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OPTIMIZATION OF CRUSHING SIZE FOR HEAP LEACHING OF OXIDIZED COPPER ORE AT THE BERKARINSKOE DEPOSIT: FROM LABORATORY STUDIES TO INDUSTRIAL IMPLEMENTATION

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ABSTRACT
This paper presents the results of studies on the optimization of crushing size for heap leaching of oxidized copper ore at the Berkarinskoe deposit (East Kazakhstan Region). The initial technological regulation for heap leaching was developed on the basis of comprehensive laboratory studies including chemical, phase-chemical, granulometric, mineralogical, X-ray diffraction, and thermogravimetric analyses, as well as laboratory percolation column tests on −10 mm material, which yielded copper extraction of 78.8% over 90 days. Following industrial implementation, pilot-scale column tests on −25 mm and −30 mm fractions showed that the −25 mm fraction achieves 70% copper extraction in 100 days with acid consumption of 99.4 kg/t ore (10.4 kg/kg Cu), versus 128 days and 114.7 kg/t ore (11.3 kg/kg Cu) for the −30 mm fraction. The two pilot columns were charged with different ore types — oxidized ore (K-1, −25 mm) and mixed ore (K-2, −30 mm) – which differ markedly in phase composition (9.4% versus 54.4% secondary copper sulfides), so the comparison reflects ore type as well as crushing size; this is accounted for in the interpretation. The 3.5 m columns simulated the heap height and the planned two-lift stacking. The −25 mm crushing size was identified as the optimal parameter, enabling crushing plant throughput of 90,000 t/month while maintaining extraction within regulation limits. Percolation properties remained stable throughout all tests, confirming the favorable physical characteristics of the ore. The study provides empirical, pilot-scale scale-up data linking the laboratory-based technological regulation to industrial crushing-size optimization for an operating heap leach facility.

INTRODUCTION

Heap leaching combined with the solvent extraction–electrowinning (SX–EW) process has become the dominant technology for processing oxidized copper ores worldwide, accounting for approximately 20% of global copper production and offering significant economic and environmental advantages over conventional pyrometallurgical methods (Schlesinger et al., 2022; Petersen, 2016). The efficiency of heap leaching is directly dependent on a number of ore-specific parameters, among which the crushing size plays a critical role: it determines both the accessibility of copper minerals to the leaching solution and the percolation properties of the ore bed, while simultaneously defining the capacity and energy consumption of the crushing and screening plant (Ghorbani et al., 2011; Ghorbani et al., 2016).

Particle size selection in heap leaching represents a fundamental trade-off. Finer crushing increases mineral liberation and accessibility for the leach solution, accelerating reaction kinetics and improving copper recovery; however, excessive fines can compromise heap permeability, induce channeling, and ultimately reduce extraction efficiency (Bouffard, 2008; Watling, 2006). Coarser crushing reduces capital and operating costs of comminution and improves the structural stability of the heap, but may limit copper recovery if the ore mineralogy locks copper minerals within larger particles.

The Berkarinskoe deposit, located in the East Kazakhstan Region, is an operating heap leaching facility processing oxidized copper ore with grades ranging from 0.92% to 1.52% Cu. The initial technological regulation for the operation was developed based on comprehensive laboratory investigations that provided a detailed characterization of the ore material composition and established the key leaching parameters for a crushing size of −10 mm.

However, industrial operation of the heap leaching facility revealed the need to optimize the crushing size in order to increase the throughput of the crushing and screening plant, reduce unit crushing costs, and improve the efficiency of heap construction and ore stacking. In this context, the transition to coarser crushing — specifically to −25 mm and −30 mm — was considered as a practical solution, provided that copper extraction remained within acceptable limits defined by the technological regulation.

The scientific novelty and practical significance of this work lie in the direct linkage between a laboratory-derived technological regulation and its verified industrial-scale optimization. Rather than reporting laboratory leachability alone, the study provides empirical pilot-scale data (3.5 m bed height) that quantify the trade-off between crushing-size thresholds, copper-extraction kinetics, acid consumption, and crushing-plant throughput for an operating facility — data that are rarely reported for the full laboratory-to-industry transition. Accordingly, the objectives of the study were: (i) to characterize the chemical, phase, mineralogical, and physical–mechanical properties of the Berkarinskoe oxidized ore; (ii) to establish the baseline leaching behaviour underlying the existing −10 mm regulation; and (iii) to evaluate, through pilot-scale percolation column tests that simulate the full heap height and the planned two-lift (two-tier) stacking, whether the production transition to coarser crushing — −25 mm for the oxidized ore and −30 mm for the mixed ore — preserves copper extraction within the regulation limits while increasing crushing-plant throughput.

MATERIALS AND METHODS

Deposit Characteristics and Ore Sampling

The Berkarinskoe deposit is located in the East Kazakhstan Region of Kazakhstan. The deposit contains 2,405,220 t of oxidized ore (average Cu 1.28%) and 1,687,224 t of mixed ore (average Cu 1.61%). Copper content in oxidized ores ranges from 0.92% to 1.52%. The main technological sample of oxidized ore (BR-3) used for the initial laboratory studies had a copper content of 1.23%. For the pilot-scale column tests, the two different ore types processed at the facility were used: oxidized ore (sample K-1, Cu 1.37%, crushed to −25 mm) and mixed ore (sample K-2, Cu 1.46%, crushed to −30 mm), corresponding to the production transition to coarser crushing for both ore types. The maximum lump size of run-of-mine ore from the open pit is 500 mm.

The two pilot columns were charged with the two different ore types processed at the facility: K-1 with oxidized ore and K-2 with mixed ore, each crushed to the size adopted for it in production (−25 mm and −30 mm, respectively). The samples are therefore representative of the respective ore types as they are actually fed to the heap. Because oxidized and mixed ores differ fundamentally in the ratio of oxidized copper to secondary copper sulfides, K-1 and K-2 differ markedly in phase composition (detailed below); consequently the two columns do not constitute a particle-size-controlled experiment, and this is explicitly taken into account when interpreting the comparative results.

Chemical, Phase, and Granulometric Analyses

The material composition of the oxidized ore was studied using chemical analysis, phase-chemical analysis, and granulometric analysis with copper assaying by size fraction. X-ray diffraction (XRD) analysis was performed to identify the principal crystalline phases. Thermogravimetric analysis (TGA) was used to characterize thermal stability and decomposition behavior. Physical and mechanical properties – Protod'jakonov hardness coefficient (f), abrasivity index, specific gravity, bulk density, angle of repose, and moisture capacity — were determined according to standard procedures. Percolation rates were measured through static ore beds of −5 mm, −10 mm, and −20 mm fractions.

Mineralogical Examination

To study the mineralogical composition of the copper-bearing ore, core samples with ore mineralization were selected. Petrographic and mineragraphic investigations were carried out in the physicochemical research laboratory using an OLYMPUS BX51 Pol. polarizing microscope equipped with a SIMAGIS 2P-2C video camera and SIAMS Mineral C7 image analysis software. Polished sections ("anshlif") were prepared from representative ore samples and examined in reflected light at magnifications of ×50 to ×400.

Initial Laboratory Column Leaching Tests (−10 mm)

Laboratory percolation column tests were conducted on −10 mm and −20 mm fractions (variants BR-10, BR-20, and BR-10A with acid pre-agglomeration) irrigated with dilute sulfuric acid solution over 90 days. These tests formed the basis for the development of the technological regulation for the Berkarinskoe heap leaching operation.

Pilot-Scale Column Tests for Crushing Size Optimization

Following industrial implementation of the heap leaching operation, pilot-scale column tests were initiated in September 2024. Two columns were operated in parallel: K-1 (−25 mm) and K-2 (−30 mm). Columns were fabricated from polyethylene pipe SDR17 (internal diameter 340 mm, height 4,750 mm) with an irrigation area of 0.09 m². The ore bed height was 3.5 m, chosen to simulate the full height of an industrial heap lift and to represent the planned two-lift (two-tier) stacking of the heap under the transition to coarser crushing. Leaching solution containing 25–30 g/L H_2SO_4 was applied at an irrigation density of 8–10 L/m²/h. Tests were conducted until 70% copper extraction was achieved. Pregnant leach solution (PLS) was sampled regularly to monitor copper concentration dynamics and calculate cumulative extraction and acid consumption. Leaching was conducted under ambient, atmospheric conditions with dilute sulfuric acid as the sole lixiviant; no oxidant was added and the oxidation–reduction potential (ORP) of the solutions was not monitored, because the objective of the pilot programme was to evaluate the effect of increased crushing size relative to the existing technological regulation, not to study sulfide-oxidation kinetics.

Calculation of leaching indicators. The cumulative copper extraction at a given time, $\varepsilon(t)$, was calculated from the cumulative mass of copper reporting to the pregnant leach solution (PLS) up to that time, expressed as a percentage of the total copper charged to the column:

$$\varepsilon(t) = \frac{\sum ViCi}{m \cdot \beta} 100\,\% \tag{1}$$

where: ε(t) — cumulative copper extraction, %;

Vi — volume of PLS collected in interval *i*, L;

Ci— copper concentration in interval *i*, g/L;

m — mass of ore charged to the column, kg;

β — copper head grade of the ore (mass fraction, kg Cu/kg ore).

The specific acid consumption was calculated as the total mass of sulfuric acid added (corrected for the residual free acid in the PLS) divided by the mass of ore loaded (kg/t ore) and by the mass of copper extracted (kg/kg Cu):

$$qore = \frac{Aadd - Ares}{more} \tag{2}$$

$$qCu = \frac{Aadd - Ares}{mCu} \tag{3}$$

where: A_{ad} — cumulative mass of sulfuric acid added, kg;
A_{res}— mass of residual free acid in PLS, kg;
m_{ore}— mass of ore loaded, t or kg (must be consistent with units);
m_{Cum}— mass of copper extracted, kg.

The target extraction level of 70% was adopted from the technological regulation of the Berkarinskoe operation as both the completion criterion for each pilot test and the basis for comparison between the two crushing sizes.

RESULTS AND DISCUSSION

Chemical and Phase Composition

Chemical analysis of the main oxidized ore sample (BR-3) established a copper content of 1.23%, iron 5.28%, aluminum 7.92%, silicon dioxide 59.96%, and silver 22.0 g/t (Table 1). Phase-chemical analysis showed that 83.6% of copper occurs in acid-soluble forms, of which 70.5% are readily leachable carbonates (malachite, azurite) and chalcanthite. This high proportion of acid-soluble copper forms was a key factor in confirming the suitability of the ore for sulfuric acid heap leaching and establishing the basis of the technological regulation. Notably, no acid-consuming carbonate gangue was identified in the oxidized ore, which is favorable for acid consumption management during leaching.

Table 1. Multi-element chemical analysis of ore samples, Berkarinskoe deposit

Component	Oxidized ore BR-3 (2017)	Mixed ore (2019)	Mixed ore (2021)	Unit
Cu	1.23	1.07	1.24	%
Fe	5.28	6.55	5.62	%
Al	7.92	8.46	6.88	%
SiO_2	59.96	55.86	55.76	%
Ca	1.10	1.95	2.13	%
Ag	22.0	17.4	19.6	g/t
Note – compiled by the authors				

Mineralogical Description of the Ore

The host rocks are represented by fine-clastic tuffs and acid-composition porphyries. The altered fine-clastic tuff is a pyroclastic rock of acid, moderately alkaline composition with relict or crystallo-vitrioclastic structure and massive texture. Initially, the rock appears to be an acid (subalkaline) effusive. Under higher magnification, numerous small (0.3 mm) fragments of feldspar crystals (crystalloclasts), isolated quartz crystals, devitrified glass fragments (vitroclasts), and isolated larger (up to 1–2 mm) fragments of the groundmass with trachytoid structure (litoclasts) are visible. The matrix between the pyroclastic fragments is an unindividualized quartz-feldspar aggregate with fine (0.02 mm) sericite flakes. The ore minerals present are: I — black, rare incomplete subidiomorphic crystals 0.2 mm; II — green, thin films along fragment margins; III — replaced by earthy epidote (typically after magnetite).

The altered acid porphyry with ore minerals has a fine-porphyritic structure with a felsitic to fine-felsitic groundmass. Rare fine phenocrysts (0.3–0.6 mm) consist of short prismatic and tabular alkali K-Na feldspars. The groundmass is an unindividualized microfelsitic quartz–feldspar aggregate with subordinate hydrosericite microflakes. The ore material (gray) is unevenly distributed but, at low magnification, is clearly confined to thin (0.01 mm and wider) thread-like branching quartz veinlets. The size of ore aggregates depends directly on the thickness of these veinlets, reaching up to 1 mm. The ore minerals are completely xenomorphic – shapeless, amoeboid, lobate forms 0.01–0.8 mm in size. The ore texture is veinlet, irregularly disseminated, and nest-disseminated. Ore minerals include malachite, azurite, chalcanthite, chrysocolla, tenorite, chalcocite, and covellite. Isolated occurrences of native copper and electrum are also observed.

Malachite, azurite, chalcanthite, and chrysocolla commonly occur in association, filling fractures in the host rocks as crusts and films with thicknesses from 0.05–0.3 mm to 1 mm. Chalcanthite in rock cavities forms colloform coatings on quartz crystals, films 0.05–0.1 mm thick along fractures, and nests in cavities 2–4 mm in size with inclusions of malachite and azurite. Malachite forms fine-grained films along fractures in the rock and, less commonly, acicular aggregates 0.05–1.0 mm in size (isolated grains up to 15 mm). Azurite occurs as nests of crystals from 0.1–0.3 mm to 3×14 mm along fractures filled with chalcanthite.

Figure 1. Polished section. Crusts of azurite (blue), malachite (green), and goethite (black) along cleavage planes of the core

Note – compiled by the authors

Tenorite in intensely oxidized rocks forms veinlets with mosaic twinning structure and dendritic intergrowths when replacing chalcocite. The thickness of the veinlets is 0.02–3.0 mm. In the bulk of the host rocks, rare uneven dissemination of chalcocite is observed, with grain sizes from 0.003 to 0.05×0.075 mm, occasionally up to 0.10×0.40 mm , as well as nests composed of acicular malachite 0.3–0.5 mm in size with remnants of chalcocite and covellite.

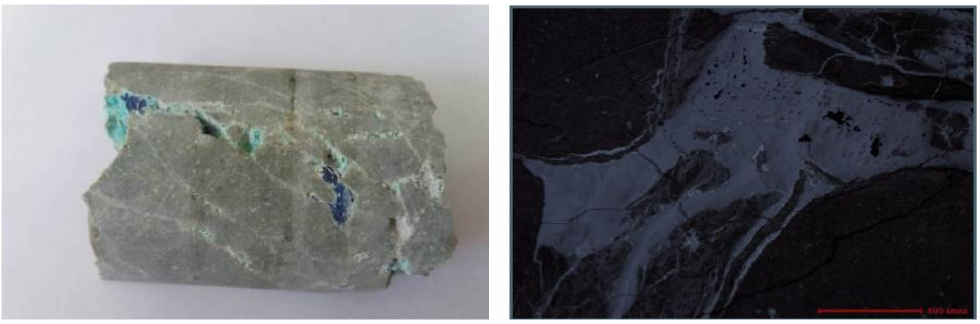

Figure 2. Polished sections: top — nests of azurite (blue) in association with chalcanthite (light blue) along fractures in the core; bottom — veinlets of tenorite with mosaic twinning structure, ×50 (scale bar 500 µm)

Isolated globules of native copper measuring 0.005×0.025–0.05 mm have been observed within iron hydroxides. Isolated inclusions of electrum measuring 0.002×0.005–0.006 mm occur within the non-ore matrix of the rock and within iron hydroxides.

The mineralogical observations are fully consistent with the phase-chemical analysis results showing 83.6% acid-soluble copper. The dominant copper-bearing minerals (malachite, azurite, chalcanthite, chrysocolla, and tenorite) are all amenable to sulfuric acid leaching at ambient temperature, while the silicate gangue (quartz, feldspar, sericite, chlorite) does not consume significant amounts of acid. Together with the absence of carbonate gangue, this mineralogical assemblage confirms the suitability of the Berkarinskoe ore for heap leaching with sulfuric acid as the lixiviant.

Physical and Mechanical Properties

The Protod'jakonov hardness coefficient is f = 8 (hard rock), abrasivity index 16 mg (below average), specific gravity 2.73 g/cm³, bulk density 1.70 g/cm³, angle of repose 29°, and moisture capacity 7.0%. These properties confirmed the ore's amenability to conventional crushing with low fines generation — a critical factor for heap percolation stability (Ghorbani et al., 2011).

Granulometric Analysis

Granulometric analysis of sample BR-3 at P93.6 = 20 mm showed that 47.7% of the ore falls in the −20+10 mm fraction (Table 2). Acid-soluble copper is uniformly distributed across all size fractions at 81–91%, confirming consistent leachability regardless of particle size. Percolation rates measured through static ore beds were 84,232 dm³/(m²·h) for minus 20 mm, 80,489 dm³/(m²·h) for minus 10 mm, and 44,924 dm³/(m²·h) for minus 5 mm material — all well above the minimum required for heap leaching.

Table 2. Copper distribution by size fraction, sample BR-3 (P93.6 = 20 mm)

Size fraction, mm	Yield, %	Cu, %	Acid-sol. Cu (rel.), %	Cu distribution, %
−30+20	6.4	0.96	83.33	5.2
−20+10	47.7	1.06	87.74	42.8
−10+5	23.6	1.30	89.23	26.0
−5+2.0	12.0	1.10	81.82	11.2
−2.0+0	10.3	—	87–90	14.8
Total	100.0	1.18	87.29	100.0
Note – compiled by the authors				

Initial Laboratory Column Tests

Laboratory percolation column tests on minus 10 mm material (variant BR-10) achieved copper extraction of 78.8% over 90 days, with projected recovery of 80–81% over 4 months. The minus 20 mm fraction (BR-20) yielded 73.6% in 90 days, with projected recovery of 76–77% over 4 months. Pre-agglomeration with acid (variant BR-10A) provided no significant improvement, confirming that agglomeration is unnecessary for this ore type given its favorable natural percolation properties (Bouffard, 2008). These results established the technological regulation for the Berkarinskoe heap leaching operation, with minus 10 mm as the design crushing size. However, following industrial implementation, operational experience demonstrated that this crushing size constrained the throughput of the crushing and screening plant and created challenges for efficient heap construction and ore stacking. This motivated the investigation of coarser crushing sizes as an operational optimization measure.

Pilot-Scale Column Tests: Crushing Size Optimization

Pilot-scale column tests were initiated in September 2024 on minus 25 mm (K-1) and minus 30 mm (K-2) fractions with ore bed height of 3.5 m (Table 3). The phase composition of the ore loaded into K-1 showed 73.8% copper in oxidized forms, 9.4% in secondary sulfides, and 16.8% as primary sulfides. The mixed ore (K-2) had a fundamentally different phase composition, with only 42.9% oxidized copper, 54.4% secondary sulfides, and 2.7% primary sulfides — a difference inherent to the two ore types that is of central importance to the interpretation of the comparative results discussed below.

Table 3. Parameters and results of pilot-scale column leaching tests

Parameter	K-1 (−25 mm)	K-2 (−30 mm)
Ore type	Oxidized	Mixed
Ore weight, kg	448.45	465.45
Cu content, %	1.37	1.46
Oxidized Cu forms, %	73.8	42.9
Days to 70% extraction	100	128
Acid consumption, kg/t ore	99.4	114.7
Acid consumption, kg/kg Cu	10.4	11.3
Note – compiled by the authors. The "secondary copper sulfides" row was added to make the phase-composition difference between the columns explicit		

Column K-1 (−25 mm) achieved 70% copper extraction in 100 days with acid consumption of 99.4 kg/t ore (10.4 kg/kg Cu) – within the established regulation limit of 11.9 kg/kg Cu. Column K-2 (−30 mm) required 128 days with higher acid consumption of 114.7 kg/t ore (11.3 kg/kg Cu). Peak copper concentration in the PLS reached 14.5 g/L in the first days of leaching in both columns, with similar dynamics over the initial 10-day period. Beyond this point, the leaching rate of the −30 mm material (K-2) progressively lagged behind that of the −25 mm material (K-1).

This lag must not be attributed to particle size alone, because K-1 and K-2 were different ore types rather than two size splits of one sample. The dominant difference between the columns is mineralogical: whereas 73.8% of the copper in the oxidized ore (K-1) occurred in readily acid-soluble forms with only 9.4% in secondary sulfides, the mixed ore (K-2) contained only 42.9% oxidized copper and 54.4% secondary copper sulfides (chalcocite, covellite). Secondary copper sulfides dissolve far more slowly in sulfuric acid than copper carbonates and require an oxidant – ferric iron or dissolved oxygen — to leach effectively; because no oxidant was added and ORP was not controlled in these tests (see Materials and Methods), the copper hosted in secondary sulfides in K-2 could be recovered only to the limited extent of its slow, acid- and oxygen-restricted dissolution. The higher specific acid consumption of K-2 (11.3 versus 10.4 kg/kg Cu) is likewise consistent with this larger proportion of refractory sulfide copper. A particle-size effect acts in the same direction — the larger −30 mm particles present longer diffusion path lengths, as predicted by shrinking-core models for coarser material (Ghorbani et al., 2011) — but it is secondary to, and cannot be separated from, the ore-type (mineralogical) difference. Consequently the slower kinetics of K-2 reflect primarily its more refractory mixed-ore mineralogy, with coarser crushing as a contributing factor, and the present data do not allow a particle-size contribution to be isolated quantitatively.

Table 4. Cumulative copper extraction dynamics, pilot-scale column tests

Days of leaching	K-1 (−25 mm), %	K-2 (−30 mm), %
30	44	39
60	60	55
90	68	64
120	73	69
135	74	71
Note – compiled by the authors		

The oxidized ore at −25 mm (K-1) reached the target extraction faster than the mixed ore at −30 mm (K-2) across all time intervals; at day 120, extraction reached 73% for K-1 versus 69% for K-2. However, since K-1 and K-2 were different ore types crushed to different sizes, this difference cannot be read as a particle-size optimization. The practical conclusion supported by the data is that both ore types, at their respective production crushing sizes (−25 mm oxidized, −30 mm mixed), reach the 70% target within the extraction and acid-consumption limits of the technological regulation, confirming that the transition to coarser crushing and two-lift heap stacking is viable for both ore types fed to the Berkarinskoe operation.

Percolation Stability and Industrial Implications

No deterioration in percolation properties was observed in either column throughout the testing period. Bed permeability remained stable at all crushing sizes, consistent with the low clay content and low slime-forming tendency of the ore established during the initial characterization. This confirms that coarser crushing to minus 25 mm does not negatively affect heap percolation stability — a critical requirement for industrial heap leaching operations (Petersen, 2016; Watling, 2006).

The transition from −10 mm to −25 mm crushing represents a significant operational improvement: it enables an increase in crushing plant throughput to 90,000 t/month (this figure was obtained from a throughput calculation for the crushing-and-screening section, reflecting the higher capacity of the crushing circuit when producing a coarser −25 mm product instead of the original −10 mm product), reduces unit crushing energy consumption, and facilitates more efficient ore stacking and heap construction, while maintaining acid consumption within the technological regulation limit of 11.9 kg/kg Cu.

CONCLUSIONS

The initial laboratory characterization established that 83.6% of copper in the Berkarinskoe oxidized ore occurs in acid-soluble forms, predominantly readily leachable malachite, azurite, and chalcanthite. The ore exhibits favorable physical properties — low hardness (f = 8), low clay content, and stable percolation — supporting heap leaching at various crushing sizes without agglomeration.

Mineralogical examination confirmed that copper minerals are distributed as crusts, films, and nests along fractures and as fine xenomorphic grains in thin quartz veinlets. The dominant copper-bearing phases (malachite, azurite, chalcanthite, chrysocolla, tenorite) are all amenable to sulfuric acid leaching, while the silicate gangue (quartz, feldspar, sericite) does not consume significant acid.

Granulometric analysis confirmed uniform distribution of acid-soluble copper (81–91%) across all size fractions and high percolation rates, providing the physical basis for evaluating coarser crushing sizes.

Laboratory column tests on −10 mm material established baseline extraction of 78.8% over 90 days and formed the basis for the technological regulation of the Berkarinskoe heap leaching operation.

Following industrial implementation, pilot-scale column tests demonstrated that the transition from −10 mm to coarser crushing is technically justified for both ore types. For the oxidized ore at −25 mm (K-1), 70% copper extraction is achieved in 100 days with acid consumption of 99.4 kg/t ore (10.4 kg/kg Cu), within established regulation limits, while the crushing-plant throughput is increased to 90,000 t/month.

The mixed ore at −30 mm (K-2) required 128 days to reach 70% extraction with higher acid consumption (114.7 kg/t, 11.3 kg/kg Cu). Because K-2 was a different ore type — mixed ore with a substantially higher proportion of refractory secondary copper sulfides (54.4% versus 9.4%) — its slower kinetics and higher acid consumption reflect primarily its mineralogy rather than the coarser crushing size; nonetheless it too reached the regulation target, confirming that the mixed ore is also amenable to heap leaching at −30 mm.

Percolation stability was maintained throughout all pilot-scale tests, confirming that coarser crushing to −25 mm does not negatively affect heap filtration properties. The adoption of −25 mm as the operational crushing size increases crushing plant throughput to 90,000 t/month, reduces unit crushing costs, and improves heap construction efficiency — representing a well-grounded operational optimization for the Berkarinskoe heap leaching facility.

The principal limitation of the pilot programme is that K-1 and K-2 were different ore types (oxidized and mixed) crushed to different sizes, so the column results characterize each ore type at its production crushing size rather than isolating the effect of particle size. To quantify a particle-size effect specifically, future work should compare crushing sizes on splits of a single homogenized sample of constant mineralogy, and should monitor ORP and oxidant addition to quantify the contribution of secondary-sulfide oxidation to copper recovery and acid consumption.

CONFLICT OF INTEREST: The authors declare no conflict of interest.

INSTITUTIONAL REVIEW BOARD STATEMENT: Not applicable. The study was purely technical and did not involve human participants or animals.

INFORMED CONSENT STATEMENT: Not applicable.

DATA AVAILABILITY STATEMENT: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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