toxicity, low cost and relative stability.

The use of iron ore tailings to create functional materials is now widely discussed among scientists. The structural characteristics of iron ore tailings, namely the fact that the minerals in the tailings have different and complex framework structures: almost all minerals contain silica tetrahedra connected with other atoms, such as Si, Al and Mg, as well as the fact that silica tetrahedra are very sensitive to alkali, indicates that the structural characteristics of iron ore tailings can be changed if necessary (Bai *et al.*, 2020).

That is why recently the tendencies have been observed in the use of iron ore wastes towards functional materials , namely: mesoporous materials (Xu and Deng, 2018; Bai *et al.*, 2020; Deng *et al.*, 2020; Dong *et al.*, 2020; Han *et al.*, 2021), geopolymers (Duan *et al.*, 2016), zeolites (Zhang and Li, 2018), kaogulants (Almeida and Schneider, 2020) and some other sorbents(Sarkar, Sarkar and Biswas, 2017; Zhang and Li, 2018).

Reagents for wastewater treatment of dyes. The ingress of dyes through wastewater into water bodies reduces light penetration, compromising the primary productivity of water bodies and thereby upsetting the balance in aquatic ecosystems. In addition, some dyes are mutagenic, carcinogenic, teratogenic and, by passing through various levels of the trophic chain, can be harmful to human health. In this regard, the most effective methods and reagents for removing dyes from wastewater are being searched for.

As a rule, wastewater is treated from dyes by means of coagulation, aerobic or anaerobic biological treatment, electrochemical treatment, membrane filtration and adsorption. Adsorption is the most popular method, but the limitations of its use are mainly due to the high cost of adsorbents. For this reason, the development of adsorbents with reduced cost through the use of industrial wastes is an attractive alternative.

Iron ore tailings can be classified by their composition as high-silicon, high aluminum, high calcium and magnesium, low silica and polymetallic type tailings. Generally, high-silicon iron ore tailings are among the most common iron ore tailings (Dong *et al.*, 2020). For wastes with a high silicon content (about 70%) and with the presence of a silica skeleton formed by a [SiO4] tetrahedron, it is possible to use iron ore tailings as an inexpensive source of silicon to produce functional silicates, namely mesoporous silica materials, which can be used for dye water purification. Table 13 presents the chemical composition of iron ore tailings, on the basis of which the conducted research proves the possibility of obtaining mesoporous materials.

The main mechanism of each method of synthesis of mesoporous silica materials is to extract silicon from iron ore tailings by reaction with sodium hydroxide, and then the extracted sodium silicate is directly applied to synthesize mesoporous silica using a number of additional reagents (Han *et al.*, 2021). However, these methods inevitably have disadvantages related to the low leaching rate of silica, the complexity of the process, and the generation of secondary wastes. Also, the use of structure-guiding reagents and surfactants increases costs. Thus, researchers are faced with the task of developing a simpler and more efficient method of obtaining mesoporous silica materials from iron ore tailings.

The authors of the article (Han *et al.*, 2021) propose a new strategy for the synthesis of mesoporous silica materials obtained from iron ore tails after alkaline melting and acid leaching. Alkaline melt treatment changes the crystal structure of the iron ore tailings framework, the subsequent acid leaching treatment selectively dissolves metal ions to form an abundant porous structure, while generating SiO nanoparticles$_2$ with interparticle mesopores. The resulting material has good adsorption properties for dye removal.

Another way to obtain mesoporous adsorbents is to use iron ore tailings as a special mixture of silicate minerals after transforming their structure with sodium silicate, providing them with reactive Mn-OH groups and high specific surface area. Studies show that the resulting composite has excellent selective adsorption capacity and high adsorption rate in a mixed solution of cationic dye, thus helping to solve the problem of wastewater pollution by cationic dyes, which are resistant to biodegradation due to their complex aromatic structure (Bai *et al.*, 2020).

In (Dong *et al.*, 2020), a convenient and inexpensive one-step hydrothermal process for the synthesis of mesoporous material was demonstrated, which made it possible to obtain a mesoporous zinc silicate composite that can also be used in wastewater treatment.

Chemical composition [wt. %]	China (Bai *et al.*, 2020)	China (Dong *et al.*, 2020)	China (Han *et al.*, 2021)
SiO_2	67.8	67.48	71.32

MgO,	2.66	2.66	2.906
Al_2O_3,	7.80	7.80	6.30
CaO	8.53	8.53	3.121
Fe_2O_3	8.56	8.56	7.88
K_2O	-	2.65	2.28
Na_2O	-	0.72	1.73
TiO_2	-	0.39	0.532
MnO	-	-	0.108
MnO_2	-	0.18	-
ZnO	-	0.01	-
LOI	-	1.03	2.85

Table 13: Chemical composition of tailings used for mesoporous materials

Iron ore beneficiation wastes are also considered as sources of iron and silicon for the production of mesoporous materials such as mesoporous α-Fe_2 O and MCM-41.

In the synthesis of mesoporous α-Fe_2O_3, iron is initially extracted from iron ore tailings using acid leaching, which is subsequently used as a source for the synthesis of Fe nanoparticles after precipitation$_2$ O (Xu and Deng, 2018). α-Fe_2O_3 can decompose a wide range of pollutants and exhibit excellent photocatalytic activity due to its small particle size, high specific surface area, non-toxicity and chemical stability. That is why this simple and inexpensive technology of material production is so important.

When creating the mesoporous material MCM-41, iron and silicon are extracted from Iron ore tailings by acid and alkaline leaching, which makes it possible to obtain the material of the required quality with the possibility of its further use in wastewater treatment (Deng *et al.*, 2020).

An adsorbent based on iron ore enrichment waste, consisting mainly of hematite and quartz, was also obtained for cationic and anionic dyes, where adsorption proceeds mainly due to the action of electrostatic forces. At the same time, depending on the properties of the dyes, it is necessary to control the pH of the reaction medium. It has also been found that it is possible to desorb almost completely the adsorbed contaminants, which would allow the resulting adsorbent to be reused in subsequent adsorption cycles (Puiatti *et al.*, 2021).

Reagents for metal removal. As well as for dye wastewater treatment, adsorption technologies are considered one of the most convenient, inexpensive and relatively promising approaches to treating wastewater from metals.

One suitable material is a porous geopolymer. Iron ore waste contains small particles containing silica along with iron oxides, alumina and other minor minerals, which allows the waste to be used for its production. In (Duan *et al.*, 2016), fly ash and iron ore tailings rich in SiO_2 and Al_2O_3 (Table 14) were used as starting materials to produce geopolymer by geopolymerization, resulting in a reagent capable of removing heavy metals from wastewater with 90.7 percent efficiency.

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	TiO_2	LOI
Fly ash	29.47	51.72	2.25	0.15	5.21	0.05	0.35	0.03	1.83	8.58
Iron Ore Tailings	34.72	16.22	12.31	8.92	7.63	0.54	1.52	0.13	0.30	13.18

Table 14: Chemical composition of fly ash and iron ore beneficiation waste used for geopolymer production [15]

At the same time, iron ore tails rich in SiO_2 and Al_2O_3 (Table 15) can be used as raw materials in the production of zeolite materials. It was found that iron ore tailings mainly consist of material with crystals such as α-quartz, mullite, hematite and magnetite and can be transformed into zeolites or zeolite-like materials in alkaline solutions by hydrothermal treatment.

Zeolites with complex micropores have long been actively studied as an important class of industrial porous materials in various fields of the chemical industry, such as adsorption and gas separation, ion exchange, wastewater treatment, form-selective catalysis.

Zeolite A, as one of the most important commercial zeolites, is a porous aluminosilicate compound with excellent properties such as nontoxicity, high porosity, stability, high ion exchange capacity. To synthesize zeolite A from high-siliceous iron ore enrichment waste by hydrothermal method, the entire volume of waste can be used. The synthetic method is environmentally safe due to the lack of acid pretreatment and the absence of secondary solid wastes generated during processing, and the resulting material is excellent for metals adsorption (Zhang and Li, 2018).

SiO_2	Al_2O_3	Fe O_{23}	CaO	MgO	K O_2	Na O_2	Cl	TiO_2	P O_{25}	SO_3	MnO	SrO
67.58	8.70	7.42	5.78	4.37	2.32	2.15	0.69	0.33	0.26	0.23	0.10	0,06

Table 15: Chemical composition of iron ore enrichment waste used to produce zeolite A (Zhang and Li, 2018)

Removal of such heavy metals as Pb(II) and Hg(II), as well as arsenic, cadmium, selenium, can be carried out by an adsorbent based on iron ore sludge, the main component of which is hematite (hydrated iron oxide). Also such characteristic as a large surface area of the particles positively affects the adsorption of heavy metals (Sarkar, Sarkar and Biswas, 2017).

Oxides	%	Element	%
Fe_2O_3	80	Fe	58.50
FeO	3.50	S	0.08
Al_2O_3	6.60	P	0.15

SiO_2	5.80	Cl	0.02
P_2O_5	0.35	F	0.10
TiO_2	0.30	Cu	<0.01
CaO	0.20	Zn	<0.01

Table 16: Chemical composition of iron ore sludge used for adsorbent production (Sarkar, Sarkar and Biswas, 2017)

Reagents for treatment of a number of other water pollutants. In addition to wastewater treatment of heavy metals and dyes, iron ore enrichment wastes can be used in a number of other operations that improve the quality of the aquatic environment, which should be mentioned.

There is an opportunity to use waste as a sorbent for treatment of electroplating wastewater from inorganic pollutants - chromium, iron, copper, lead, zinc, nickel, cadmium, ammonia, which have a toxic, carcinogenic and mutagenic effect on living organisms (KALMYKOVA D. A., 2021).

The use of iron ore enrichment wastes is possible in the production of coagulants. Among iron-based coagulants, one of the most used is iron chloride, which is characterized by a rapid decrease in turbidity due to the formation of strong and heavy flakes and by the fact that it is applicable in a wide pH range. The characteristics of iron ore tailings (Table 17), namely iron concentration, fine particle size, large material surface area, and low concentration of toxic elements, indicate the potential for the synthesis of iron chloride. The waste-derived coagulant is a metal composed of trivalent iron (98.49%) and aluminum (1.48%) and low concentrations of undesirable metals such as Mn, Pb, Cu, Cr, Zn and As, which is effective in terms of removing residual suspended solids, turbidity and color (Almeida and Schneider, 2020).

Elemental composition	Concentration [%]
Si	31.05
Fe	16.98
Al	1.59
Ti	0.07
Mn	0.02
Mg	0.0038
P	0.04
Surface area [m^2 g^{-1}]	10.66
Particle size, [μm]	0.07-300

Table 17: Characteristics of iron ore tailings used for coagulant (Almeida and Schneider, 2020)

Prospectivity of iron ore dressing wastes use is not doubtful, nevertheless at the present moment further research is needed to find the simplest and most cost-effective technologies to ensure the use of iron ore dressing wastes as raw materials for production of the most effective reagents.

The use of iron ore beneficiation waste in the construction industry. At present, research on the integrated use of iron ore beneficiation waste is mainly focused on the production of construction materials, because the construction industry can not only ensure the consumption of large amounts of waste and zero discharge of by-products, but also reduce the load on the natural resources used. The list of construction materials in the production of which iron ore waste can be used is quite long. In this paper, we will focus in more detail on such materials as cement, concrete, filling materials and materials for road construction.

The use of Iron ore tailings in cement production. The cement industry has been searching for alternative raw materials for production for some time now, because the ever-increasing demand for building materials has led to the overexploitation of clay resources and considerable damage to the environment.

The main chemical components of iron ore tailings are silicon dioxide, aluminum oxide, calcium oxide, magnesium oxide and iron oxide, which is similar to the chemical components of cement. For this reason, iron ore beneficiation wastes are used to develop more environmentally friendly cementitious composites (Ranade *et al.*, 2013).

Cementitious materials such as Portland cement can be produced from iron ore tailings, which is the most commonly used construction material and has a huge application in residential, commercial and industrial areas. This material is usually produced by calcining lime and clay, resulting in the release of large amounts of carbon dioxide, which is now a common concern among the scientific community.

To assess the possibility of introducing iron ore dressing waste as an additional cementitious material for the production of Portland cement, it is necessary to pay attention to the chemical (Table 18), particle size distribution composition of the tailings, as well as the pozzolanic activity index (Magalhães *et al.*, 2020). Improvement of pozzolanic activity and hydration properties of iron ore tailings is possible through mechanical activation, as it can cause amorphization of iron ore tailings powders (Yao *et al.*, 2020).

Chemical composition [%]	Brazil (Magalhães *et al.*, 2020)	China (Yao *et al.*, 2020)	China (Young and Yang, 2019)	China (Luo *et al.*, 2016)	China (Q. Wang *et al.*, 2020)
SiO_2	23.00	62.04	29.14	45.41	26.55
Al_2O_3	3.20	5.8	5.01	19.07	11.00
Fe_2O_3	66.98	22.06	17.01	10.86	34.88

CaO	-	4.27	13.20	12.41	12.42
MgO	-	3.4	16.27	7.23	2.98
SO_3	-	0.91	1.74	0.44	2.09
MnO_2	0.56	-	-	-	-
P_2O_5	0.22	-	-	-	-
Na_2O	-	0.52	0.41	-	0.21
K_2O	-	-	1.10	-	1.26
Cl^-	-	-	-	-	0.01
LOI	-	-	16.04	1.22	8.47

Table 18: Compositions of Iron ore tailings used in cements

The predominance of aluminum, silicon and iron oxides by mass is a prerequisite. Special attention should be paid to iron oxide, which provides opportunities for additional use of the properties of iron ore tailings for the production of Portland cement with various pigments, which will eliminate the need for subsequent color coating layers, such as mortars and paints (Young and Yang, 2019).

SO_3 and Cl are hazardous substances that can contain wastes, so it is important to keep their content low. The presence of iron ore waste improves the reactivity of the product because the tailings contain trace elements (CuO, TiO2, MnO,etc.), which can contribute to the solid-phase reaction. The temperature and time of sintering of the material is also reduced, which can be explained by the presence of trace elements and certain minerals in the composition, which leads directly to the cheapening of the production process (Luo *et al.*, 2016).

Cement clinker, on the basis of which Portland cement and cement are subsequently produced, can be produced from iron ore tailings with high magnesium content and low silicon content (Yao *et al.*, 2020), and iron ore tailings containing large amounts of limestone are also suitable (Q. Wang *et al.*, 2020).

Grain size is an important variable in evaluating Portland cement additives, as the finer particles fill the pores in the cement paste, improving physical properties through filler effects.

When these requirements are met, physical parameters such as water absorption, porosity, bulk density and apparent density of mortars made with iron ore tailings are equivalent to those made with reference Portland cement.

Partial replacement of clinker by beneficiation wastes in the production of composite cement is effective for use on a large scale due to reduced energy consumption, since the calcination temperature of iron ore tails is lower than the sintering temperature of clinker (Magalhães *et al.*, 2020). It is noteworthy that iron ore tailings in the composition of cement pastes can increase the sulfate resistance of the product due to the slowing down of SO4 input from outside^{2-} and gypsum formation (Xiong *et al.*, 2017).

Beneficiation wastes may also be used as aggregate in the base course and pigment in the colored layer in stable cement tiles, which are generally used for wall and floor cladding indoors and outdoors. To enable such applications, the tails should not contain hazardous chemicals such as chlorites and sulfates or substances that can affect cement hydration. Preferably, they should provide optimal particle size distribution zones (Fontes *et al.*, 2018).

The use of Iron ore tailings as a raw material for cement production can solve the problem of recycling large quantities of iron ore tailings, as the research conducted to date proves the similarity of the chemical and physical properties of waste with natural raw materials.

Speaking about the properties of the obtained materials, it can be noted that the mechanical and physical properties of the produced cement products are comparable to the characteristics of the reference samples, there is an increase in resistance to acid attack, improved reactivity and combustibility of the raw mixture, which contributes to the sintering process.

Introduction of iron ore beneficiation waste into concrete production. Concrete is one of the most commonly used building materials worldwide. The production of concrete uses a huge amount of raw materials extracted from the environment, which are used as aggregates. Iron ore beneficiation waste can be incorporated into concrete as a substitute for sand or cement , thereby reducing the consumption of traditional aggregates and, as a result, reducing the consumption of natural raw materials.

Despite the fact that at the moment a large number of studies have been conducted to assess the properties of concretes based on iron ore tailings, there are few studies that would generalize the data obtained. This can be explained by the fact that the properties of iron ore tailings vary quite a lot, which makes it significantly difficult to identify clear patterns in the change in the properties of obtained concretes from the physical and chemical properties of the tailings.

When introducing Iron ore tailings into concrete as aggregates, it is necessary to evaluate the particle size, apparent density, fineness modulus, porosity, and water adsorption capacity (Table 19), because they can differ significantly from the properties of natural aggregate and thus affect the properties of the resulting concrete. Waste particles are often angular and irregular in shape. The chemical composition of iron ore tailings varies, but a higher proportion of SiO_2, Al_2O_3 and Fe_2O_3 is observed (Table 20).

Region	Filler	Modulus of grain size	Apparent density [kg/m^3]	Water adsorption capacity [%]	Specific weight	Source
India	NA*.	3.87	-	2.0	2.61	(Kumar, no date)
India	IOT**	3.78	-	15.87	2.66	

India	IOT	307	-	0.96	2.27	(Narasimhaiah *et al.*, 2021)
China	IOT	0.,07	-	- -	- -	(Zhang *et al.*, 2020)
India	IOT NA	- -	3310 2700	2.29 0.1	- -	(Zhao *et al.*, 2021b)
China	IOT NA	2.8 2.6	3120 2840	1.22 1.42	- -	(Lv *et al.*, 2021; Zhao *et al.*, 2021b)
China	IOT NA	1.58 3.18	3426 2580	- -	- -	(Gong *et al.*, 2022)
China	NA	2.71	2630****	- -	- -	(Cheng *et al.*, 2020)
India	NA IOT	3.06 2.54	-	0.88 -	2.5 2.67	(Shwetha R. A., 2017)
China	IOT	0.36	2580	-	-	(Finih P. et al., 2019)
Malaysia	IOT NA	1.05 2.77		7.0 3	1.27 1.64	(Umara Shettima *et al.*, 2018)
Malaysia	IOT	1.05		7.0	1.27	(Shettima *et al.*, 2016)

Table 19: Physical properties of aggregates

NA* - natural aggregate; IOT * - iron ore tailings

**** - density, kg/m3

	IOT	IOT	IOT	IOT	NZ	IOT	IOT	IOT	IOT	IOT	NA	IOT	NA
SiO_2	34.65	72.84	70.32	38.8	49.6	73.02	56	75.23	73.85	38.3	49.4	56	98
Al_2O_3	28.65	4.74	5.1	15.2	16.1	4.38	10	2.64	5.92	15.8	14.9	10	0.4

Fe_2O_3	0.12	8.88	10.93	15.8	7.2	12.66	8.3	1131	15.4	15.6	7.5	8.3	0.1
CaO	28.42	5.05	4.71	14.8	15.1	1.90	4.3	1.47	0.48	15.8	14.4	4.3	0.9
MgO	5.7	6.06	4.51	5.9	4.9	3.42	-	2.10	1.20	5.8	4.9	1.7	0.2
Na_2O	0.441	-	1.3	2.5	1.6	1.11	-	0.49	1.05	2.5	1.5	-	-
K_2O	0.249	-	1.14	0.1	0.2	1.10	1.5	0.40	1.00	0.1	0.4	1.5	1.4
SO_3	-	0.05	0.26	0.5	0.3	0.36	-	0.08	-	0.5	0.1	-	-
Cl^-	-	-	0.016	0.02	0.01	-	-	-	-	0.01	0.01	-	-
TiO_2	-	-	-	4.9	2.8	-	-	0.06	-	4.9	2.7	-	-
MnO	-	-	-	0.31	0.26	-	1.7	-	-	0.20	0.20	-	0.02
ZnO	-	-	-	0.42	0.23	-	0.1	-	-	0.01	0.02	0.1	-
PbO	-	-	-	-	-	-	0.4	-	-	-	-	0.4	-
CUO	-	-	-	-	-	-	0.2	-	-	-	-	0.2	-
Loss on drying	0.98	-	-	-	-	-	-	-	-	-	-	-	-
LOI	0.092	0.89	1.1	0.4	1.3	2.04	3.3	-	5.87	0.4	1.3	3.3	0.1

Table 20: Chemical composition of aggregates [%] (Kumar, no date; Tian *et al.*, 2016; Finih P. et al., 2019; Lv *et al.*, 2019, 2021; Almeida and Schneider, 2020; Cheng *et al.*, 2020; Chen *et al.*, 2022; Gong *et al.*, 2022)

NA* - natural aggregate; IOT * - iron ore tails

An important property is pozzolanic activity, which affects the binding properties and can lead to a decrease in the quality of concreting. Due to the stable crystalline structure of the waste it is quite low. This can be corrected by mechanical, chemical or thermal activation (Zhao *et al.*, 2021b).

In order to assess the quality of the concrete obtained, it is necessary to pay attention to such a property as the workability of the concrete mixture, which is usually determined by the slump of the cone. The value of the slump of concrete depends on the coefficient of substitution of aggregates for iron ore tailings (Table 21) and has a close relationship with the properties of other materials used in the concrete.

Percentage of aggregate to be replaced	Influence on workability	Source
25 - 45%	↓	(Tian *et al.*, 2016)
30 %	↓	(Mendes Protasio *et al.*, 2021)
10 - 30 %	↑	(Finih P. et al., 2019)
40 - 60%	↓	(Zhao *et al.*, 2021b)

25 - 100 %	↓	(Shettima *et al.*, 2016)
25 - 100 %	↓	(Umara Shettima *et al.*, 2018)
30%	↓	(Sushmitha and Dhanabal, 2021)
10 - 40 %	↓	(Kumar, no date)
10 - 50 %	↑	(Narasimhaiah *et al.*, 2021)

Table 21: Dependence of workability on the percentage of introduction of iron ore enrichment waste

The decrease in settlement value with increasing tailings content is usually explained by two main reasons. Tailings particles have a more angular and coarse texture compared to sand, thereby impeding the free flow of concrete. It may also be due to the fact that fine iron ore waste particles have a large surface area . This can be corrected by adjusting the amount of water added, mineral additives or plasticizers.

In (Finih P. et al., 2019)it can be seen that the initial value of cone settlement increased with increasing the content of tailings. The authors of the work explain this by the fact that the fine powder (directly tailings) in the concrete mixture increases the fluidity of the mortar, and thus, the resistance to movement of coarse aggregate decreased. However, the slump value decreased with increasing waste content when it was more than 30%. This was because too much tailings with finer powder could make the concrete mixture thicker. The paper (Narasimhaiah *et al.*, 2021) describes an increase in the workability of the resulting concrete also due to a greater grindability of the tailings compared to the natural sand.

Evaluating the properties of the obtained concretes, it is impossible not to mention the mechanical properties, one of which is the compressive strength. Of course, the result will depend on the percentage of replacement of traditional aggregate, particle size modulus and shape of the particles.

On the one hand, when tailings replace sand of similar coarseness, there is no obvious change in compressive strength. However, when the coarseness of the tailings is smaller, the value of compressive strength first increases and then decreases as the level of tailings replacement increases. The reasons for the increase in concrete compressive strength are the surface roughness, which improves the adhesion between the tailings and the cement paste. Also, if the waste particle size is smaller than traditional aggregate, it can fill voids in the cured concrete and improve the compactness of the concrete in appropriate proportion. The decrease in compressive strength, on the other hand, is caused by the low bond strength due to the reduction of cement paste per unit area of waste with a high specific surface area (Zhao *et al.*, 2021b).

Since the characteristics of iron ore waste and other components vary from study to study, the optimal replacement ratio varies from one study to another (Table 22).

Percentage of aggregate to be replaced	Influence on compressive strength	Source
25-45%	25 - 35% ↑; 35% max; 35% to 45% ↓	(Tian *et al.*, 2016)
10-30 %	10 % max; 10-30 % ↓	(Mendes Protasio *et al.*, 2021)
10-60 %	10 - 30% ↑30% max; 30 - 60% ↓	(Finih P. et al., 2019)
20 - 100 %	20 - 40 %↑40% max; 40 - 100% ↓	(Zhang *et al.*, 2020)
100 %	Higher than the reference sample	(Shwetha R. A., 2017)
100 %	Identical to the reference	(Lv *et al.*, 2021)
10-50 %	10 - 30% ↑30% max; 30 - 50% ↓	(Narasimhaiah *et al.*, 2021)
10-100%	10 - 50% ↑50% max; 50 - 100% ↓	(Umara Shettima *et al.*, 2018)
10-100%	10 - 25% ↑25% max; 25 - 100% ↓	(Shettima *et al.*, 2016)
10 - 40 %	10% max; 10 - 40% ↓	(Kumar, no date)
25 - 75%	25-50% ↑; 50 % max; 50 - 75% ↓	(Zhao *et al.*, 2021b)

Table 22: Effect of replacing conventional aggregate with iron ore tailings on compressive strength

The longevity of concrete depends on many parameters, some of which are water absorption, frost resistance and resistance to carbonation.

The water absorption of concrete is often determined when introducing tailings into hydraulic concrete and underground structural concrete. Typically, water and chloride absorption test methods are used to evaluate the water absorption of concrete.

According to the research carried out, at 10%, 20%, 30% and 40% replacement of cement with siliceous iron tails, the impermeability of concrete is better than that of the reference sample. With 10%, 20% and 30% amount of cement substituted, the impermeability of concrete increases with increasing amount of cement substituted, but with 40% amount of cement substituted, the impermeability of concrete decreases slightly. This is explained by the fact that mechanochemically activated siliceous iron tails have both active and filling effects, which can make the internal structure of concrete more homogeneous, thus reducing the impermeability of concrete. When 30% of cement is replaced by tails, the activity and filling effect of the tails combine to give them their best effect, resulting in a minimum penetration depth. However, when 40% of the cement is replaced by tailings, the penetration depth increases slightly, which can be explained by the fact that, with 40% cement replacement, the proportion of cement clinker is relatively small, which leads to a corresponding decrease in the amount of hydration product, which will affect the density of the concrete (Cheng *et al.*, 2020)

The addition of iron ore enrichment wastes instead of sand aggregate also increased the impermeability of concrete mortars. A decrease in water permeability and a decrease in chloride-ion penetration with increasing tailings content was observed, which occurs due to the filling of macropores and micropores in solutions by small particles, leading to a gradual compaction of the internal structure (Zhang *et al.*, 2020). The authors (Lv *et al.*, 2021) explain the resistance to chloride-ion permeation by the characteristics of the interfacial transition zone, which reduces the permeability.

In (Tian *et al.*, 2016), the degree of impermeability of concrete with 35% replacement and natural sandcrete are basically the same, indicating that the inclusion of iron ore tailings had no effect on the impermeability of concrete.

An important indicator is the frost resistance of concrete, which evaluates the durability of concrete in cold conditions. In laboratories, it is usually defined as the ability of the material to withstand freeze-thaw cycles. After several successive cycles of freezing and thawing, the external condition of the samples is checked and changes in performance are measured.

Regardless of whether iron ore beneficiation waste is used as a substitute for fine aggregate or cement, concrete generally has the same frost resistance as control concrete because the rough surface and finer particle size in proper proportions can help fill the internal pores of concrete, which increases the mechanical bonding force between aggregates (Zhao *et al.*, 2021b).

For example, in (Cheng *et al.*, 2020) when replacing 30 percent of cement with siliceous iron tails the frost resistance of concrete is higher than that of the control group, and when replacing 10 percent, 20 percent and 40 percent of cement the frost resistance of concrete is similar to that of the control group. In (Gong *et al.*, 2022) the best frost resistance is achieved when replacing the sand aggregate of 50 percent. In the works (Tian *et al.*, 2016; Lv *et al.*, 2019; Chen *et al.*, 2022), when replacing the sand with iron-ore tails, no significant changes in frost resistance compared to the reference samples were observed.

But at the same time in (Tian *et al.*, 2016)the frost resistance of the resulting concrete is slightly lower than that of the control mixture. The frost resistance of concrete decreased because the binding properties of some minerals in the sand from iron ore tailings weaken at low temperatures, and some of the sand on the surface crumbles. This leads to a decrease in compressive strength later on.

A parameter such as resistance to carbonation is important because although carbonation does not have a negative effect on strength, it is highly detrimental to the steel in the concrete. The depth of carbonation should be less than the concrete coating over the life of the structure.

In (Tian *et al.*, 2016), the authors conclude that the replacement of natural aggregate with tailings has no significant effect on the resistance to carbonization. In (Xiong *et al.*, 2017) the study observed an improvement in the carbonization resistance of concrete as the percentage of enrichment waste instead of fine aggregate increased. This decrease in carbonization in the concrete sample can be explained by the number of compacted pores. The authors (Zhao *et al.*, 2021b)come to the same conclusions.

In (Cheng *et al.*, 2020) the authors evaluated the change in the resistance to carbonization of concrete in which tails replace cement. The results show that at 10%, 20%, 30% and 40% replacement of cement the resistance of concrete to carbonization is inferior to that of the control group, and the resistance to carbonization tends to decrease with increasing amount of substitute, but the resulting concrete still meets the requirements of practical construction works. This is due to the fact that after the cement is partially replaced with waste cement, the amount of cement clinker in the concrete becomes less, which means that the concrete will have a lower alkalinity, resulting in a lower resistance of concrete to carbonization when more cement is replaced with tailings. However, the tailings filling effect can improve the homogeneity and compactness of the concrete, thereby preventing the penetration and diffusion of CO_2 into the concrete, which can contribute to the resistance of the concrete to carbonization. As the effects of the above two aspects reach a balance, the carbonization resistance of the concrete will not increase or decrease, but if one aspect is stronger or weaker than the other, the carbonization resistance of the concrete will change.

I would like to note that in the construction industry to the concrete materials have different requirements, depending on the purpose of application of a particular material, in this regard, the properties that the materials must have are different. Also due to the variability of chemical, physical, mineralogical properties of iron ore tailings their introduction in one case or another can lead to different results.

In addition to the properties listed above, when assessing the applicability of concretes as building materials, studies pay attention to such mechanical properties of concrete as the axial tensile strength of concrete, modulus of elasticity, splitting tensile strength of the specimens tested, flexural strength of the specimens tested, etc. Speaking of durability, shrinkage during drying of concretes, abrasion resistance, and thermal conductivity are also important indicators.

To form a complete picture about the possibility of introducing iron ore tailings of various compositions, it is necessary to conduct further experimental studies to determine the patterns of influence of waste on the properties of concrete. To date, we have conducted limited research work on this topic, which revealed that the physical, chemical properties of iron ore tailings are similar to natural aggregates.

The use of Iron ore tailings as backfill material. Waste iron ore processing can be used as backfill material for filling the space of underground mine workings - mines, pits, open cuts, which is of great interest for enterprises engaged in underground mining, because in this case, the costs of transporting waste, payments for land acquisition for waste storage and, most importantly, reduces the impact on the environment.

In order to prepare a hardening deposit with specified strength properties taking into account the specific mining and geological and mining and technical conditions of the mine, the following components are required: binders, aggregates and water. Since the tailings contain CaO, MgO, Fe_2O_3 and Al_2O_3 , they are potentially active in hydration and can be used as aggregates.

In (Rybnikova L. S., 2018) examples of the successful use of tailings as backfill material at Vysokogorsky mining and processing plant and Gaisky mining and processing plant are given, as a result of which the enterprises managed to preserve agricultural lands and avoid fees for waste disposal. Similarly, it was demonstrated in (Shchekina, 2020)that 100% of the tailings waste can be used as cemented paste as stowing material, while ensuring the stability of underground workings.

When developing composite binders for filling materials, it is necessary to take into account the affinity of the structures not only in the binder-filler system, but also in the mortar-empty rock system. According to the authors (Krishna *et al.*, 2021), slags and wastes of wet magnetic separation of iron ores in mortar compositions will provide the affinity of mortar structures with the parent rock and create a dense, homogeneous matrix by its chemical composition to ensure the durability of massif and its fracture resistance.

The physical and chemical properties of tailings, as a kind of artificial sand aggregate, mainly depend on the mineral composition and particle size, which must be analyzed in order to select the right binder for the production of the filling material. During the production of the filling material, its rheological properties, namely viscosity and fluidity, are assessed, since the filling material is usually conveyed by pipelines. It is also necessary to test the filling material for uniaxial compression. Thus, in a study (Lu *et al.*, 2018) for iron ore tailings with high gypsum content, the best binder was selected to create a filling material.

On the other hand, tailings from iron ore beneficiation can be viewed as underutilized minerals extracted from the subsurface. This view, on the one hand, is due to the possible presence in the tailings of residual target material or associated previously unclaimed components, which can be extracted using better beneficiation technologies in the future.

For this reason, the work(Deng, Cao and Zhang, 2021) considers the application of geopolymer obtained on the basis of enrichment tails, which in addition to the filling material can be used in mortars and concrete, as well as in bricks, adsorbents, porous materials, plugging materials and the direct choice of its application depends on economic factors.

The use of Iron ore tailings in road construction. Speaking about the use of enrichment waste in the construction industry, it is impossible not to mention the possibility of using waste in the production of materials used in road construction. As a rule, they are used as aggregates in asphalt-concrete mixtures. In this case it is important to evaluate the compatibility of the mixture ingredients and compliance with the parameters of strength and durability of the resulting materials. In this regard, it is very important to assess the physical, chemical and mechanical characteristics of iron ore waste before using it as an aggregate and correctly select the proportion of iron ore residue additives.

Iron ore tailings can be used instead of limestone aggregate in asphalt mastics. Evaluating the granulometric composition of the tailings, it is important to note that the iron ore tailings are essentially already pre-crushed material to the desired degree, and a second crushing is not required , which already at this stage allows to reduce the production costs. Also, due to the fact that the specific surface area of the particles, according to the study (Wei *et al.*, 2022) is almost twice as large, such aggregate has a higher ability to adsorb asphalt.

Speaking about the chemical composition of the waste, we can say that the tailings contain more Fe O_{23} in comparison with the limestone filler, which leads to higher aggregate density. The higher content of acidic components (SiO_2) implies a lower potential for adhesion to asphalt, and the more ordered structure of the waste material has a positive effect on the hardening efficiency of the asphalt mastic. More in-depth studies on cracking, fatigue, and adhesion properties of bituminous mastics are needed to unequivocally judge the possibility of using waste in asphalt mastic (Wei *et al.*, 2022).

Speaking of other materials, the authors confidently conclude that Iron ore tailings are suitable aggregates for micro-coatings of cold asphalt mixes, and there is a need to develop standards for the industrial implementation of this technology (Apaza Apaza *et al.*, 2021). The waste is also suitable for the production of concrete, which can be used for sidewalk construction (J *et al.*, 2017). Use in road structures is possible because the tailings easily meet the strength requirements of the base course and sub-base layers. Such stabilized soils are most often used in the construction of roads and sidewalks, embankments, backfills, landscaping, etc. where they are not in direct contact with structural elements and supports (Barati *et al.*, 2020).

Ceramics. Review of foreign and domestic research on the recycling of various industrial wastes in the production of ceramic building products - bricks, stone, tiles shows that in some cases, the use of large-tonnage industrial wastes, primarily, mining and metallurgical and fuel and energy complexes in ceramic materials leads to improved properties of materials(D.V. Makarov, 2016)(Shcherbina and Kochetkova, 2016b; Weishi *et al.*, 2018; Fontes *et al.*, 2019; Z. Wang *et al.*, 2020; Li *et al.*, 2021).

Additional extraction of iron. The possibility of maximum extraction of iron for subsequent use from iron ore enrichment wastes before their introduction into construction materials in some cases is a cost-effective solution. To date, a large number of studies on post-extraction using different technologies have been conducted (Darezereshki *et al.*, 2018; Panda *et al.*, 2018; Tang *et al.*, 2019; Sun *et al.*, 2020).

Conclusion. Waste from iron ore processing is one of the main by-products of the mining industry, which provoke environmental safety problems. The continuous development of ferrous metallurgy, as well as the gradual transition to the mining of reserves with ores of low quality that require beneficiation, leads to an even greater increase in the amount of waste.

Recently, iron ore tailings as a secondary resource have received considerable attention, research on their comprehensive use is mainly focused on the production of construction materials due to the efficiency of consumption of large volumes of tailings, the lack of waste of the recycling process and the possibility to preserve traditional natural resources. In addition to construction materials, the possibility of producing chemical reagents and fertilizers is being explored, since the physical and chemical properties of iron ore tailings have a number of unique properties that can be exploited.

This review article presents the results of the literature published over the past decade on the potential uses of iron ore beneficiation wastes.

In the course of a detailed analysis of scientific papers the following conclusions were made. To date, a sufficient amount of research has been done on the issue of finding ways to utilize IOT but the solution to this issue is still in its infancy. Production of fertilizers on the basis of enrichment wastes is still limited by the insufficient level of research conducted on this topic, production of functional materials for wastewater treatment needs further research to find the easiest, inexpensive and effective way of their production, as the currently existing technologies are quite complex and often require the use of additional reagents.

As for the construction industry, research on the use of IOT as aggregates in the production of cement, concrete, pavers, road building materials needs to be summarized and standards developed for the direct introduction of technology into production.

1.6 Research Methodology

1.6.1 Sampling and sample preparation for analysis

iron ore tailings were sampled from the tailings of Stoilensky GOK, which is located in Stary Oskol, Belgorod Region. The coordinates are 51°15'43 "N. Coordinates 51°15'43 "N, 37°43'36 "E. Samples were taken from the upper horizon of the tailings dump in accordance with GOST 17.4.3.01 2017. The tailings dump was divided into sampling sites, and point samples were taken from each site to form a combined sample (*GOST 17.4.3.01-2017. Interstate standard. Protection of Nature. Soils. General requirements for sampling:*, 2018)The samples were transported in vessels made of chemically neutral materials. The selected samples were dried and stored in a dry place for further use.

Figure 4: Figure 4 - Drying of Iron ore tailings

Before transferring samples taken at the plant to the laboratory for analysis, it is necessary to make a combined sample, which is subsequently reduced by quartering in order to obtain a sample of necessary and sufficient mass. Quarting is carried out as follows: after mixing the sample, the material cone is flattened, divided into four equal parts by mutually perpendicular lines, two opposite quarters are taken in the sample or continue sequentially quarting, reducing the sample in two, four and so on times.

1.6.2 Methodology of laboratory experiments

In order to characterize the iron ore tailings of Stoilensky GOK we analyzed the chemical, mineralogical, granulometric composition and characterized the morphology of grains. Characterization of the the residues after iron recovery from iron ore tailings included laser granulometry and elemental composition using the same procedures used for iron ore tailings.

1.6.3 Determination of the chemical composition of iron ore tailings

The chemical composition was determined by X-ray fluorescence (XRF). To implement this method, a XRF-1800 (Shimadzu) X-ray fluorescence spectrometer was used in the laboratory. Sample preparation and analysis were carried out in accordance with GOST 33850-2016.

When performing X-ray fluorescence spectrometry, it is necessary to conduct the sample preparation stage correctly, because it has a significant impact on the accuracy of the results. The analyzed sample of iron ore tailings is placed in a crucible for melting and flux is added in the ratio of 1:3. The crucible is then placed in a muffle furnace or a special device for automatic sample fusion. The crucible is incubated at 1000 °C to 1200 °C for sufficient time to produce a visually homogeneous melt. The holding time should not exceed 30 minutes. This is how the melted (vitreous) disc is obtained. The prepared samples to be analyzed are placed in the irradiation chamber of the X-ray fluorescence spectrometer. The samples are irradiated and the spectrum is recorded. The resulting spectrum of intensities of the characteristic fluorescence of the elements being determined is processed using software according to previously established calibration dependences and the contents of macroelement oxides expressed in mass percent (*GOST 33850 - 2016.Soils. Determination of the chemical composition by X-ray fluorescence spectrometry.*, 2016)are established.

The results of the chemical analysis of Stoilensky iron ore tailings are presented in Table 23. According to the results of X-ray fluorescence analysis, the tailings of Stoilensky GOK can be attributed to the high-silicon type, which is one of the most common types of iron-ore tailings.

SiO_2	Fe_2O_3	MgO	CaO	Al_2O_3	K_2O	Na_2O	P_2O_2	MnO	TiO_2	LOI
71,4	18,0	4,17	3,38	2,03	0,742	0,628	0,206	0,092	0,055	2,20

Table 23: Chemical composition of iron ore tailings according to XRF data (wt. %)

1.6.4 Granulometric analysis of iron ore tailings

Granulometric analysis of the iron ore tailings was carried out using a Horiba LA-950 laser diffraction particle size analyzer. The analysis method was implemented in accordance with GOST R 8.777-2011.

Samples to be analyzed must be in the form of aerosol and suspension. If powders are to be analyzed, they are prepared using liquid or gaseous dispersion media. Analysis of ground-metric composition consists of the following stages: checking the background in the measuring channel, measuring the scattering pattern of aerosol/suspension, which involves multiple registration of the light scattering pattern by a multielement photodetector for a characteristic measurement time, calculating the average signal for each element, saving the measurement results, choosing the model for calculating the particle size by scattering indicator according to the international standard (Mie theory, Fraunhofer theory), calculating the average particle size by indicator

The granulometric analysis of iron ore tailings is shown in Figure 5 and Table 24. According to the analysis, the most frequent particles are 0.5 mm in size.

Fraction size, mm	<0,005	0,005 - 0,01	0,01-0,05	0,05-0,1	0,1-0,25	0,25-0,5	0,5-1	1-3
Contents fractions, %	2.412	4.453	13.495	9.983	9.602	18.405	30.12	11.53
UnderSize, %	2.412	6.865	20.36	30.342	39.944	58.35	88.47	100

Table 24: Granulometric composition of iron ore tailings

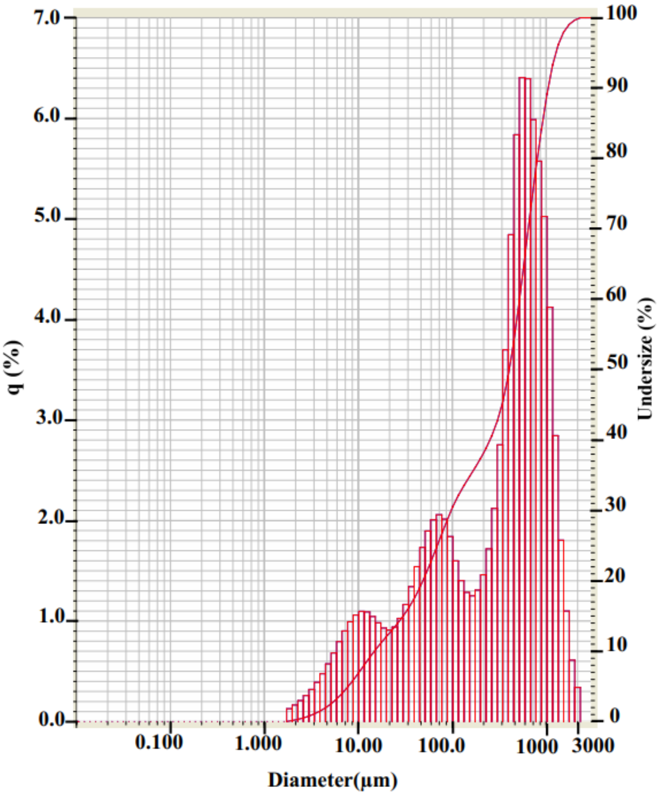


Figure 5: Granulometric composition of iron ore enrichment waste

1.6.5 Determination of mineralogical composition of iron ore tailings

The mineralogical composition was determined by X-ray diffraction (XRD). X-ray phase analysis was carried out on an XRD-6000 powder X-ray diffractometer with a high-temperature chamber HA1001. The phase search was performed using the JSPDC international index card. Determination of the phase analysis was carried out according to OFS.1.2.1.1.0011.15.

In this analysis special attention should also be paid to sample preparation. The crushed powder, which is a polycrystalline body, is compressed and used for imaging in the form of a tablet up to 25 mm in diameter. Attention should be paid to the thoroughness of grinding the powder, because a powder consisting of large crystals gives indistinct, low-intensity radiographs. Grinding should be carried out in an agate mortar with an agate pestle in order to exclude sample contamination. The size of crystals should be in the range of 5 to 10 μm. Excessive abrasion also leads to disturbance of the crystal structure of the preparation and, consequently, to deterioration of the radiograph quality. If the crystal size is less than 0.1 μm, the interference lines may be blurred, and if the phase amount is small, its lines may merge with the background (*State Pharmacopoeia of the Russian Federation. GPM.1.2.1.1.0011.15 X-ray powder diffractometry.* XIII, 2016).

The diffractogram of the iron ore enrichment waste (XRD) is shown in Figure 6. The mineral part of the solid waste is quartz (SiO_2) with an admixture of magnetite (Fe_3O_4), hematite (Fe_2O_3) and polymorphic modifications of complex calcium oxide and iron (iron with different valence). The intensity of quartz diffraction peaks is significantly higher than that of other minerals, indicating that quartz is a major mineral. The diffractogram interpretation is confirmed by the chemical composition of XRF analysis (Table 6), where SiO_2 is also the main component (71.4%, wt.%).

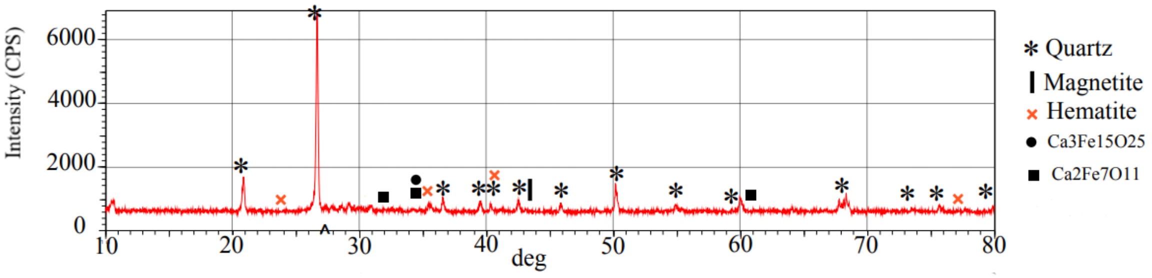


Figure 6: X-ray phase analysis of iron ore enrichment waste

1.6.6 Grain morphology of Iron ore tailings

Grain morphology was obtained using a JSM-7001F scanning electron microscope. A microscope is a tool that allows magnification of an image of an object under study to measure and analyze its microstructure. The resolution of the microscope, the ability to distinguish the minimum dimensions of elements in the image, depends on the electron beam diameter and the interaction region.

During scanning, a beam of primary electrons is sequentially directed to different areas of the surface under study. For each scanning point the intensity of backscattered electrons is registered. This process is accompanied by the creation of an intensity matrix I (X, Y) corresponding to each point.

Surface scanning is performed with a certain step and the number of these steps determines the pixel resolution of the resulting image. The pixel resolution means the number of image points horizontally and vertically.

The transition between different scanning points is made by changing the current in the deflection coils. When several detectors are used, a different intensity matrix is formed for each of them. The detectors serve to collect electron flux from the interaction region.

So, at the center of the scanning process is a detailed and consistent examination of the sample surface. This makes it possible to create a detailed image in which each point corresponds to a unique intensity value. The information obtained allows to analyze and measure microstructure elements with a high level of accuracy (SAKHAROV N. V., 2020).

Scanning electron microscopy of iron ore tailings of Stoilensky GOK revealed some interesting features related to the morphology of the samples, namely: particles have angular and irregular shape (a,d), at the closest approach we can see protrusions and uneven surface (b,d,e,f), which, in turn, increases the surface area of tailings particles and makes the appearance of microparticles rougher (Figure 7). At the same time, the images obtained confirm the results of the particle size distribution: a large number of particles smaller than 500 µm can be seen in the figure (c), as well as a small number of particles larger than 1000 µm (a). Images (e,f) show that small particles tend to agglomerate.

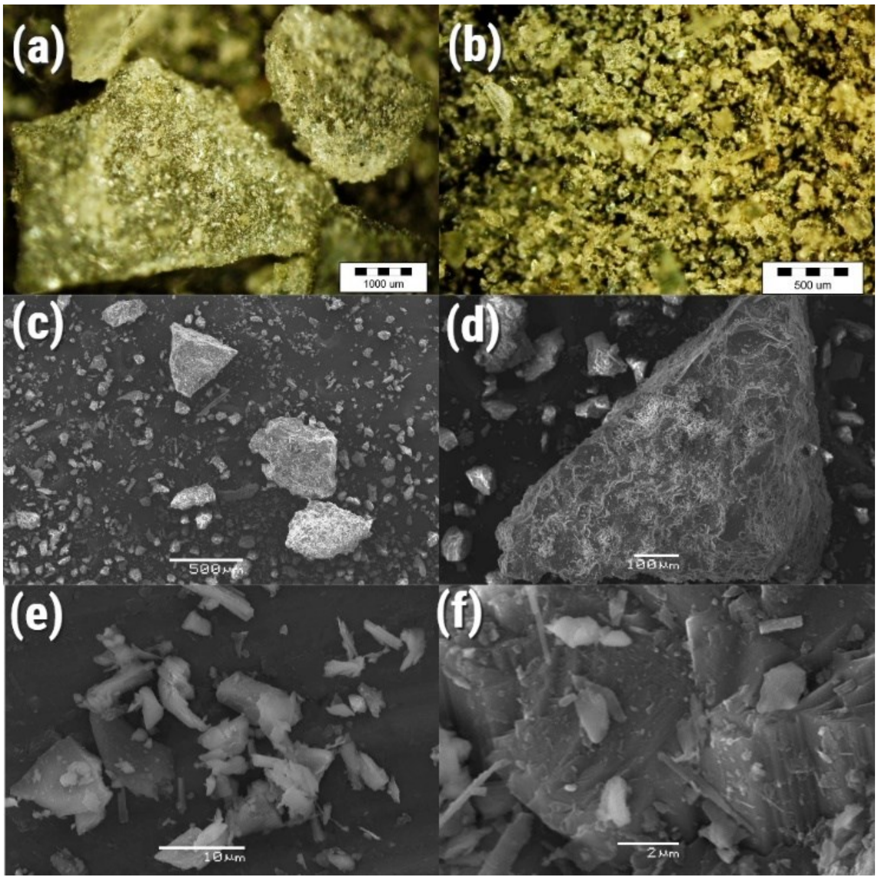


Figure 7: **Morphology of IOT**

1.7 Theoretical and Experimental Studies

1.7.1 Prerequisites and theoretical substantiation of the possibility of using iron ore tailings as a coagulant

The convergence of the results of various methods of analyzing the properties of iron ore tailings at Stoilensky GOK indicates the reliability of the studies carried out. This makes it possible to analytically assess the possibility of using modern technologies for processing and utilization of iron ore tailings.

Analyzing the chemical composition of iron ore tailings (Table 16), we should note a high iron content (18%) relative to iron ore waste from other deposits, which is a valuable raw material. Taking into account the amount of accumulated iron ore tailings on the territory of the mine today: 380 million tons, we can conclude that the tailings dump of Stoilensky GOK may become a suitable raw material base for the production of iron-containing materials, which will lead to the expansion of the production chain of iron ore mining and minimize the number of tailings to be dumped into the tailings dam.

In addition to iron extraction technologies have been described that allow producing reagents for iron-based wastewater treatment from iron ore tailings. Often such technologies are characterized by multistage processes, as well as hardware complexity. In research work, the possibility of iron leaching by hydrometallurgical methods from waste to use the resulting solution as a coagulant for wastewater treatment is described (Sorokina, 2009; Sverguzova, 2016; Kuzin, 2019; Almeida and Schneider, 2020; Tao *et al.*, 2021). Iron oxides generally have a low to very low solubility in water, and acid leaching decreases in the following order: hydrofluoric acid > hydrochloric acid > sulfuric acid. The main properties that affect the dissolution of iron are: the temperature of the reaction, the concentration of the reagent, the specific surface area of the particles, and the phase composition of the raw materials (Almeida and Schneider, 2020).

In the iron ore tailings of Stoilensky GOK iron is represented in the form of hematite and magnetite, and the particles are characterized by a fine size (Table 17) and surface roughness (Figure 7), which indicates a large specific surface area. These factors are sufficient grounds for the assumption that under properly selected conditions of the reaction, a solution containing iron in ionic form can be obtained from iron ore enrichment wastes, which can be subsequently used as a coagulant for wastewater treatment.

Coagulation is an important process in water and industrial wastewater treatment. Inorganic coagulants are divided into two categories: aluminum-based coagulants and iron-based coagulants (Snezhko, 2004). Iron salts, which are used for treatment, have a number of advantages compared to aluminum salts. For example, there is an improvement in the coagulation process when iron salts are used for lower temperature water treatment. The iron salts are also highly effective over a wide pH range. Deposition of the sludge is also much faster. There is no contamination of the inlet with aluminum ions.

At the same time, it is impossible not to mention the disadvantages, such as the need for their careful dosing. In case of insufficient or excessive dosing of the coagulant, iron ions slip into the treated water. This can largely be eliminated by adding aluminum salts simultaneously or sequentially. Therefore, the use of mixed coagulants, which are a mixture of aluminum and iron compounds, gives a greater effect in water treatment. In this regard, obtaining new coagulants based on iron and aluminum compounds is an urgent task (Sorokina, 2009).

Iron-based coagulants are usually obtained by acid treatment of iron material (Almeida and Schneider, 2020), but it can also be obtained from alternative sources, such as mill scale from steel production (Snezhko, 2004; Kuzin Evgenij Nikolaevich, 2021; Tao *et al.*, 2021), electric arc furnace dust (Sverguzova, 2016).

Below we consider the potential for the production of iron chloride as well as iron-aluminum-based complex coagulant from iron ore enrichment wastes at Stoilensky GOK. Under laboratory conditions we investigated the main variables of the process of iron-aluminum-based complex coagulant production, including acid concentration, temperature, reaction time, stirring, and the solid-liquid ratio (s:liquid). The resulting coagulant was analyzed in terms of its chemical composition and its effectiveness in water treatment was evaluated.

1.7.2 Preparation of coagulant using sulfuric acid and hydrochloric acid

Production of a coagulant using sulfuric acid. This study examined the potential to produce an iron-aluminum-based complex coagulant from iron ore tailings using sulfuric acid. The effects of major process variables including acid concentration, temperature, reaction time, solid:liquid ratio, and the effects of stirring were evaluated under laboratory conditions.

Each leaching condition investigated was performed twice (n = 2), and the results are presented as a mean value. Analysis of metals in solutions after leaching to produce a coagulant was carried out by inductively coupled plasma (ICP) spectroscopy using an ICPE- 9000 Shumadzu Atomic Emission Spectrometer. According to the procedure of the quantitative chemical analysis M - 02-1109-08, the boundaries of the relative total error of the results of measurements of mass concentration of elements ±δ, % (at confidence probability P=0,95), which will be determined further, are given in table 25.

Al	13	Cr	13	K	13	Mn	13	Sr	14

Ba	13	Cu	13	Li	13	Na	13	V	15
Ca	17	Fe	11	Mg	13	P	-	Zn	17

Table 25: Boundaries of the relative total error* ±d, % (P=0.95).

The amount of sulfuric acid required to dissolve the iron present in the iron ore enrichment waste was determined by reaction (1). Taking into account stoichiometry, 15 ml of $H_2 SO_4$ 30% is necessary for 15 g of waste (≈ 18% Fe2O3).

$$Fe\ O_{23} + 3H_2\ SO_4 \rightarrow Fe_2\ (SO4)_3 + 3H_2\ O \quad (1)$$

In order to select the optimal concentration of sulfuric acid to leach the greatest amount of iron, experiments with different concentrations were conducted (table 26, figure 8) followed by evaluation of leaching efficiency. The best results were achieved with sulfuric acid concentrations of 40 and 50 percent.

№	Concentration of sulfuric acid [%]	Temperature [C]	Time [min]	s:l	Fe concentration [mg/l]	Al concentration [mg/l]	Fe leaching efficiency [%]	Al leaching efficiency [%]
1	20	20	180	1:1	6410	1150	5.1	10.7
2	25	20	180	1:1	7355	1225	5.8	11.4
3	30	20	180	1:1	8485	1395	6.7	13.0
4	35	20	180	1:1	8635	1405	6.9	13.1
5	40	20	180	1:1	10900	1500	8.7	14.0
6	50	20	180	1:1	10600	1270	8.4	11.8

Table 26: Efficiency of leaching of iron and aluminum contained in waste, depending on the concentration of H2SO4

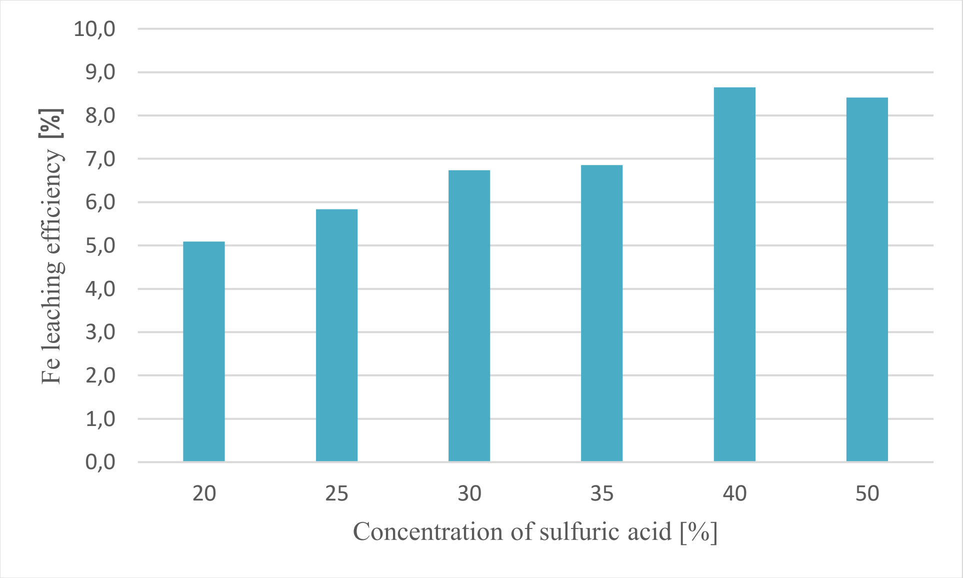


Figure 8: Efficiency of leaching of iron contained in the IOT depending on the concentration of $H_2\ SO_4$ with a leaching time of 3 hours

The reaction temperature is a key parameter in leaching reactions and has a significant influence on the percentage of extracted iron and aluminum. Thus, the dependence of iron leaching efficiency on the reaction temperature was determined (Table 27, Fig. 9). The best result was achieved at a reaction temperature of 100° C.

№	Concentration of sulfuric acid [%]	Temperature [C]	Time [min]	s:l	Fe concentration [mg/l]	Al concentration [mg/l]	Fe leaching efficiency [%]	Al leaching efficiency [%]
1	40	20	180	1:1	10902	1486	8.7	13.8
2	40	50	180	1:1	15700	1890	12.5	17.6
3	40	75	180	1:1	18500	2500	14.7	23.3
4	40	100	180	1:1	31900	3230	25.3	29.9

Table 27: Efficiency of leaching of iron and aluminum contained in the waste, depending on the temperature of the reaction.

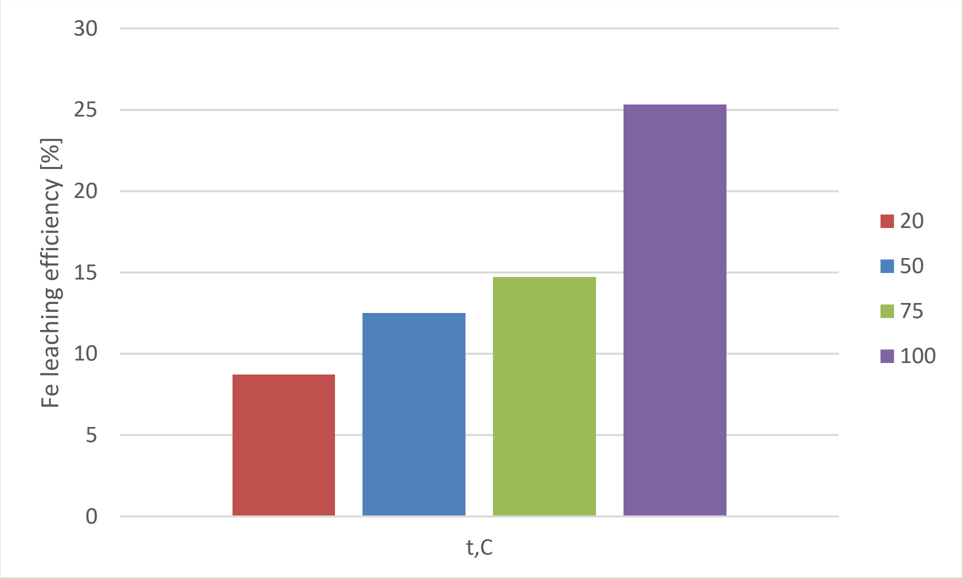


Figure 9 - The effect on leaching efficiency of reaction temperature

Leaching experiments were performed for 15, 30, 60, 120, and 180 minutes in order to determine the shortest reaction time required (Table 28, Figure 11). The results showed that the leaching processes stabilized at 25% after 60 minutes.

Figure 10: Leaching process.

№	Concentration of sulfuric acid [%]	Temperature [C]	Time [min]	s:l	Fe concentration [mg/l]	Al concentration [mg/l]	Fe leaching efficiency [%]	Al leaching efficiency [%]
1	40	100	15	1:1	18100	2270	14.4	21.1
2	40	100	30	1:1	26900	2830	21.3	26.3
3	40	100	60	1:1	32500	3320	25.8	30.9
4	40	100	120	1:1	32800	3380	26.0	31.5
5	40	100	180	1:1	31900	3230	25.3	30.1

Table 28: Efficiency of leaching of iron and aluminum contained in waste as a function of reaction time

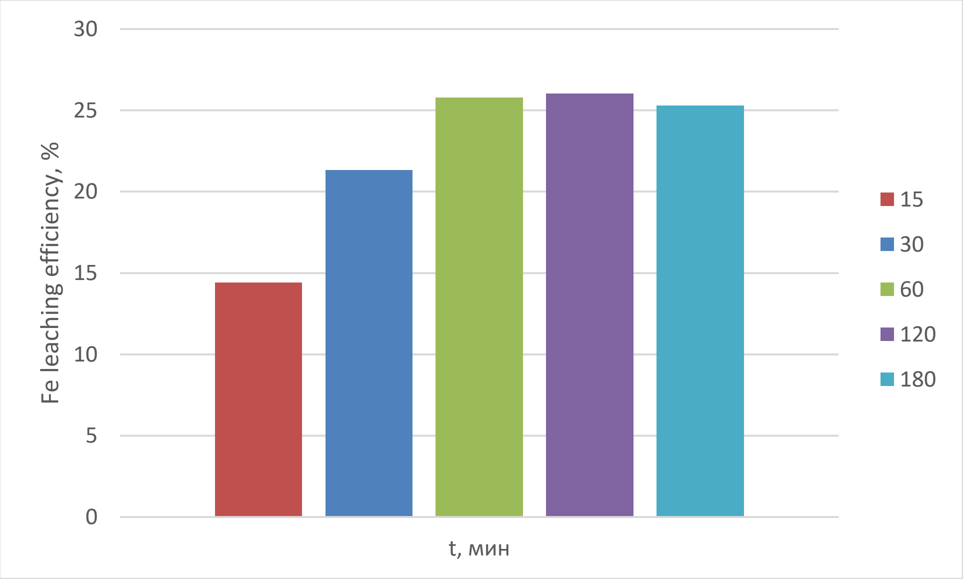


Figure 11: The effect on iron leaching efficiency of reaction time

The results of the study show relative stability of iron yield when the solid:liquid ratio changes at 100° C (figure 12, table 29), from which we can conclude that increasing the amount of sulfuric acid substance through volume has no effect on the leaching efficiency.

№	Concentration of sulfuric acid [%]	Temperature [C]	Time [min]	s:l	Fe concentration [mg/l]	Al concentration [mg/l]	Fe leaching efficiency [%]	Al leaching efficiency [%]
1	40	100	60	1:1	30900	3330	24.5	31.0
2	40	100	60	1:3	9810	950	23.4	26.5
3	40	100	60	1:5	5560	605	22.1	28.1

Table 29: Efficiency of leaching of iron and aluminum contained in the waste, depending on S:L.

The percentage of extracted iron can be significantly increased by means of the stirring process [131], because the contact area of iron ore enrichment waste particles with acid increases considerably. For this reason, experiments on iron leaching were carried out at the following temperatures: 20, 50 and 75 degrees Celsius. The stirring speed was 150 rpm. The ratio t:g in order to create a stirring medium was chosen to be 1:3. The results are presented in Table 30. Figure 13 shows a graph comparing the results obtained at different temperatures with and without stirring. The graph shows that stirring significantly increases the percentage of extracted iron at 75 degrees.

№	Concentration of sulfuric acid [%]	Temperature [C]	Time [min]	s:l	Fe concentration [mg/l]	Al concentration [mg/l]	Fe leaching efficiency [%]	Al leaching efficiency [%]
1	40	20	60	1:3	3920	323	9.3	9.0
2	40	50	60	1:3	6960	936	16.5	26.1
3	40	75	60	1:3	11100	1115	26.4	31.1

Table 30: Efficiency of leaching of iron and aluminum contained in the waste, depending on the temperature of the reaction under stirring

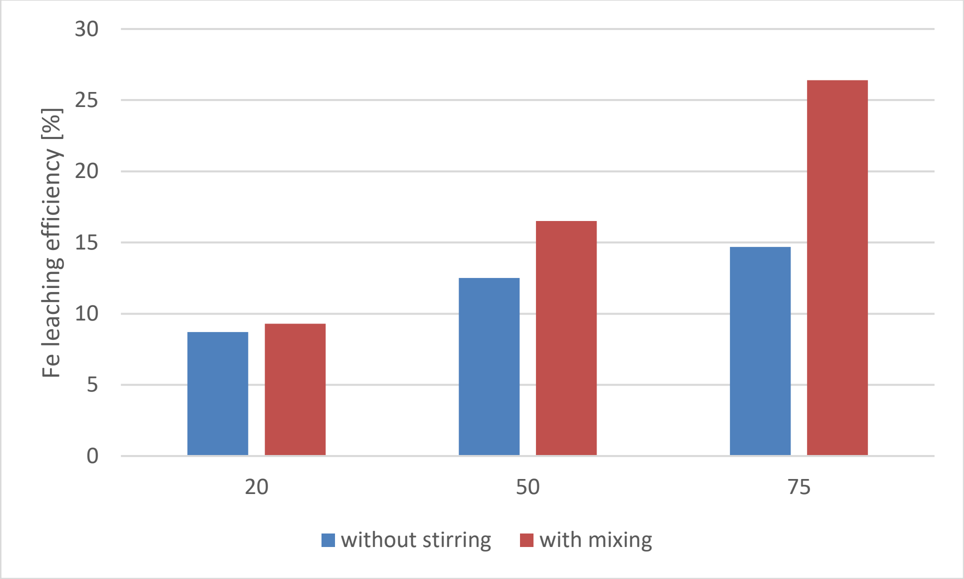


Figure 12: Graph comparing the results obtained at different temperatures with and without mixing

A comparison was also made of the change in leaching efficiency during agitation from S:L at 50 degrees Celsius. The results are given in table 31. Experiments with further reduction of the ratio were not conducted, because the concentration of iron in the resulting solution decreases significantly (the leaching efficiency is always the same), which will further lead to an increase in the consumption of the obtained coagulant. The lowest ratio t:g should be selected based on the reactor parameters.

№	Concentration of sulfuric acid [%]	Temperature [C]	Time [min]	S:L	Fe leaching efficiency [%]	Al leaching efficiency [%]
1	40	50	60	1:3	16.5	26.4
2	40	50	60	1:6	15.7	25.1

Table 31: Efficiency of leaching of iron and aluminum contained in the waste, depending on S:L

Thus, laboratory studies revealed that the highest efficiency of iron leaching was achieved at a sulfuric acid concentration of 40%. The greatest amount of extracted iron was achieved at a temperature of 100^0 C. The shortest reaction time required at 100 degrees was 60 minutes. During the experiments, the leaching efficiency was compared at different S:L ratios. The results showed no change in leaching efficiency. For this reason, the t:g ratio was chosen as the lowest possible ratio for the reaction. Also, it was found that stirring the mixture significantly increases the yield of iron in the solution.

To test the obtained solution as a coagulant, a combined sample of 15 point solutions was made up. Each of the 15 samples was obtained as follows: iron ore enrichment waste is treated with sulfuric acid solution of 40% concentration, the ratio of iron ore enrichment waste to acid reagent is maintained at least 1:1 g/ml. The process of obtaining the coagulant is carried out for 60 minutes with a temperature of 100^0 C. The obtained combined sample contains Fe compounds (in the form of sulfates (III)), - 10.58% and Al compounds (in the form of sulfates), - 2.07%.

Further under laboratory conditions was tested the effectiveness of the obtained coagulant. According to GOST R 51642-2000, within the framework of evaluation of coagulation properties of the obtained complex coagulant, experiments were conducted on a model solution of chromaticity, for creation of which sodium humate was used (*GOST R 5 1 642-2000. COAGULANTS FOR HOUSEHOLD AND DRINKING WATER SUPPLY. General requirements and method for determining effectiveness*, 2000). Assessment of model solution chromaticity was performed using a DR5000 spectrometer.

To prepare a model color solution, a 50 g weight of sodium humate was taken and transferred into a 2 dm flask^3 , then filled with 1 dm^3 of distilled water at 40 C and stirred. Pre-closing the flask with a cork, the solution was incubated for 24 hours. After that the obtained solution was filtered through a paper filter. Then the solution was diluted with distilled water until the color of the model solution was equal to 50° according to the standard chromaticity scale (GOST 3351) and used as a model chromaticity solution (*GOST R 5 1 642-2000. COAGULANTS FOR HOUSEHOLD AND DRINKING WATER SUPPLY. General requirements and method for determining effectiveness*, 2000).

The effectiveness of the coagulant significantly depends on the pH of the treated water. According to (A.S. Danilov, 2018), the pH range in which the obtained coagulant showed the highest efficiency was determined. In five 150-200 ml beakers, 50 ml each of the model chromaticity solution is placed. An equal dose of coagulant (6 mg/L) is introduced into each beaker, and the pH is adjusted to 1.2, 3.4, 5, 6.7, 8, 9, 10, 11, and 12 respectively using 0.1N solutions of NaOH and HCl. Then the solution is stirred for 3 min and filtered. The filtrate is analyzed for the remaining chromaticity. The chromaticity of the model solution is determined using a DR5000 spectrometer, having previously constructed a calibration graph (Figure 14) on a chromo-cobalt chromaticity scale (*GOST 3351-74. DRINKING WATER METHODS FOR DETERMINATION OF TASTE, ODOUR, COLOR AND TURBIDITY*, 1974).

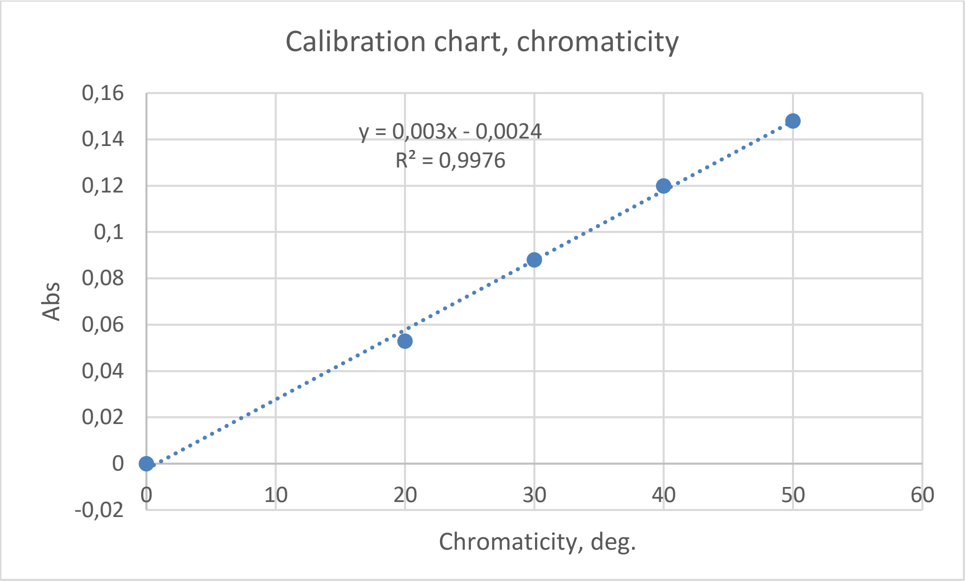


Figure 13: Calibration chart for determining the chromaticity of the model solution

Figure 14: Effect of pH on the coagulation process

Coloration of the initial solution	Abs, before coagulation	pH	Abs, after coagulation	Chromaticity of the solution after cleaning
50	0.141	1	0.143	50
50	0.141	2	0.145	50
50	0.141	3	0.148	50
50	0.141	4	0.047	17
50	0.141	5	0.030	11
50	0.141	6	0.025	9
50	0.141	7	0.015	6
50	0.141	8	0.047	17
50	0.141	9	0.044	15
50	0.141	10	0.039	14
50	0.141	11	0.053	19

50	0.141	12	0.088	30

Table 32: Effect of pH on the coagulation process

During the experiment, it was found that the coagulant exhibited the greatest effectiveness at pH=7, with its performance demonstrated in a wide range of pH from 4 to 12.

Next, an experiment was conducted to determine the lowest effective dose of coagulant for cleaning. Preliminary beakers for the experiment were washed with distilled water. Next, 1.0 dm^3 of the model chromaticity solution obtained in advance was poured into the beakers, the stirrers were lowered into the beakers and the coolant and stirrer were turned on. Stirring speed should be 140 rpm. The temperature control time is until the suspension reaches the test temperature of (20 ± 1) °C. A dose of working solution of coagulant is added to the beakers for coagulation of the model suspension and stirred for three minutes. After that the stirring speed is automatically switched to 40 rpm and stirred for 15 minutes. The stirrers are turned off and removed from the beakers. The solution is then allowed to stand for 30 minutes. According to GOST 31868- 2012, after sedimentation the sample is filtered and the color is measured. The dose of coagulant that reduces color from 50 to 20 degrees is considered an effective dose for the model color solution.

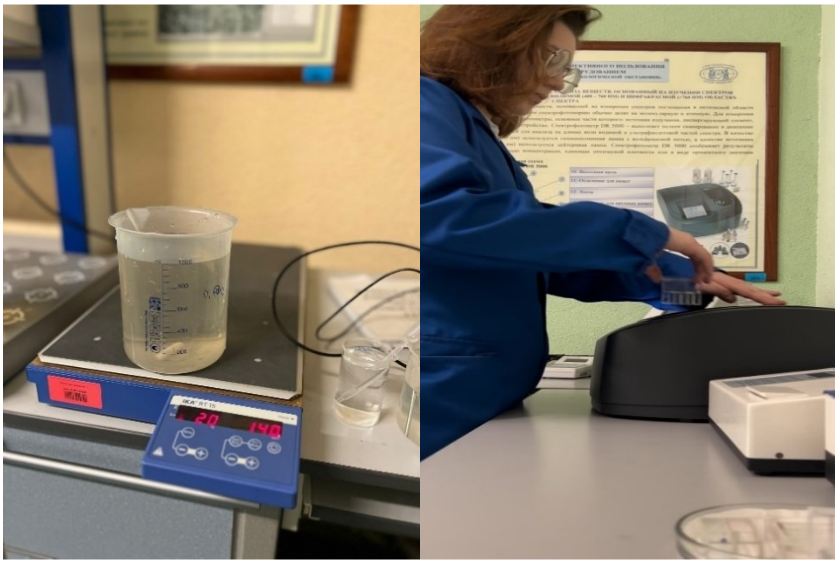


Figure 15: Determination of the optimal dose of coagulant application

Based on the results of the experiment, a graph (Figure 16) was plotted, showing the dependence of changes in the chromaticity of the model solution on the coagulant dose introduced, from which you can determine the minimum required dose of coagulant.

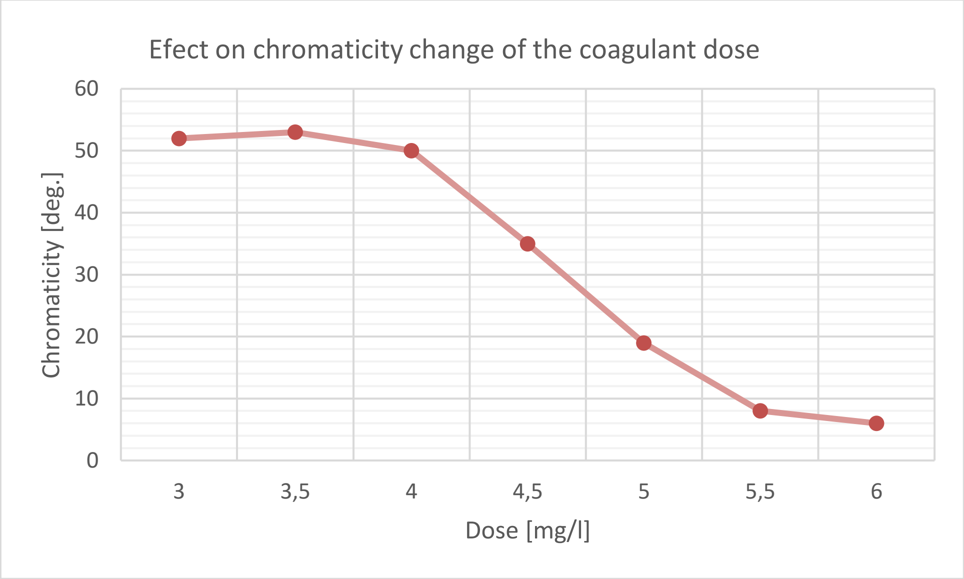


Figure 16: Determination of the optimal dose of coagulant application

According to the results of the experiments, it can be concluded that the effective dose of coagulant for iron oxide for the model solution of coloration is 5 mg/L. This requires taking 0.118 ml of the initial solution per 1 liter of water to be treated.

In order to identify the presence of impurities in the coagulant composition a quantitative analysis of the chemical composition of the obtained coagulant was carried out. The results are presented in Table 33.

Al	3180	Cr	4.76	K	1970	Mn	210	Sr	1.35
Ba	0.849	Cu	3.19	Li	4.11	Na	80.6	V	6.94
Ca	56.7	Fe	29600	Mg	6800	P	801	Zn	7.04

Table 33: Chemical composition of the coagulant [mg/l]

Since the presence of heavy metals was detected in the composition of the coagulant, experiments were carried out to assess the secondary contamination of treated water with heavy metals as a result of using the coagulant. A quantitative analysis of the composition of the model coloration solution was determined when the optimal dose of coagulant (5 mg/L) was applied before and after the treatment procedure. The results of the analyses are presented in Table 34.

	Al	Ba	Ca	Cu	Fe	K	Mg	Mn	Na	S	Sr	Zn
Before	0,0217	0,0025	1,36	<0,01	0,0467	1,25	0,197	0,0024	0,791	0,351	0,003	<0,005
After	0,0219	0,0011	2,03	<0,01	0,0515	1,89	0,746	0,0094	20,7	16,9	0,0141	<0,005

Table 34: Chemical composition of the model solution [mg/L].

It can be seen that heavy metal contamination of treated water during the introduction of coagulant did not occur, indicating the feasibility of using the obtained coagulant as a reagent for wastewater treatment.

Obtaining coagulant using hydrochloric acid. On the basis of wastes of iron ore enrichment of Stoilensky GOK possible to obtain coagulant of iron chloride using hydrochloric acid. To assess the possibility of obtaining such a coagulant were carried out experiments on its production under the following conditions: weight of the sample 15, volume of solvent - 25 ml, leaching time - 3 hours, the concentration of hydrochloric acid - 37%, the temperature of the reaction respectively 20 and 40 ℃. It was also decided to test the leaching on crushed waste samples with a particle size smaller than 25 µm as a variable factor. The results of the experiment are presented in Table 35.

Sample	Particle size	Temperature [C]	Time+end HCl	Iron content in the solution [mg/l]	Fe leaching efficiency [%]
1	< 3 mm	20^{0}	3 hours, 37%	23300	30.8
2	<0.25 mm	20^{0}	3 hours, 37%	28900	38.2
3	<0.25 mm	40^{0}	3 hours, 37%	25500	33.7
4	< 3 mm	40^{0}	3 hours, 37%	25700	34.0

Table 35: Experimental results of obtaining iron chloride coagulant

We can see that increasing the reaction temperature to 40 degrees and reducing the particle size made no significant difference in the percentage of leached iron.

Experiments were performed with different sample weights (Table 36). The average percentage of iron oxide leaching was 37.9 percent.

Suspension weight [g]	Iron content in the solution [mg/l]	Fe leaching efficiency [%]
1	822	32.6
3	2960	39.2
5	5270	41.8

Table 36: the results of the experiment with different weights

To understand the reliability of the results, the primary processing waste of iron ore concentration was washed 2 times with distilled water, dried and characterized by elemental composition. Table 37 shows the results of X-Ray analysis before and after leaching.

	SiO2	Fe2O3	MgO	CaO	Al2O3	K2O	Na2O	P2O5	MnO	TiO2	LOI

Until	71.4	18.0	4.17	3.38	2.03	0.742	0.628	0.206	0.092	0.055	2.20
After	83.5	10.5	3.32	1.44	1.82	0.858	0.321	0.073	0.069	0.061	0.54

Table 37: Results of XRF analysis before and after leaching

The results of the XRF analysis clearly show that 7.5 percent of the iron in oxide form was recovered by leaching. Table 38 shows the results of the leached percentage of iron according to the ICP analysis. The arithmetic mean of the leached iron oxide is 6.8 percent.

Suspension weight, g	Leached iron oxide, %
1	5.8
3	7.1
5	7.5

Table 38: Results of leached percentage of iron according to ICP

For a clear comparison of the results, let us summarize them in Table 39.

	Percentage of extracted Fe [%]
RFA	7.5
ICP	6.8

Table 39: Results of iron leaching

In general, it can be concluded that under the accepted leaching conditions, the leaching efficiency is in the range of 37 to 42 percent.

Two experiments were conducted to evaluate the coagulation properties of ferric chloride. In the first one the ability of coagulant to purify solutions from chromaticity was tested (figure 17), in the second one the ability to accelerate sedimentation of small particles was tested. According to GOST R 51642-2000, sodium humate was used to create a model solution for coloration. Experiment on sedimentation of fine ash particles was also carried out. The results of the experiments confirm the performance of iron chloride coagulant obtained on the basis of iron ore enrichment wastes.

Figure 17: Coagulation process on the chromaticity solution

Quantitative analysis of iron chloride coagulant impurities was carried out. The chemical composition of the coagulant is shown in Table 40. This case also requires further experiments on purification of the model solution to establish the optimum pH, coagulant dosage, as well as experiments on co-precipitation of impurities present in the coagulant.

Al	1410	Cr	126	K	782	Mn	167	Sr	26
Ba	5,5	Cu	3,19	Mg	2910	Na	35,9	Ti	75
Ca	7460	Fe	28900	Ni	68,4	Zn	6,7		

Table 40: Chemical composition of the coagulant [mg/l].

It should be noted that the efficiency of iron leaching with hydrochloric acid (37%) without significant heating is significantly higher than with sulfuric acid with heating (25.3%).

However, the reagent (hydrochloric acid) used in the experiment has a number of significant drawbacks: high volatility, toxicity of vapors, increased cost. For this reason, in this work it was decided to conduct experiments on obtaining coagulants using sulfuric acid. However, given the possible prospects of wastewater treatment with coagulant based on ferric chloride, this technology also has promising prospects for further study.

1.7.3 Characteristics of the residues after iron recovery from iron ore tailings

At the stage of leaching with sulfuric acid is formed residues, which is subjected to the procedure of washing. Washing was performed twice, using a volume of water about twice the volume of the primary processing waste. After filtration, the material was dried at 100°C and the weight was measured. Chemical (Table 41) and particle size distribution analyses (Figure 18) were performed to characterize the resulting residues.

SiO_2	76.7 – 78.9
Fe_2O_3	10.5 – 10.6

Al_2O_3	1.47 – 1.52
CaO	2.54 -2.56
MgO	2.74 – 2.82
MnO	0.046 – 0.062
K_2O	0.434 – 0.522
Na_2O	0.431 – 0.589
P_2O_5	0.056 – 0.071
TiO_2	0.009 – 0.008
LOI	2.23- 2.25

Table 41: Chemical composition of the primary processing waste according to XRF data [mass, %]

According to the particle size analysis, the particle size distribution of the residues without mixing is in the range from 2 to 1000 microns, with particles of 63 microns being the most common in the primary processing waste.

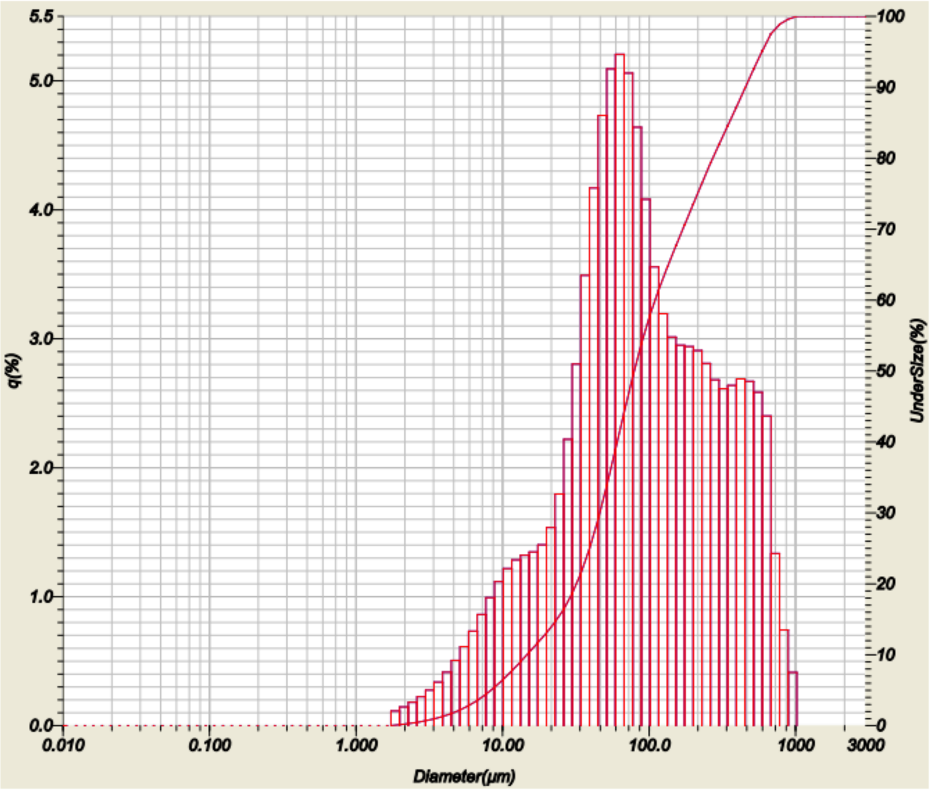


Figure 18: Granulometric composition of the residues

. In order to characterize the obtained residues after leaching with stripping, chemical (Table 41) and particle size distribution were analyzed (Figure 19). According to the particle size distribution analysis, the particle size distribution ranges from 2 to 1000 μm, with particles of 72 μm being the most common in the primary processing waste.

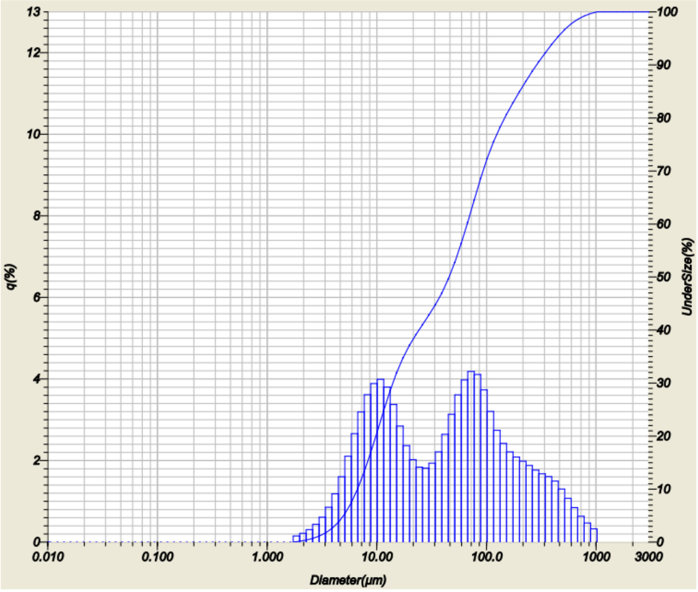


Figure 19: **Granulometric composition of the residues**

4. Results and discussion

1.8 Obtaining coagulant

General characteristics of the tailings of Stoilensky GOK are presented in Table 16, 17, Figures 3-6. Iron ore tailings have a size distribution in the range up to 3000 microns. Elemental analysis showed the presence of material with high silicon content, followed by iron and magnesium oxide. X-ray phase analysis confirms the results, showing that quartz, hematite, and magnetite are the predominant crystalline phases. The characteristics of iron ore enrichment wastes: iron concentration, fine particle size, large surface area of the material and low concentration of toxic elements indicate the possibility of synthesizing iron-based coagulants.

It has been revealed that iron-based coagulants can be obtained using sulfuric and hydrochloric acids. Since hydrochloric acid has a number of significant drawbacks: high volatility, toxicity of vapors, increased cost, in this work it was decided to conduct experiments to establish the optimal conditions for obtaining a complex coagulant based on iron and aluminum using sulfuric acid. It follows from the review of literature data that iron-aluminum coagulants have a number of advantages compared to those containing one ingredient (Sorokina, 2009).

In the course of laboratory studies the optimal conditions for obtaining a complex coagulant were revealed: the highest efficiency of iron leaching was achieved at a concentration of sulfuric acid of 40%. The greatest amount of extracted iron was achieved at a temperature of 100^0 C. The shortest reaction time required at 100 degrees was 60 minutes. During the experiments, the leaching efficiency was compared at different s:l ratios. The results showed no change in leaching efficiency. For this reason, the t:g ratio was chosen as the lowest possible ratio for the reaction. Also, it was found that stirring the mixture significantly increases the yield of iron in the solution. The resulting suspension is subjected to the process of filtering through a filter with a pore size not exceeding the minimum grain size of the waste iron ore enrichment, after which the solid phase from the filter is washed to obtain a neutral pH value of the washing solution. The solid phase is sent for utilization as a raw material for the construction industry, which will be discussed in more detail below.

The need to maintain the concentration of sulfuric acid at 40% is due to the high efficiency of iron and aluminum extraction. The ratio of IOT to acid reagent is maintained at a level not less than 1:1 g/ml as the minimum possible for obtaining the coagulant. Heating of the reaction mixture for at least 60 min provides an acceleration of the process of obtaining the coagulant. The choice of the reaction temperature is conditioned by the boiling point of sulfuric acid solution as well as by the maximum extraction of iron and aluminum from iron ore enrichment wastes. Stirring increases the yield of iron in the solution by increasing the surface area of the reaction.

The obtained coagulant showed a sufficient degree of purification from chromaticity at pH = 4 - 11. The maximum degree of purification was achieved at pH = 7. In the course of laboratory studies, the lowest effective dose of the coagulant was also confirmed using the example of the model solution of chromaticity, which was 5 mg/l in iron oxide. Despite the presence of impurities of other elements in the coagulant composition, water contamination with heavy metals does not occur because co-precipitation occurs. Table 39 shows the results obtained in the water purification tests. The residual content of heavy metals in the treated water was very low, which corresponded to the order of the Ministry of Agriculture of Russia from 13.12.2016 N 552 "On approval of water quality standards for water bodies of fishery significance, including standards for maximum permissible concentrations of harmful substances in waters of water bodies of fishery significance". However, an excess of sulfur in the solution was registered.

	Chemical composition of the model solution before purification [mg/L]	Chemical composition of the model solution after purification, [mg/L]	Standards for harmful substances in waters of water bodies of fishery significance [mg/L]
Al	0.0217	0.0219	0.04
Ba	0.0025	0.0011	0.74
Ca	1.36	2.03	180.0
Cu	<0.01	<0.01	0.001
Fe	0.0467	0.0515	0.3
K	1.25	1,89	50
Mg	0.197	0.746	40.0
Mn	0.0024	0.0094	0.01
Na	0.791	20.7	12.,0
S	1.052	50.6	100
Sr	0.003	0.0141	0.4
Zn	<0.005	<0.005	0.01

Table 42: Chemical composition of the model solution [mg/L]

Trial experiments on obtaining iron chloride coagulant using concentrated hydrochloric acid were carried out. As a result, a reagent was obtained that confirmed its performance on a model chromaticity solution. The efficiency of iron leaching with hydrochloric acid (37%) without heating is higher than with sulfuric acid with heating (25%). At the same time, when carrying out further investigations of iron chloride coagulant production it is necessary to understand a number of limitations of this technology: hydrochloric acid has a high volatility, toxicity of vapors, as well as an increased cost. Table 43 shows the impurities present in coagulants. The main differences are: the coagulant obtained using sulfuric acid unlike the coagulant obtained using hydrochloric acid contains Cu, Li, P, V. Conversely, the coagulant obtained using hydrochloric acid contains Ni, Ti,

	Coagulant obtained using sulfuric acid, [mg/L]	Coagulant obtained using hydrochloric acid [mg/L]
Al	3180	1410
Ba	0,849	5,5
Ca	56,7	7460
Cr	4,76	126
Cu	3,19	-
Fe	29600	28900
K	1970	782
Li	4.11	-
Mg	6800	2910
Mn	210	167
Na	80.6	35.9
P	801	-
Ti	-	75
Ni	-	68.4
Sr	1.35	26
V	6.94	-
Zn	7.04	6.7

Table 43: Results of quantitative analysis of impurities present in coagulants

1.9 3.2 Disposal of the residues after iron recovery from iron ore tailings

Evaluating the obtained results of the residues after sulfuric acid leaching, the following conclusions can be made. After the leaching process, the chemical composition of the waste changed significantly: the share of silicon oxide increased, while the percentage of iron oxide, magnesium, calcium, aluminum, etc. decreased. (Table 44). The decrease in the amount of impurities, as well as the increase in the percentage of silicon oxide compared with the waste of iron ore beneficiation increases the potential use of the primary processing waste as a substitute for sand in the construction industry.

SiO_2	76.7 – 78.9
Fe_2O_3	10.5 – 10.6
Al_2O_3	1.47 – 1.52
CaO	2.54 -2.56
MgO	2.74 – 2.82
MnO	0.046 – 0.062
K_2O	0.434 – 0.522
Na_2O	0.431 – 0.589
P_2O_5	0.056 – 0.071
TiO_2	0.009 – 0.008
LOI	2.23- 2.25

Table 44: Chemical composition of the primary processing waste after sulfuric acid leaching according to XRF [%]

It should be noted that the silicon oxide in the Iron ore tailings was in the form of quartz, which emphasizes the similarity of the resulting primary processing waste with quartz sand. The hardness of quartz on the Moss scale is 7 units, which indicates the resistance of the primary processing waste material particles to high loads.

Evaluating the changes in particle size distribution, we can conclude about a significant decrease in particle size during the leaching process. For clarity of changes let's summarize in the table 45. The indicator showing the most frequent particle size also changed: from 0.538 mm to 0.063 and 0.072 mm.

Fraction size [mm]	<0,005	0,005 - 0,01	0,01-0,05	0,05-0,1	0,1-0,25	0,25-0,5	0,5-1	1-3
Contents Fractions to [%]	2.412	4.453	13.495	9.983	9.602	18.405	30.12	11.53
UnderSize to [%]	2.412	6.865	20.36	30.342	39.944	58.35	88.47	100
Contents Fractions after leaching without mixing [%]	2.188	4.312	27.309	24.075	21.361	13.285	7.47	-

UnderSize to [%]	2.188	6.500	33.809	57.884	79.245	92.530	100	-
Contents Fractions after leaching without mixing [%]	5.337	15.452	31.942	19.596	16.534	7.37	3.769	-
UnderSize to [%]	5.337	20.789	52.731	72.327	88.861	96.231	100	-

Table 45: Granulometric composition

Analyzing the content of the fractions in Table 45, we can see that the largest fraction 1-3 mm is absent in the sediment after leaching, also the content of the fraction 0.5-1 mm, which prevailed, significantly decreased, which also confirms that the particle size has decreased significantly. And this should be taken into account when discussing possible options for utilization of the primary processing waste.

In order to draw conclusions about the possible options for the disposal of primary processing waste as a substitute for sand, it is necessary to assess the properties according to existing regulations. Depending on the methods of extraction and the characteristics of the raw material, sand can be river sand, quarry sand, epheline sand, quartz sand. Quality requirements for sand are reflected in GOST 32824-2014 "Public roads" (*GOST 32824-2014. Automobile roads of general use. Natural sand. Technical requirements.*, 2015), GOST 8736-2014 "Sand for construction works" (*GOST 8736-2014. Sand for construction work. Specifications.*, 2015).

According to (*GOST 8736-2014. Sand for construction work. Specifications.*, 2015), sand is classified based on the following indicators: grain modulus, grain composition, dust and clay particles, clay content in clumps, bulk density, radioactivity, as well as the presence of impurities.

The first indicator, namely the fineness modulus is determined by the percentage of the total residue on the sieves and depends directly on the grain composition of the material. According to GOST 8736-2014, the total remainder on the sieve N & 063, mesh size is 0,63 mm, in our case amounts to 4% and 2%, respectively (Table 46), which puts it in the category of fine or very fine. The fineness modulus for fine sand is 0.7 to 1. For very fine sand up to 0.7. Fine and very fine sand is classified as second class. In this case, to determine the class of sand also requires analysis of the content of dust and clay particles in the sand, as well as clay in clumps.

The next indicator is the grain composition. Grain composition is investigated by two criteria: the total residue on the sieves, the content of grains of a certain size. Complete residuals on the sieves are determined by sifting a sample of raw materials on the sieves of the following diameters: 2.5 mm, 1.25 mm, 0.63 mm, 0.315 mm, 0.16 mm, less than 0.16 mm. The results are presented in Table 43. For fine and very fine sand the content of the fraction less than 0,16 mm is not normalized.

	2.5 mm	1.25 mm	0.63 mm	0.315 mm	0.16 mm	Less than 0.16
private	0	0	4.5	15.7	14	-
full	0	0	4.5	20.2	34.2	65.8%

Table 46: Table 46 - Total residue on the sieves of the primary processing waste without mixing [%]

	2.5 mm	1.25 mm	0.63 mm	0.315 mm	0.16 mm	Less than 0.16
private	0	0	1.6	7.2	10.5	-
full	0	0	1.6	8.8	19.3	80.7%

Table 47: Table 47 - Total residue on the sieves of the primary processing waste after mixing [%]

Evaluation of the primary processing waste in accordance with [134] is reflected in Table 48.

Modulus of grain size	Up to 0.7
Grain composition	Presented in Table 43 according to GOST 8735-88
Content of dusty and clayey particles	Not defined
Bulk density	Not defined
Radioactivity	Not defined
Permissible content of rocks and minerals attributable to harmful components and impurities	
Amorphous varieties of silicon dioxide soluble in alkali (chalcedony, opal, flint, etc.)	Not detected
Halide compounds (halite, sylvin, etc.) that include water-soluble chlorides	Not detected
Mica content	<2%, consistent with
Contents of sulfur and sulfuric acid compounds	not more than 1.0%, consistent with
Coal	Not detected
Organic impurities (humic acids)	Undefined

The shape and character of the grain surface	Undefined

Table 48: Characteristics of primary processing waste

One of the problems of the characterized primary processing waste is the presence of 10 percent iron, which can introduce restrictions on its use. For example, GOST 2138-91 says that the content of iron oxide in the molding sand should not exceed 1 percent. Review of the research literature, presented above, proves the possibility of using the material with high iron content in such building materials as cement, concrete, road construction materials. However, in each case, research and selection of the formulation is required.

A good example of the use of technogenic materials is epheline sand. This is a technogenic material that is obtained during the extraction of gold, silver and other precious metals. Most often it belongs to the fine or medium fraction. In addition to quartz it contains a large percentage of oxides of aluminum, calcium, iron, magnesium and titanium. The sand can contain impurities of toxic substances (mercury, cyanide), which is related to the specifics of its extraction. According to (*Effel sand*, no date), the producer's fine ephelium sand contains 57% silicon dioxide, 15% aluminum trioxide, and 2.5 iron oxide. In addition, it contains compounds of calcium, magnesium, titanium, and other metals. The use of ephelium sand not only significantly reduces the cost of building materials, but also contributes to the purification of the environment from the products of industrial mining of precious metals. For safety reasons, it is not used where frequent contact with human skin is possible: in sandboxes, on children's and sports grounds, in plaster, masonry mortars and so on. Similarly, the waste of primary processing can be used. This also confirms that the primary processing waste we obtained is competitive and can be used in the construction industry.

Thus, the limitations associated with the use of primary processing waste are the following: increased iron content, as well as the fine size of the particles. The most suitable direction in such a case is leveling of sites, arrangement of septic tanks and drainage, for backfilling of supports and foundations or backfilling.

The most suitable example of use and a possible prototype for future research is "Bedding mix for landscaping" for paving stone and paving tiles (bedding layer), construction of parking lots and parking lots in the process of landscaping based on the active mixture of steel-melting sift of own production of LLC "BFB". The mixture is a 0*2 fraction of steelmaking slag of converter production (*'Mixture for the underlying layer in the improvement of territories'* | *BFB LLC*, no date).

Steelmaking slag is also known to contain iron oxides in its composition (about 15% (Zorya V. N., 2015)), which did not prevent it from being used in the mixture for the underlaying layer in landscaping. Accordingly, we can make an assumption about the advisability of using the waste primary processing for the same purpose. This assumption should be confirmed by further research on the compliance of the quality of the bedding layer with state standards.

5. The economic viability of the project

In order to understand whether the project is attractive for investment, It's needed to be evaluated by using the following indicators: NPV (net present value); PP (payback period); PI (profitability Index).

Reagent costs for reagent production:

1. IOT - 0 rub/t.
2. Sulfuric acid (40%) - 7000 rubles /t [139].
3. Acid dilution water - 36.5 rubles /m^3 .

Reagent	Tonns	Price [rubles/t]	Cost [rubles]
Waste from iron ore processing	1 tons	-	-
Sulfuric acid (40%)	891 L	7 rubles /kg = 9.1 rubles /L	8108
Water	2109 L	0.0365 rubles /L	77

Table 49: Reagent costs

Since the waste is mixed with sulfuric acid solution 1:3, thus, for 1 ton of disposed waste 3000 liters of acid solution will be needed. The cost of the reagent equivalent of 3000 liters of coagulant will be 8185 rubles, and 1000 liters - 2728 rubles.

Next, let's consider capital investments for implementation of the technology of obtaining a complex coagulant on the basis of iron and aluminum. The proposed apparatus and technological scheme is as follows. The reactor is the main apparatus for the reaction of interaction of the acid agent with iron ore tailings. Acid is fed from the acid tank to the reactor to leach iron and create an acidic environment (pH = 1). From the hopper, a iron ore tailings is fed to the reactors through a feeder. The gases released in the process of reaction are directed to the gas trap. After the waste loading is completed, the reaction mixture remains for 1 hour and is pumped to the settling tank reactor. After separation of the mixture the clarified part (coagulant) is pumped to the coagulant tank and the sludge is sent to the unit where it is washed for further utilization.

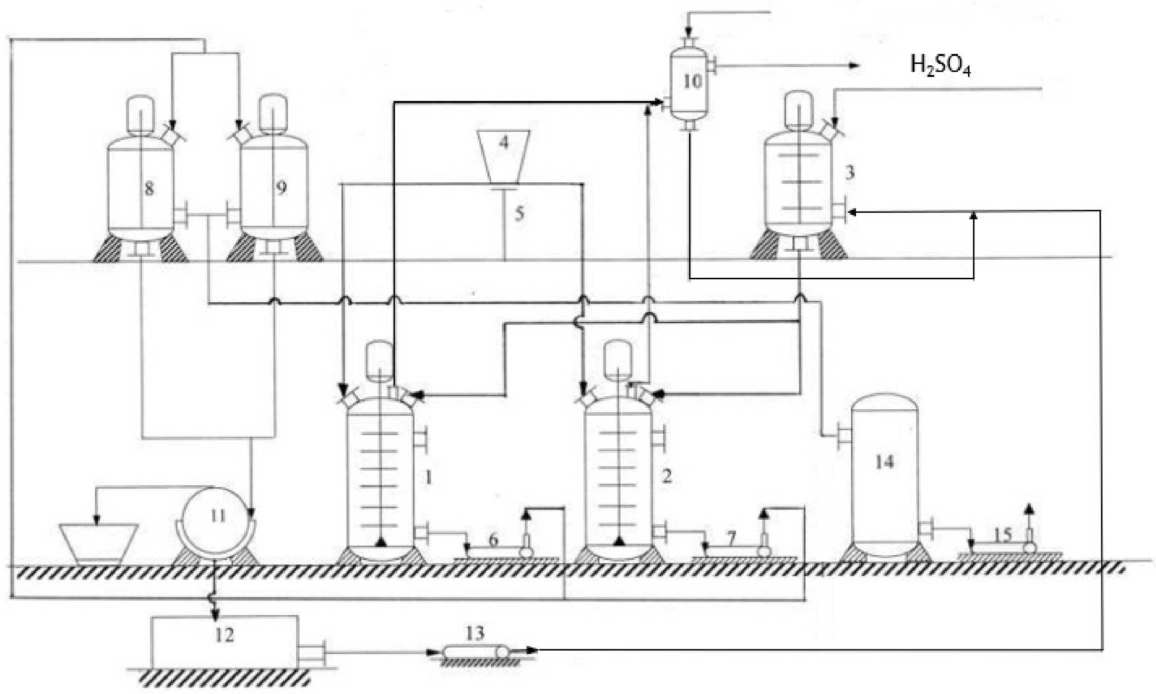


Figure 20: Process flowsheet to obtain coagulant

The capacity for Iron ore tailings is 100,000 tons: 365 days = 274 t per day and 274 t : 24 h = 11.4 t per hour. Oxidation process in the reactor lasts for 1 hour. The mass of concentrate fed into the reactors in this case: 11.4 t · 1 h = 11.4 t. Together with iron ore enrichment waste (w:t = 3) 34.2 m^3 of acid is fed into the reactor. The density of 40% sulfuric acid solution is 1302.8 kg/m^3 , then the mass of 34.2 m^3 of acid is 44.528 t.

The slurry density is equal to the sum of the mass fractions of the components multiplied by their density. Hence, 0.75 · 1302.8 kg/m3 + 0.25 · (0.714· 2600 kg/m3 + 0.18 · 5242 kg/m3 + 0.0417· 3580 kg/m3 + 0.0338· 3370 kg/m3 + 0,0203· 3990 kg/m3 + 0.00742· 2320 kg/m3 + 0.00628· 2270 kg/m3 + 0.00206 · 2390 kg/m3 + 0.00092· 5180 kg/m3 + 0.00055· 4235 kg/m3) = 1774 kg/m3.

Then the volume of slurry will be equal to 55.928 · 10^3 / 1774 kg/m^3 = 31.5. Let's choose a reactor with a capacity of 35m^3 (*Titanium Reactor* , no date).

Type of costs	Capital costs [rubles]
Reactor	7000000
Cost of auxiliary equipment	2500000
Delivery, storage costs, spare parts	400000
Equipment installation	950000
Pipe laying	120000
Instrumentation and installation	750000
Total	**11720000**

Table 50: Total capital costs for the purchase and installation of equipment for coagulant production

Let us take a closer look at the operating costs. Let's assume that 100,000 tons will be disposed of in this way per year. Then, the costs for reactants and electricity (according to the information in the reactor passport) are presented in Table 20.

Electricity costs are determined by the formula:

$$Эл = \sigma_Э \cdot N \cdot t \qquad (2)$$

where σэ is the price of electricity, in the calculations taken as 4.9 rubles/(kWh) [141] for industrial enterprises in Stary Oskol;

N - total installed capacity of electrical equipment, equal to 100 kW.

$N = 4{,}9 \cdot 100 \cdot 8760 = 4292400$ rubles/year.

Title	Consumption for L/ton	Annual flow rate [m^3]	Wholesale Price, [rubles/m^3]	Annual Costs [rubles]
Sulfuric acid, (40 %)	3000	300000	2728	818 507 850
Electricity (kW)	-	-	4,9	4292400

Table 51: Expenses for reagents and electricity are presented

Let's assume that the required number of attendants is 9 people, whose monthly salary is 80000. Then per year:

$Зп = 80000 \cdot 4 \cdot 12 = 8640000$ rubles

rThe company's insurance premiums for employees are 30% of payroll. The operating costs of the plant are listed in Table 52. It is also necessary to take into account the depreciation of the equipment. The depreciation rate based on the price of the main equipment (reactor) is given below:

$H_A = \frac{C}{T_Н} = \frac{5000000}{10} = 500000$ rubles

where TH is the normative service life of the reactor we take 10 years.

Costs	Cost/year
Wages for workers	8640000
Insurance premiums	2592000
Lubricants, wiping materials, small spare parts	200000

Ongoing repairs	160000
Depreciation	950000
Other expenses	88000
Total	12630000

Table 52: Operating costs for coagulant production

Let's calculate the cash flow, which is the difference between the income and expenses of the company or project. The capital and operating annual costs of the project are listed above. The life cycle of the project will be 10 years. Calculating the income from the sale of coagulant, we will proceed from the production capacity (300000 m^3 per year), as well as the chosen price. The price of the product will be chosen based on the cost of the product and publicly available information about the prices of coagulants. According to the information on the websites of industrial coagulant suppliers (*Industrial Chemistry*, no date; *Industrial chemicals wholesale with delivery across Russia | TATSORB*, no date), the prices per kg of coagulant are presented in Table 53.

The cost of coagulant is the production cost per unit of product:

$$\text{Сс} = \frac{\text{Эксплуатац.затраты}}{\text{Единицы продукции}} = \frac{834980250}{300000000} = 2{,}78\ \text{руб}/\text{л} \text{ = 3,2 rubles/kg}$$

Name of the coagulant	Price
Iron chloride 40% (liquid) - Iron (III) chloride technical	26-38 rubles/kg
Ferrous sulfate (III) aqueous solution	41-55 rubles/kg
Ferix-3 iron sulfate solution	from 41 rubles/kg
Equital liquid coagulant for swimming pools	36 rubles/kg
Aluminum polyoxychloride OXA-B (18%)	
Aluminum polyoxychloride Aqua-Aurat-10	34-38 rubles/kg
Aluminum polyoxychloride MetaPAC-10	34-38 rubles/kg
Aluminum polyoxychloride Aqua-Aurat-15	45-49 rubles/kg

Aluminum polyoxychloride POHA-10 (10%)	34-38 rubles/kg

Table 53: Prices for coagulants in solution

The prices of the coagulants listed in the table are significantly higher than the cost of the coagulant obtained in this work. This is due to the percentage of iron and aluminum in each solution. The coagulant iron sulfate contains 36 percent iron in the form of sulfate. According to the conducted studies, the coagulant based on iron ore tailings obtained by stirring and at a temperature of 75 degrees contains the form of sulfates (III), - 3.9% and Al in the form of sulfates – 0.71%. According to calculations, 9.4 kg of coagulant based on iron ore enrichment waste contains the same mass of active substance as 1 kg of 36% iron sulfate. The cost of 9.4 kg is 30 rubles, which is lower than the analog.

Next, we will calculate the net cash flow from the introduction of coagulant production technology at the enterprise over a time period of 10 years. The price of the coagulant will take 2.8 r / l. The calculation is presented in table 54.

The Year	NPV [rubles].	Present value [rubles].
0	-11720000	-11720000
1	6881591	-4838409
2	6255992	1417583
3	5687265	7104848
4	5170241	12275089
5	4700219	16975308
6	4272927	21248235
7	3884479	25132713
8	3531344	28664058
9	3210313	31874371
10	2918466	34792837

Table 54: - Net cash flow from the introduction of coagulant production technology

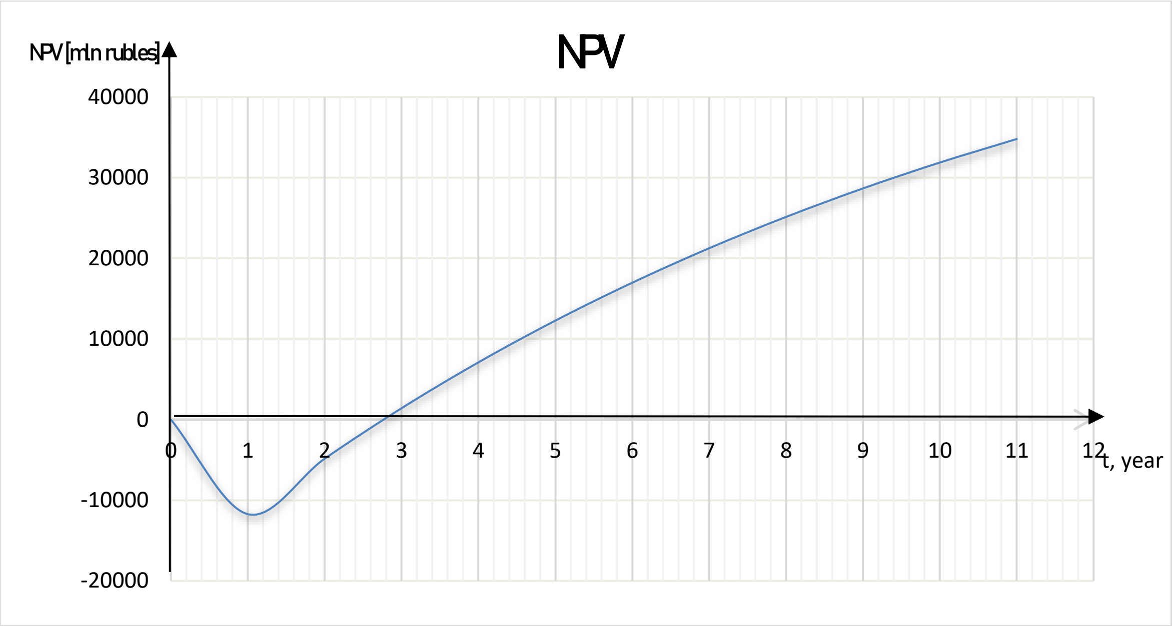


Figure 21:Graph of accrued net worth

According to the graph of NPV we can see that the project pays for itself in 2.7 years. NPV, in turn, for a period of 10 years will be 34792836 rubles.

NPV	34792836
RR	2,7
PI	4,0

Table 55: Performance indicators of the project

Having studied the technical documentation of Stoilensky GOK, we can see that the company uses Nalco (PULV) 9901 reagent as a flocculant to reduce turbidity in thickeners. The working solution of flocculant has a concentration of 0.05% of the reagent. Accordingly, the most attractive market is the use of the obtained coagulant for own needs of the enterprise.

Stoilensky is located at the Kursk Magnetic Anomaly deposit, where in addition to SGOK, iron ore is developed by Mikhailovsky and Lebedinsky GOK. Since the technological processes of the GOKs are similar, the obtained coagulant can be offered as a cheaper alternative for use by these enterprises as well.

It should also be noted that there is an online platform for selling the obtained coagulant. On November 28, 2022, the vertically integrated company NLMK, which includes Stoilensky GOK, announced the launch of a secondary raw materials marketplace on its official website (*Vtorion — the first marketplace of secondary raw materials*, no date). This digital marketplace is unique in Russia. It makes the process of selling products based on secondary raw materials more accessible and contributes to the expansion of the enterprises' production chain.

In addition to the sale of coagulants through this platform, the search for consumers and subsequently the sale of primary processing waste for the needs of the construction industry.

As a result of calculating the economic performance of the project, we can conclude that as a result of the project there is an economic effect, which is associated with the production of a new commodity product based on waste.

6. Conclusion

Iron ore tailings is one of the main byproducts of the mining industry, which provokes environmental safety problems. The continuous development of the iron and steel industry, as well as the gradual transition to mining reserves with low-quality ores that require beneficiation, leads to an even greater increase in the amount of waste. For this reason, iron ore tailings as a secondary resource have recently received considerable attention from researchers.

Such characteristics of Iron ore tailings as iron concentration, particle size, large surface area of particles and low concentration of toxic elements of Stoilensky GOK pointed to the possibility of synthesis of coagulants based on iron and aluminum.

In the course of laboratory studies the optimal conditions for obtaining a complex coagulant were revealed: the highest efficiency of iron leaching was achieved at a concentration of sulfuric acid of 40%. The greatest amount of extracted iron was achieved at a temperature of 100^0 C. The shortest reaction time required at 100 degrees was 60 minutes. During the experiments, the leaching efficiency was compared at different t:g ratios. The results showed no change in leaching efficiency. For this reason, the t:g ratio was chosen as the lowest possible ratio for the reaction. Also, it was found that stirring the mixture significantly increases the yield of iron in the solution. Results obtained in water treatment tests where a complex coagulant obtained from iron ore tailings was effective in reducing chromaticity are presented. Experiments were carried out to obtain an iron chloride coagulant using hydrochloric acid, which also showed its effectiveness on a model solution of chromaticity.

To understand the feasibility of the project, we assessed the economic efficiency of the project: calculated indicators such as NPV, PP (payback period), PI (profitability index of investment), which prove the profitability of the project.

The residues after iron recovery from iron ore tailings obtained after filtration and washing is similar to quartz sand in chemical composition. The granulometric composition of the primary processing waste after the leaching procedure is up to 1 mm, which allows to recommend it for use as a fine aggregate in civil engineering. It should be noted that quartz sand (SiO_2) is a valuable mineral raw material, because most of the extraction takes place in river beds and banks. Its exploitation can lead to adverse consequences for the environment, such as erosion of riverbanks, degradation of riverbeds and deterioration of river water quality. Therefore, the use of the resulting primary processing waste in the construction industry in return is a promising direction.

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8. List of Figures

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10. List of Abbreviations

CCU	The coarse crushing unit
CSS	The crushing and sorting section
IOT	Iron ore tailings
KMA	Kursk Magnetic Anomaly
MFCU	Medium and fine crushing unit
SGOK	Stoilensky GOK
TMF	Tailings management facility