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SELECTION OF BACKFILLING TECHNOLOGY WORKS IN THE KSAWER CHAMBERS COMPLEX OF THE WIELICZKA SALT MINE

1. Introduction

The concept of backfilling works in the Ksawer Chambers complex at Upper Level II (IIw), Lower Level II (IIn) and Level III of the Wieliczka Salt Mine constitutes an implementation of the conclusions of the geomechanical analysis conducted for the Jakubowice and Ksawer Chambers area. Based on the analysis of the technical condition of the Chambers, geological-mining, technical and technological considerations, and in particular the requirement of preserving as much as possible of the historic mine substance, an optimal technology was presented for backfilling works in the Ksawer Chamber.

2. Characteristics of the Ksawer Chambers complex

The Ksawer Chambers complex is located in the eastern part of the mine in a spatial arrangement crossing Levels IIw, IIn and III. The complex includes, among others:

— at Level IIw, Chambers: IIw/22, IIw/23, IIw/24, IIw/25, IIw/26, IIw/27, IIw/36 (Fig.1),
— at Level IIn, Chambers: IIn/219, IIn/220, IIn/221, IIn/222, IIn/223, IIn/224, IIn/225, IIn/226, IIn/227, IIn/228, IIn/229, IIn / 230 (the Parnas Chamber) (Fig.2),
— at Level III, Chambers: III/300, III/302, III/303, III/299, III/298, III/297, III/296, III/295, III/294, III/293.

The technical characteristics of the Chambers and geomechanical analysis results have been described in detail and chambers were selected for securing and backfilling work [1]. It should be mentioned that the shape of the area is very complex, and its spatial configuration

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highly diversified. Excavations to be backfilled in the first stage of work are shown in Figures 1 and 2. Below, only the most important factors are presented resulting from the technical condition of the Chambers necessary for drafting the first phase of excavation backfilling project.

The technical condition of the Chambers varies from good stable to bad (collapse). Chambers IIw/22, IIw/26 and IIw/36 in the collapse condition, while Chambers IIn/219, IIn/220 and IIn/221 located below are in a medium condition, but are slowly and systematically deteriorating. The technical condition of Chambers IIn/222, IIn/223, IIn/224 and IIn/225 is bad, and some of those had lost stability, which has manifested itself in local collapses in Chamber IIn/223. Chambers located below and classified as part of the Ksawer Chambers complex at Level III are in a fairly good condition (apart from local cracks in unmined salt bed, delaminations, cracks, gangue exposition) and, as a result of a detailed analysis, were excluded from the first stage of backfilling work.

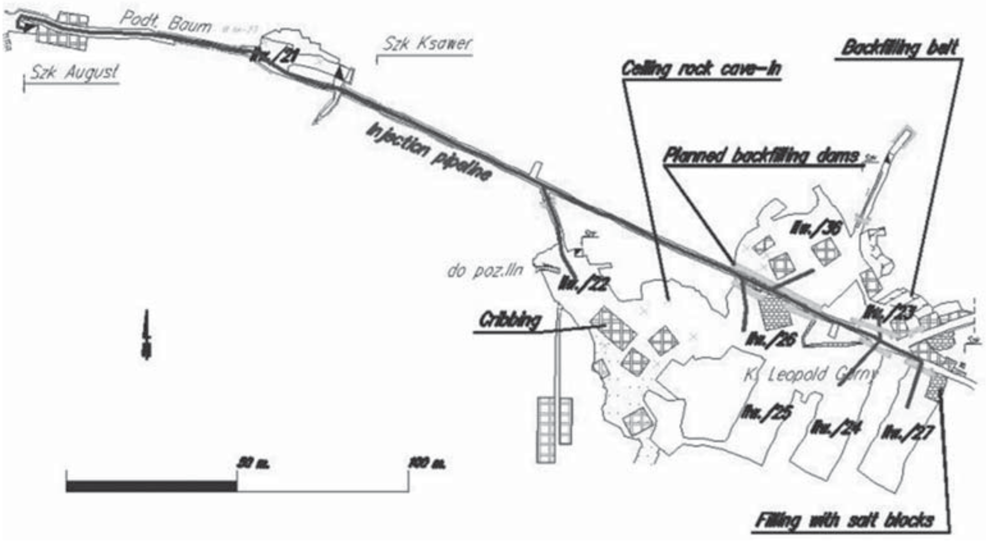

Fig. 1. Ksawer Chambers area at Upper Level II planned for backfilling in the first stage

3. Geological Conditions

The Ksawer Chambers are located in the north-western slope of the crystal cave dome, in varied formations belonging to salt-bearing Wieliczka bed and formations underlying the salt bed classified as Skawina layers [2]. In the area under consideration, the salt bed is divided into a layered bed and the overlying blocky bed in the form of blocks of green laminated or stained glass salt, embedded in salt claystone micrite (marly claystone with halite crystals). In the layered bed, green salt beds and salt shafts can be distinguished a well as bronze salt separated from those by a layer of salty and clayey interlayers. The area is strongly folded and tectonically disturbed. The Chambers were created in bronze salts in the north-western

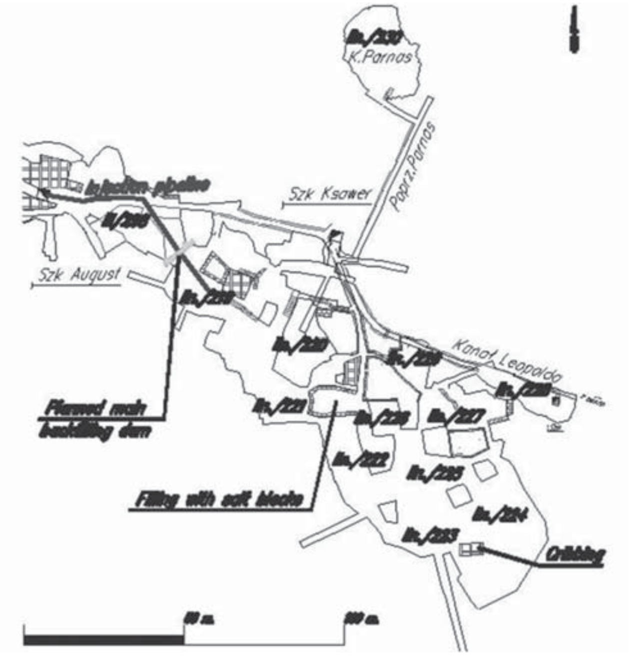

Fig. 2. Ksawer Chambers area at Lower Level II planned for backfilling in the first stage

part of the Crystal Cave area and are in the area of contact between the layered and the blocky bed. As a result of the variation in geological structure and tectonic activity in the area, increased pressure of the rock mass has been observed there, which poses major problems in maintaining the stability of the excavation. The presence of bronze salt of the blocky bed in the ceiling, which are weaker and more susceptible to deformation, and in several regions of the Ksawer Chambers complex substantial cave-ins of considerable vertical extent, have resulted which may constitute a potential threat to the surface in the area.

4. Analysis of technical and technological capacities for planned backfilling work

4. 1. Overview of backfill materials presently used at the Wieliczka Salt Mine

Backfilling work has been carried out at the Wieliczka Salt Mine intermittently from the nineteenth century to the present day. During this period, the following materials were used for backfilling: clay, debris, boiler slag, sand from a local quarry, sand from the Szczakowa Mine and injection mixtures. Until 1980s, only dry filling material was used; presently, the backfilling of post-mining voids is performed with hydraulically fed backfilling sand. Significant advances in the possibilities of conducting backfilling work were made possible thanks to the opening of the injecting mixtures production plant in 2010. Injection slurries have been used e.g. for the sealing work at the Witos Chamber complex at Level III. Another material which offers a great potential for excavation backfilling is foamed concrete, which was used for the backfilling of a section of Upper Maria Teresa II Chamber at Level IIn.

Hydraulic backfilling is the most common method applied at the Wieliczka Mine, due to its excellent backfilling properties, low unit price, proven backfilling technology, capacity exceeding 500 m³ per shift and a low failure rate of the backfilling installation. The disadvantages of the technology include transporting to backfilled excavations large quantities of brine, which is used as a medium for the hydraulic transport of backfilling sand; its quantities may exceed the value of 1/1 in proportion to the sand. Moisture introduced into the excavations along with the brine causes the deterioration of rock strength parameters, including the swelling of clays occurring as interlayers in the salt bed, which could lead to the caving in of ceiling rock. This results in the inability to use hydraulic backfill in areas of particular historical or areas made available to tourists.

The main advantage of dry sand backfilling, supplied to the excavation by means of compressed air, is that no moisture is introduced into the chambers. However, this method is characterised by a low capacity and there is no pneumatic equipment which would enable feeding sand in the conditions of the Wieliczka mine.

Injection mixtures have good backfilling qualities, and they offer the advantage of introducing only small amounts of salt into the excavations. Even though the injection mixture is fed hydraulically, brine outflow is limited as brine is bound during the solidification of the binding agent. This is important in carrying out backfilling work in areas of historic value. The method's disadvantage is the relatively high cost of the material. A similar drawback is observed in the case of foamed concretes, which, on the other hand, are simple to prepare and do not require technically complex and expensive installations. Foams are supplied in bags, and they only need to be mixed with water in a special aggregate and fed a pipeline to the excavation specified. Foamed concretes do not emit water during setting, either.

4. 2. Selection of backfilling material

In the immediate vicinity of the Ksawer Chambers complex, which is located in the historic eastern region of the Mine, a number of historic sites, valuable also in terms of natural science, are situated. These include the Leopold Canal and the Ferro, Hrdina, Margielnik, Magdalena Chambers, and the unique complex of the Crystal Caves. Backfilling material fed into the excavations cannot introduce large amounts of brine, which causes changes in air humidity, and due to this, hydraulic filling cannot be used. Despite its advantages, dry filling cannot be applied in this area of the mine due to insufficient capacity, high costs and technical limitations.

Foamed concretes and injection mixtures are materials which do not cause the increase in humidity in the mine atmosphere and ensure sufficient capacity per shift in the backfilling process.

Table 1 shows the basic strength parameters of foamed concrete and injection mixtures used in the backfilling of the excavations in the Wieliczka Salt Mine. Injection slurries may also have other parameters, depending on their composition. The data presented clearly demonstrate that injecting slurries are the material whose parameters are close to those found in the Wieliczka rock mass [1, 3].

TABLE 1
Properties of foamed concrete and injection slurrie used at the Wieliczka Salt Mine

Name of mixture	**Density [kg/m³]**	**Compressive strength after 7 days [MPa]**	**Compressive strength after 28 days [MPa]**	**Setting time [min]**
EKOPIANA	420	1.8	2.2	≥ 5
DURAFOAM	420	1.8	2.2	≥ 5
Injection mixture 1w	1970	9.38	13.33	≥ 450
Injection mixture DS	1900	11.25	31.25	≥ 450

In terms of strength parameters, injection mixtures have an advantage over cement foams, especially that with the increase of compressive strength of foamed concrete, setting time is reduced, which is a disadvantage because of the length of transport routes and the possibility of binding of foams in pipes.

4. 3. Technical capacity of transporting backfilling material

The application of either foamed concrete or injection mixtures for backfilling the Ksawer Chambers requires widely varying technical solutions related to transporting the backfilling material. In the case of foamed concrete, it is necessary to keep transportation routes to a minimum due to its short setting time. Ideally, the foamed concrete generator should be located at a Upper Level II at the Baum longitudinal, directly adjacent to the area to be backfilled. However, in the Baum longitudinal area, no mine transport infrastructure exists, and the excavation is in a poor condition. Transporting tens of thousands of tons of material through the excavations at Level IV over a distance of 3000 m and then to Level II would constitute a logistically difficult and costly project. It appears that the only acceptable solution to this problem consists in creating a backfilling base with the generating unit and warehouse in the vicinity of the Wilson shaft on the surface.

After being produced at the surface, the foamed concrete filling should be transported by gravity by a pipeline laid along the Wilson shaft to the shaft bottom at Level IIn, and then distributed through pipelines:

- Level IIn — from the Wilson shaft bottom along the Schwind longitudinal, the Schwind transverse, the stair exit to the Baum Chamber to the Baum longitudinal or through the borehole from the Baum transverse to the Schwind longitudinal at Level IIw.
- Level II — along the Baum longitudinal to the Ksawer or August shaft with branching off to chamber backfilling posts or backfilling drilling holes. The space to be backfilled with foams will be reduced by installing backfilling dams.

In addition, a pipeline along the August shaft would transport foam to Level III in order to bring backfilling material directly into the Chamber IIn/219 behind the largest backfilling dam for its stabilisation.

The use of injection mixtures allows the installation of the manufacturing site to be situated at a considerable distance from the excavations to be backfilled, as the setting time of injection mixtures is relatively long compared to the flow time. Injection mixtures can be produced at the injecting node operating on the surface of in the area of the Kosciuszko the shaft, and then transported to the excavations by gravity, through a pipeline installed on the Kosciuszko shaft pipe. Injection mixtures brought to Level III would then be transported by (Fig. 3):

— Level III — Galicia longitudinal, Struga transverse, Koerber longitudinal, Żralski transverse, Pistek gallery, Hauer longitudinal, August transverse, Leopold Canal, and August shaft to Level IIw.
— Level II — August shaft bottom, Baum longitudinal eastward, with distribution to the backfilled excavations or backfilling drilling holes.

As in the case of the foam backfilling, the space to be filled with the injection mixtures must be reduced by creating backfilling dams. Under this scenario, it is necessary to allow additional pumping units in the area of the crossing of the August transverse with Leopold Canal at Level III.

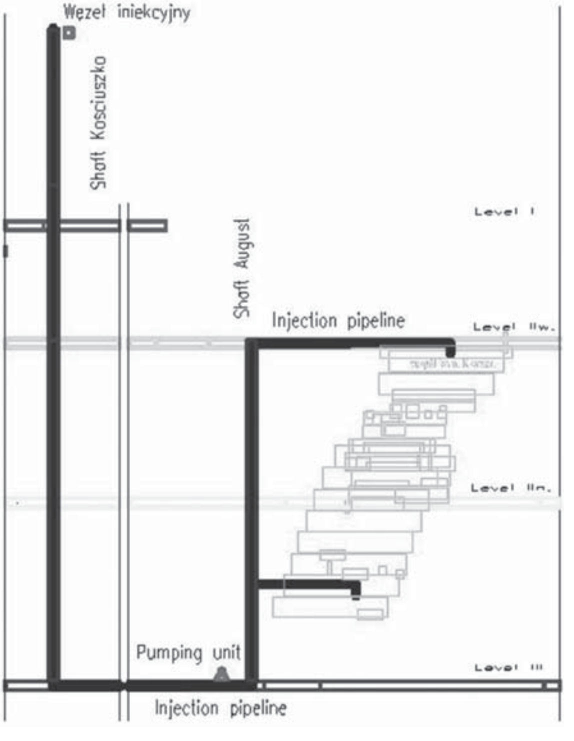

Fig. 3. Injection mixtures transport scheme

The use of both foamed concrete and injection mixtures requires the construction of a pipeline installation. In the case of injection mixtures, the proposed pipeline route is longer, but it does not require the creation of a pipeline in the Wilson shaft pipe as for foamed concrete. Conducting backfilling work with injection mixtures can be facilitated by the existing pipeline installation between the injection node, through the Kosciuszko shaft pipe, Galicja longitudinal and Struga transverse, to the Koerber longitudinal.

4. 4. Preparation of dams at the backfilling fields

The fact that the Ksawer Chambers are located in the historic mine area and the proximity of unique Crystal Caves makes isolating the backfilling field from other excavations critical.

Classic backfilling dams used in hydraulic backfilling works are wooden stillage structures stands with planks on which backfilling canvas is stretched. The structure's purpose is to withstand the pressure of sand and the evacuation of the outflowing brine. In the case of backfilling with injection mixtures of foamed concrete, the backfilling dam structure is required to be tightly sealed from the excavation which are not being backfilled.

The fact that the area is dived into levels requires eight backfilling dams to be constructed at Upper Level II and 5 dams at Lower Level II.

In addition, in the backfilling field region, two vertical excavations are located: an unnamed shaft from the ramp in Chamber IIw/36 and the Ksawer shaft, for which independent dams will be created. It will be especially important to create dams for the unnamed shaft connecting vertically Chamber IIw/36 with the historic Leopold Chamber and the Leopold Canal. It is practically impossible to create a dam for the shaft in the Leopold Canal area due to the difficulties in reaching the bottom part of the Leopold Chamber. Moreover, this solution would require a backfilling the shaft between Chamber IIw/36 and Level IIn. An alternative solution would to be create a dam in the form of a tight sealing in the ramp above the shaft inlet. Such a dam requires labour-intensive work, including access from Chamber IIw/36, which is in a poor condition. Restoring Chamber IIw/36 to a secure condition in order to create an injection seal will create additional opportunities the for conservation of the 19^{th} c. brine line with two leaching towers, enrichment crates, vats and brine transportation troughs towards the Leopold Canal [4].

The biggest technical problems are posed by the creation of the main dam cutting off the backfilled Ksawer Chamber complex from Chamber IIn/219 (Fig. 4). The dam with a surface area of approximately 150 m^2 will be located at the bottom of the Ksawer IIn/219 Chamber, which inclines from east to west, and reaches at this point considerable transversal dimension. An additional problem is posed by the combination, through local collapse, of the base of Chamber IIn/219 with partially backfilled upper part of the Suka Chamber. Before the main backfilling is constructed, it will be necessary to isolate the Chamber from the Leopold Canal, and then backfilling the top of the Suka Chamber. This will enable the reconstruction, raising and levelling the base in the area where the backfilling dam is to be constructed. Moreover, during the flooding of this part of the Chamber, structural elements of the new dam

Fig. 4. The concept of the backfilling dam in Chamber IIn/219

will be will be stabilised in this area. The main backfilling dam will be erected in the form of horizontal segments with guy ropes to be stabilised during the casting of each segment [5]. The most difficult element of such an extensive dam is the point of contact between the dam structure and the Chamber side walls and the backfilling material. It will be necessary to apply side-wall cuts to be performed gradually while casting each segment of the dam. The cut will accommodate formwork and insulating film, which, once formed, will be set in the cut with the quick-setting with parameters similar to those of the injection mixture. Casting dam segments will be conducted from the August shaft in a controlled manner, directly from the backfilling pipeline.

5. Summary

The backfilling of the Ksawer Chambers complex requires applying a different manner of conducting backfilling work than those used so far in the particular conditions of the Wieliczka Salt Mine. The fact that the Ksawer Chambers are located in the eastern part of the Mine among historic excavations of significant historic value, and in the immediate vicinity of the Crystal Caves complex, which are unique in natural and geological terms, makes it essential to carefully select the technological elements of the backfilling works to be conducted. In order to preserve the historic excavations, it is necessary to fill the area of Ksawer Chambers to be closed down with a backfilling mixture with strength parameters which will guarantee the halting of the process of the rock mass destruction. At the same time, the backfilling mixture selected cannot cause an outflow of brine, which increases mine air humidity, and as a consequence, of the rock mass.

Injection mixtures based on concrete, alkaline adhesives, and saturated brine constitute backfilling material which meets the above criteria. These mixtures are produced in the injecting node operating on the surface in the vicinity of the Kosciuszko Shaft according to individually selected recipes. Those meet the criterion of not increasing the atmospheric humidity of the Mine, as they totally absorb the brine during the mixture setting and have sufficient strength parameters. Injection mixtures are also characterised by good flow properties and penetrating excavations with side wall and ceiling rock cave-ins and accumulations of rock debris, such as those in the Ksawer Chambers complex. Transporting injection mixtures to the backfilling field requires constructing a pipeline and installing a pump unit to assist the flow. Operating parameters of the injection node ensure a daily backfilling output of approximately 150 m^3, which is a sufficient for the scope of the works. For creating dams in the backfilling field at Level IIw, typical solutions used in the Mine are sufficient; however, constructing tight backfilling dams at Level IIn in the area of contact between the Ksawer Chambers and the Leopold Canal shall pose considerable technical challenges. The configuration of the Chambers, with the whole complex inclining towards the Leopold Canal, and the considerable dimensions of the backfilling dam shall require developing an innovative approach which has not yet been applied at the Wieliczka Salt Mine.

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