urban science

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Principles of Sustainable Development of Georesources as a Way to Reduce Urban Vulnerability

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Abstract: Humanity development is associated with higher spiritual and social behaviour and financial shape, which is an undeniable factor of urbanisation. Previously, in areas of georesource concentration, cities and settlements were formed with people exploiting these georesources. However, imperfect technologies lead to rapid depletion of reserves and industrial and environmental disasters, which affect the vulnerability of cities and the people living in them. The analysis of applied technologies has demonstrated that potash extraction is accompanied by a low recovery ratio, high mine accidents, and environmental problems. The principles of sustainable development of geo-resources for the creation of mining technologies that ensure industrial safety, environmental sustainability, and extending the life of the mining enterprise to save working places will reduce the vulnerability of cities. This article proposes the use of the room-and-pillar mining method with the replacement of natural supports with artificial ones. Three-stage stoping with backfill is considered. Numerical modelling has shown stabilisation of mining and geomechanical processes, which confirms the prospectivity of the method with backfill. For these purposes, this research presents a new backfill composition based on local industrial waste. Schemes of backfill preparation and feeding into the mined-out space are proposed. The proposed technology, based on the principles of sustainable development of georesources, is the foundation for an economically profitable, environmentally friendly, and socially responsible mining enterprise. The implementation of the principles of sustainable development of georesources will allow for the preservation of cities and reduce their vulnerability.

Keywords: city; sustainable development; georesources; potash deposit; backfill; industrial waste; room-and-pillar mining; stress–strain behaviour

Citation: Kongar-Syuryun, C.; Klyuev, R.; Golik, V.; Oganesyan, A.; Solovykh, D.; Khayrutdinov, M.; Adigamov, D. Principles of Sustainable Development of Georesources as a Way to Reduce Urban Vulnerability. *Urban Sci.* **2024**, *8*, 44. https://doi.org/10.3390/urbansci8020044

Academic Editor: Luis Hernández-Callejo

Received: 19 February 2024
Revised: 14 April 2024
Accepted: 23 April 2024
Published: 6 May 2024

1. Introduction

The growth of the world population predetermines the development of cities, as well as increases the demand for food products and fertilisers [1,2]. Potash is a raw material to produce inorganic fertilisers, so the extraction of this type of mineral increases every year [3,4]. At present, there is a depletion of potash reserves with relatively favourable positions (shallow depth, sufficient thickness, sufficient thickness of watertight strata, etc.) [5,6]. The balance between potash extraction and potash fertiliser consumption requires an increase in the capacity of existing mining facilities [7], which involves mining off-balance reserves or working in more difficult mining and geological conditions [8]. In some cases, mining is carried out in underpopulated areas where increased attention is paid to surface preservation [9].

However, the existing technologies of mineral extraction and processing do not ensure the complete safety of the population working at mining and processing enterprises, as well as urban and industrial buildings and structures. Potash deposits are traditionally mined by methods with natural support [10,11]. This technology is accompanied by high mineral losses [11], which is far from being the only problem. Intensification of potash extraction increases the load on pillars and consequently changes the stress–strain behaviour of overlying rocks [12]. This may subsequently lead to the discontinuity of watertight strata, mine flooding, and surface subsidence [13]. Since many underground mines are located beneath settlements, such disturbances cause failures within the city limits, resulting in the destruction of residential and public buildings. In addition, mining enterprises have a significant impact on the environment and local communities [14]. The extraction and processing of raw materials generates waste that is stored on the surface [15,16].

For historical reasons, humanity has settled in the areas most favourable for habitation. Such areas include lands with mineable resources. Depletion of mineral resources leads to the closure of a mining enterprise. Often, mining enterprises are town-forming ones. Consequently, at the time of its operation, this enterprise ensures the functioning of public institutions, and social facilities (hospitals, schools, kindergartens, etc.) and provides jobs for the population. The liquidation of such an enterprise leads to a loss of earnings, which worsens the social and economic situation of the urban population. Along with economic problems, there are ecological disasters associated with the concentration of industrial waste in such cities. All of these problems increase the vulnerability of settlements and cause the need to leave cities, which leads to their extinction and turns previously prosperous settlements into ghost towns.

Mineral extraction must be based on three aspects: safety, environmental friendliness, and profitability. Sustainable development of the enterprise requires balancing these positions [17]. High technological and operational standards must guarantee safety for miners [18], inhabitants [19], and the environment [8]. Innovative technologies are designed to ensure the high productivity of a mining enterprise and increase its financial sustainability in the context of globalisation while maintaining and improving safety and reliability [20,21].

The principles of sustainable development of geo-resources for the creation of mining technologies providing industrial safety and environmental sustainability, allowing to increase the life of the mining enterprise to save working places, and reducing the vulnerability of cities for their continued existence are seen as a very urgent task.

The technology of potash mining with artificial support will allow to reduce mineral losses, more effectively control the stress–strain behaviour of rock mass, and, consequently, exclude watertight strata violations and surface subsidence [22]. The technology of solidifying backfill is a new technical method of mining water-soluble ores [23,24]. Analyses of experience show that hardening backfill is mainly used for mining valuable ores [25,26].

Hardening backfill provides reliable support for the covering rocks, increases the safety of mining operations, reduces mineral losses and dilution, creates favourable conditions for the complete replacement of ore pillars with artificial support, and strengthens the remaining pillars with a smaller cross-section, which contributes to the concentration of mining operations [27]. The greater the depth of deposit, the greater the importance of hardening backfill, because it becomes the main way of controlling the rock pressure by creating a strong artificial mass in the mined-out space in a relatively short time [28].

The main reason restraining the widespread use of hardening backfill is the significant cost due to high prices for cement [29]. In spite of the high cost of hardening backfill, it has been widely used in underground mining for more than 100 years [27].

Depending on the local conditions, the main mining methods with backfill are currently: horizontal layers; room and pillar mining; sublevel stoping; descending layers; and so on [30].

For the room-and-pillar method, the ore field is divided either into panels or into levels, which are excavated by several stages (first stage, second stage, third stage, and so on). After ore extraction, each room is filled with hardening backfill. In some cases, combined backfill can be used for filling the rooms of the second or third stage with dry or hydraulic backfill [31].

The analysis shows that hardening backfill is used for thick deposits as well as for metallic ore extraction.

It follows from the above that one of the significant reasons limiting the use of backfill at potash mines is the high cost of materials and stowing operations with relatively low value of the final product; soluble in water; flat dip; and low thickness. All this predetermines the necessity to develop the composition of hardening backfill, its production, and transport technology [32,33] for potash mining.

This paper initially presents a geological overview, the technology used, and the challenges at the Verkhnekamsk potash deposit. The next sections propose backfill composition based on industrial waste and technology for preparing and feeding it into the mined-out space. A new technology of pillar extraction at potash mines is proposed, and the prospects for its application are substantiated.

2. Study Subject

2.1. Mineral Deposit Location

The Verkhnekamsk deposit is one of the world's largest potash deposits. It is located in Russia, in the Western Urals, in the Perm region (Figure 1). The Verkhnekamsk potassium–magnesium salt deposit is the main component of the Solikamsk potassium-bearing basin, located in the left-bank part of the Kama river valley. In the north, this deposit is limited by Lake Nyukhti, located in the Krasnovishersk region; in the south, it extends to the Yayva river basin. The length of the explored part of the deposit from north to south is 140 km, from west to east, about 60 km, and the total area is 3500 km^2. The thickness of the ore-bearing strata is about 80 m, and its depth is 400 m. The deposit consists of understratum rocksalt, potassium and potassium–magnesium salts, and mantle rocksalt. Potash horizons are represented by alternating red-layered sylvinites with rock salt interlayers. The thickness of individual potash strata ranges from 0.75 to 5 m. The deposit was formed 250 million years ago as the Perm Sea dried up. It contains 69.5% of potassium, 19.7% of magnesium, and 56.6% of rock salts from the total Russian balance reserves.

Figure 1. Location of the Verkhnekamsk potash deposit.

2.2. Mineral Deposit Structure

The stratigraphic sequence of the region is shown in Figure 2. The Verkhnekamsk deposit consists of two major evaporite sequences. The upper sequence, the carnallite sequence, mainly comprises halite with interbedded layers of variegated sylvinite, carnallite, and mixed salts. The base of this sequence contains a horizon of variegated sylvinite, approximately 1.25 m thick, termed the B horizon. The lower sequence, the sylvinite sequence, is made up of red and banded sylvinite horizons interbedded with halite. There are six sylvinite horizons, which, from the top to the base of the sequence, are termed A, Red 1, Red 2, Red 3a, Red 3b, and Red 3v. The bottom three horizons have thin (<1 m) intercalations of halite and are combined to form the Red 3 horizon. The top horizon A occurs directly beneath the B horizon from the carnallite sequence, and these are combined to form the AB horizon. Commercial sequences are Red 2 and AB (silvinite). The average thickness varies from 3.1 m to 5.1 m. The content of potassium chloride in the Red 2 seam is 23.2 ÷ 32.4%, and in the AB seam it is 5.8 ÷ 60%.

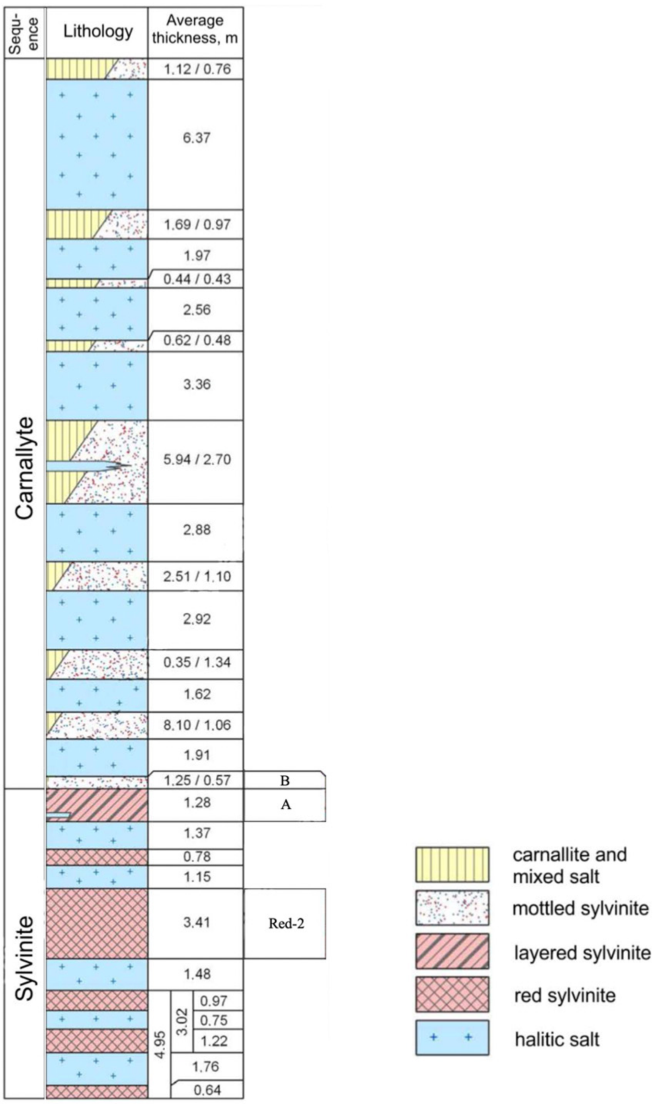

Figure 2. Stratigraphy of the Verkhnekamsk potash deposit.

2.3. Mining Technology

The Verkhnekamsk deposit is characterised by free-of-water salts and water-bearing host rocks. This deposit has an overlaying, thick aquifer. The rocks above the mineable seam, including the sylvinite–carnallite zone, mantle rocksalt, and the lower part of saltmarl strata, are 75–105 m thick watertight strata, which prevents suprasalt water from penetrating into the mined space. The need to preserve the continuity of watertight strata is a determining factor in the choice of mining method parameters [34]. Such conditions require the use of the mining method with stope support [11,13,35]. At present, room and rib pillar mining are used (Figure 3). This method is characterised by high mineral losses—up to 65% [36]. The remaining pillars should provide rigid support for watertight strata or smooth deformation without breaking their continuity. The width of room is equal to the width of the combine's executive body and the free movement of vehicles [37], and the width of pillars varies from 5.2 m to 10.4 m depending on specific mining and geological conditions.

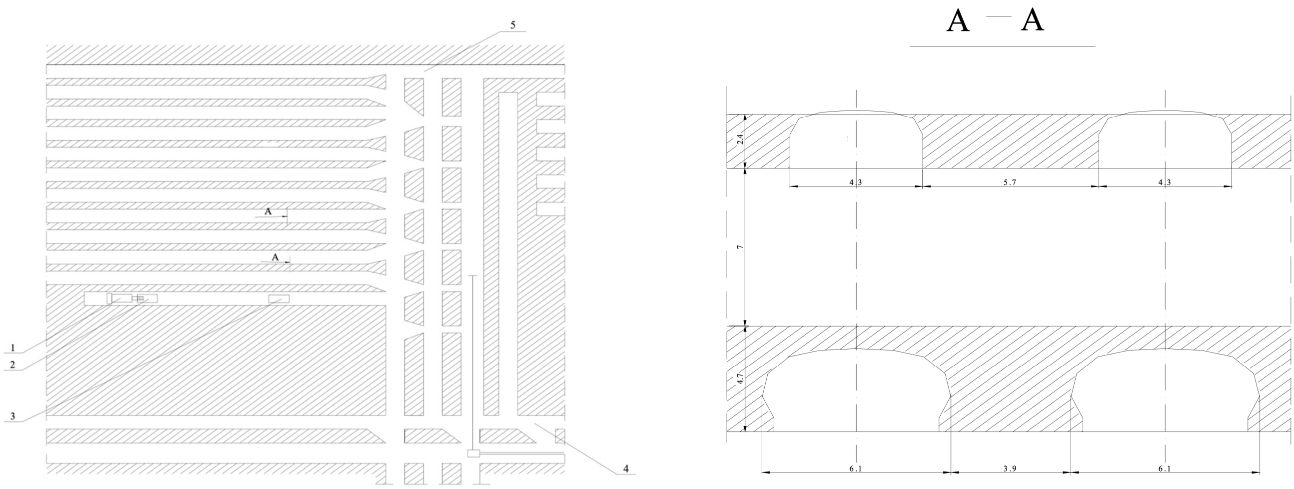

Figure 3. Mining method at the Verkhnekamsk potash deposit. 1—combine; 2—bunker reloader; 3—self-propelled car; 4—transport road; and 5—ventilation drift.

2.4. Induced and Ecological Problems

Global experience shows that groundwater and brine intrusion result in the flooding of potash mines and the loss of total reserves [38]. In the case of mining with natural support, the larger the outcrop area, the greater the stress on the remaining pillars. The pillars deform, subside, and gradually collapse [39]. Deformations of pillars lead to subvertical disturbance of rocks [40] and to methane emissions [41]. As a result, the continuity of watertight strata is disturbed. Then, formed cracks and stratifications cause water to break through into the mine, leading to flooding and karst hole, which increase over time (Figure 4). To date, about 50% of potash mines have been flooded, and reserves have been lost [42].

(**a**) (**b**)

Figure 4. Development of karst hole, Solikamsk: (**a**) November 2014; (**b**) June 2015.

Two mines at the Verkhnekamsk deposit were flooded in 1986 and 2006 due to the disturbed overlying rocks, resulting in sinkholes at the water intrusion sites.

In 1986, changes in the approved technology led to deformation and subsequent destruction of the pillars. Contrary to the accepted design calculations, it was decided to reduce the width of pillars during the exploitation of the deposit. This resulted in an increase in the load per unit area of the pillar. The collapse of pillars occurred in a relatively short period and led to an induced earthquake [43]. The mine was located far from a populated area, and no surface buildings were affected.

In 2006, deformation of pillars occurred in older sections of the mine. These areas were mined in the 1960–1970 s of the last century. Deformation of pillars became possible due to the increase in the total area of mining operations and the duration of loads, which is mainly attributed to the "fatigue" of pillars [44]. This caused a change in the stress–strain behaviour of rock mass and the development of cracks in it, which led to the discontinuity of watertight strata [45]. The break in the watertight strata brought water seepage into the mine, causing gradual erosion of the pillars and their subsequent destruction [46,47]. Underground mining operations were carried out within the city limits and resulted in the destruction of structures on the surface (Figure 5).

(**a**) (**b**)

Figure 5. Destruction of surfaces and buildings as a result of a man-made disaster in 2006 (Perm region, Russia): (**a**) sinkhole at the territory of an administrative facility, 2011; (**b**) sinkhole at the territory of a school, 2015, Berezniki.

The first prerequisites for an accident began in October 2006 at one of Uralkali's first mine sites, where water was found to be seeping into the mine due to a breach in the water protection layer.

The first ground failure occurred on 28 July 2007 at the mine site near the technical salt plant. Since then, all technical work at the mine has been stopped, and liquidation work has been initiated.

In April 2011, an increase in the rate of land subsidence to 37 mm per month was recorded in the territory of the administrative facility of the Berezniki Mine Construction Department (BMCD) of Uralkali Company. The subsidence rate was constantly increasing. In December 2011, another subsidence occurred north of the BMCD building (Figure 5a).

The rate of surface subsidence and the size of the sinkhole were increasing. In January 2012, a second sinkhole was recorded at 130 m from the traffic circle in the territory of BMCD. The collapse sites increased in diameter, and in February 2011, the sinkholes joined and filled with water (Figure 5a).

Mining operations were carried out under the settlement of Berezniki, and the sinkholes began to fade into the territory of this settlement in April 2013. Thus, after the flooding of the mine and increased ground movement within the city limits, there was a danger of the destruction of residential buildings and structures of the municipal economy. By February 2104, cracks appeared on the building of School No. 26, and by January 2015, a sinkhole was formed on the territory of the school (Figure 5b). Municipal and regional authorities began to take measures to relocate residents from emergency houses, and the dangerous area was fenced off. As a result of this disaster, dangerous zones (exclusion zones) appeared in the settlement, which reduced the safety and comfort of life and increased the stress of the population.

Closure of the enterprise, land failures in the city limits, destroyed residential, administrative, and social buildings, as well as the worsening ecological disaster caused by dust from salt industrial mass, are forcing people to leave the city, which has lost more than 20 thousand residents in 7 years.

In conventional potash mining, the issue of mine safety and the protection of the mine from flooding is addressed by continuous monitoring of pillars and watertight strata. All mines perform seismological monitoring to record the failure of load-bearing elements and constant surveying of shear processes [48], which is now being supplemented by satellite interferometric technologies [49]. Control methods can predict the occurrence of a hazard but cannot prevent it.

Another feature of potash deposits is the relatively low content of the useful component. Therefore, potash processing generates a large volume of waste, amounting to 60–70% of the extracted ore. The bulk of this waste goes to salt dumps and sludge depository sites (Figure 6). Placing waste on the surface is associated with the withdrawal of significant land plots [50]. The impact of waste leads to salinisation and pollution of soil, groundwater, underground [51], and surface water bodies [52], and the air environment. The larger the potash fertiliser production, the larger the land area for salt dumps and sludge depository, and therefore the greater the environmental damage [53].

Figure 6. Waste dump, Berezniki.

3. Methods

The use of hardening backfill on potash mines raises a number of complex technological and geomechanical issues that do not arise with conventional mining methods. These include rational composition and related issues of preparation, transport, and control of stress–strain behaviour of seams and host rocks due to geomechanical processes, including problems of gap-filling in rooms. Some of the solutions are proposed below.

3.1. Backfill

Hardening backfill must meet the requirements to ensure the specified properties of the artificial fill mass [54]. These requirements are determined by mining-and-technical conditions of deposit development [55], the purpose of backfill [56], methods of its preparation [57], transport and placement [58], conditions and terms of hardening, intensity of mining [59], and other factors.

The quality of backfill and fill mass is determined by several indicators [60]. The main ones include strength, compression [61], rheological [62], and technical properties [63]. The artificial fill mass must ensure smooth deformation of the overlying rock strata and minimum shrinkage under pressure. The characteristic strength at mining enterprises varies from 1.0 to 10 MPa, being in most cases 5–7 MPa.

3.1.1. Backfill Components

Aggregate.

Potash ores are a low-value raw material. Therefore, the company needs technologies that have a minimal impact on the final price of the product to be financially competitive in the globalised world market. Aggregate makes up the bulk of backfill. Specially mined sand, gravel, and crushed stone are traditionally used as aggregate. The purchase or in-house production of aggregate is a significant cost of material [50,64]. The use of salt waste (dry waste) as aggregate is the most obvious option for potash mines. Potash waste is a hygroscopic product prone to caking and clumping and consists mainly of sodium chloride [65]. Depending on the processing method, waste is subdivided into halurgical and flotation waste. Their chemical compositions basically coincide, and they differ in particle size distribution. The coarseness of halurgical waste is higher by about 4.5 times.

The present paper shows an experiment where halurgical waste (moisture content 10 ÷ 12%) was used as aggregate. The particle size distribution is presented in Table 1 [66]. Table 1 indicates a stable size range of aggregate, which excludes additional costs for grinding. Another advantage of salt waste is its ability to crystallise and harden at the moment of moisture release. Salts belong to self-hardening materials [67]. Therefore, the introduction of additional components (binders/additives) or the use of another type of impact on the waste is the activation of the strength-gaining process. This indicates the possibility of creating an artificial mass with the required characteristics at minimal cost.

Table 1. Particle size distribution of halurgical waste.

Particle size, mm	>7	7–5	5–3	3–2	2–1	1–0.5	0.5–0.25	<0.25
Ratio%	7.4	7.3	17	16.3	20.9	19.5	8.6	3.0
Average particle size, mm				2.54				

Grouting fluid.

Previous data on hydraulic backfill at potash mines show that strength is directly dependent on the moisture content of the resulting mass, that is, on the amount of saturated solution introduced. It was found that strength increases in proportion to the decrease in moisture content, both at mechanical and hydraulic laying. This occurs due to the formation of bridges of crystallisation salt between particles of waste [68]. The hardening process proceeds slowly as moisture evaporates. A saturated salt solution is used as a grouting fluid since the aggregate dissolves in water [67,68].

Binder.

Experience shows that cement, blast-furnace granulated slags, lime, ash-and-slag waste from TPPs and SDPPs [69,70], gypsum, calcium chloride, or sodium silicate [71,72] are used as binder. Bischofite, magnesia cement, caustic magnesite, and expanded clay can also serve as materials for hardening backfill. Earlier studies demonstrated that salts have a negative (de-strengthening) effect on cement stone [73]. Consequentially, the use of binder based on ordinary cement is impossible. Experiments on the creation of hardening materials based on waste from potash ore processing have shown the advantage of magnesium binders [74,75], so the use of magnesium-containing components as a binder could be an acceptable option.

Previous studies have demonstrated good results with the use of blast furnace-granulated slags as a binder [76]. Chusovskoy Metallurgical Plant is located in the Perm region, 180 km from the mining site. A large amount of blast furnace-granulated slag has accumulated for almost 150 years of the existence of this plant. The chemical composition of slags from Chusovskoy Metallurgical Plant demonstrates the presence of magnesium (Table 2) [66].

Table 2. Chemical composition of slags from the Chusovskoy Metallurgical Plant (%).

SiO_2	Al_2O_3	CaO	MgO	S	SO_3	MnO	Fe_2O_3	FeO	etc.	M_o	M_c
31.1	10.2	50.6	4.3	1.4	0.2	-	-	-	2.2	1.33	3.04

According to the classification, these slags are classified as active on the basic module (1) and as highly active on the silicate module (2):

$$M_o = \frac{\%CaO + \%MgO}{\%SiO_2 + \%Al_2O_3} = 1.33 \quad (1)$$

$$M_c = \frac{\%SiO_2}{\%Al_2O_3} = 3.04 \quad (2)$$

Consequently, the use of blast furnace-granulated slag from Chusovskoy Metallurgical Plant as a binder for backfill is seen as a promising option.

3.1.2. Experiments

Earlier studies of activation treatment of backfill components in a disintegrator [65,77] or application of additives [78–80] showed positive results. In this regard, two types of slags were used in the experiments: without activation treatment and with activation treatment in the disintegrator.

Active slags of Chusovskoy Metallurgical Plant, after mixing with water (in the form of crushed powder with water), are able to harden independently. However, the rate of strength gain is very low. Sufficient strength is achieved only after several months of storage in a humid environment, which reduces the speed of mining operations. To increase the setting rate, in addition to saturated brine, waterglass, and calcium hydroxide solutions were used as grouting fluids (Table 3).

Table 3. Backfill composition test results.

No	Composition					UCS, MPa			
	Grouting Fluid		Binder		Aggregate				
	Type	V, л/м^3	Slag, % of Solid		Waste, % of Solid	Time, Days			
			Inactivated	Activated		7	28	60	90
1	Saturated brine		30		70	0.9	1.6	2.1	2.4
2				30	70	1.05	1.95	2.5	2.7
3	Waterglass ρ = 1.3 g/cm^3	135	30		70	0.85	1.95	3.05	3.3
4		135		30	70	1.1	2.3	3.35	3.7
5	Calcium hydroxide ρ = 1.15 g/cm^3	125	30		70	1.05	2.0	2.65	2.8
6		125		30	70	1.2	2.3	2.9	3.12

Tests of the samples showed an increase in the strength of compositions #3–6. Consequently, waterglass, and calcium hydroxide solutions act as activating additives and have a positive effect on the strength of the material. Waterglass slowed down the strength gain in the initial stage but dramatically increased the strength after 28 days. As a result, the samples with waterglass reach a higher strength than the samples with calcium hydroxide solution.

3.2. Stowing Operations

The technological scheme of stowing operations consists of surface and underground parts. The surface part is a set of equipment for mechanisation of backfill preparation. The underground part is a set of equipment for feeding backfill into the rooms.

3.2.1. Backfill Preparation

The scheme of hardening backfill preparation is presented in Figure 7. The binder, through the batcher, enters the disintegrator for activation and crushing to the required particle size distribution. Activated binder and aggregate are fed alternately onto a conveyor and fed in layers into the mixing drum. The grouting fluid and activating additives are pre-mixed and fed into the mixing drum via a pipeline through the batcher. In the mixing drum, the whole mass is mixed and then transported to the rooms by pipeline. Backfill quality control is carried out on the basis of ready-mix output. The laboratory of the complex determines the composition, density, specific gravity, fluidity, delamination, and percentage of components. On the basis of the obtained data, adjustments are made to the composition.

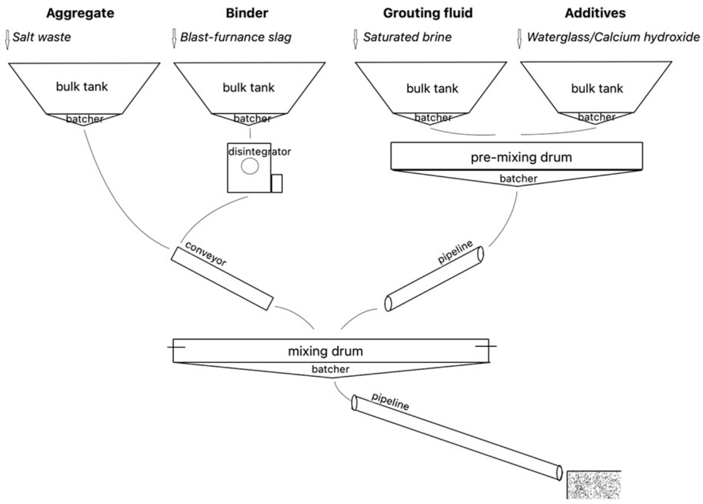

Figure 7. Technological scheme of backfill preparation.

3.2.2. A Scheme for Feeding Backfill into the Rooms

Scheme of feeding of backfill into the rooms is presented in Figure 8.

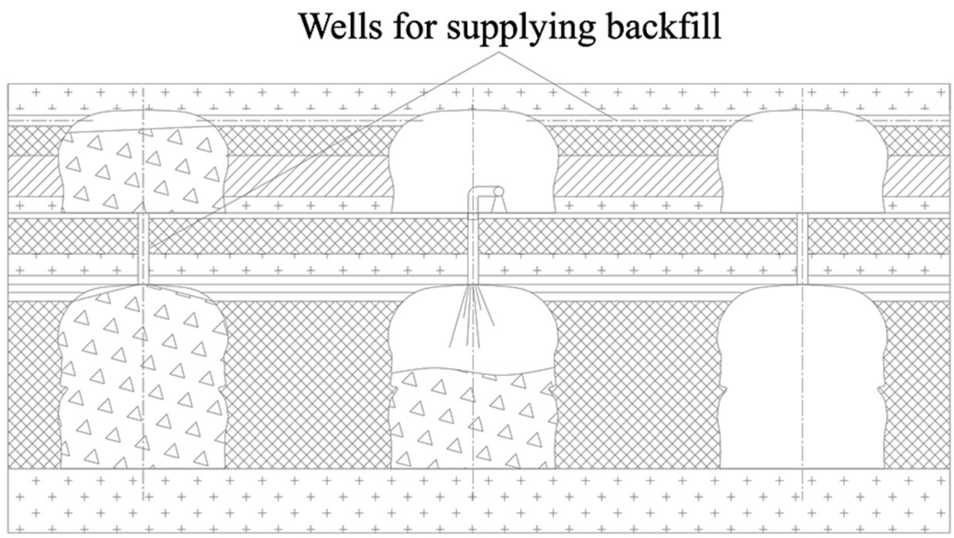

Figure 8. Scheme of feeding of backfill into the rooms.

Backfilling of the lower seam Red 2 is carried out from the overlying seam AБ by wells. The advantage of this scheme is the exclusion of the installation of a sectional pipeline through the seam Red 2. Backfilling of the upper seam Ab is carried out through the wells drilled in the protective pillars of ventilation drifts or in the pillars on the side of the isolating wall. Backfill supply technology is chosen considering particle deposition during transportation [81] of a non-Newtonian fluid flow through a small diameter pipeline [82] and taking into account the pressure drop in the flow over long distances [83], the distribution of flow velocities, and particle motion vectors in the flow [84].

The location of the pipeline in the roof in a longitudinal slot will allow it to fill the rooms up to 95–100%. In this case, the maximum number of feeding holes along the entire length of the pipeline is achieved. This scheme allows for minimising gap volumes [85,86].

In addition, a longitudinal slot, passed at the moment of room-stoping, redistributes stresses and directs them deep into the rock mass [87]. Such compensatory measures increase the stability of the mined-out space.

3.3. Influence of Stoping on the Seam

The use of a backfill in several-stage stoping implies that the artificial fill mass will support the weight of the top and roof strata. It is known that room gaps are one of the main problems that reduce the safety of pillar extraction. The level of overlying rock displacement depends on the size of the room gap. At slight and smooth displacements, deformations will occur without sharp stress fluctuations and without watertight strata breaking. These factors must be considered in preserving the continuity of watertight strata to avoid water entering the mine.

Figure 9 shows a three-stage stoping schedule. The width of the room is 4 metres. Each next stage starts after 60 days of backfill hardening in the room of the previous stage. The first stage includes stoping rooms #1, 4, and 7 with 8 m wide rib pillars between them. The second stage includes stoping rib pillars, forming rooms #2, 5, and 8. Here, one side of the room borders with backfill, and the other side borders with pillar-natural rock. The third stage includes the stoping of the remaining pillars, forming rooms #3, 6, and 9. Here, the work is carried out between two previously filled rooms.

Room	Stage	Days																							
		1	2	...	10	11	12	...	70	71	72	...	80	81	82	...	140	141	142	...	150	151	152	...	210	211	212
1	I	1	2	...	10	1	2	...	60																		
2	II									1	2	...	10	1	2	...	60										
3	III																	1	2	...	10	1	2	...	60		
4	I		1	...	9	10	1	...	59	60																	
5	II										1	...	9	10	1	...	59	60									
6	III																		1	...	9	10	1	...	59	60	
7	I			...	8	9	10	...	58	59	60																
8	II											...	8	9	10	...	58	59	60								
9	III																			...	8	9	10	...	58	59	60

Figure 9. Stoping schedule.

The available programmes allow modelling various processes in rock mass during mining operations: subvertical fracturing and deformations [40], discontinuity of the water-protection layer [35], the impact of blasting on the remaining pillars [88], or technological operations occurring in the workings: air movement [89], distribution of blasted mass [90,91], and so on. The possibilities of the proposed programmes are very extensive.

4. Results and Discussion

Modelling using a rheological model of rocks described by Norton's [92–94] law of creep has confirmed the prospectivity and feasibility of several-stage stoping. Modelling was performed in FLAC software by Itasca Consultants GmbH. Figure 10 shows the results of vertical deformation measurements at 15 m (Figure 10a) and 50 m (Figure 10b) vertically from the seam roof after 13, 85, 153, 360, and 3600 days. As expected, the deformations increase with the formation of each new room. However, there is a decrease in the deformation intensity with the hardening of the backfill and ensuring the bearing capacity. The modelling results provide insight into vertical deformation in the long term. Most of the vertical deformation occurs for up to 153 days. Such dynamics can be explained by the presence of unfilled rooms and the gradual strengthening of backfill. After the 153rd day, vertical deformations slow down, and after the 360th day, they practically stop. This indicates that backfill has gained its total strength and has assumed the entire load, and room gaps have been filled by previously deformed and collapsed roofs. In the interval from 360 to 3600 days, practically no deformation changes are expected.

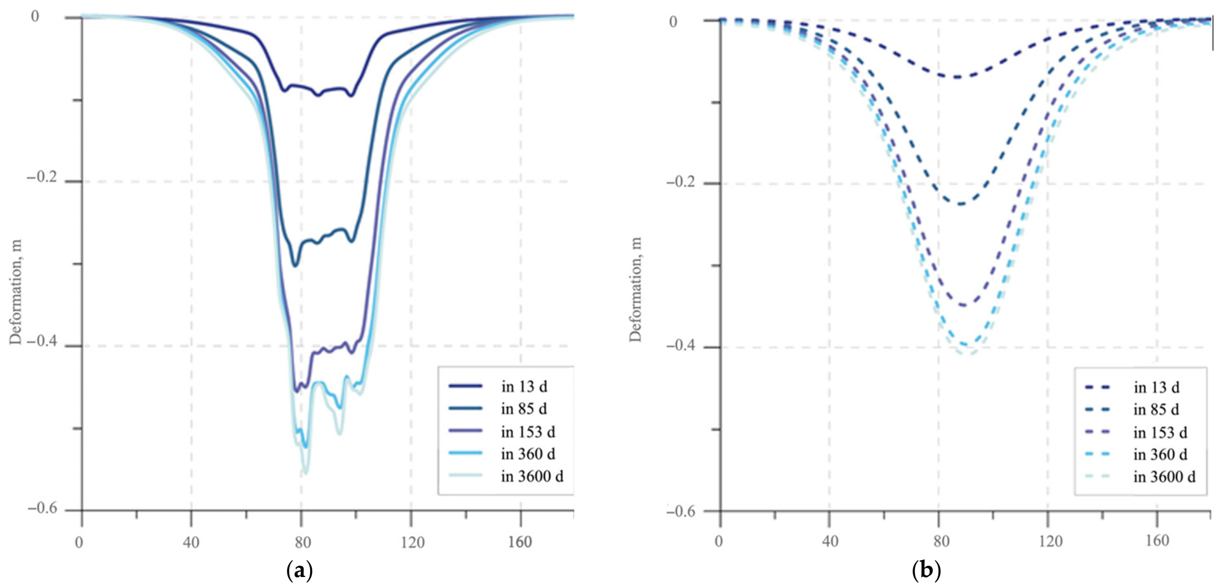

Figure 10. Vertical deformation. (**a**) Deformation 15 m above the roof; (**b**) Deformation 50 m above the roof.

Figure 11 shows contour plots of stresses for days 143, 360, and 3600 after the start of mining. The modelling of salt mass behaviour in the mining area demonstrates a sharp decrease in stress after day 143. After 360 days, the highest stresses are expected only in the immediate vicinity of the backfill. After 3600 days, the investigated seam takes a state close to the natural one. After completion of stowing in phase III, abrupt stress–strain changes in the mass are unlikely.

This paper proposes a potash mining method with backfill to control the stress–strain behaviour of rock mass more effectively. This will preserve the surface and keep the buildings from collapsing. Minerals left in the pillars will be extracted, which will increase the operating life of the enterprise and save working places. In addition, the use of backfill is associated with an additional process chain in mining technology: the production of backfill and its supply to workings. The construction of the backfill complex will provide the city with additional jobs.

A backfill composition based on industrial waste was proposed in this study. Halite waste was used as aggregate, and granulated blast furnace slag from the Chusovskoy metallurgical plant was used as a binder. Activation additives in the form of waterglass and calcium hydroxide solutions can increase the final strength by 37.0% and 15.5%, respectively. However, the experiments showed different intensities of strength gain. Waterglass slowed down the rate of strength gain of samples at the initial stage (up to 28 days), but at the final stage (after 90 days), the samples with waterglass showed 18.6% higher strength than samples with calcium hydroxide.

The Verkhnekamsk deposit has a large length, so the use of gravity transport for the whole deposit seems to be difficult. In the following studies, the actual issues to be solved are the development of transportation methods, the study of the rheological properties of backfill, and the choice of the complex stowing location. A variable technological scheme for the preparation and regulation of backfill components is proposed to control and change their properties.

The use of the room-and-pillar mining method with backfill based on industrial waste will increase the recovery rate, increase mine safety, and realise the idea of waste-free (low-waste) production.

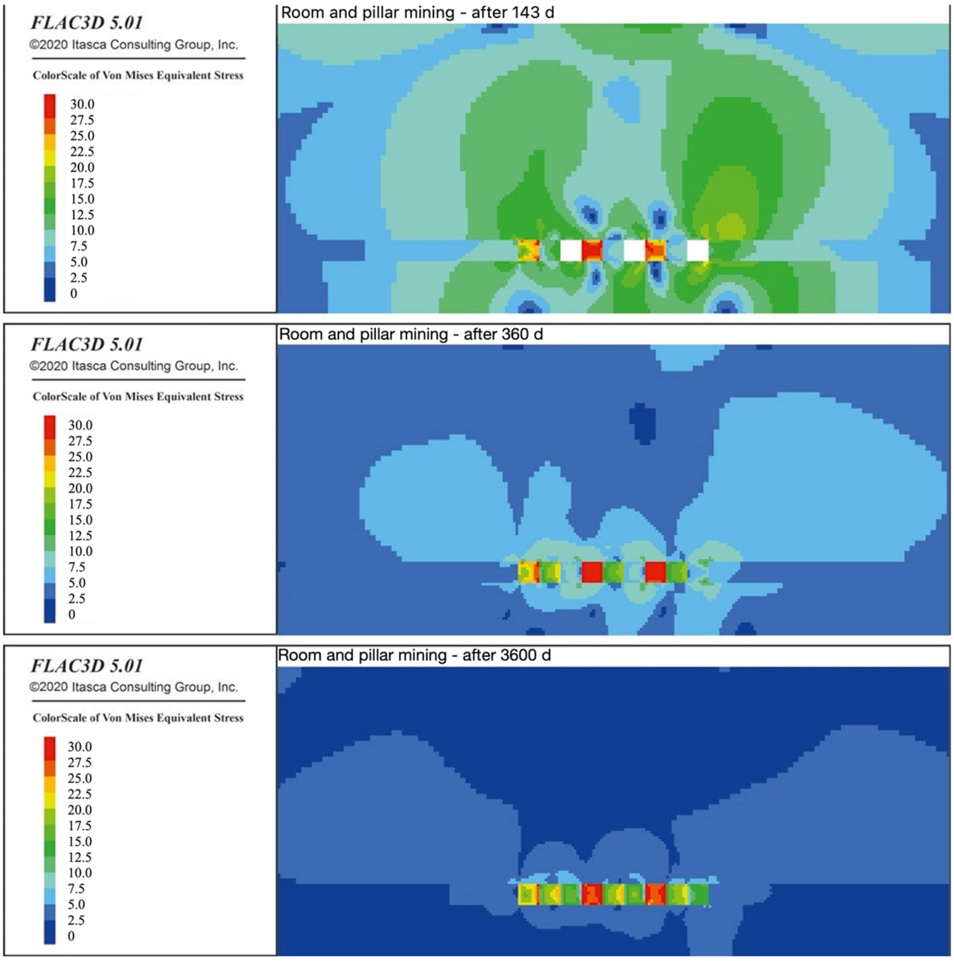

Figure 11. Salt mass behaviour in the mining area, stress distribution.

5. Conclusions

This study substantiates the advantages and prospects of using the mining method with backfill at the Verkhnekamsk potash deposit. Backfill composition, the technological scheme of preparation, and the feeding of backfill into the rooms are proposed.

The following conclusions can be drawn based on the research conducted:

1. The use of local waste materials in backfill composition is technologically and economically effective. The possibility of using salt waste as an aggregate and granulated blast furnace slag as a binder is proven.
2. Saturated brine should be used as grouting fluid if the aggregate is salt waste.
3. Activation additives such as waterglass and calcium hydroxide solution increase the strength of the fill mass.
4. The proposed scheme of feeding backfill into the rooms allows to maximise filling up to 95–100%.
5. In the case of parallel stoping and stowing at the working area (with the minimum necessary technological lag), unsteady mining-and-geomechanical processes tend to

stabilise within the first year after the start of mining, and in the following ten and more years, they remain practically static.

6. Replacing the traditional method of georesource extraction with backfill technology will allow for the extraction of reserves from the left pillars, which significantly increases the mineral resource base of the mining enterprise and extends its operational life.
7. The proposed technology, based on the principles of sustainable development of georesources, is the basis for an economically profitable, environmentally friendly, and socially responsible mining enterprise.
8. The proposed principles of sustainable development of georesources at different stages of mining (from ore extraction to final products) are the basis for preserving cities and reducing their vulnerability.

Author Contributions: Conceptualisation, C.K.-S. and M.K.; methodology, C.K.-S. and M.K.; software, R.K.; validation, V.G.; formal analysis, V.G.; investigation, A.O.; data curation, D.S. and D.A.; writing—original draft preparation, M.K.; writing—review and editing, C.K.-S.; visualisation, D.S. and D.A.; supervision, M.K.; project administration, C.K.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Dr. Marat Khayrutdinov was employed by the company Itasca Consultants GmbH (Germany). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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