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Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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PRODUCTION OF FERROALLOYS FROM MANGANESE AND CHROMITE TECHNOGENIC WASTES

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Abstract. *Relevance.* Substandard mineral and technogenic raw materials can be regarded as an additional feedstock source, given the limited availability of high-quality ores for producing ferromanganese and ferrochrome alloys. Recovery of manganese and chromium from ore fines and gravity-concentration sludges will increase overall metal recovery from mineral feedstock and contribute to environmental protection by reducing waste accumulation. *Objects of study.* a technological sample of manganese sludge from the Zhairem Mining and Processing Plant, manganese concentrate, manganese pellets, and ferromanganese alloy; a technological sample of sludge chromite tailings from the Donskoy Mining and Processing Plant, chromium concentrate, and ferrochrome alloy. *Methods.* Mineralogical, chemical, X-ray phase (XRD), X-ray fluorescence (XRF), and scanning electron microscopy were used to characterize the raw materials and products. *Results.* Manganese-bearing waste was processed in three stages: gravity separation to obtain a concentrate, pelletizing of the concentrate, and smelting the pellets into ferromanganese. The resulting high-carbon ferromanganese, containing 66.41% manganese and 6.43% carbon, corresponds to grade FeMn68C7.0 (China), with phosphorus and sulfur levels within acceptable limits; the compositions of the alloy and smelting slag were analyzed. A method was developed for producing a chromite concentrate (49.81% Cr_2O_3) from fine-grained chromium-bearing waste by leaching magnesium compounds, followed by gravity concentration of the resulting solid product. Chromium pellets were then formed from this concentrate by adding to the charge the mineral fraction of ferrochrome slag, iron-bearing diatomite, and liquid glass; roasting forms complex ferrosilicocalcium compounds that increase pellet strength, yielding fired pellets suitable for smelting into high-carbon ferrochrome. *Conclusion.* The research demonstrated the feasibility of smelting ferromanganese and ferrochrome alloys using pellets produced from enriched manganese and chromite waste, confirming that such technogenic raw materials can be converted into commercial-grade ferroalloys.

Keywords: man-made waste, manganese concentrate, chromite concentrate, manganese pellets, chromite pellets, ferroalloys

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МАРГАНЕЦ ЖӘНЕ ХРОМИТ ТЕХНОГЕНДІ ҚАЛДЫҚТАРЫНАН ФЕРРОҚҰЙМАЛАР ӨНДІРУ

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Аннотация. *Өзектілігі.* Ферромарганец және феррохром қорытпаларын өндіруге арналған жоғары сапалы кендердің шектеулі қолжетімділігін ескере отырып, сапасыз минералды және техногенді шикізатты шикізаттың қосымша көзі ретінде қарастыруға болады. Марганец және хром кендерінің кен ұсақтары мен гравитациялық концентрацияланған шламдарынан марганец пен хромды қосымша алу минералды шикізаттан жалпы (ұшынан аяғына дейін) металл алуды арттырады және қоршаған ортаны қорғауға ықпал етеді, себебі бұл олардың жиналу көлемін азайтады. *Зерттеу нысандары:* Жайрем тау-кен байыту комбинатынан алынған марганец шламының технологиялық үлгісі, марганец концентраты, марганец түйіршіктері, ферромарганец қорытпасы, Дон таукен байыту комбинатынан алынған шлам хромит қалдықтарының технологиялық үлгісі, хром концентраты және феррохром қорытпасы. *Әдістер.* Бастапқы шикізаттың және алынған өнімдердің құрамын анықтау үшін келесі аналитикалық әдістер қолданылды: минералогиялық, химиялық, рентгендік фазалық (рентгендік), рентгендік флуоресценция (XRF) және сканерлеуші электронды микроскопия. *Нәтижелер.* Мақалада марганец құрамдас қалдықтарды өңдеу әдістерін зерттеу нәтижелері талқыланады. Зерттеу үш кезеңде жүргізілді: біріншіден, концентраттар алу үшін марганецті гравитациялық күшпен бөлу; екіншіден, марганец кенін түйіршіктерге өңдеу; үшіншіден, түйіршіктерді ферромарганец қорытпаларына балқыту. Марганец құрамы 66,41% және көміртегі мөлшері 6,43% болатын жоғары көміртекті ферромарганец қорытпасы FeMn68C7.0 маркасына (Қытай) сәйкес келеді. Ферроқорытпадағы процестің тиімділігін шектейтін қоспалардың (фосфор және күкірт) концентрациясы қолайлы шектерде. Балқытудан кейін пайда болған ферромарганец қорытпасының және шлактың құрамы талданды. Шикізатта бар магний қосылыстарын сілтілеу арқылы ұсақ дисперсті хром құрамдас қалдықтардан хромит концентратын (хром оксидінің мөлшері 49,81%) алу әдісі, содан кейін қатты өнімнің гравитациялық концентрациясы ұсынылады. Алынған концентраттан хром түйіршіктері феррохром өндірісінің шлакының минералды бөлігін, темір құрамдас диатомитті және сұйық әйнекті партияға қосу арқылы жасалды. Кейінгі түйіршіктерді күйдіру түйіршіктердің беріктігін айтарлықтай арттыратын күрделі ферросилиций-кальций қосылыстарын түзеді. Алынған қуырылған түйіршіктер жоғары көміртекті феррохромға балқытуға жарамды. *Қорытынды*. Жүргізілген зерттеулер байытылған марганец және хромит қалдықтарынан алынған түйіршіктерді пайдаланып, ферромарганец және феррохром қорытпаларын балқытудың орындылығын көрсетті.

Түйін сөздер: жасанды қалдықтар, марганец концентраты, хромит концентраты, марганец түйіршіктері, хромит түйіршіктері, ферроқорытпалар

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ПРОИЗВОДСТВО ФЕРРОСПЛАВОВ ИЗ ТЕХНОГЕННЫХ МАРГАНЦЕВЫХ И ХРОМИТОВЫХ ОТХОДОВ

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Аннотация. *Актуальность.* Некондиционное минеральное и техногенное сырьё может рассматриваться как дополнительный источник марганца и хрома в условиях ограниченности запасов высококачественных руд, используемых для производства ферромарганцевых и феррохромовых сплавов. Доизвлечение ценных компонентов из рудной мелочи, шламов гравитационного обогащения марганцевых руд и хромитовых хвостов позволяет повысить сквозное извлечение металлов из минерального сырья, сократить объёмы накопления отходов и снизить негативное воздействие металлургического производства на окружающую среду. *Цель.* Разработать технологические схемы переработки техногенных марганец- и хромсодержащих отходов с получением концентратов, окатышей и ферросплавов, пригодных для промышленного применения. *Объекты исследования.* Технологическая проба марганцевых шламов Жайремского горно-обогатительного комбината, марганцевый концентрат, марганцевые окатыши и ферромарганцевый сплав, а также технологическая проба шламовых хромитовых хвостов Донского горно-обогатительного комбината, хромитовый концентрат, хромитовые окатыши и феррохромовый сплав. *Методы.* Для определения состава исходных сырьевых материалов, промежуточных продуктов и полученных ферросплавов применялись минералогический, химический, рентгенофазовый и рентгенофлуоресцентный методы анализа, а также растровая электронная микроскопия. Переработка марганецсодержащих отходов включала гравитационное обогащение, окускование полученного концентрата и последующую плавку окатышей. Для переработки хромсодержащих отходов использовались выщелачивание магнийсодержащих соединений, гравитационное обогащение твёрдого продукта, окомкование шихты и обжиг окатышей. *Результаты.* Переработка марганецсодержащих отходов осуществлялась в три этапа: гравитационное обогащение с получением концентрата, изготовление марганцевых окатышей и их последующая плавка с получением ферромарганцевого сплава. Получен высокоуглеродистый ферромарганец, содержащий 66,41 % марганца и 6,43 % углерода, что соответствует требованиям марки FeMn68C7.0. Содержание фосфора и серы в сплаве находилось в пределах допустимых значений. Проведён анализ химического и фазового состава ферромарганцевого сплава и образовавшегося при плавке шлака. Разработан способ получения хромитового концентрата с содержанием оксида хрома 49,81 % из мелкодисперсных хромсодержащих отходов путём выщелачивания магнийсодержащих соединений с последующим гравитационным обогащением твёрдого продукта. На основе полученного концентрата изготовлены хромитовые окатыши. В состав шихты вводились минеральная часть шлака феррохромового производства, железосодержащий диатомит и жидкое стекло. В процессе обжига формировались комплексные ферросиликатные и кальцийсодержащие соединения, способствующие повышению прочности окатышей. Полученные обожжённые окатыши пригодны для выплавки высокоуглеродистого феррохрома. *Выводы.* Результаты исследования подтверждают возможность комплексной переработки техногенных марганец- и хромсодержащих отходов с получением кондиционных концентратов, прочных окатышей и ферросплавов. Применение предложенных технологических схем способствует повышению извлечения марганца и хрома, расширению сырьевой базы ферросплавного производства и сокращению объёмов накопленных промышленных отходов.

Ключевые слова: техногенные отходы, марганцевый концентрат, хромитовый концентрат марганцевые окатыши, хромитовые окатыши, ферросплавы

Introduction. At present, there is growing interest in the extraction of target components from technogenic raw materials, including beneficiation tailings, mining dumps, slags, and low-grade mineral raw materials (Murthy et al., 2011; Liu et al., 2019; Yuan et al., 2020; Elliott et al., 2020)

The ferroalloy sector of Kazakhstan's metallurgical industry is based on unique chromite and manganese ore reserves. Against the backdrop of declining high-grade chromite and manganese ores, technogenic wastes generated during their beneficiation have become increasingly important. Over the period of exploitation of large deposits such as Dubersai, Akzhar (Donskoy Mining and Processing Plant), and Ushkatyn-3 (Zhairem Mining and Processing Plant), tens of tons of chromite ore beneficiation tailings with chromium oxide contents of up to 30% and several million tons of manganese ore tailings containing up to 16% manganese have been accumulated (Kazchrome Annual_Report, 2024).

These materials constitute a potential secondary resource for recovering valuable metals (Abdykirova et al., 2016; Gladyshev et al., 2018).

Chromite and manganese ore beneficiation tailings are characterized by fine particle size. For further metallurgical processing of the finely dispersed concentrates obtained from these materials, agglomeration processes such as sintering, briquetting, or pelletizing are necessary. Modern agglomeration technologies significantly improve the techno-economic performance of the smelting process. Among agglomeration methods, sintering is most commonly applied (CVRD ferroalloy plant, Dunkirk, France; Aksu Ferroalloy Plant, branch of JSC "TNK Kazchrome", Kazakhstan) (Korotich et al., 2003; Faria er al., 2015; Singh et al., 2011; Zhang et al., 2013).

The process ensuring sufficient strength of agglomerated materials can be addressed through the use of pellet firing process during which the synthesis of complex compounds-ferrosilico-calcium fluxes-occurs. Currently, high-quality bentonite is primarily used as a binder in pellet production. In iron ore pelletizing, Callovian clays have been proposed as a substitute for bentonite; their mechanical activation in the presence of soda improves their technological properties, including increased specific surface area and enhanced ion-exchange capacity (Terekhin et al., 2025; Gzogyan et al., 2025).

In the present study, diatomite, an accessible natural mineral, is proposed for the synthesis of ferrosilico-calcium fluxes. Kazakhstan possesses significant deposits of diatomite unprocessed materials. One of the primary sources is the Zhalpak deposit, whose varieties contain 25.8-73.1% SiO_2 and 2.4-27.4% Fe_2O_3 (Kuldeev et al., 2019). Diatomite samples are lightweight sedimentary rocks composed mainly of silica with varying degrees of hydration. Dispersed submicrometer-sized micro silica particles exhibit a porous structure and pronounced adsorption properties (Flower et al., 2013; Mohamedbakr et al., 2010).

The use of a ferrosilico-calcium binder synthesized from iron-bearing diatomite in the agglomeration process of manganese-bearing raw materials enables this approach enables the production of high-strength fired pellets with optimized composition, without additional fluxing agents. The similarity of the physicochemical properties of manganese and chromite raw materials determines the similarity of their grinding, beneficiation, agglomeration, and ferroalloy smelting methods. Therefore, pelletizing technology used for manganese raw materials can also be applied to agglomerating fine chromite.

The proposed technology for producing manganese and chromite pellets suitable for further metallurgical processing enables more rational utilization of mineral resources. It expands the raw material base of metallurgical enterprises producing manganese and chromium. Involving sludge wastes from manganese and chromium production in processing will reduce their volumes and improve environmental conditions (Braga et al., 2013; Shevko et al., 2021).

This work focuses on establishing the feasibility of smelting high-carbon ferromanganese and ferrochrome alloys using pellets produced from beneficiated chromite and manganese wastes.

Methods and materials. A 199 kg manganese-containing sludge sample composed of particles within the size range of -5.0 to 0 mm was collected from the Zhayremsky GOK processing site. The size fraction distribution of the synthetic manganese-bearing material was determined by dry sieve analysis using the -5.0+0 mm fraction. Following size classification, the concentrations of manganese and iron were determined in each size fraction to evaluate the size-dependent redistribution behavior of the major metallic components.

To assess the role of particle size in the redistribution of metallic components, the distribution of manganese and iron across the obtained size fractions was analyzed. The results are presented in Figure 1, illustrating the contribution of each size class to the overall elemental distribution.

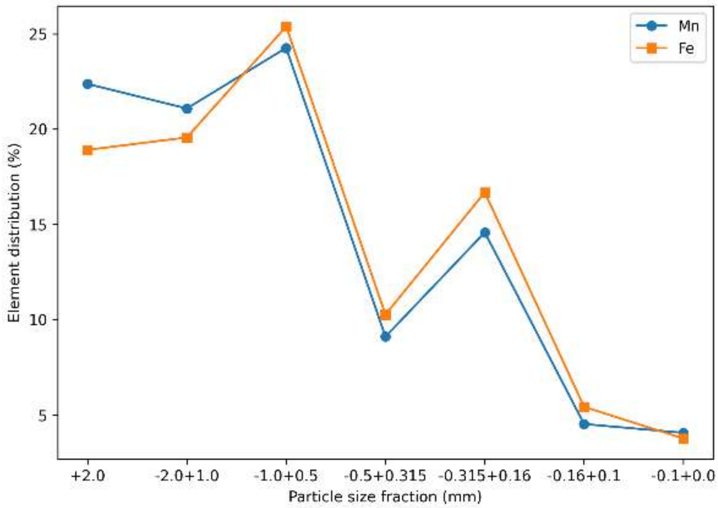


Figure 1. Distribution of manganese and iron across particle size fractions of technogenic material.

In order to quantitatively evaluate the degree of elemental redistribution during size classification, beneficiation factors were calculated for manganese relative to the bulk composition. Figure 2 shows changes in the manganese beneficiation factor depending on the particle size range.

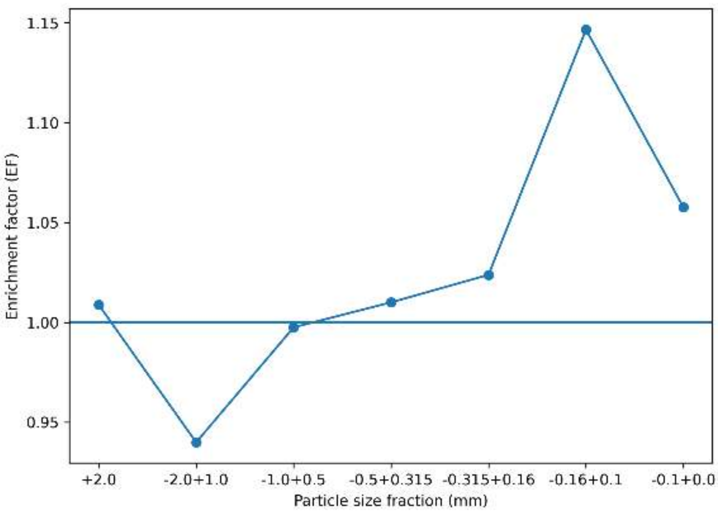


Figure 2. A dependence of the manganese beneficiation factor on particle size.

A selectivity index (Mn/Fe) was calculated to understand better how manganese differs from iron across size fractions. Figure 3 shows how manganese selectivity changes with particle size fraction.

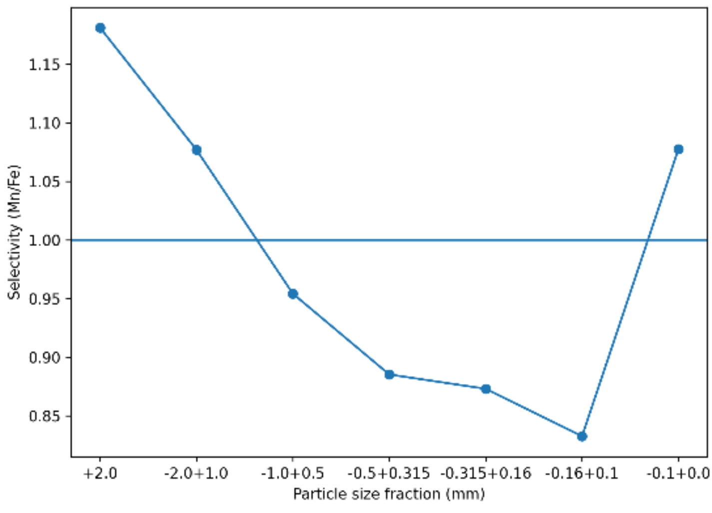


Figure 3. Selectivity of manganese over iron (Mn/Fe) across particle size fractions.

The manganese-containing sludge sample, as determined by X-ray fluorescence examination, comprises the following mass percentages: Mn - 15.26; Fe - 5.40; Ca - 18.63; Si - 7.04; Al - 1.38; O - 48.64; other elements - 3.65.

The ore sample was examined by X-ray diffraction (XRD). The sample diffractogram was acquired with a Bruker D8 Advance diffractometer. The diffractograms were analyzed using the ASTM Powder Diffraction File and those of pure minerals. Mineralogical characterization by X-ray diffraction confirmed the predominance of calcite ($CaCO_3$) at 55.1%, Gismondine ($CaAl_2Si_2O_8 \cdot 4H_2O$) at 9.2%, and Quartz ($SiO_2$) at 8.6% as the principal minerals that constitute rocks in the ore. Manganese minerals include $Mn_7O_8(SiO_4)$ at 13.9% and Bixbyite ferrian $FeMnO_3$ at 13.2% (Fig. 4).

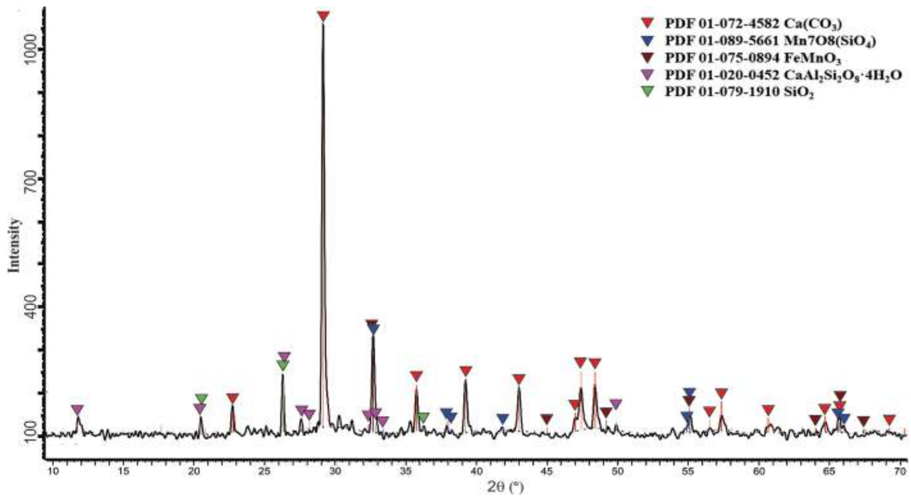


Figure 4. Diffractogram of a manganese-laden sludge sample.

Investigations were conducted to identify suitable conditions for enhancing manganese-rich sludge using a jigging apparatus and a table of concentration. The ideal parameters for the separation of sludge sized 2.5-0.071 mm are: manganese grain size of 9-8 mm, bed height of 35-45 mm, pulsation frequency of 360 oscillations·min^{-1}, and oscillation amplitude of 9 mm. Sludge having a particle size of -0.073 + 0 mm was enriched using a laboratory concentration table.

This study utilized diatomite rock from the Zhalpak deposit (Aktobe Region, Kazakhstan) as a binding agent in pellet manufacture, while coke served as the reducing agent. The X-ray diffraction data shows the predominant phase of diatomite rock is quartz SiO_2 at 69.4%. Goethite $Fe^{+3}O(OH)$ at 7.0%, Barium Manganese Silicate $Ba_2MnSi_2O_7$ at 6.7%, Garnet/Magnesium Silicate $Mg(SiO_3)$ at 4.2%, Ca–Al silicate $Ca_{0.88}\text{-}_{0.12}Al_{1.77}Si_{2.23}O_8$ at 3.7%, Metascolecite/Calcium Aluminium Silicate Hydrate $Ca_8Al_{16}Si_{24}O_{80} \cdot {}_{16}H_2O$ at 3.6%, Bigcreekite $Ba(Si_2O_5)(H_2O)_4$ at 3.2%, and Srebrodolskite $Ca_2Fe_2O_5$ at 2.2% are additional phases that were found (Fig. 5).

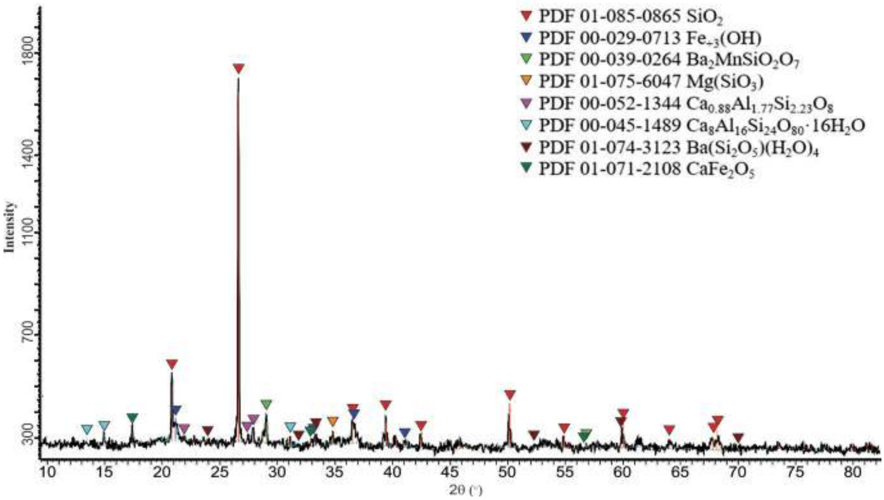


Figure 5. Diffractogram of a diatomaceous earth sample.

Pellets composed of enhanced manganese concentrate were produced through pelletizing using a high-speed Eirich granulator–mixer. During the pelletization process, there was a liquid phase that was a solution of 1.5% carboxymethylcellulose. The granulation process used a steel drum that spun at 180 rpm, a swirler that spun at 3500 rpm, and a drum that was tilted 30 degrees. The samples were heated to 110–115 °C until they had lost all but 2.9% of their moisture by mass after being air-dried for a full day. The firing happened in an electric furnace that was held at a constant temperature of 1100–1200 °C for an hour. Manganese pellets were experimentally smelted in a Tamman furnace, with temperature measurement conducted using a BP-5/20 tungsten–rhenium thermocouple. The specified composition was placed into 300 cm^3 graphite crucibles. At ambient temperature, the crucibles were introduced into the furnace and subsequently heated at a controlled rate of 12 $°C\cdot min^{-1}$ to 1500 °C for high-carbon ferromanganese manufacture, then maintained at this temperature for 30 minutes. Upon completion of smelting, the Tamman furnace was deactivated, and the crucibles were removed at 700 °C. Upon reaching room temperature, the crucibles were fractured, and the slag and metallic components were segregated. Mass measurements were performed to assess the material balance.

Results and discussion. Research on the beneficiation of manganese-laden sludge by gravity techniques indicated the feasibility of producing a finely dispersed concentrate enriched in manganese, containing 28.9% and an iron concentration of 10.71%, achieving recoveries of 68.8% and 72.5%, respectively (Table 1).

Table 1. Outcomes of gravitational separation of manganese-laden sludge.

Product name	Yield, %	Content, %		Extraction, %	
		Mn	Fe	Mn	Fe
Manganese concentrate, grade -2.5+0.071 mm	33.8	28.9	10.2	63.5	63.67
Concentrate from a -0.071+0 mm concentration table	2.8	27	16.8	5	8.7
Combined concentrate	36.6	28.57	10.71	68.8	72.5
Tailings	53.2	7.1	2.10	24.76	20.66
Gravity table tails	10.2	10.1	3.7	6.74	6.97
Total tails	64.0	7.54	2.33	31.48	27.63
Initial sludge	100.0	15.26	5.40	100	100

The subsequent magnetic separation of the concentrate elevated the manganese concentration to 37.8%, achieving a recovery of 93.0% during processing, or 64.0% from the starting slurry. The iron concentration was 9.62%. The manganese concentration obtained is suitable for further metallurgical processing.

Two different formulations were used to make manganese-infused pellets. The testing findings of the fired samples indicated that higher firing temperatures corresponded with an increase in compressive strength. Manganese-containing pellets were produced from two compositions: manganese concentrate - 88%, kaolin - 9%, coke - 3%; manganese concentrate - 87%, diatomite - 10%, coke - 3%. Firing was conducted at 1100-1200 °C. With increasing firing temperature, the compressive strength of the pellets increased from 29.1 to 31.4 kg/pellet for composition 1 and from 32.4 to 37.3 kg/pellet for composition 2. The highest compressive strength was exhibited by samples utilizing manganese concentrate combined with high-iron diatomite as a binding agent.

The X-ray diffraction results of manganese-bearing pellets intended for processing, calcined at 1200 °C, indicated that the use of kaolin as a binder result in the formation of Jacobsite, Ulvöespinel ferrian, and Ferrobustamite phases during calcination. When diatomite is incorporated into the mixture as a binder, the phase composition of the fired pellets alters: the spinel phase is replaced by Hedenbergite aluminian, a complex pyroxene, along with the presence of Jacobsite and Bustamite calcian. Manganese-containing pellets were obtained from compositions of two formulations: 1) manganese concentrate - 88%, kaolin - 9%, coke - 3%; 2) manganese concentrate - 87%, diatomite - 10%, coke - 3%. Firing was conducted at temperatures of 1100, 1150, and 1200 °C. The test results of the fired samples showed that at higher firing temperatures, pellet compressive strength increased: for composition 1, from 29.1 to 31.4 kg/pellet; for composition 2, from 32.4 to 37.3 kg/pellet.

Diatomite has been insufficiently researched as a binding agent for pellet fabrication in metallurgical smelting, in contrast to kaolin. Kaolin was utilized as a binding agent for comparison with diatomite. The mineralogical composition of the furnace charge constituents influences the sintering temperature of the pellets and the development of phases that dictate their properties.

Research indicates that diatomite serves as a more effective binder in the charge composition for manganese pellet manufacture compared to kaolin. The synthesis of intricate calcium aluminosilicates of the hedenbergite variety $Ca(Fe_{0.821}Al_{0.179})(SiAl_{0.822}Fe_{0.178}O_6)$ with diatomite enhances the strength under compression of the resultant manganese pellets to 37.3 kg per pellet.

Charge formulation for the flux-assisted smelting of high-carbon ferromanganese was estimated to produce ferroalloy. Table 2 details the composition of the processing charge and the outcomes of the chemical analysis of the products from high-carbon ferromanganese smelting.

Table 2. Composition of charge and results of chemical analysis for high-carbon ferromanganese smelting products.

	Metrics	Values of dicators	FeMn68C7.0 (China)
1	Material usage, grams:		
	Manganese granules	199	
	Coke	41.48	
	Lime	12.76	
2	The resulting alloy mass, g	106.48	
3	Mean elemental composition of the alloy product, %		
	Mn	66.40	65.1-72.1
	Fe	21.30	
	C	6.42	≤ 7.1
	Si	3.96	2.6-4.6
	P	0.066	0.3-0.4
	S	0.027	≤ 0.05
4	Slag obtained, g	76.49	
5	Mean elemental composition of the slag phase, %		
	MnO	6.08	
	FeO	0.55	
	SiO2	37.55	
	MgO	2.83	
	Al2 O3	7.61	
	CaO	40.08	

The chemical analysis indicates that the alloy contains an average manganese containing 66.40% and a 6.42% carbon. The levels of deleterious contaminants, phosphorus and sulfur, are within permissible limits. The high-carbon ferromanganese alloy is classified as $FeMn_{68}C_{7.0}$ (PRC) grade.

Samples of the alloy (Fig. 6a) and slag (Fig. 6b) produced during experimental smelting the samples were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM) of the microstructure.

Figure 6. Products of high-carbon ferromanganese smelting: (a) alloy, (b) slag.

The X-ray phase analysis results of manganese pellet smelting products indicated that the alloy comprises multiple phases containing manganese, primarily consisting of manganese-iron-carbon compounds, Manganese Iron Carbide $Mn_{1.8}Fe_{1.2}C$, $(Fe_{2.5}Mn_{2.5})C_2$, and iron-carbon compounds, specifically Cohenite Fe_3C (Fig. 7).

The slag comprises: Kirschsteinite $Ca(Fe_{0.77}Mg_{0.2})(SiO_4)$, aluminium oxide carbide Al_2OC, calcium silicate $CaSi_2$, aluminium magnesium Mg_2Al_3, and ankerite $Ca(Fe^{+2}, Mg)(CO_3)_2$ (Fig. 8).

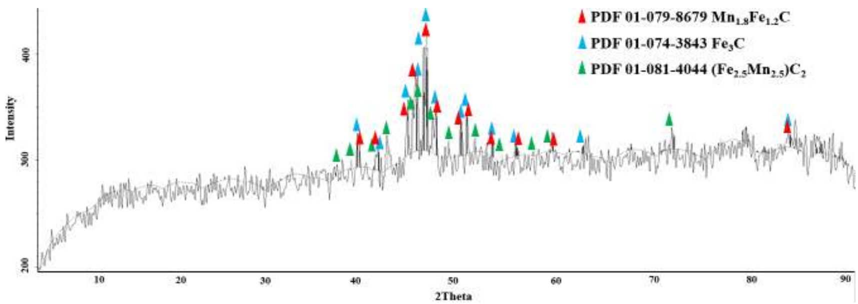


Figure 7. Diffractogram of the CFeMn alloy sample.

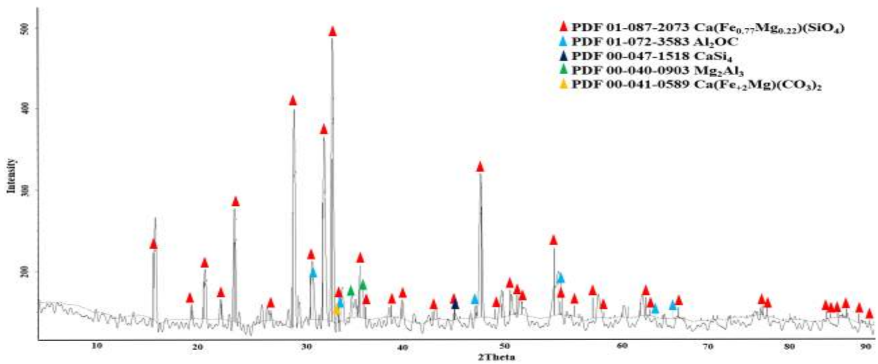


Figure 8. Diffractogram of a slag sample obtained during CFeMn smelting.

The high-carbon ferrochrome alloy has a microstructure that is full of cracks and grains of different sizes (Fig. 9, Fig.10). The concentrations of alloy components determined by point microanalysis EDS are as follows: Mn - 65.57%, Fe - 25.51%, C - 5.90%, Si - 2.53%, which closely align with the elemental content of the CFeMn alloy as per chemical analysis results, corresponding to the composition $CFe_{4.3}Mn_{11.1}$ (Fig. 9, Fig. 10). This signifies the uniformity of the alloy's chemical composition across different localized areas. The chemical composition data closely match the amounts of slag components obtained from point EDS microanalysis (Fig. 11). SEM study of slag samples indicates that a small quantity of manganese transfers into the slag.

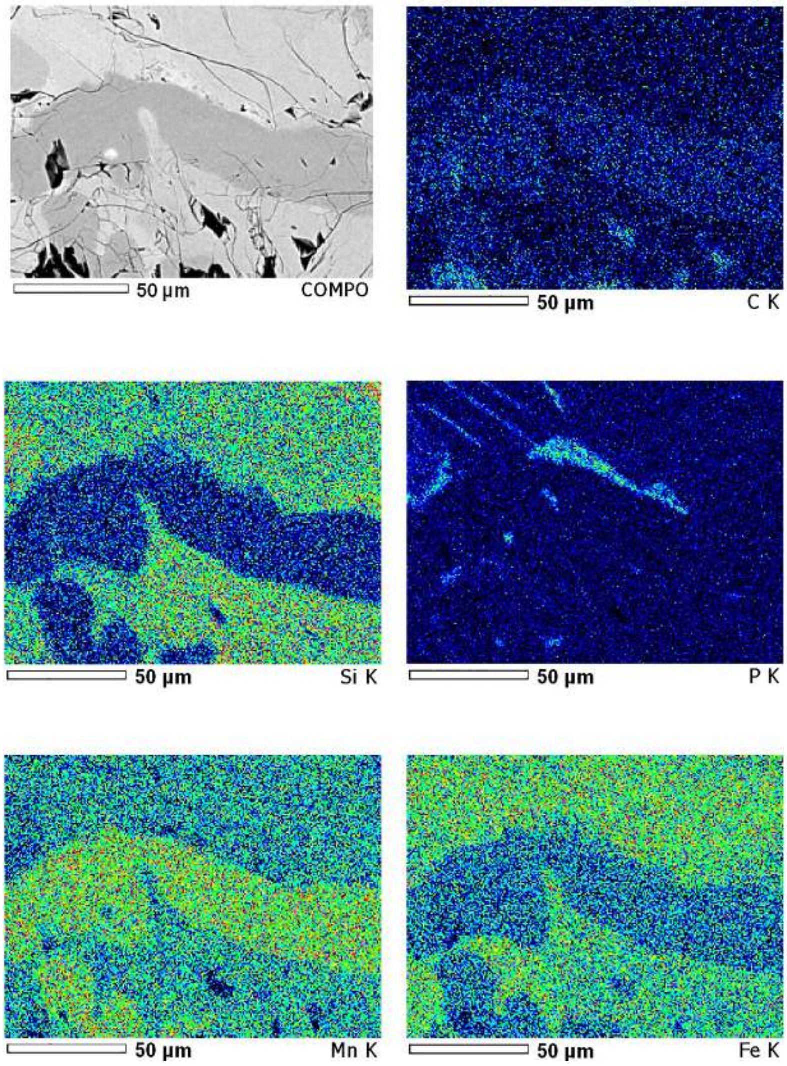
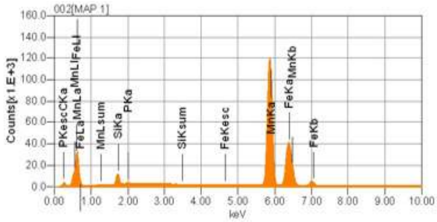
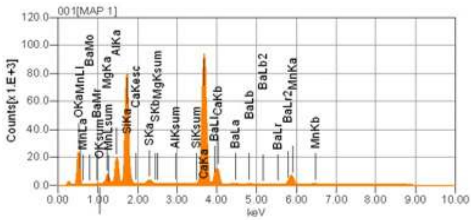


Figure 9. Microstructure of the CFeMn alloy.



Chemical formula		ms%	mol%	Sigma	Net	K ratio	Line
C	5.90	21.87	0.62	421560	0.0000000		K
Si	2.53	4.00	0.38	2885503	0.0000000		K
P	0.49	0.70	0.34	571508	0.0000000		K
Mn	65.57	53.11	0.69	591886940.0000000			K
Fe	25.51	20.32	0.70	210928130.0000000			K
Total	100.00	100.00					

Figure 10. Elemental EDS mapping of the CFeMn alloy.



Chemical formula		ms%	mol%	Sigma	Net	K ratio	Line
O	46.30	65.28	0.56	4914877	0.0000000		K
Mg	1.72	1.60	0.13	1737764	0.0000000		K
Al	3.72	3.11	0.11	4943761	0.0000000		K
Si	16.02	12.86	0.11	240447800.0000000			K
S	0.56	0.39	0.10	771191	0.0000000		K
Ca	26.50	14.91	0.13	404713220.0000000			K
Mn	4.03	1.65	0.29	3252698	0.0000000		K
Ba	1.16	0.19	0.44	804079	0.0000000		L
Total	100.00	100.00					

Figure 11. Slag composition derived from CFeMn smelting, based on EDS point microanalysis data.

A method has also been developed for producing chromium pellets from technogenic chromite waste suitable for high-carbon ferrochrome production. Chromium-bearing beneficiation tailings of chromite ores are represented by the following minerals: lizardite, magnesiochromite, apophyllite, chlorite, olivine, and fluorite.

Chemical beneficiation of finely dispersed chromite raw material was carried out by thermal sulfation with ammonium sulfate and small additions of sulfuric acid at 250-350 °C, followed by leaching with recycled solutions. From the cooled filtrate, ammoshenite $MgSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$ - a complex ammonium-magnesium fertilizer-was crystallized; up to 31% of MgO was transferred into a water-soluble form. The solid residue (containing 39.7% Cr_2O_3) obtained after sulfate leaching was further beneficiated using a shaking table or spiral separator to obtain a concentrate containing up to 50 wt.% Cr_2O_3 and a light fraction represented mainly by magnesium silicate - forsterite, a refractory material used for lining metallurgical furnaces.

Subsequent gravity beneficiation of the obtained products, separated into narrow size fractions on shaking tables, made it possible to get a marketable chromite concentrate with the following composition (wt.%): 51.06 Cr_2O_3; 11.65 Fe_2O_3; 19.21 MgO; 3.88 Al_2O_3; 15.54 SiO_2; 0.007 P_2O_5; 0.089 SO_3.

The optimal charge composition for producing fired chromium pellets was determined as follows: chromite concentrate (50% Cr_2O_3) - 88%; mineral part of ferrochrome production slag - 4.5%; iron-bearing diatomite - 3 wt.%; special coke - 3 wt.%; liquid glass - 1.5%. At temperatures 1200-1250 °C, the samples' structure becomes densified and strengthened without melting the pellets. Mechanical strength of the thermally treated pellets under compression is 42.5 kg per pellet. The composition of the chromium pellets (wt.%): 48.06 Cr_2O_3; 13.47 Fe_2O_3; 20.6 MgO; 5.1 Al_2O_3; 16.2 SiO_2; 0.01 P_2O_5; 0.012 SO_3. During pellet firing, complex ferrosilico-calcite compounds are formed-hedenbergite, paragonite-2M1 ($NaAl_2(AlSi_3)O_{10}(OH)_2$), and chloritoid-A ($FeAl_2SiO_5(OH)_2$)-which enhance pellet strength.

Smelting of the fired chromium pellets was carried out at 1750 °C to obtain high-carbon ferrochrome. The charge composition was as follows: 88.5% chromite concentrate, 3.0% mineral part of ferrochrome slag, 4.0% iron-bearing diatomite, 3.0% special coke, and 1.5% liquid glass.

The principal distinguishing feature of the proposed technological scheme is the processing of chromite sludges using chemical beneficiation methods followed by gravity beneficiation on shaking tables, separation into narrow size classes before beneficiation, and treatment of each product in a separate beneficiation cycle.

Conclusions. The beneficiation of manganese-laden sludge produced a concentrate appropriate for ferromanganese smelting regarding manganese concentration. Pellets exhibiting elevated compressive strength were fabricated from the manganese concentrate. The incorporation of diatomite, a natural mineral, as a binder results in the formation of hedenbergite, a silicate with the complex composition $Ca(Fe_{0.821}Al_{0.179})$ $(SiAl_{0.822}$ $Fe_{0.178}O_6)$, which enhances the pellets' strength properties.

Calcined manganese pellets, when melted at 1500 °C, yield a ferromanganese alloy. The physical and chemical examinations indicate that the mean manganese level determined in the high-carbon ferromanganese alloy is 66.41%, carbon is 6.43%, and the levels of impurity elements (silicon, phosphorus, and sulfur) are within acceptable limits. The resultant alloy is designated as FeMn68C7.0.

A method has been developed for the integrated processing of fine-grained chromite wastes to produce marketable chromite concentrate and magnesium compounds. A charge composition has been suggested for making chromium pellets. It would include finely dispersed chromite concentrate, the $CaO–SiO_2$–bearing mineral fraction of refined ferrochrome slag, an iron-bearing diatomite (a source of amorphous SiO_2), and liquid glass. When pellets are fired, they form complicated ferrosilico-calcite compounds like hedenbergite, paragonite-2M1 ($NaAl_2(AlSi_3)O_{10}(OH)_2$), and chloritoid-A ($FeAl_2SiO_5(OH)_2$), which make them stronger. Tests on fired composite pellets showed that it was possible to make high-carbon ferrochrome.

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