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Environmental Impact Assessment of Ferrous Slags Application as Backfill Material for Technical Rehabilitation of Lands Degraded by Mining

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Abstract

The article highlights a problem of ferrous slags utilization for industrialized regions with low demand on slag products due to unfavorable market situation. The identified prospective option for ferrous slags utilization as backfill material in technical reclamation projects will be a sustainable solution to this problem. Potentially ferrous slags can be used as backfill material in technical reclamation projects for lands disturbed by mining. Particularly, ferrous slags can backfill the worked-out space at opencast mines and quarries. The developed methodology allows making a preliminary environmental impact assessment of prospective ferrous slag application as backfill material in mine reclamation projects in cases of extreme conditions when backfill slag layer sink in quarry water.

Keywords: Ferrous slags; Industrial by-products utilization; Methodology; Backfill material; Reclamation of lands disturbed by mining; Underground water

Introduction

The problem of industrial by-products utilization is a relevant case for industrialized countries, especially for developing countries and countries with economies in transition. Typical preconditions to this problem are low level of inter-sectoral cooperation, insufficient funding of industrial by-products processing technology development, and lack of effective policies that support recycling economy. Due to mentioned preconditions as well as to other relevant factors, the industrial by-products implicitly accumulate at disposal sites.

Processing industry accounts for nearly 10% of total annual accumulation of unclaimed by-products and wastes in Ukraine. According to 2018 statistics, about 70% of total unclaimed by-products and wastes volume generated by processing industry attributed to ferrous metals production [1]. Ferrous metallurgy is one of the most powerful economic sectors that generates export earnings to Ukraine's budget and, therefore, it is important to shape its future development on recycling economy principles. About 80% of bulk ferrous industry by-products are ferrous slags. Two-thirds of this volume are blast-furnace slags (a pig iron production by-product), and one-third - steelmaking slags (a steel production by-product). Thus, about 11 million tons of slag is annually generated by Ukrainian ferrous metal industry, while less than a half of this volume is utilized. The main industries for ferrous slags consumption are road construction, cement industry and general construction. However, current rate of ferrous slags utilization does not allow avoiding its accumulation in dumps.

All existing regulations and technical specifications only provide recommendations for potential ferrous slag products consumers. However, there is no clear state-driven program that will enable boosting inter-sectoral cooperation for efficient industrial by-products consumption. It should be mentioned that some attempts to increase volumes of ferrous slags use by Ukrainian economy emerge in a form of state institutions initiatives. For instance, a new Standard on slag aggregates for road construction was adopted in 2020 [2]. It regulates application issues for such undervalued resources as ferrous slags.

It is unlikely to achieve a sustainable scale of ferrous slags utilization in the near future. Therefore, additional or alternative utilization options must be searched considering market situation. Blast furnace granulated slags and air-cooled BF slags are widely used as binding materials as well as filling aggregates for hardening backfill mixtures preparation for the underground mines technogenic cavities backfilling [3,4].

Another promising and economically viable option for ferrous slags utilization is backfilling quarry's mined-out spaces. To ensure sustainability of this option, one must assess potential environmental consequences in case of direct ferrous slags contacts with quarry water [5]. A number of national and international scientists have studied environmental safety aspects of ferrous slags application as road construction aggregates [6,7], while open cast mine backfilling by ferrous slags needs some additional environmental safety assurance.

Usually, mining enterprises extract millions of tons of mineral resources along with the waste rock. After finishing excavation works at open cast mines or quarries, the volume of deposited waste rocks is usually too short to backfill the mined-out space to restore the disturbed land. If there is an interest in restoring initial landscape, the disturbed lands must be backfilled by additional rocks. Decommissioned open cast mine cavities are better suited for backfilling than underground mine cavities. In addition, it is apparent that mentioned reclamation technology for open cast mines will be economically more viable [8,9]. Elaboration of this option for ferrous slags utilization may help solving environmental and social problems with unclaimed by-products depositing for many industrial regions.

Therefore, environmental safety assurance gap of potential quarry water and ferrous slags contact must be filled for disturbed lands reclamation option.

Purpose statement

This article proposes research methodology for studying ferrous slags impact on quarry water quality in case of their direct contact. The objective is to provide a new stepwise research algorithm and offer reliable study methods for quarry water quality changing assessment after direct contact with ferrous slags. If study demonstrates tolerable environmental consequences for quarry water quality, it will raise assurance in applying ferrous slags as backfill material for technogenic cavities. Another important point is to analyze how concentration of pollutants in contact water depends on water-slag ratio and on period of water-slag contact. This will help to make safety assessment of ferrous slags application as backfill material in open cast mine cavities.

Main part

A problem of ferrous slags deposits

There are two giant industrial enterprises PJSC "Ilyich Iron and Steel Works" and PJSC "Azovstal Iron and Steel Works" that operate in Mariupol, Ukraine, Annual production exceeds 7 million tons of pig iron and about 7 million tons of liquid steel. There are, about 4 million tons of by-products ferrous slags are generated annually as by-products. Ferrous slag products sales significantly constrained by a number of unfavorable factors e.g., logistics, railway wagons shortage, and lack of large-scale regional infrastructure projects, as well as lack of recirculating economy policies. This puts Mariupol metallurgical enterprises into a harder market conditions than other Ukrainian metallurgical plants with better geographical location towards main ferrous slag consumers [10]. Unfavorable market conditions result in slag storage at disposal sites and in prospective need for additional slag storage spaces.

Figure 1: Map of ferrous slag dumps locations (indicated by red circles) around Mariupol.

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Figure 1 demonstrates a Google map with two Steel Mills and slag dumps locations around Mariupol. Figure 1 shows two ferrous slags storage sites. The slag storage site at Azovstal's territogy is no longer in operation. The operating slag storage site (Balka Hrekovata) which is located in North-East direction from Mariupol near Sartana village.

Current total volume of accumulated ferrous slags around Mariupol at the storage sites is near 65 million tons [11,12]. Annual commercial slag sales volume and social slag program aimed to promote local infrastructure development account for about 30% of annual slag generation by both Steel Mills. Therefore, elaboration of new options for ferrous slag application is quite relevant for the Steel Mills in a long-term perspective taking into account market situation.

Developing research algorithm to study ferrous slags environmental safety as backfill material for land reclamation projects

The problem of ferrous slags utilization can be solved by backfilling technogenic cavities of lands disturbed by mining. In case of Mariupol Steel Mills, the local decommissioned quarries or opencast mines that earlierextracted granite, limestone, clay or other minerals can be considered as opportunities for backfilling by ferrous slags. First, ferrous slags must comply with safety requirements in relation to environment and human health to be considered for backfilling. Then, as a preparatory stage for reclamation of disturbed lands with ferrous slags, it is necessary to pump out all accumulated quarry water and plug all sources of underground quarry water inflows. Nevertheless, the probability of slag backfill layer and underground water contact still exists. Therefore, the task is to study potential consequences of slag and water contacting. Appropriate research methodology must be developed.

The proposed 6-stage research methodology allows studying potential consequences of applying ferrous slags as backfill materials in mine reclamation projects. The methodology is presented at Figure 2.

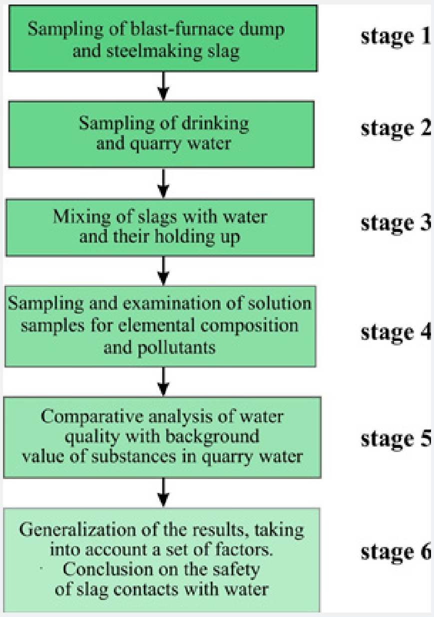

Figure 2: Methodology for studying consequences of ferrous slags contact with quarry water (e.g. for the extreme cases of sudden inundation of slag layer during implementation of mine reclamation project).

Stage 1: Studying environmental safety of ferrous slags application as backfill materials for technogenic cavities must start from taking samples of ferrous slags (blast furnace slag and basic oxygen furnace slag) for laboratory tests. The characteristics chemical composition is determined according to existing physical and chemical methods or according to actual laboratory test data for batched slag products: CaO, SiO_2 $Al2O_3$, MgO, MnO, FeO, K_2O, TiO_2, and sulphur content. Then, granulometric composition of metallurgical slags should be determined by sieve analysis. The bulk weight and moisture content of material should also be tested and recorded.

Stage 2: In the process of quarry backfilling with slag, it can be flooded by inflowing underground water, especially in case when the level of underground water inflow is higher than existing quarry mining horizon.

At this stage it is necessary to conduct chemical analysis of quarry water samples (control samples), which may potentially contact with slag backfill layer. Quarry water (control water sample) must be tested on background trace elements content and concentration of pollutants (mg/dm^3).

Stage 3: Ferrous slags samples must be mixed with quarry water (control water) in trial containers. The 6-liter plastic containers with volumetric scale (per liter) recommended for this exercise (Figure 3). Recommended volume of control water per test is 3 liters. Recommended weight of slag samples will vary with a step: 1.5kg, 3.0kg and 4.5kg. Total volume of slag and water within trail container should also be recorded.

Figure 3: Containers with ferrous slags mixed with control water for studying physical and chemical properties of contact water.

These trials allow us studying changes of chemical composition of contact water depending on slag-water ratio. The proposed slag-water ratios modelling extreme conditions – a case when slag backfill layer innundates due to underground quarry water inflow.

Extraction of contact water samples from trial containers for laboratory tests is recommended after 1, 15 and 30 days periods (primary trial periods). It is recommended to mark and hold all trial containers outside during testing periods. During extraction of contact water samples for laboratory tests, it is also recommended to record the following physical properties: visual turbidity, sedimentation and odor.

In order to assess further potential for trace elements and pollutants migration from slag to quarry water, the slag samples should be re-mixed with a fresh control water samples and kept for the same trial periods of 1, 15 and 30 days (secondary testing trial). Extracts of contact water samples after secondary testing trial should also be taken for laboratory testing.. In addition, the same physical properties (turbidity, sediment and odor) of contact water after secondary trial periods must be recorded. Determination of trace elements concentration dependence on trial period will be based on contact water chemical test results. It is recommended to log contact water physical properties data in a format provided at Table 1.

Table 1: Data Log on contact water physical properties.

Mixture, No	Mixture Composition			Physical Parameters					
	Slag, kg	Water, l	Total mixed volume, l	Testing period, days	Volume of water absorption by slag, l	Volume of water sample, l	Water turbidity (yes/no)	Sediment (yes/no)	Odor (yes/no)
1a									
1b									

Note: a – primary trial; b – secondary trial.

Stage 4: Series of mixing ferrous slags samples with control water trials take place during a fixed time period (1, 15 and 30 days). After finishing trial period, an extract of contact water (at least 0.5 liters) is taken from trial container. Contact water sample

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must be tested on chemical composition (trace elements). It is recommended to study chemical composition of control water and contact water by using atomic emission spectrometry with inductively coupled plasma [13]. The iCap 7000 Duo spectrometer (Figure 4) allows detecting mass presence of 33 chemical elements. In the framework of contact water laboratory testing, it is proposed to select main elements that can potentially occur in ferrous slags composition, e.g: Al, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, P, Na, Pb, S, Sr, Zn, Si, Ag, As, Co, Ni. The list of elements must be selected individually with regards to specific conditions of slag production.

Figure 4: ICap 7000 Duo spectrometer for determining chemical composition of contact water.

It is recommended to log contact water trace elements composition and its hardness data in a format provided at Table 2. Besides taking sample of contact water (0.5 liters) for determining elemental composition, additional contact water sample (2.0 liter) must be taken from trial container for testing chemical properties and concentrations of pollutants. The concentrations of typical chemical substances (pollutants) in contact water must be determined according to recognized methodologies [13-20]: suspended solids, dry residues, pH, chlorides, sulphides, ammonium nitrogen, phosphates, nitrates, nitrites, oil products, total iron, calcium, magnesium, sulphates, etc. It is recommended to record contact water chemical testing results in a format provided at Table 3.

Table 2: Data Log on contact water trace elements composition.

Mixture Solution No...	**Trace elements Mass Fraction, mg/dm^3**																			**Hardness, mg-eq/dm^3**
	Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	P	Na	Pb	S	Sr	Zn	Si	Ag	As	Co	
1a																				
1b																				

Note: a – primary trial; b – secondary trial.

Table 3: Data Log on concentration of pollutants in contact water.

Mixture Solution No...	**Concentration of Pollutants, mg/dm^3**											
	Suspended solids	Dry residue	pH	Chlorides	Sulphides	Ammonium nitrogen	Phosphates	Nitrates	Nitrites	Oil products	Total iron	Sulphates
1a												
1b												

Note: a – primary trial; b – secondary trial.

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Stage 5: After contact water laboratory tests on trace elements composition and pollutants concentration is finished, it must be compared with the same laboratory tests of control water (initial water). In order to model the extreme situation when backfill slag layer inundates in quarry water), one should take into account an existing level of underground water horizon (m) and calculate: total possible volume (m^3) and intensity (m^3/h) of underground water as well as atmospheric precipitation inflows to quarry cavities. Thereafter, total volume (m^3) and formation intensity (m^3/h) of slag backfill layer must also be calculated. Then, Excel function of predicting experimental data according to math law will help to determine concentrations of trace elements and pollutants at any slags-water ratios. In order to reduce slag layer filtration factor, it is recommended to apply compaction during thereclamation process.

Stage 6: Comparative analysis of control water and contact water quality will allow making preliminary conclusion on environmental safety of ferrous slags application as backfill materials for particular disturbed land reclamation case.

Final environmental safety conclusions on ferrous slags application as backfill materials for a potential reclamation case can be made when the following critical factors are taken into account:

a) Regional geological chart of underground water consumption wells around quarry where ferrous slags backfilling is considered.

b) Characteristics of quarry bottom rocks, its filtration properties and underground water levels.

c) Backfill material ability to compact under mechanical pressure by machinery and compress under upper backfill layers weight.

d) Filtration factors of backfill material (including compacted case).

e) Backfill material's physical and chemical decomposition ability, and ability to form new crystal lattices which may strengthen the backfilled mass.

Monitoring of possible backfilled mass interaction with the underground water after reclamation project implementation, can be organized by drilling observation wells around reclaimed land with periodic water sample testing. The proposed methodology can be useful for studying environmental safety of ferrous slags application for disturbed lands reclamation projects.

Case study

Research study according to proposed methodology was made for Illych Steel Mill ferrous slags interaction with quarry water from local barren granite quarry. The quarry water laboratory tests on trace elements and concentration of pollutants were made according to paragraph (Stage 4) of this methodology. Laboratory test results on quarry water chemical composition provided in Table 4, and laboratory test results on concentration of pollutants in quarry water provided in Table 5.

Table 4: Trace elements presence in quarry water.

Trace Elements Mass Fraction, mg/dm^3																			Hardness, $mg\text{-}eq/dm^3$
Al	Ca	Cd	Cr	Cu	Fe	K	Mg	Mn	P	Na	Pb	S	Sr	Zn	Si	Ag	As	Co	
<0.1	127	<0.1	<0.1	<0.1	<0.1	2.7	95	<0.1	<0.1	128	<0.1	288	2.2	<0.1	3.2	<0.1	<0.1	<0.1	14.4

Table 5: Concentrations of pollutants in quarry water.

Concentration of Pollutants, mg/dm^3											
Suspended solids	Dry residue	pH	Chlorides	Sulphides	Ammonium nitrogen	Phosphates	Nitrates	Nitrites	Oil products	Total iron	Sulphates
22.4	1246	6.75	68.1	<0.05	<0.1	0.23	4.93	<0.03	0.016	<0.1	910.5

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Interaction of ferrous slag (air-cooled blast furnace slag) and quarry water was studied according to paragraph (Stage 3). It was a first series of 1-day period experiments with 1:2, 1:1 and 2:1 slag-water ratio.

Illustration of extracted contact water samples (BF slag and quarry water) from trail containers provided at Figure 5. Acquired experimental data on trace elements content and concentrations of pollutants in contact water allowed building dependencies for different slag-water ratios. The diagram at Figure 5 allows concluding: the lower quarry water volume contacts slag – the lower trace elements mass will appear in contact water, e.g., hyperbolically for Ca and S, and linearly for Na and Si. Comparison of trace elements content in contact water Figure 6 (a) and trace elements content in control water (Table 4) showed that during 1-day period of slag-water contact no significant environmental impact takes place. The observed increase of Si content will not be a serious harm to the quality of underground waters. Also at 1:2 slag-water ratio Ca content increases in contact water. However, environmental impact caused by Ca content increase is also tolerable for underground water quality. On a large-scale, the expected effect will be in slight increase of local underground water hardness.

Figure 5: Extracted contact water samples and trail container with slag.

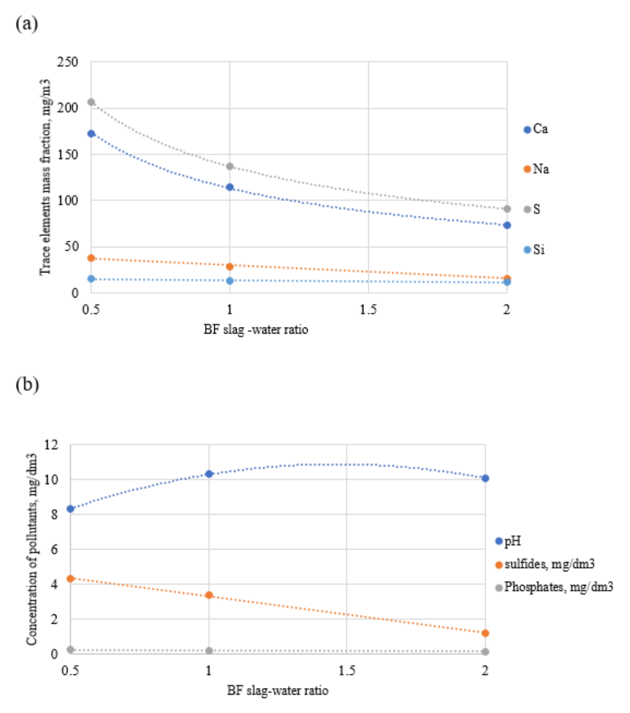

Figure 6: Dependencies of trace elements content

a) and pollutants con-centrations.
b) for variable slag-water ratios.

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The Figure 6(b) diagram demonstrates that pH increases in contact water with the shorter water quantity according to polynomial law; the sulfides concentration decreases linearly from 4.3 to 1.2 mg/dm^3; the phosphates concentration almost remains unchanged. Considering the obtained laboratory data from 1-day blast furnace slag and quarry water contacting it can be preliminarily concluded that ferrous slag as a backfilling material will not cause any significant impact on the underground water quality even in case of a slag layer flooding.

Conclusion

The proposed methodology allows determining environmental impact of ground water contact with ferrous slags application as backfill materials for reclamation of technogenically-disturbed lands. The proposed methodology provides an instrument for express assessment of ferrous slags applicability as a backfill material for disturbed lands reclamation projects based on a predictive study of slag-water interaction with determination of dependences of trace elements and pollutants that can appear in contact water at variable slag-water ratios and variable contacting periods. The proposed methodology is a useful toolkit for assessing environmental risks for technogenically -disturbed lands reclamation projects where ferrous slags are considered as a backfilling material. Final determination of ferrous slags environmental safety as backfilling materials for a particular reclamation case can be made when considered additional critical factors such as like hydrogeological conditions, physical and chemical properties of backfill materials, and operating local water consumption wells.

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