Causes and Prevention for Sinkhole in Limestone Mine

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Abstract—In recent years, the placement of backfill in underground mines has emerged as a new paradigm in research as it not only improves safety but also allows disposal of byproducts including coal ash. In this regards, this paper addresses the backfilling challenges in limestone mine to prevent sinkhole and subsidence. Limestone mines, generally regarded as being safer than coal and metal mines, have been subject to unsupported mining methods. However, the increasing number of sinkholes worldwide has highlighted the need for research on preventive measures. The purpose of this study was to improve the safety of limestone mines, which account for more than 70% of Korea’s resources. This paper investigated sinkholes and subsidence in limestone mines from geological and mine development perspectives, and examined the case studies of backfill in limestone mine as a solution.

Keywords—Sinkhole, Subsidence, Limestone mine, Backfill

I. INTRODUCTION

In recent years, numerous sinkholes have formed in many areas of the world threatening the safety of people. Sinkholes typically appear near mines rather than in cities, as a type of surface subsidence. They are caused by various mechanisms, including water seepage, rainfall, earthquakes, limestone dissolution, and underground excavations, among other factors. In the case of mines, sinkholes and subsidence areas mainly form when the depth of the mine work is shallow and geological discontinuities or weak overburden exist. [1]

In this study, we examine the causes of sinkholes, particularly in cases of limestone mines, and suggest backfilling as a remedial measure to prevent mine accidents related subsidence areas and sinkholes. The common form of subsidence in underground limestone mining areas is due to the formation of sinkholes. [2] Sinkholes associated with mining pose a serious threat to life and property due to the lack of surface indications before their formation.

In limestone mines, caves of various sizes are developed due to the dissolution of limestone, and weak forms of overburden such as shale or mudstone become interbedded. If these parts of weak rock and caves become exposed on the surface of a roof or pillar, the stability will greatly decrease and cracks will form, leading to a failure of the roof or pillar.

The cracks can eventually become large, forming an area of surface subsidence and/or a sinkhole. In particular, subsidence and roof failures in mine working areas can generate additional fractures and increase the size of existing cracks, also encouraging the transmissive properties of a failure. [3]

The main issue for both active and abandoned mines is the stability of the underground mining area. In order to increase the firmness and reduce the risk that pillars will collapse, backfill is most commonly used material among all other methods. [4] This study reviews the available literature related to the limestone mine cases and describes the types of backfill and backfill technologies according to different underground mining methods.

II. CAUSES OF SINKHOLE IN LIMESTONE MINE

Most limestone mines are exposed to danger because mineways and working faces are maintained in unsupported states. Rockbolts and shotcrete are hardly used to provide support in limestone mines since applying these reinforcement methods involves higher production costs.

In the field, safety issues that have been identified include roof falls, weak zones, and water discharges. These problems lie in the joints and faults of limestone, and spalling of shale slabs in pillar, and roof falling occur when wedge blocks formed from the intersection of weak zones and discontinuities become separated from roofs or sides walls.

Week Geological Conditions

Limestone mines have large and small cavities along with relatively weak parts made up of materials such as shale and mudstone inside the mine formation. In some cases, there are numerous complicated changes of rock even within a short distance. In addition, it is difficult to keep the underground cavities stable after excavation due to unstable geological structures such as faults, joints and folds. Rock masses around voids create stress concentrations and local fracture zones, which are transferred along such geological weak structures. [5] That is, the presence of such voids represents a potential hazard because the roof rock may eventually collapse, and it is difficult to predict the time of such a collapse. [6]
Shallow Depth

Subsidence occurs frequently in limestone formations because the distribution of sedimentary strata is wide and broad. Specifically, limestone is soluble in water, which contains dissolved carbon dioxide and organic acids. When water passes through a limestone formation, a cavity can form, and the range of sizes can be very wide. If there are weak planes such as joints, bedding planes and/or faults in an area where a cavity has developed, a collapse of a cave roof will occur. Thus, the dissolution of limestone creates karst topography and the irregularity of bedrock affects the development of sinkhole subsidence.

Carbonate rocks such as limestone are soluble in acidic water. Thus, cavities can form in underground strata. The water percolates into the soil and creates CO₂, which is dissolved in water from the atmosphere or soil, becoming H₂CO₃. It then penetrates into the soil and reacts with CaCO₃ and CaMg(CO₃)₂ in the carbonate rock formation. Calcite (CaCO₃) and dolomite (CaMg(CO₃)₂), the principal minerals comprising limestone, are dissolved in the presence of an acid to produce Ca²⁺, Mg²⁺ and HCO₃⁻. If the acid is able to flow through the rock, ions will be removed and a cavity or solution conduit will form. This is why subsidence areas and sinkholes appear in limestone deposits. In addition, sudden or gradual subsidence of the top soil can occur by the infiltration of unconsolidated deposits above the limestone cavities, though this depends on the scale and the shapes of the materials involved. [7]

Failure of Pillars

Limestone ore is mined in a room that is separated by rib or square pillars. Pillar designs take into account the shapes, widths, and heights necessary for each case. They are also determined according to the depth of the mine working area, the ore thickness, the stress condition and the strength requirements. The recovery rate of ore depends on the pillar design. In some cases, this can be as high as 80 to even 92%.

Under the room and pillar mining method, pillars act as supporting structures for the upper load and help to prevent roof falls. In reality, the pillars may be re-mined to meet grade and production requirements, resulting in non-uniform sizes. Stress concentration at walls or roofs causes fractures due to shear and delamination. Excessive loads on the pillars or blasts can lead to cracks and subsequently exfoliation. The sliding of wedge blocks created from discontinuities eventually weakens the pillars. [5]

III. MINING WITH BACKFILL

In general, backfill is an artificial support method used in the mining and civil engineering industries. Broadly, backfill refers to any waste material such as coal ash or mine tailings that are placed into voids in an underground mine in order to perform some engineering function or for the purpose of disposal. [10]
The main function of backfill is as a type of ground support and to improve the mining recovery rate. Backfill is placed between the pillars and the secondary stope, so it is enable to remine the residual pillars or to decrease the size of the pillars. It can also provide a freestanding wall, which can inhibit the progressive collapse of a near rock mass by imposing a state of kinematic compulsion on the displacement of key pieces at a stope boundary of low-stress settings. Thus, if backfill is properly confined, it will allow minimal dilution of the rock mass by acting as a support element in the mine structure, as shown in Figure 1(a). Additionally, backfill provides a working platform to mine the upper part of the ore body, as shown in Figure 1(b). Furthermore, backfill ensures the long-term stability of the mine, limits excavation exposure, and allows waste disposal through the filling of voids in underground mines. [11], [12], [13], [14]

When selecting a mining method, the mining conditions, available equipment, industrial regulations, and degree of financial feasibility all should be considered. For an underground limestone mine, if the ore body on a horizon or mild slope, the room and pillar mining method is applied, while if the ore body is in a steep slope, the sub-level stoping method will typically be used.

**Room and Pillar mining**

Room and pillar mining is a mining method which allows the complete mining of ore, leaving a minimum number of pillars to support hanging walls.

It is widely used when ore bodies extending over large areas are horizontal or dipping and when the vein width is not wide. Room and pillar mining has long been applied. At present, it is regarded as the most common underground mining method used in underground limestone mines given the development and dissemination of large underground hydraulic equipment.

Limestone is mined in a room while leaving ribs or square pillars. The recovery rate of ore mined in such a manner is as high as 80 or even 92% depending on the pillars. When designing the pillars, many factors, such as the ore thickness, depth, and strength should be considered. After excavating the ore bodies, the spaces between two pillars or a pillar and an abandoned face can be backfilled in order to re-mine the pillars and for the general purpose of mine safety. In the past, low-grade limestone or mine waste was used to fill these voids. However, in recent years, a mixture of cement and mine waste such as mine tailings and/or combustion byproducts has been used to augment the strength of the backfill material. After filling in the area between the pillars, they can be re-mined by backfilling in a process referred to as post-pillar mining. There are several advantages of post-pillar mining. It increases the recovery rate of the ore and the production quality when the residual pillars contain high-grade ore. [15], [16]
Sublevel Stopes and Pillars

The most common backfill mining methods is the sublevel open stope method, which is used in a broad range of applications. Sublevel stoping is best method when the ore bodies lie in steeply inclined dips in the presence of strong wall rocks and where the ground conditions allow large openings to develop without causing undue dilution. This method is applied when large-tonnage ore bodies are of low to medium grades. If an ore body is large, it will develop with transverse stopes and pillars or those that are perpendicular to the strike of the ore bodies. If the ore bodies have narrow widths of 30 to 40m, they will be mined longitudinally. When applying this method, which is the most efficient and least expensive method, there is no limit to the size of the ore bodies. When it is properly used in combination with backfill materials, 100% of the ore can be recovered.

The general approach to backfill can be simplified into three steps. First, the ore bodies are divided into a series of major stopes and pillars, and the size of the backfill depends on the ground conditions and the sizes of the ore bodies. Second, the primary stopes are mined as in a 1-3-5 sequence. Finally, mining of the pillars in the 2-4-6 sequence is done.

![Diagram of Sublevel Stoping](image)

**Figure III TYPICAL MINING METHODS: SUBLEVEL STOPING [13], [16]**

IV. BACKFILL TECHNOLOGIES

Backfill technologies are mainly applied in large-scale underground mines.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Hydraulic Fill</th>
<th>Paste Fill</th>
<th>Rock Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Placement State</td>
<td>60 to 75wt.% solids</td>
<td>75 to 85wt.% solids</td>
<td>Dry</td>
</tr>
<tr>
<td>Underground Transportation System</td>
<td>Borehole/pipeline via gravity</td>
<td>Borehole/pipeline via gravity, can be pumped</td>
<td>Raise, mobile equipment, separate cement system</td>
</tr>
<tr>
<td>Binder Application</td>
<td>Cemented or Uncemented</td>
<td>Cemented only</td>
<td>Cemented or Uncemented</td>
</tr>
<tr>
<td>Water to Cement Ratio (w/c)</td>
<td>High w/c ratio low binder strength</td>
<td>Low to high w/c ratio.</td>
<td>Low w/c ratio, high binder strength</td>
</tr>
<tr>
<td>Placement Rate</td>
<td>100 to 200 Tonne/hr</td>
<td>50 to 200 Tonne/hr</td>
<td>100 to 400 Tonne/hr</td>
</tr>
<tr>
<td>Segregation</td>
<td>Slurry settlement and segregation, low strength development</td>
<td>No segregation</td>
<td>Stockpile and placement segregation, reduced strength and stiffness</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Low stiffness</td>
<td>Low or high stiffness</td>
<td>High stiffness if placed correctly</td>
</tr>
<tr>
<td>Operating Costs</td>
<td>Low distribution costs; lowest cost for an uncemented fill</td>
<td>Lowest cost for a cemented fill</td>
<td>High operating costs</td>
</tr>
<tr>
<td>Binder Quantity</td>
<td>Requires large quantity of binder</td>
<td>Usually lower quantity of binder required</td>
<td>Moderate binder quantities</td>
</tr>
<tr>
<td>Barricades</td>
<td>Expensive</td>
<td>Inexpensive</td>
<td>Not necessary</td>
</tr>
<tr>
<td>Water Runoff</td>
<td>Excessive water runoff</td>
<td>Negligible water runoff</td>
<td>No water runoff</td>
</tr>
<tr>
<td>Capital Costs</td>
<td>Low capital costs</td>
<td>High than for slurry fill</td>
<td>Moderate capital costs</td>
</tr>
<tr>
<td>Tight Filling</td>
<td>Cannot tight fill</td>
<td>Easy to tight fill</td>
<td>Difficult to tight fill</td>
</tr>
</tbody>
</table>

TABLE I
THE TYPES OF MINE WASTE BACKFILL
In underground mines, there are massive pillars which have been left in place for stability, though this limits the recovery rate of the ore. The orebodies left in the pillars can be recovered safely by backfilling between two pillars. In addition, backfill provides long-term stability and reduces the high stress of the rock mass due to deep mining. Initially, mine waste was used to fill the voids left by blasting and mining operations. As an alternative to the rockfill method, the mining industry is trying to lower prices of fill material and improve the stability. Hydraulic filling (slurry fill) with Portland cement was initially quite successful, though very little has actually been done in accordance with the limitations in establishing the parameters for an efficient design. In recent years, high-density paste backfill has been developed, resulting in an increase in the stability of the mine and contributing to improvements in the efficiency of backfill operations. Table 1 shows the backfill properties according to the types of mine waste and transportation methods. [17], [18], [19], [20] [21]

Paste fill became popular as a means of backfilling with the development of backfill mining in the 1990s. [10] The main advantages of paste backfill are given below. [22], [23], [24]

1. The material cost is low due to the use of waste materials such as mine waste rock, coal combustion byproducts, and mine tailings.
2. The transportation of paste material, such as hydraulic fill material and pipe systems, is easy to design and realize.
3. The solidification time can be controlled from approximately 1 to 7 days without dewatering while lowering drainage costs and decreasing onsite cleaning costs.
4. The investment conditions are similar to those of hydraulic backfill but the cost is lower by half.
5. A short mining cycle and reduced waiting times become possible because the material hardens and expresses its initial strength quickly.

The paste backfill system is similar to hydraulic backfilling. However, the solid content of the paste material is higher than used with hydraulic backfill, and only a minimum amount of mixing water is required. Consequently, there is less of a possibility of water bleeding. For this reason, there is no need to pump water to the surface, and the use of this method ensures the stability of the underground mine working area.

The significant benefits of paste backfilling over hydraulic backfilling include short mining cycle times, potential equivalent strengths using less binder, and lower costs. A binder is used to increase the strength, and ordinary Portland cement (OPC) is typically used alone or is blended with various binders such as sulphate-resistant Portland cement, blasting slag, or fly ash. Mine voids can be sufficiently filled with a highly viscous binder, which secures the stability of the surrounding rock masses. [25], [26], [27], [28], [29], [30]

Furthermore, there are potential environmental advantages when applying paste backfill. Paste fill materials require approximately 65wt.% or more of waste, implying that it is possible to reduce the amount of surface area needed to dispose of them, resulting in a reduction of capital and operating costs related to conventional waste disposal structures. [17], [28], [29], [30]

Aref et al. (1992) created a conceptual model that should be considered when designing a high-density paste backfill system, as shown in Figure 5. Also, they described that such a model is critical when determining backfill material sources and satisfying backfill quality levels and scheduling requirements. [13], [15], [29], [31]
It is desirable to use appropriate materials and to set the mixing conditions for the proper backfill design. Brackebusch (1994) found that the mixture should contain at least 15wt.% of particles which are less than 20 μm in diameter, and Aref et al. hold that at least 45wt.% of particles less than 45 μm in size should be considered. [13], [15], [29], [31] These findings confirm that the amount of the micro-size particles used is the most important material design factor in a paste backfill system.

Below are the requirements for applying a paste backfill system. [13] [32] [33]
- The system must contain at least 15wt.% of particles less than 20 μm in diameter.
- No separation of the solid and the liquid in the pipeline must occur.
- The materials must behave as a non-Newtonian fluid.
- The results of a slump test should be less than 230mm.
- Water should not come up to the surface when filling.

As shown in Figure 6, the minimum components of paste fill materials are mine tailings, binders, and mixing water. [26] Mine tailings represent a primary component to determine the applicability of the paste backfill method, which accounts about 80wt.% of paste fill materials. Recently, numerous studies have been carried out in an effort to investigate the applicability of different material designs, such as those pertaining to mine waste rocks, tailings, and coal combustion byproducts for paste backfill systems and applied paste backfill technologies in many countries. [14], [17], [29], [30]

The particle size distribution of mine tailings is the most important factor because it affects the degree of transferability. The water content and solid content of the filling material both rely on the mineralogy properties of the mine tailings. Moreover, the chemical properties affect the strength of the paste backfill and are associated with any environment problems which may arise. [26]
The study was carried out by Ove Arup & Partners. The underground limestone mines were developed at about 10 to 250 m below the surface and mined at a thickness of 5 to 13 m. The resulting empty cavities had a height of 4 to 10 m, and a width of 5 to 20 m. Some limestone mines collapsed during mining, while others collapsed after being abandoned partially or in whole. However, chimneys formed by partial collapse within these mines eventually progressed into crown holes, leading to sinkholes at the surface as shown in Figure 7. [34], [35]

The mines were backfilled according to the three phases described below.

1. Preliminary investigations were performed to examine the general nature of the mines and their overlying ground conditions.
2. To proceed with remedial work when severe subsidence was deemed likely to occur or in the presence of cavities, more scientific and precise investigations were conducted on the mines and their overlying ground conditions.
3. Protection or remediation was carried out. Protection involved fencing of the areas surrounding crown holes.

Some mines at a depth from 50 to 150 m were known to be in an open state, and the void was about 500,000 m$^3$. Filling materials were inserted through boreholes to fill the void at minimal cost.

Rock paste, a compound of colliery spoil and water, was successfully inserted into the void via a 200 m steel pipeline. The volume of the pumped paste was approximately 25,000 m$^3$. Flooding did not occur in the filled area, and this allowed scientists to visit the mines to confirm that the rock paste had been successfully inserted through the vertical boreholes.

**Stabilization of Sugar creek limestone mine [36]**

Sugar Creek limestone mine, owned by LNA, is located near Kansas City. The sugar creek cement plant was built in 1905, and an open-pit mine began operating in the early 1990s for cement production. The open-pit mine development of Iola limestone formation was initiated by the Kansas City Group, and underground mine development of Bethany Falls Limestone layer was started. The room and pillar mining method was applied, and rooms of various dimensions remained. Pillars of various sizes were left behind to support the roof. The rooms of the Bethany Falls Limestone mine had a size of 12.2 to 15.2 m, and a height of 3.3 to 4.3 m. The pillars had a diameter ranging from 6.1 to 7.6 m, and the width height ratio or pillar was set at a stable configuration of 2:1. However, the Sugar Creek mine did not follow local practice, and left behind long pillars. In this area, the width height ratio of 1:1 was unstable. The collapse of the mine led to subsidence, which was localized as dome-outs within the mine.

![Figure VI Stages In The Formation Of A Crown Hole Above The Upper Wenlock Limestone. [34]](image-url)
In the 1990s, Sugar Creek mine was declared off-limits by the MSHA after an equipment operator discovered a sinkhole at a depth of 12.2 m. The installation or placement of equipment on the upper portion of the mine was prohibited. Mineral Solutions, Inc. was in charge of stabilization of Sugar Creek mine. The filling of the surface subsidence started in 1999, and dry scrubber ash was used to fill the underground limestone mine on December 19, 2001. The dry scrubber ash slurry was obtained from two neighboring power plants, amounting to 100 tons (90,700kg) and 900 tons (816,300kg), respectively. The dry scrubber ash was mixed with water to a slurry state. Cased boreholes with a diameter of 8 to 10 inches (0.2 to 0.25 m) were drilled to pass through about 53.3 m of soil and rock overburden. The slurry was inserted into the boreholes, and the total amount of dry scrubber ash slurry was 165,000 tons (149.7 million kg) up to 2003. Since the MSHA prohibited entry to the mine, ultrasonic distance measuring sensors and video photography were utilized for observation and data analysis.

**The use of flyash in limestone mine, Kansas city**

An abandoned limestone mine of 100 acres can be found 200 ft below Kansas City, and land development was forbidden in this area due to instability of the underground roof. The abandoned limestone mine was developed based on the room and pillar mining method. A sufficient amount of shale slakes from the roof and upper parts of the mine pillars were produced over time, and the pillars could no longer bear the weight of the overlying bedrock. The pillars broke and the collapse propagated to the surface to form sinkholes. Also known as domeouts, this collapse generated void volumes of 5,800 to 35,000 m$^3$.

This area was a wasteland before the Charles Garney, the founder of Briarcliff Development Co. attempted recovery and development. Briarcliff Development Co. and UCS Technologies, a residuals management company, formed a team with Burns McDonnell and proposed using flyash from a nearby thermal power plant as backfilling material. Boreholes were drilled and cased into the roof of the domeouts. Each domeout must be drilled with at least two boreholes: one as an injection hole and one to vent any air and water in the upper section. A dry ash berm was piled from the mine ground to the roof, and flyash slurry was not allowed to leak to other parts of the mine. The domeout backfill prevents slabbage of shale at the roof or side walls. The domeouts of this limestone mine were filled with 18,000 tons of fly ash during a period of more than 15 years. This area today consists of houses, offices, boutique shops, and high-rise buildings. [37], [38]

**VI. CONCLUSION**

The growing number of sinkholes around the world is a threat to our safety. This study was conducted to identify the causes of sinkholes and to present solutions to safety issues. In particular, this work is aimed at reducing the risks associated with developing limestone resources, as well as examining backfilling technology for improved safety of mine and surrounding regions.

Research on limestone mines has been limited as they have been considered less dangerous compared to other mines. Despite this general presumption, limestone mines are subject to a number of sinkhole-inducing conditions: weak zones such as joints and faults, development of shale and other soft rocks, dissolution, roof falls, and failure of pillars. To address these issues, this study examined the use of backfill in mines at home and abroad. Moreover, we investigated the types of backfill and respective advantages, and reviewed requirements for paste backfill—the most economical type of backfill.

This study holds significance in that it is investigated the risk factors of limestone mines and laid the foundation for backfilling technology based on mining methods, thereby providing a practical reference for the later backfill projects.

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