POLITECNICO DI TORINO

Master of science in Petroleum and Mining Engineering

State of the art of mining backfilling methods

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Abstract

This thesis provides a detailed analysis of the current state of mining backfilling methods. It explores the various techniques and materials used to fill the voids created by mining activities. The thesis categorizes backfill types into different categories such as cementitious, silica alumina-based, rockfill, hydraulic, pneumatic, and mechanical backfills. It also examines their application in different mining situations, including upward and downward stoping. The study emphasizes the importance of backfilling in improving mine safety, efficiency, and environmental sustainability. It highlights the trend towards using sustainable materials sourced from industrial by-products and processed mine waste. The thesis also discusses the desired properties of backfills, including strength, durability, and environmental stability. It explores the use of advanced monitoring systems and computational models to optimize backfill performance. Overall, the thesis emphasizes the dynamic nature of mining backfilling technology, which is constantly evolving due to continuous innovation and the mining industry's commitment to environmental stewardship and operational excellence.

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I. INTRODUCTION

The importance of mining backfilling goes far beyond just making mining operations easier. It plays a crucial role in ensuring the stability of mine structures, reducing the likelihood of surface subsidence and strengthening safety measures in mining activities. Additionally, backfilling practices have a significant impact on environmental conservation. By using mine waste as backfill material, the industry might reduce its negative impact on the environment, addressing the important issues of waste management and resource preservation. This emphasizes the vital role of backfilling in promoting sustainable mining practices and its contribution to the overall environmental agenda.

This research aims to provide a thorough examination of the different types of backfilling materials commonly used in the industry, including cementitious backfills, paste backfills, and rockfills, among others. Each type of material is carefully analyzed in terms of its properties, suitability, and the specific difficulties it presents in the mining environment. Furthermore, this study delves into a range of backfilling techniques, such as hydraulic, pneumatic, and mechanical methods, while also exploring novel approaches and cutting-edge technologies that are being employed to improve and maintain efficient backfilling operations.

It is noteworthy to mention that a considerable portion of the thesis delves into an in-depth exploration of the environmental and sustainability consequences linked to the process of mining backfilling. This involves conducting a comprehensive evaluation of the environmental effects connected to different materials and techniques used in backfilling, as well as examining how these practices align with the goals of sustainable mining. On the other hand, a thorough economic and cost analysis is carried out to shed light on the financial aspects involved in implementing different backfilling strategies. This analysis aims to highlight the potential for achieving cost efficiencies and operational enhancements through the adoption of specific backfilling methods.

By conducting a comprehensive review of relevant literature, this thesis aims to compile and integrate existing academic research on the subject of mining backfilling methods. In doing so, it incorporates a variety of case studies to illustrate how different backfilling strategies have been implemented and the resulting outcomes in real mining projects. This extensive literature review serves as a foundation for the subsequent analytical and discussion sections of the thesis, where various backfilling approaches are critically evaluated in terms of their advantages and disadvantages. Additionally, this review proposes criteria that can be used to select the most suitable backfilling methods and highlights the latest advancements and innovations in backfilling technology.

The analytical chapters aim to bring together theoretical concepts and real-world applications, providing a comprehension of the different elements that affect the choice and execution of backfilling techniques in mining activities. This entails an examination of technical, environmental, and economic aspects, alongside the influence of regulatory frameworks on backfilling practices. Moreover, the thesis delves into the present-day obstacles faced by the mining sector regarding backfilling, suggesting potential avenues and future orientations that may influence the advancement of backfilling methodologies.

This thesis seeks to provide an understanding of mining backfilling methods and their significance in ensuring the sustainability and safety of mining operations. By carefully examining different backfilling materials and techniques, as well as their environmental, economic, and regulatory implications, this research aims to contribute to both academic and practical discussions in the field of mining engineering. The findings of this study will serve as valuable insights for future investigations and operational practices, guiding the development of innovative backfilling strategies that can effectively address the challenges faced in modern mining operations.

1.1 Background and Significance of Mining Backfilling

The practice of mining backfilling has a long-standing history in the field of mining engineering and has evolved over many years to become a complex solution that addresses various challenges related to operations, the environment, and safety in mining operations. The origins of backfilling can be traced back to the early recognition of the need to effectively manage the empty spaces left behind after extracting minerals. These voids presented significant dangers, such as unstable ground, sinking, and increased damage to the environment. As time went on, the mining industry began to explore and adopt different techniques to fill these voids with various materials, thereby reducing risks and capitalizing on potential advantages.

The importance of mining backfilling has been gaining more and more attention in the realm of sustainable mining practices. With the ever-increasing global demand for minerals and resources, the mining industry is under heightened scrutiny when it comes to its environmental impact and commitment to sustainability. Backfilling presents a versatile solution by facilitating the reuse of waste materials, effectively reducing the environmental impact of mining activities. This practice not only helps in managing waste but also plays a significant role in preserving natural landscapes and minimizing surface subsidence, ultimately enhancing the safety and sustainability of mining operations as a whole.

From an operational standpoint, the process of backfilling serves to increase the stability of mines and enables the extraction of nearby ore deposits that would otherwise remain untouched due to concerns about stability. This in turn maximizes the extraction of valuable resources and enhances the economic feasibility of mining endeavors. Additionally, the practice of backfilling has undergone advancements to incorporate a wide range of materials, such as tailings, waste rock, and cementitious substances. The selection of these materials is based on factors such as their accessibility, cost, and appropriateness for specific backfilling purposes.

Advancements in technology and engineering techniques have gone hand in hand with the evolution of backfilling practices. In order to enhance the efficiency and effectiveness of backfilling operations, modern methods such as hydraulic, paste, and pneumatic backfilling have been devised. The selection of these methods is dependent on numerous factors, which encompass the type of mining operation, the physical and chemical characteristics of the backfill material, as well as the project's specific environmental and safety goals.

The importance of mining backfilling lies in its contribution to environmental sustainability. With the mining industry increasingly striving to align with global sustainability targets, the adoption of effective backfilling practices becomes crucial in minimizing the negative environmental consequences associated with mining operations. By employing waste materials as backfill, the industry can dramatically diminish its reliance on scarce natural resources while also reducing the amount of waste that ends up in landfills or tailings dams. This not only helps to mitigate the environmental impact of mining activities but also facilitates the development of a more circular economy within the mining sector.

In addition to that, the integration of backfilling methods is closely interconnected with regulatory and compliance frameworks. Numerous regions have implemented guidelines and laws that require or incentivize the adoption of eco-friendly and sustainable mining techniques, which include the practice of backfilling. Adhering to these regulations not only guarantees the fulfillment of environmental and safety standards but also improves the acceptance and support from local communities and stakeholders, thereby fostering stronger relationships between mining companies and these groups.

The economic consequences of utilizing mining backfilling should not be underestimated. Although there may be substantial initial expenses involved in setting up backfilling operations, the long-term advantages such as increased resource extraction, enhanced stability of mines, and decreased costs for environmental remediation all contribute to the overall financial feasibility of mining projects. Consequently, conducting economic and cost evaluations of various backfilling techniques is crucial during the planning and decision-making stages of mining operations. This ensures that the selected backfilling strategy aligns with both operational goals and financial limitations.

Finally, the background and importance of mining backfilling emphasize its position in the realm of contemporary mining methods. It represents the industry's transition towards practices that are more environmentally friendly, productive, and secure, which in turn highlights the intrinsic link between preserving the environment, achieving operational excellence, and ensuring economic feasibility. As mining operations continue to adapt in light of technological progress and growing expectations regarding environmental and social responsibility, the utilization of backfilling techniques will remain at the forefront of the industry's endeavors to reconcile the need for mineral resources with the imperative of sustainable development.

1.2 Objectives and Scope of the Thesis

The main purpose of this thesis is to conduct a comprehensive examination of the latest advancements in mining backfilling methods. The focus is on gaining a deep understanding of how these practices have evolved, been implemented, and how they have impacted the mining industry. This investigation involves a thorough analysis of the different materials and techniques used in backfilling, while also considering their effects on the environment, economy, and day-to-day operations. Through the synthesis of current knowledge, practices, and innovations in mining backfilling, the goal of this research is to shed light on the factors that influence the selection and optimization of backfilling methods and to identify areas where further advancements can be made.

The focus of this thesis encompasses various important factors. Firstly, it centers on examining the technical aspects of different backfilling methods, such as hydraulic, pneumatic, and mechanical techniques, as well as exploring emerging technologies that are shaping the future of backfilling practices. Secondly, the research aims to evaluate the environmental sustainability of these methods, particularly in terms of their impact on waste management, land restoration, and the overall ecological footprint. Thirdly, the economic aspects of backfilling practices will be thoroughly analyzed, giving specific attention to cost-benefit analyses, operational efficiencies, and the long-term financial implications for mining projects.

This research is guided by four research questions, starting with; what are the technical and operational benefits and challenges associated with different mining backfilling methods, and how do these influence the selection of a particular backfilling strategy? It implies dissecting the various backfilling methods employed in the mining industry, evaluating their technical specifications, operational efficiencies, and the challenges associated with them. Secondly, how do mining backfilling practices contribute to environmental sustainability within the mining industry, and what are the potential areas for improvement? It aims to focus on the environmental impact of backfilling practices, assessing how these methods contribute to waste reduction, land rehabilitation, and the mitigation of adverse ecological effects.

What are the economic implications of adopting different backfilling strategies, and how do these affect the financial viability of mining operations? It aims to investigate the cost factors associated with various backfilling methods, including initial investment, operational costs, and long-term economic benefits. It examines how economic considerations shape the adoption of backfilling strategies and their impact on the overall financial health of mining projects.

1.3 Thesis Methodology

The methodology employed in this thesis has been meticulously crafted to conduct an extensive literature review, specifically concentrating on the various techniques used in mining backfilling. This particular approach has been chosen to facilitate a thorough exploration of the wealth of existing knowledge, by assimilating information from a wide range of sources in order to gain a comprehensive understanding of the present scenario, the challenges faced, and the advancements made in the field of mining backfilling. By adopting a research strategy that primarily relies on literature, this study enables a comprehensive examination of published studies, industry reports, regulatory frameworks, and case studies, thereby offering a multi-dimensional perspective on the practices employed in backfilling within the mining industry.

The research process begins by conducting a thorough and comprehensive search for relevant literature. This search follows a systematic approach, aiming to identify scholarly articles, technical reports, conference proceedings, and regulatory documents that are specifically related to mining backfilling methods. To accomplish this, various databases are utilized, including Scopus, Web of Science, Google Scholar, and industry-specific databases. The search is conducted using a carefully selected set of keywords that are directly related to mining backfilling. These keywords include, but are not limited to, terms such as "mining backfilling methods," "backfill materials," "environmental impact of backfilling," and "economic analysis of mining backfill." The search strategy is designed to be all-encompassing, ensuring that a wide range of publications are included in the research. The aim is to gather information that contributes to a comprehensive understanding of backfilling practices, the challenges associated with their implementation, and the advancements that are driving their evolution.

After the literature is gathered, a framework for inclusion and exclusion criteria is created in order to sift through the collected data and guarantee that the sources included in the review are both relevant and of high quality. Various factors, such as the publication date, how closely the sources align with the research questions, the rigor of the methodology used in the studies, and the impact factor of the publications, are considered to determine which studies are the most suitable. This thorough selection process guarantees that the review is built on reliable and noteworthy contributions to the field of mining engineering.

The selected literature is analyzed using a thematic synthesis approach, which involves identifying and examining key themes, patterns, and inconsistencies within the literature. This process entails coding the literature to identify themes related to backfilling materials, methods, environmental and economic impacts, and the influence of regulatory standards. By conducting this in-depth analysis, the research aims to create a comprehensive understanding of the current state of mining backfilling, shedding light on areas where there is agreement among scholars while also pinpointing gaps in knowledge and suggesting potential directions for future research.

In addition, the methodology incorporates a critical review of the literature. This involves not only providing a summary of the findings but also analyzing them in terms of their impact on the field, the strengths and weaknesses of the methods used, and the practical and policy implications that could be derived from them. By employing this critical perspective, the research aims to integrate the existing literature in a way that enhances knowledge and establishes a strong basis for addressing the research questions posed in the thesis.

Finally, the methodology employed in this thesis is centered around utilizing literature as a foundation for conducting a comprehensive and analytical exploration of mining backfilling methods. The primary objective of this research is to shed light on the current state of knowledge regarding backfilling in the mining industry, including the prevailing practices, obstacles faced, and novel advancements. By systematically gathering, evaluating, and integrating relevant literature, this study seeks to present a holistic view of the field while also pinpointing areas where the existing literature falls short, thereby paving the way for future investigations into mining backfilling practices.

II. LITERATURE REVIEW

2.1 Types of Backfilling Materials

The extraction of minerals from underground mining leads to the creation of various voids, such as stopes, caves, rooms, goafs, and gobs. These voids present a risk of instability, potentially endangering nearby mineral-rich pillars or causing subsidence that can impact surface infrastructure during or after mining operations. To address these challenges, advancements in mining technology have introduced several strategies for filling or backfilling these spaces. Among these methods, rock backfill, hydraulic backfill, cemented paste backfills, and silica alumina-based backfill techniques have been selected based on economic considerations and specific objectives such as mine development or closure.

2.1.1 Cementitious Backfill

Cemented paste backfill (CPB) is a mixture that consists of waste tailings, water, and cement. The waste solid content in CPB can range from 70% to 85%. The water used in the mixture can be clean or obtained from mine processing activities. To enhance the properties of the mixture, a hydraulic binder is added, typically making up 3-7% of the total weight. Within the mining industry, CPB has become one of the most innovative and rapidly evolving technologies in waste management and backfilling. It provides an economical solution for supporting structures and ensuring safety in underground mining operations. Moreover, CPB offers significant environmental advantages. Various studies have been conducted to explore its effectiveness and benefits [1]-[6].

Once they have undergone the process of being cured and hardened, CPBs serve a crucial function in the formation of robust, column-like structures that provide support for mining activities conducted in underground settings. This not only contributes to the establishment of safer working conditions for miners but also emphasizes the dual advantages of CPBs in terms of both operational safety and environmental sustainability. Numerous studies conducted by Grice (2001), Kesimal et al. (2003), Yilmaz et al. (2004), Fall and Pokharel (2010), Mahlaba et al. (2011), Pokharel and Fall

(2013), as well as Ghirian and Fall (2013), have further emphasized the significance of CPBs in these aspects [8]-[13]

The selection and use of underground backfill materials depend on factors such as the type of fill, mining method, and existing infrastructure. Cemented paste backfill materials are commonly made from thickened or filtered slurry of mill tailings, which are then mixed with cement and water. Different types of cement, such as Portland cement, sulfate-resistant cement, and ground granulated blast furnace slag, can be used alongside water to create a mixture with a high slump. This mixture is designed to make it easier to transport the paste to underground voids.

The use of materials containing sulfide as binders in backfill compositions has become less popular due to concerns about their impact on the environment and safety. To improve the ability of the Controlled Permeability Backfill to be pumped, additional agents can be included. The specific components of the CPB mix, such as the type and size distribution of the aggregate, the type and proportion of the binder, the amount of water, and any other additives, are determined based on the desired mechanical properties of the hardened backfill, such as strength, density, and permeability, as well as the intended method of transportation. It is crucial to consider the availability of both solid particles and binders during this process [11].

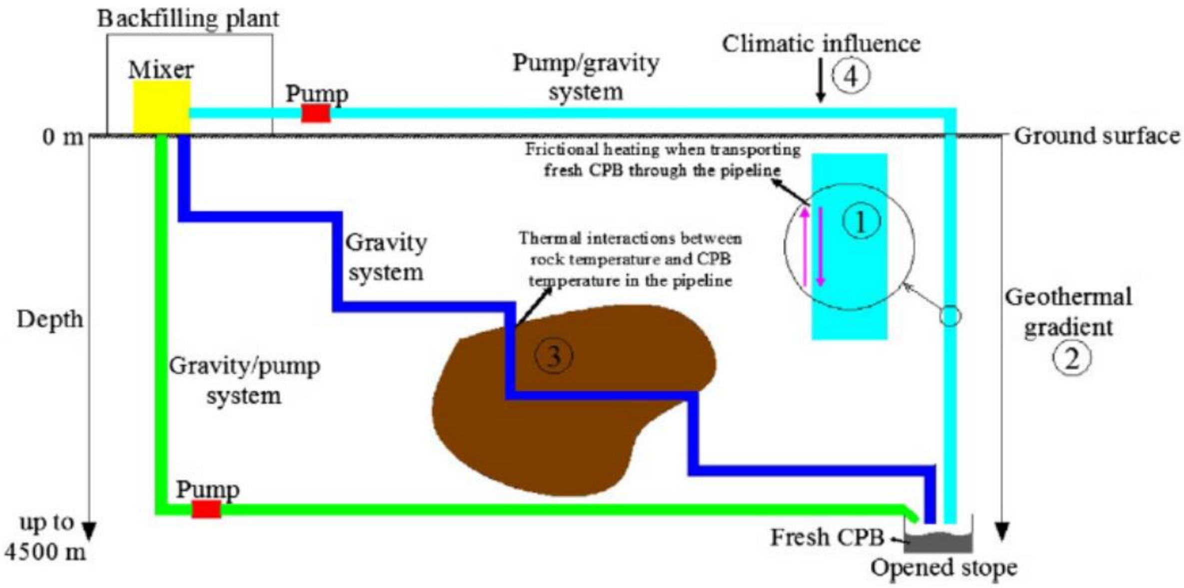
The composition of the CPB mix typically consists of 3-7% binder by weight and 70-85% tailings. In order to ensure that there is no settling or separation of particles during pipeline transportation, it is necessary for the CPB to contain an adequate amount of fine particles. One notable characteristic of CPB is its high water content, with a water-to-cement ratio ranging from 2.5 to 7%. This water content surpasses the hydration requirements of the cementitious materials. The high water content is crucial for maintaining the consistency and flowability of the mixture, allowing it to be easily pumped through pipelines.

CPB is transported underground through the use of gravity or by being pumped through pipelines. The smooth movement of fresh CPB is a significant factor in its transport, as it relates closely to its fluidity or ability to flow easily [40]. CPB operations typically make up around 20% of the overall costs involved in mining operations [14]. The fluidity of fresh CPB not only allows for efficient pumping and delivery to designated areas, but it is also crucial in preventing blockages in the pipes, which can result in substantial financial losses for mining operations.

When the transportation system of cemented paste backfill experiences clogging, it is necessary to immediately stop operations and dismantle the pipeline network to remove the blockage. This not only causes delays in production but also leads to additional costs, emphasizing the importance of maintaining a smooth and unclogged transportation system. The rheological properties or behavior of CPB, which determine its fluidity or flowability, are influenced by various factors. These factors include the density and concentration of the CPB mixtures, the characteristics of the components of the CPB mixture, and the pH level, which are known as internal elements. Additionally, external elements such as temperature and the combined effects of temperature and time on the progress of cement hydration and shear time also play significant roles in impacting the rheological behavior of fresh CPB.

The rheological properties of CPB can undergo changes depending on the thermal loading conditions it experiences and how it is transported over short or long distances. These changes can be a result of the friction between the CPB and the walls of the pipeline, as well as variations in underground mining environments and depths. These variations demonstrate that CPB's behavior is constantly evolving and that it is highly influenced by the surrounding environment. As a result, each underground mine's backfill transportation system must be specifically designed to accommodate the unique temperature and site-specific conditions. This highlights the importance of a customized approach to the design and management of CPB systems in order to ensure efficient operation and cost-effectiveness.

Figure 1. *CPB transportation system to underground voids and influence of thermal factors. It shows the flow from the backfilling plant at the surface, where the mixture is prepared, to the opened stope deep underground. The process is facilitated by a combination of gravity and pumping systems, with the depth reaching up to 4500 meters. The system also accounts for the geothermal gradient and climatic influence, which affect the temperature of the CPB during transport and placement, highlighting the interaction between the backfill material and the ambient conditions within the mine. [12]*



The requirements for cemented paste backfill structures include factors such as their mechanical performance, barricade stability, environmental impact, and durability. When CPBs are placed in underground stopes or other empty spaces, they need to be able to withstand certain loading stresses in order to ensure the safety of workers. It is important to find a balance between the mechanical properties of the CPB that provide structural support and its flowability for easy transfer. The design must also consider the hydraulic conductivity of the CPB to allow for effective drainage without compromising the integrity of the barricades. Additionally, the design takes into account the use of both permeable free-draining and impermeable retaining walls. These factors have been discussed in various studies [9] [11] [19].

Environmental performance and durability are important factors in the design of CPBs, and they are greatly affected by the permeability of these materials. One major concern is the potential for acid mine drainage after the mine is flooded, and the susceptibility of CPBs to AMD is primarily determined by the reactivity or oxidation potential of the mining waste materials that make up the CPB matrix. The presence and amount of sulfide minerals in the CPB system can increase this potential for reactivity. Additionally, the permeability of the CPB matrix plays a crucial role in controlling the flow of fluids, such as oxygen and water, within the backfill. This, in turn, has an impact on the environmental consequences of using CPBs. Various studies have examined these factors and their effects on CPB performance [23] [28] [31].

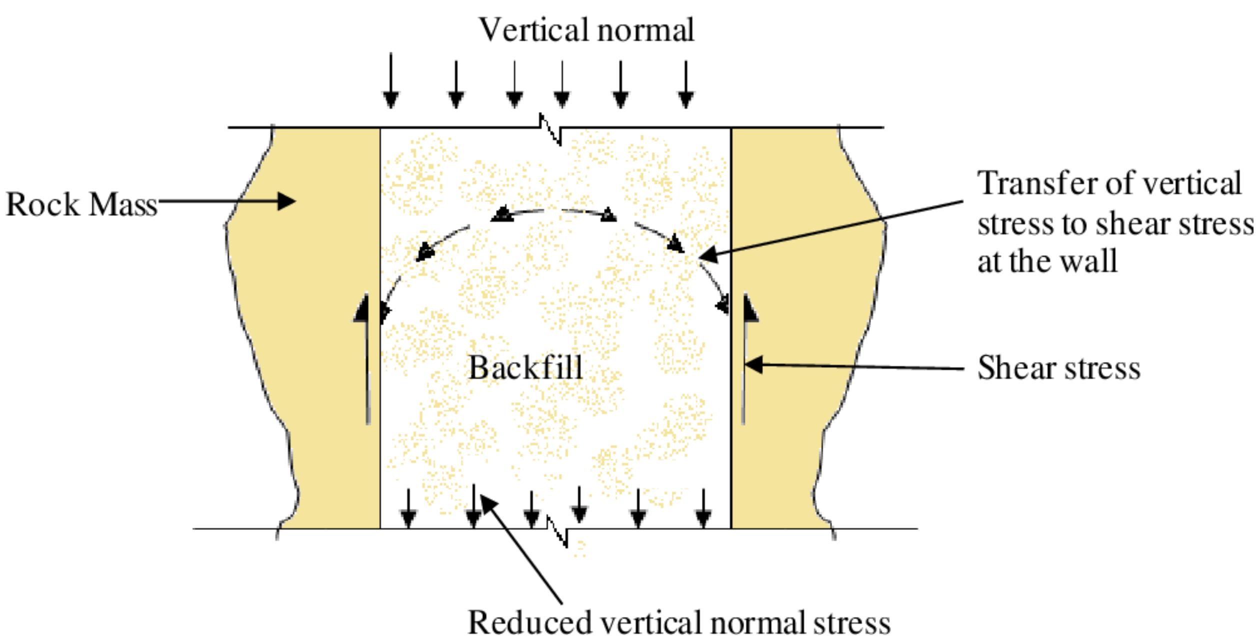
The strength required for the design of CPB varies depending on its intended use underground. When used for ground support, it is necessary to have a uniaxial or unconfined compressive strength of at least 5 MPa. However, for free-standing CPB structures, a common requirement is for the UCS to be less than 1 MPa. Various studies have shown that the UCS requirement for CPB can range from 0.2 MPa to 5 MPa, depending on the specific application and the UCS of the surrounding rock mass, which can vary from 5 MPa to 240 MPa. This emphasizes the importance of a customized approach to CPB design, considering both the structural and environmental factors in order to optimize safety, functionality, and sustainability in underground mining operations.

Arching effect

The arching effect is a phenomenon that occurs in geomaterials and can be observed both in natural settings and in controlled laboratory experiments. It involves a change in the distribution of stress within a geomaterial, where the resistance to shearing helps to keep the yielding mass in its original position. This, in turn, affects the way stress is distributed between the yielding section and the surrounding soil mass. According to Jiang (2020), when a yielding section moves downward, the shear resistance acts in an upward direction, leading to a decrease in stress at the base of the yielding section. On the other hand, if the yielding mass moves upward, the shear resistance opposes this movement by acting downward, resulting in an increase in stress at the support base of the yielding section [16].

This phenomenon is particularly noticeable in structures that are built underground, as the arching action can greatly reduce the pressure from the weight of the soil above. This redistribution of stress can have an impact on the overall load that the structure experiences, including the weight of the soil, any additional weight on the surface, or the pressure from surrounding soil. As a result, the rocks or soil next to an underground structure can actually enhance its ability to support weight compared to a similar structure that is not buried [37]. This understanding of the arching effect emphasizes its significance in the design and analysis of underground structures, underscoring the importance of considering the complex interactions between the soil and the structural elements in order to optimize the safety and stability of these constructions.

Figure 2. *Arching effect in backfilled stopes in mine. illustrating how vertical normal stress from the overlying rock mass is transferred and reduced as it disperses into the backfill material. It also shows the conversion of vertical stress to shear stress at the walls of the excavation, emphasizing the importance of understanding stress mechanics to maintain the structural integrity of both the backfill and the surrounding rock mass. [37]*



The arching effect is a crucial phenomenon in mining engineering, particularly in the context of backfilled mines. It involves the redistribution of stresses within geomaterials and has significant implications for the design and evaluation of backfill structures. In-depth research conducted by Pirapakaran and Sivakugan (2017), as well as Pirapakaran (2018), using FLAC numerical methods, highlights the importance of considering the arching effect in backfill design, particularly in hydraulic filled stopes. This is supported by the findings depicted in figure above [30] [33].

The determination of horizontal pressures, which are affected by the arching effect and transmitted to the sidewalls of backfilled mines, requires a thorough analysis. In order to achieve this, various analytical and semi-analytical methodologies have been developed. These methodologies take into account factors such as the cohesion between the backfill and sidewalls, as well as the potential for frictional sliding along these sidewalls. Some notable models in this field include the Marston model and its revised versions, the Terzaghi model, the Van Horn model, and the model proposed by Belem and Benzaazoua (2018). Additionally, Belem *et al*. (2014) introduced a comprehensive three-dimensional model in, which effectively incorporates the arching effect to calculate horizontal stresses at the stope floor. This model considers both longitudinal stress (σx), which extends across the ore body, and transverse stress (σy), which runs along the ore body [4] [42].

The utilization of these models plays a crucial role in guaranteeing the strength and security of subterranean mining operations. By providing precise forecasts on the interaction between backfill materials and surrounding geological materials in different load scenarios, these models enable the improvement of backfill designs. This not only enhances the safety and effectiveness of mining activities, but also contributes to the progression of knowledge in the area of mining engineering, highlighting the significance of a comprehensive and nuanced comprehension of the arching phenomenon in the context of backfilled mines [30].

$$\sigma_h = \omega\gamma H\left(\frac{H}{B+L}\right)\times\left[1-\exp\left(-\frac{2H}{B}\right)\right]$$

The calculation of the vertical stress $\sigma_V(=\sigma_Z)$ at the base of a backfilled stope is crucial in assessing the stope's structural soundness and confirming that the backfill can adequately bear the required weight to maintain safe underground mining activities. This calculation plays a vital role in determining if the stope is capable of withstanding the forces and pressures exerted on it, thereby ensuring the safety and stability of the mining operation:

$$\sigma_V = 0.185\gamma H\left(\frac{H}{B+L}\right)\times\left[1-\exp\left(-\frac{2H}{B}\right)\right] = \sigma_Z$$

The vertical stress at the base of a backfilled stope is determined using parameters that include the backfill' s bulk unit weight (γ, in kN/m³), the height of the backfill within the stope (H, in meters), the stope's width (B, in meters), and the length of the stope in the strike direction (L, in meters). The directional constant (ω) is set to 1 for stress across the ore body (σ_h=σ_x), and to 0.185 for stress along the ore body (σ_h=σ_y). In scenarios where the backfill face is narrowly exposed, arching effects are localized to the confined backfill, influenced by the adjacent stope walls. Utilizing Terzaghi's arching model and incorporating insights from 2D finite element modeling by Askew et al. (1978), a specific equation is recommended for computing the compressive strength necessary for backfill design, as cited by Belem and Benzaazoua (2018) [4].

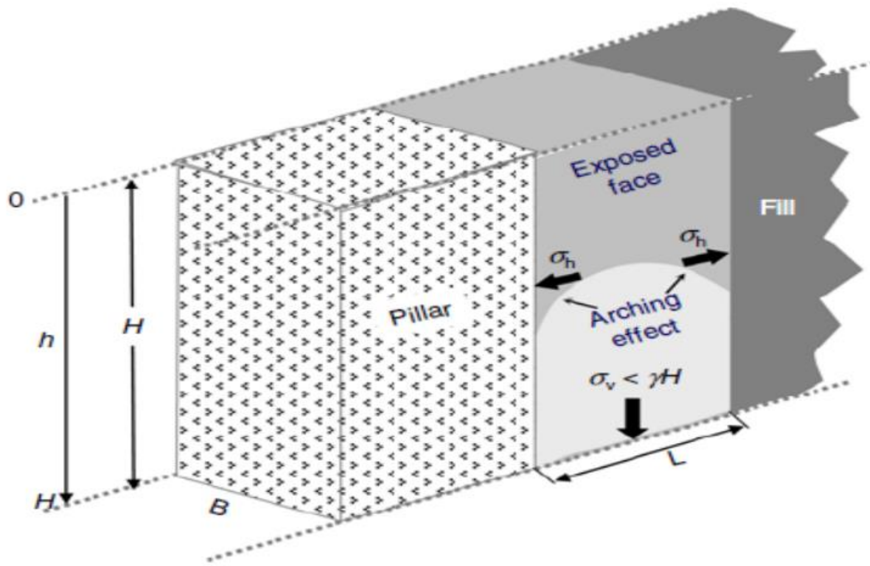
$$UCS_{design} = \frac{1.25B}{2K\tan\phi}\left(\gamma - \frac{2c}{B}\right) \times \left[1 - \exp\left(-\frac{2HK\tan\phi}{B}\right)\right] FS$$

B = stope width; K= Backfill pressure coefficient.

$$K = \frac{1+\sin^2\phi}{\cos^2\phi + 4\tan^2\phi} = \frac{1}{1+2\tan^2\phi}$$

The compressive strength for backfill design is determined by factors including the cohesive strength of the backfill (C, in kPa), derived from triaxial tests on backfill samples in the laboratory, and the backfill's internal friction angle (ϕ), also obtained from triaxial testing. Additionally, the calculation incorporates the backfill's bulk unit weight (γ, in kN/m³), the height of the backfill (H, in meters), and a predetermined factor of safety (FS). These parameters are essential for accurately assessing the mechanical properties and stability of the backfill material, ensuring its suitability for supporting underground structures safely.

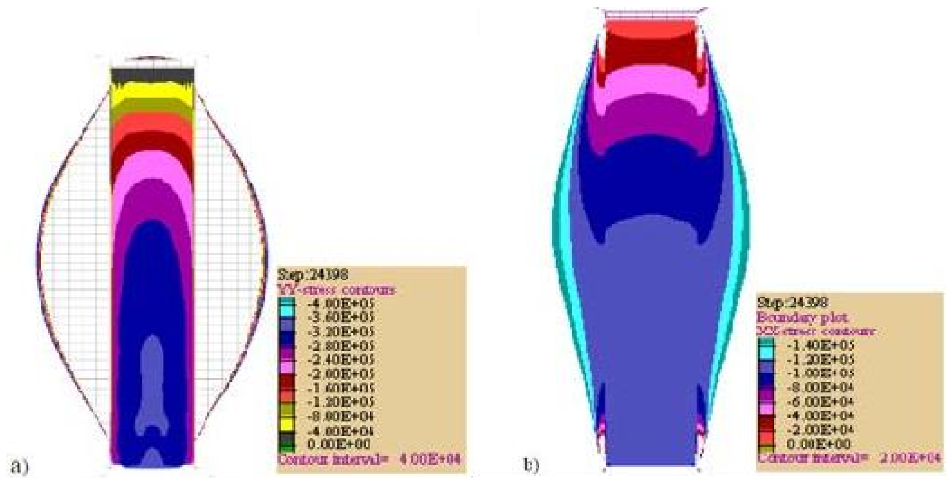
Figure 3. *Stability analysis of narrowly exposed backfill face. a three-dimensional view of a mining pillar with dimensions height (H), width (B), and length (L), where h represents the height of extraction. The arching effect is depicted on the exposed face of the pillar, indicating the distribution of stress, with σ_h representing horizontal stress and σ_v, which is less than the overburden pressure, symbolizing vertical stress. [4]*



Li et al. (2023) conducted comprehensive studies, both analytical and numerical, on the arching effects observed in narrow backfilled stopes. The numerical modeling for these stopes incorporated the excavation and filling sequence as distinct steps within the calculation process. Using FLAC-2D software, the models were brought to an equilibrium state before backfilling was introduced into the excavated stope, with the initial displacement field set to zero to ensure that wall convergence prior to backfilling was excluded from the calculation. This approach highlighted a non-uniform distribution of vertical and horizontal stresses within the backfilled stope, as depicted in the study's illustrations. It was observed that both horizontal and vertical overburden stresses increase more rapidly with depth compared to stresses along the stope's central line, a phenomenon attributed to the arching effect. Consequently, wall stresses are lower than those at the center [36].

The study's findings, illustrated in subsequent figures, compared the modeling outcomes for stresses throughout the full height of the stope against predictions made by Marston's theory and the expected overburden stress. Notably, the overburden stress aligned closely with both analytical and numerical predictions at lower backfill heights. However, at greater depths, the occurrence of the arching phenomenon resulted in vertical and horizontal stresses being lower than those predicted by the overburden weight of the backfill, underscoring the significant impact of the arching effect on stress distribution within backfilled stopes.

Figure 4. *Pattern of stress distribution in backfilled stope. (a) illustrates the vertical stress contours with a legend indicating stress magnitudes; (b) shows the boundary plot with a distinct color-coded legend, detailing different stress levels at the boundaries of the stope. These models are essential for analyzing the stress distribution patterns and are critical for the assessment and reinforcement of mine stability [43]*



Typically, Marston's theory is known to overestimate stress transfer values compared to numerical findings. However, as observed in figure 15 from the study by Li et al. (2023), Marston's theory actually underestimates the stresses. Further examination of figure 6 reveals that Marston's theory underestimates the horizontal stresses along the walls, while overestimating the vertical stress component (σ_{yy}) in conditions deemed active or at rest, with coefficients (K) of 1/2 and 1/3, respectively. Additionally, when K is set to 3, σ_{yy} is underestimated, indicating that the passive case scenario is not adequately represented in this analysis. This divergence underscores the need for careful consideration of theoretical models in predicting stress distributions within backfilled stopes, highlighting the complex interplay between theoretical assumptions and actual stress behaviors observed through numerical simulations [36].

The phenomenon of arching has a significant impact on the vertical stress at the bottom of a backfilled stope. This effect reduces the stress caused by overburden pressure. Various studies have explored the arching effect on the stability of cemented paste backfill in stopes. For instance, if arching did not exist, a CPB with a strength of 500 KPa would require a strength of 2 MPa to withstand a height of over 100 m. This would result in increased cement addition and higher operational costs. The frictional angle between the CPB and rock interface plays a crucial role in assessing and calculating the arching effects in CPB. However, obtaining sufficient information on this behavior can be challenging and expensive. As a result, the friction angle between the CPB and rock wall is often assumed to be the same as the friction angle of the CPB material.

This assumption is based on the understanding that the roughness of the rock wall leads to a higher frictional angle at the CPB-rock interface. Additionally, in most cases, the failure surface at the CPB-rock interface passes through the backfill rather than along the interface itself, due to the large-scale roughness of the stope walls. This leads to an underestimation of the friction angle at the CPB-rock boundary, resulting in an underestimation of the arching effect and overall stability of the CPB structure. Consequently, the design of CPB structures tends to be conservative. However, in cases where smooth rock interfaces exist, such as in foliated rock, the shear failure typically occurs along the CPB-rock interfaces. It is important to consider this overestimation of the arching effect and shear behavior of CPB-rock in the stability analysis of CPB structures, as it can have significant technical, economic, and safety implications.

A study conducted by Nasir and Fall (2008) aimed to investigate the shear behavior of the interface between CPB and rock using a direct shear test method. The results indicated that the shear strength of the CPB materials is greater than that of the CPB-rock interface under similar stress conditions, which can lead to unsafe designs in smooth rock walls. The magnitude of the normal stress also plays a crucial role in the shear performance of CPB-rock, particularly at high normal stresses (≥200 kPa), regardless of the curing time effect.

The backfilling rate, which is the speed at which cemented paste is pumped into a stope, is commonly known as the rate of height increase of the backfill structure. This rate is determined by the cross-sectional area of the stope, as indicated in the given equation below. This relationship emphasizes the clear connection between the size of the stope and the effectiveness of the backfilling process. It emphasizes the significance of considering the geometry of the stope when planning and implementing backfill operations.

$$\frac{\Delta H}{\Delta t} = \frac{\Delta P / \Delta t}{\gamma . A_r}$$

Where *H* represents the height of the backfill, *Dt/Dp* denotes the pumping rate (ton/hour), and A_r is the cross-sectional area of the stope. Filling larger stopes necessitates a prolonged duration, which consequently impacts the hydration rate of the cemented paste across various layers, as noted by Fall (2019). This observation highlights the interdependence between the physical dimensions of the stope, the backfilling process's operational parameters, and the chemical processes governing the backfill material's setting and hardening [13].

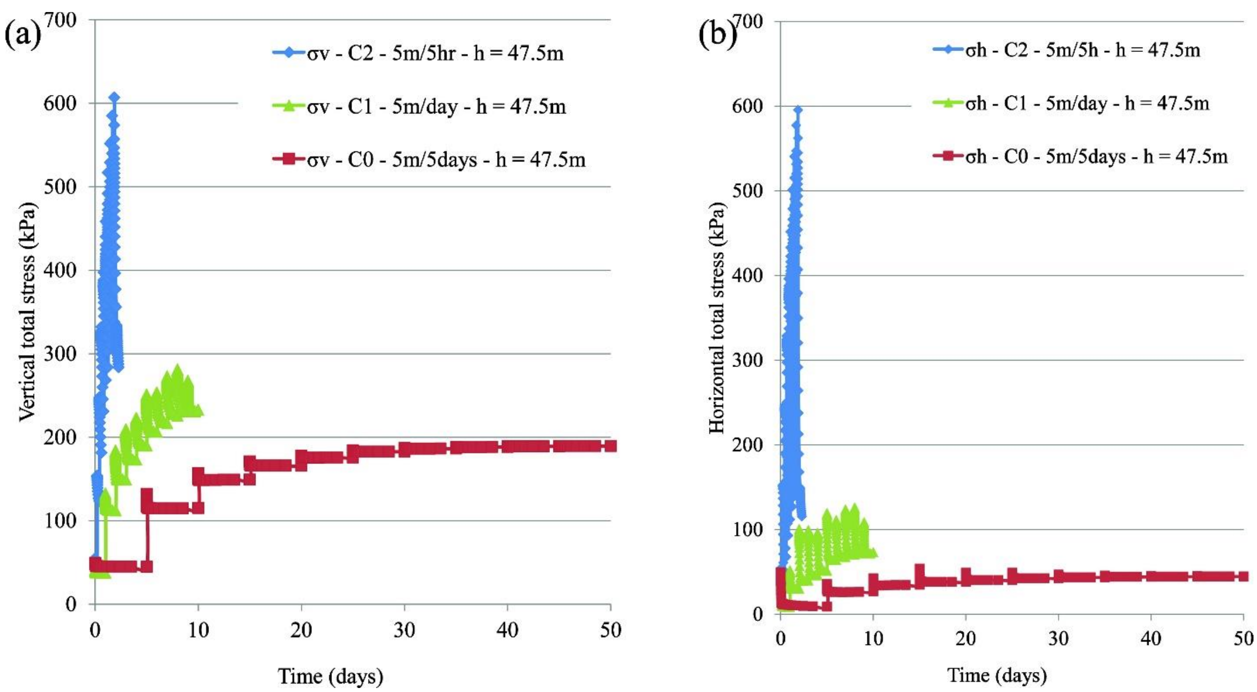
The rate at which voids are backfilled is influenced by a myriad of factors, including the geometry of the void, the strength, and the cement content ratio within the backfill material. Curing time also plays a critical role, affected by variables such as ambient and environmental temperature, water content, the permeability or hydraulic conductivity of both the backfill and barricade materials, the height of the final backfilled material, and the hydraulic conductivity and internal friction of the adjacent rocks.

Illustrative examples from two mines in Western Australia highlight the practical application of these principles. At the KB gold mine, the initial 10 meters of backfilling were completed at a vertical rise rate of 0.2–0.5 m/h, followed by a 24-hour rest period. Subsequent filling proceeded at a rate of 0.3–0.6 m/h until completion, requiring a total of 184 hours. The CPB used in this instance had a 75% solid density with a 3.1% cement content by weight, within a stope geometry approximating a rectangular prism (40m x 18m x 15m) [25].

In contrast, the SNM mine, formerly known as the Sally Malay Mine, employed a different strategy for a stope with dimensions of 23m in height and a 10m x 12m floor plan. An initial 6m fill was achieved at a 0.04 m/h vertical increase rate, with subsequent filling at a constant 0.1 m/h rate, totaling approximately 300 hours for the process. The CPB mixture mirrored that of the KB mine.

Sequential filling, a technique involving the layered addition of saturated backfill with intermediate drainage phases until complete, modifies the hydraulic conductivity of previously deposited layers with each new addition. El Mkadmi et al. (2013) explored this in their study, noting changes in hydraulic conductivity after each layer's addition. Their findings for non-cemented cases, with saturated unit weight and friction angle set at 20 and 35 KN/m³, respectively, a Poisson's ratio of 0.25, and a hydraulic conductivity of 10-7 m/s, demonstrated the impact of filling rate on stress distribution within the stope [28]. For instance, the lowest level of backfill, case C0, involved 5m thick layers filled over 5 days (1 m/day), significantly slower than other evaluated rates, illustrating the effects of varying fill rates on the stress patterns observed within the backfilled stope.

Figure 5. *Different rates of filling and change of the total (a) vertical and (b) horizontal stresses close to the lower level of the stope (h = 47.5 m). Each graph shows stress response to different filling rates: C2 at 5 meters per hour, C1 at 5 meters per day, and C0 at 5 meters every 5 days. [6]*



The temperature of cemented paste backfill is affected by various factors, such as the heat produced during hydration, the natural heat gradient of the Earth, the specific location of the mine, and the friction that occurs during the transportation of CPB through pipes and against the walls of the surrounding rock. The extent to which each of these factors influences the temperature increase in CPB depends on the characteristics of the mine (such as its location, depth, and the length of the transport), the roughness of the rock walls, and the timing at which the hydration process begins.

Deeper mining operations that involve CPB backfilling not only have to deal with longer transportation distances and delays in the initial hydration process, but they also face the challenge of increased natural heat caused by geothermal gradients. In these situations, the rock mass in deep underground mines constantly emits heat, which affects the temperature of the CPB. Furthermore, the location of the mine plays a significant role in determining the temperature of the CPB during transportation, especially in shallow mines. In regions with permafrost, where the ambient temperatures remain consistently low throughout the year, the temperature of the CPB can be affected during mixing at surface plants, transportation, and the hydration process. Additionally, seasonal changes can have a noticeable impact on the temperature of the water used in the CPB, particularly if it is sourced from surface lakes.

The various temperature sources and their changes have a significant influence on the rheological characteristics of CPB, which can ultimately impact how it behaves and performs in its intended location. In order to achieve optimal results during backfilling operations, it is crucial to have a thorough understanding of how these temperature effects affect CPB, as this knowledge will guide the formulation of CPB and inform the best practices for its handling under different environmental and operational circumstances.

Cemented paste backfill is recognized as a geotechnical material whose mechanical properties and behavior, such as compressive and shear strength, are governed by factors common to geotechnical materials including cohesion, internal friction angle, and pore water pressure. The influence of these factors on CPB is subject to variations in its composition, including the percentage of solids, binder, water content, thermal loads from hydration or geothermal gradients, curing time, surcharge load, and hydraulic conductivity [35]. It has been noted that the in situ properties of CPB can significantly diverge from those observed in laboratory-prepared CPB materials. Thus, gaining a thorough understanding of CPB behavior in the field is crucial for optimizing CPB mix design.

The discrepancy between field and laboratory values of unconfined compressive strength (UCS) can be attributed to the complex thermo-hydro-mechanical-chemical processes occurring within CPB (Abdul-Hussain and Fall, 2012; Ghirian and Fall, 2013, 2014). Laboratory investigations by Ghirian and Fall (2013, 2014) demonstrated that UCS values of CPB samples for varying column heights increase over time, a result of the synergistic effects of cement hydration and suction development within the CPB material. It was found that a decrease in the effective void ratio leads to an improvement in UCS values, highlighting a direct relationship between UCS, hydraulic conductivity, cement content ratio, and curing time. Essentially, as the cement content ratio or curing time increases, due to cement hydration, the microstructure of CPB undergoes changes leading to decreased hydraulic conductivity and increased UCS [29].

Furthermore, the modulus of elasticity of CPB is observed to increase with curing time and hydration. Experiments by Ghirian and Fall (2013) reported that cohesion values, derived from direct shear tests, were approximately half of the UCS values, with no significant variation in internal friction angle (ϕ) over time. This suggests that the development of shear strength is predominantly driven by the enhancement of cohesion, which in turn is facilitated by the bonding between tailings grains due to cement hydration [38].

Research conducted by Fall et al. (2020) on the mechanical properties of CPBs with varying Portland cement content, temperature, and water-to-cement ratio concluded that an increase in cement percentage enhances both the modulus of elasticity and UCS of CPB. Conversely, an increase in the water-to-cement ratio results in a decrease in both the modulus of elasticity and UCS. Additionally, an elevation in temperature, regardless of the cement content, leads to increases in both UCS and the modulus of elasticity, further emphasizing the critical role of CPB composition and environmental conditions in determining its mechanical properties.

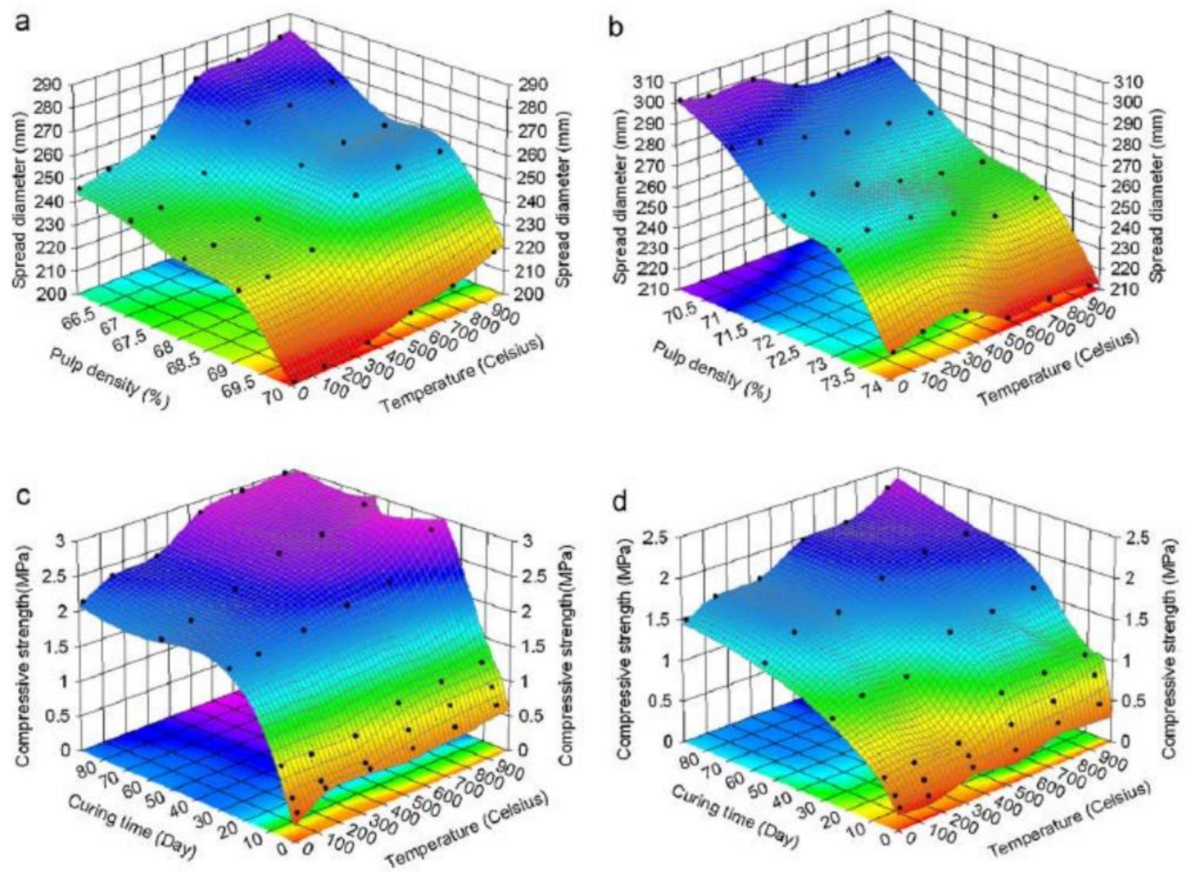
2.1.2 Silica Alumina-based Backfill

In 2012, Yao and Sun conducted a study to investigate the characteristics of a novel backfill material made from silica alumina, coal refuse, and fly ash. These materials are byproducts of the growing coal industry. The focus of the research was to examine how coal refuse and fly ash behave when exposed to different thermal activation temperatures, ranging from 20°C to 950°C. The results showed that the flowability and pozzolanic properties of coal refuse greatly improve as the activation temperature increases. On the other hand, the flowability of fly ash decreases when the temperature exceeds 550°C, due to the formation of clumps on its surface [43].

After conducting thorough research, the researchers were able to identify the perfect composition for the backfill material. They discovered that a mixture containing 5% coal refuse activated at a temperature of 750°C and 15% fly ash maintained at 20°C provided the most optimal results. This specific combination displayed excellent flowability, a high level of compressive strength, and a low bleeding rate within the backfill material. Additionally, the research also involved studying the flowability and strength properties of both coal refuse and fly ash at various thermal activation temperatures. The results of these investigations were carefully documented and presented in a publication [29].

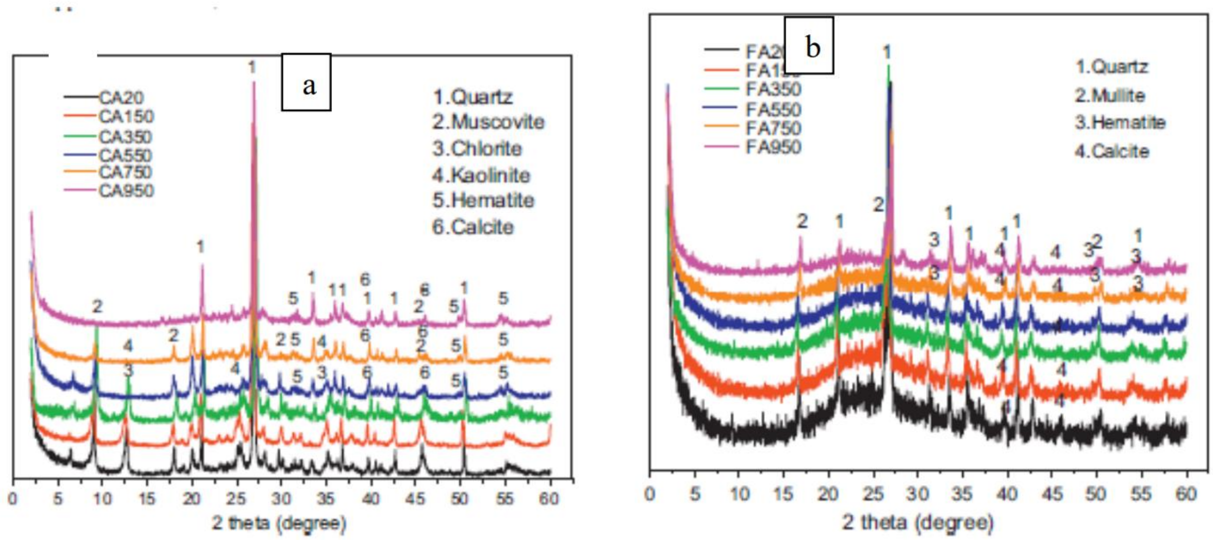
The mineral phase changes of coal refuse and fly ash were investigated using microanalysis at different thermal activation temperatures. The results showed that at 550°C, the kaolinite peaks in coal refuse decreased as they transformed into metakaolin. At 750°C, the chlorite peaks disappeared and there was a reduction in muscovite peaks. At 950°C, there were no muscovite peaks present, indicating that muscovite underwent dihydroxylation and transitioned from 2M1 type to muscovite HT type. X-ray diffraction results also revealed that the hematite peaks became more prominent after thermal activation, especially at 950°C. However, no significant mineral phase changes were observed in fly ash during thermal activation. This comprehensive analysis emphasizes the positive impact of thermal treatment on improving the functional properties of coal refuse and fly ash, making them suitable for backfill applications and highlighting their potential in sustainable mining practices [30].

Figure 6. *Presentation of the backfill material properties; (a) and (b) depict the relationship between pulp density, temperature, and the spread diameter, indicating the fluidity of the backfill mix. Graphs (c) and (d) show how curing time and temperature influence the development of compressive strength in the backfill, essential for understanding material performance under different environmental conditions. Each graph's surface is color-coded to represent the magnitude of the measured parameter, providing a visual correlation between the mixed variables and the resulting backfill characteristics. [29]* [1]



[1] (a) Flowability of the coal refuse-based backfill material, (b) Flowability of fly ash-based backfill material,- (c) compressive strength of the coal refuse-based backfill material and (d) compressive strength of the fly ash-based backfill material. Retrieved from

Figure 7. *XRD at different activation temperatures (a) shows patterns from samples with varying cement contents labeled CA20 through CA950, identifying minerals such as quartz, muscovite, chlorite, kaolinite, hematite, and calcite. (b) presents patterns from samples with different fly ash contents labeled FA20 through FA950, indicating the presence of quartz, mullite, hematite, and calcite. [29]*[2]



The hardened structure of the backfill material, which is made from silica alumina, was subjected to tests to determine its toxicity levels. These tests took place in various locations, and the results showed that none of the elements tested exceeded the limits set by the Environmental Protection Agency. This finding proves that silica alumina-based backfill material is safe for the environment. Furthermore, the researchers discovered that by adding just 1% cement to the composition of the backfill material, which mainly consists of industrial solid waste, there is a great potential for cost savings in the backfill industry. This innovative approach not only effectively utilizes waste materials, thus reducing the impact on the environment, but it also offers a significant opportunity to decrease the expenses involved in creating and applying backfill materials [29].

2.1.3 Rockfill

As mining operations go deeper underground, the amount and frequency of empty spaces like stopes, goaf, and gob naturally increase. This has led to the common practice of disposing of waste

[2] (a) coal refuse and (b) fly ash

rocks directly onto the surface of mining fields. However, managing these waste rocks poses several challenges. First, they are voluminous in nature, making it difficult to handle and store them properly. Second, these waste rocks often contain metallic elements that can contaminate the environment. This is a major concern because dust and microparticles can be dispersed by wind, while rainfall can generate leachates containing heavy and toxic elements from the dumped rocks. As a result, both the hydrologic and hydrogeologic systems can be negatively impacted. Additionally, the voids created by mining activities can cause structural instabilities and settlement issues. The collapse of these spaces can lead to rock bursts and potential ground subsidence, further exacerbating the problem.

Rock backfilling is a technique that involves the transportation of various materials, such as stone, gravel, soil, and industrial waste, to fill the empty spaces left behind by underground mining. This process can be carried out using human labor, the force of gravity, or mechanical equipment, resulting in a densely packed backfill body. The materials used for backfilling are typically obtained from waste rocks, which undergo crushing, sieving, and mixing processes. Special machinery is employed to ensure that the particle size distribution is suitable for the backfilling operation [40]. To transport these backfill materials, there are three main methods, each utilizing different types of equipment. The first method involves the use of side-dump tramcars, while the second method utilizes belt conveyors. The third method combines the use of trucks and scrapers. More detailed information regarding these methods can be found in the table below [41].

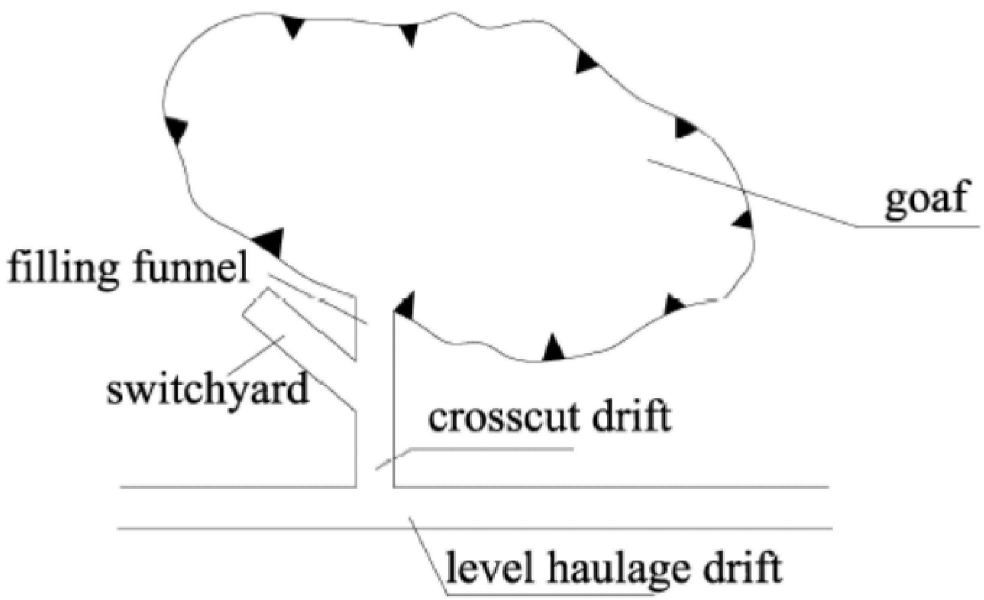
Table 1. *Advantages and disadvantages of rock backfill systems [34]* [3]

Scheme	Applicable Areas	Advantages	Disadvantages
I	Gobs small in size with good stabilities	Easy for operation; Few devices input	High labor intensity; Low efficiency
II	Filling workface nearby hanging wall	High capacity; Flexible operation	Expensive devices; Complex structure
III	Mines with truck Transportation	High capacity; Wide application range	Critical tire wear; Gas pollution

In the instance of the White Bull mine in China, rock backfill was chosen as a practical and cost-effective approach for addressing excavated gobs underground. For the transportation of waste rock, methods such as locomotive traction and tramcar haulage were employed [40].

[3] Created by the author.

Figure 8. *Rock backfills used for underground goaf refilling in China, one of the goafs that intersects with level drift is indicated below [3]*[4]



The rock backfill method is a cost-effective option for backfilling in underground mining. While it may not be suitable for all scenarios, it offers a solution for certain situations. This method involves transferring waste material from the surface to deeper levels underground, resulting in a reduction of surface waste. As a result, it helps reclaim land for other uses and minimizes environmental pollution. By moving waste rocks to areas that are not exposed to rainfall, it enhances the stability of the mined regions. Additionally, this method plays a role in reducing land subsidence and rock bursts by changing the stress patterns within the mined areas [16].

2.2 Backfilling Methods

When considering the different strategies for backfilling in the mining industry, it becomes clear that each approach presents its own set of benefits and difficulties in terms of operation. The selection of a backfilling technique holds great significance as it not only affects the effectiveness and cost-efficiency of mining operations, but also plays a role in ensuring environmental sustainability. Generally, these methods can be classified into three main categories: hydraulic,

[4] One of the goafs that intersects with level drift is shown above. Retrieved from: Wang *et al.* 2013

pneumatic, and mechanical backfilling. Each of these categories possesses distinct qualities and is suited for specific applications.

The process of hydraulic backfilling involves utilizing a mixture of water and backfill material in order to effectively fill empty spaces using a system of interconnected pipelines. This technique is highly regarded for its capacity to navigate intricate underground formations and its cost-efficiency. Nevertheless, it necessitates meticulous control of water usage and presents potential environmental hazards as a result of the release of harmful substances.

Pneumatic backfilling, however, operates by utilizing air pressure to effectively move dry or slightly moist backfill material through a network of pipes. This particular method boasts several advantages, particularly in terms of conserving water resources, rendering it highly suitable for use in arid environments. Nonetheless, it is important to note that implementing this technique requires the utilization of specialized equipment and may result in the release of dust particles, necessitating the implementation of proper dust emission management strategies.

The process of mechanical backfilling involves the use of machinery, such as conveyors and trucks, to transport and deposit backfill material. This technique is highly regarded for its adaptability and accuracy, as it enables direct management of the backfilling procedure. Despite its numerous benefits, including increased efficiency and improved quality control, mechanical backfilling does come with certain drawbacks [20]. These include the need for higher upfront investments and more regular maintenance in comparison to alternative methods.

Table 2*.Primary transport mechanisms, advantages, and main concerns [16]*

Backfilling Method	**Mechanism of Material Transport**	**Principal Advantage**	**Primary Concern**
Hydraulic Backfilling	Slurry conveyed through pipelines	Efficient in complex geometries, cost-effective	Water management, potential environmental risk
Pneumatic Backfilling	Dry material transported by air pressure	Reduces water usage, suitable for dry areas	Requires specialized equipment, dust control
Mechanical Backfilling	Direct transport via mechanical means	Versatile and precise control	Higher upfront investment, maintenance demand

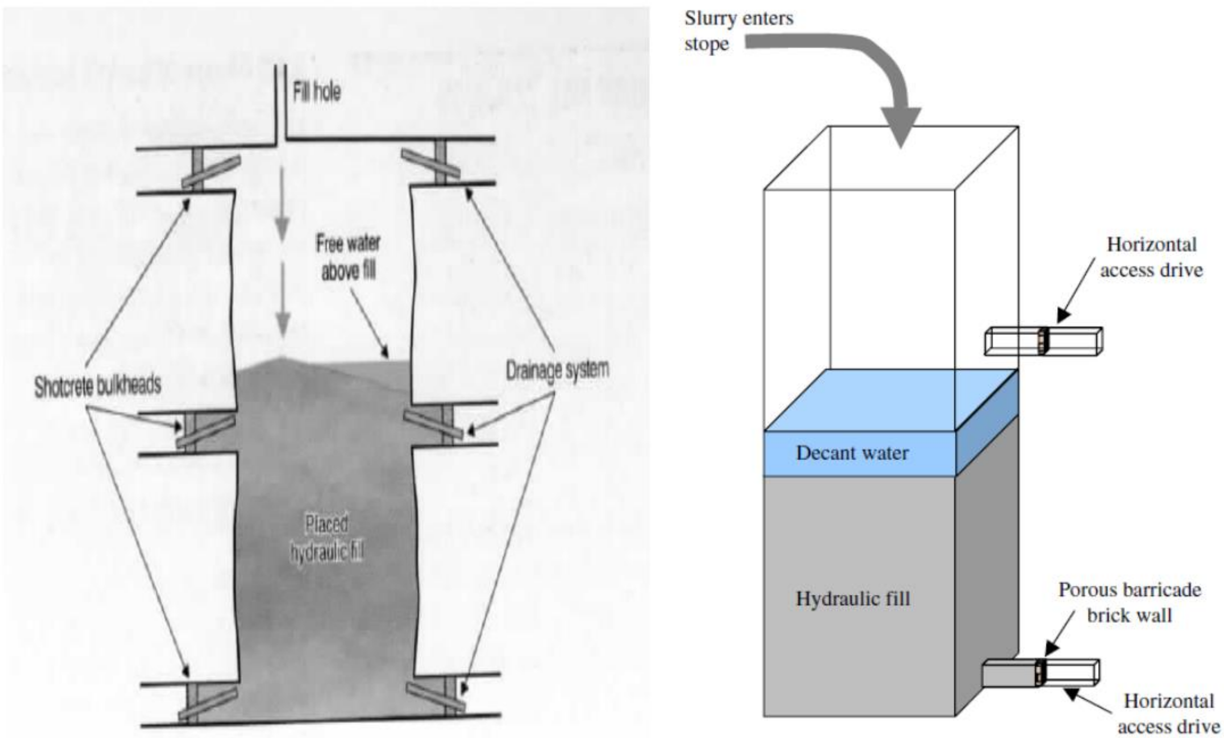
2.2.1 Hydraulic Backfilling

When designing backfill and barricades, strict guidelines must be followed, particularly in terms of controlling material properties. In situations where backfill strength is required or when dealing with waste material that has a high content of very fine particles, hydraulic backfill is increasingly being used as a substitute for cemented paste backfill [36]. Analyses of the grain size distribution of 20 hydraulic backfill samples from Australian mines, as well as cemented hydraulic and paste backfill materials, have shown that hydraulic backfill material closely aligns with cemented hydraulic backfill. The impact of cement on grain size distribution appears to be minimal. In paste backfills, the fraction of fine particles is larger compared to hydraulic or cemented hydraulic backfills, but the colloidal fraction (particles finer than 2 micrometers) is insignificant.

Hydraulic backfill is characterized by having a maximum particle size of less than 1µm, and very fine particles are typically removed to improve the permeability of the backfill material. Consequently, particles that are 10 µm or smaller should make up less than 10 percent of the total, often significantly less [37]. The slurries used in hydraulic backfill have densities ranging from 40-50% (solid volume), and the material's permeability should fall within the range of 10-5 to 10-6 m/s, with excess water being drained by gravity and assisted drainage. The porosity of the placed hydraulic backfill is typically around 50%, although there have been cases where it is as low as 30%.

Hydraulic backfill can be used with or without cement, and the uncemented approach is often the most cost-effective for mines that have small-waste particles readily available [40]. The use of hydraulic backfill involves the use of water as a means to transport various materials, including waste tailings, water-hydrophilic slag, mountain sand, river sand, and crushed sand, for filling underground voids such as stopes [39]. This method requires sealing off the access drives of the mine with bulkheads and incorporating a drainage system within these bulkheads to allow water from the backfill to drain out of the stope. The hydraulic backfill material is then introduced into the stope through a fill hole at the top, with the accumulation of free water on top of the backfill increasing its height. It is crucial to ensure that all water is drained through the bulkheads, either through seepage or decanted water [35].

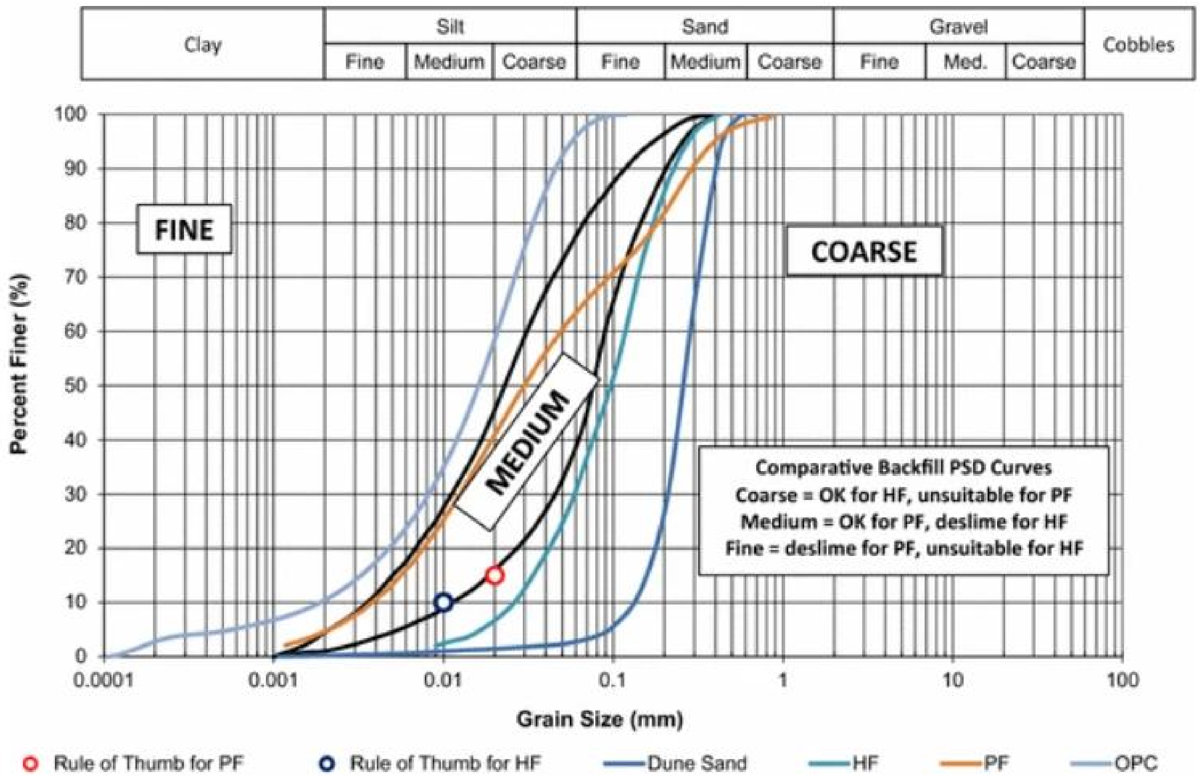
Figure 9. *Hydraulic backfill in open stope: where a slurry mixture is introduced through a fill hole, allowing the solid materials to settle at the bottom while excess water rises to the top. A drainage system is in place to manage the decant water, ensuring stability and preventing flooding. [35]*



The grain distribution in hydraulic backfill comprises sandy silt and silty sand (SM-ML), with the clay component being eliminated through a process known as desliming. This involves passing the entire backfill material through hydro cyclones in a circulation process, whereby the clay fraction is separated and subsequently disposed of in the tailings dam. The deslimed silty sandy backfill material, now in slurry form, is then conveyed to underground voids via pipelines [10]. Although a higher concentration of solid material can reduce the water content in the drained status of the hydraulic backfill, it poses challenges for the smooth transportation of the slurry through pipelines. In current practices, a solid content of 75-80% is typical; however, with a 75% solid content and a specific gravity of 3, water would comprise nearly 50% of the slurry's volume, necessitating drainage facilities. This is often achieved by employing special porous bricks to construct barricades at draw points or horizontal drives [5]. Effective drainage is crucial in the design of hydraulic backfills, as oversight in this area has led to fatal accidents due to issues such as liquefaction, rush-ins, and piping problems, especially when porous barricades are not utilized [4]

[11]. The permeability threshold for hydraulic backfill material should exceed 100 mm/h, with higher values facilitating faster drainage from the backfilled stope [2].

Figure 10. *Grain size distribution of hydraulic backfill; comparative particle size distribution curves for different backfill materials, categorizing them into coarse, medium, and fine gradations based on grain size. It illustrates the suitability of each material type for hydraulic fill and paste fill, with markers indicating the 'Rule of Thumb' for each fill type. [13]*[5]



Laboratory experiments and field observations conducted by various researchers have indicated that the permeability threshold recommended by Herget and De Korompay (1978) is on the conservative side. Specifically, Sivakugan et al. (2016) found that permeability values within the range of 7-35 mm/h, obtained under controlled laboratory conditions, yielded satisfactory outcomes in stopes, attributed to the higher values that occur under in-situ conditions.[19] Furthermore, Kuganathan (2011) and Brady and Brown (2022) have posited that permeability values between 30-50 mm/h are significantly greater than those measured in controlled laboratory

[5] From 20 mines in Australia and cemented hydraulic and paste backfills

settings for analogous backfills. [23] [31] [38] The strength and stiffness of hydraulic backfill are intrinsically linked to the relative density of the backfill material, determinable through both laboratory and in-situ testing, with laboratory tests preferred for their cost-effectiveness and simplicity. Among these tests, maximum and minimum dry density tests, direct shear tests, and oedometer tests are instrumental in assessing the strength and stiffness of hydraulic backfill materials [1].

The barricade bricks utilized to contain hydraulic backfill in underground mines are specially fabricated using a mixture of gravel, sand, cement, and water, in an approximate ratio of 40:40:5:1, respectively. Traditionally, barricade walls are erected in a vertical plane; however, recent practices involve constructing them in a curved fashion to bolster their strength, orienting the convex side towards the hydraulic backfill [31]. Illustrative examples of such barricade bricks and walls are depicted in figure 4. Although barricade brick manufacturers typically assure a minimum strength of 10 MPa, research by Sivakugan et al. (2016) reported an average uniaxial compressive strength of dry bricks ranging between 6 and 10 MPa. Moreover, the compressive strength of the bricks diminishes by approximately 25% upon wetting, with no significant disparity in strength loss observed between 7 and 90 days of wetting, indicating that the reduction in strength occurs immediately upon moisture exposure [10].

Figure 11. *(a) Porous barricade brick [12]*

Figure 12. *(b) Curved barricade wall [12]* [6]

[6] Retrieved from: Sivakugan *et al*, 2006

Hydraulic backfilling has found significant application in underground coal mining methods, specifically in the room and pillar or bord and pillar techniques utilized in the Wyoming region of the USA. The primary purpose of this technique is to prevent surface subsidence, such as sinkholes or trough subsidence, in abandoned coal mines in the Wyoming area [42]. For instance, at the Hannah mine in Wyoming, hydraulic backfilling was employed to completely fill the voids with granular material obtained from spoils of abandoned coal mines. Notably, it has been observed that hydraulic backfilling yields more favorable results in voids located below the groundwater table compared to dry voids in the Wyoming region. Furthermore, mining areas with lower rubblized zones have the capacity to accommodate a larger volume of backfill material due to better water drainage conditions [12].

Cemented hydraulic fill has proven to possess stronger compressive strength, thereby providing improved structural support in underground mining. Cut and fill applications typically require a strength of 1 MPa, while pillar recovery necessitates a strength of 5-7 MPa [35]. The addition of cement can increase the strength by up to 16% to achieve maximum stiffness. Emplacing cemented hydraulic fill can be done using two primary methods: (I) thoroughly mixing the cement in a hopper and hydraulically placing it, and (II) percolating cement slurry over a previously placed mixture of coarser minerals, which is suitable for backfill containing a mixture of different materials.

Arching is an occurrence where certain parts of a material that experiences friction start to fail, but the surrounding areas remain intact. When the failing material moves towards the neighboring walls that are stable and unyielding, the movement within the yielding material is countered by resistance along its boundaries. This resistance, along with the shear stress that develops along the contact surface, effectively keeps the yielding materials in their original positions. This whole process creates a condition known as arching, where the vertical normal stresses within the yielding material are established. Sivakugan (2016) conducted an analysis using FLAC to investigate the arching effects in hydraulic backfilled materials in narrow and circular stopes. Their aim was to modify and compare their findings with analytical solutions previously developed by other researchers [35].

The arching phenomenon can be studied using various analytical methods, including the Free Standing Vertical Face method, the Vertical Slope method, the 3-D Sliding Wedge Failure method, the Simple Arching Theory and its modifications, and the Modified Simple Arching method. In terms of numerical modeling, Pirapakaran and Sivakugan (2016) assumed that the rock mass was homogenous, isotropic, and linearly elastic, while the backfill material followed the Mohr-Coulomb failure criterion. They did not include interface elements in their model construction. The dimensions of the stope and the properties of the rock and backfill are shown in Figure 5. The rock region was modeled to achieve equilibrium under its own weight before the stope was mined out, and FLAC calculations were used to bring it to an equilibrium state [35].

The emplacement of hydraulic backfill in different layers improved performance compared to the model by Li et al. (2023) [42]. For more details on initial stress and strain considerations, could be referred to the publication by Pirapakaran and Sivakugan (2016). The modeling also included stopes with dimensions of 10 m width and 60 m height, using the same material properties for further analysis [35]. Figures in their study illustrate the vertical and horizontal stress patterns in the stope and adjacent rock after the backfill was completely emplaced, with results closely resembling those projected by Li et al. (2023). This indicates a non-uniform distribution across the width of the stope [42].

Figure 13. *Scheme of stope and rock and backfill material properties used for numerical modeling of arching [42]*

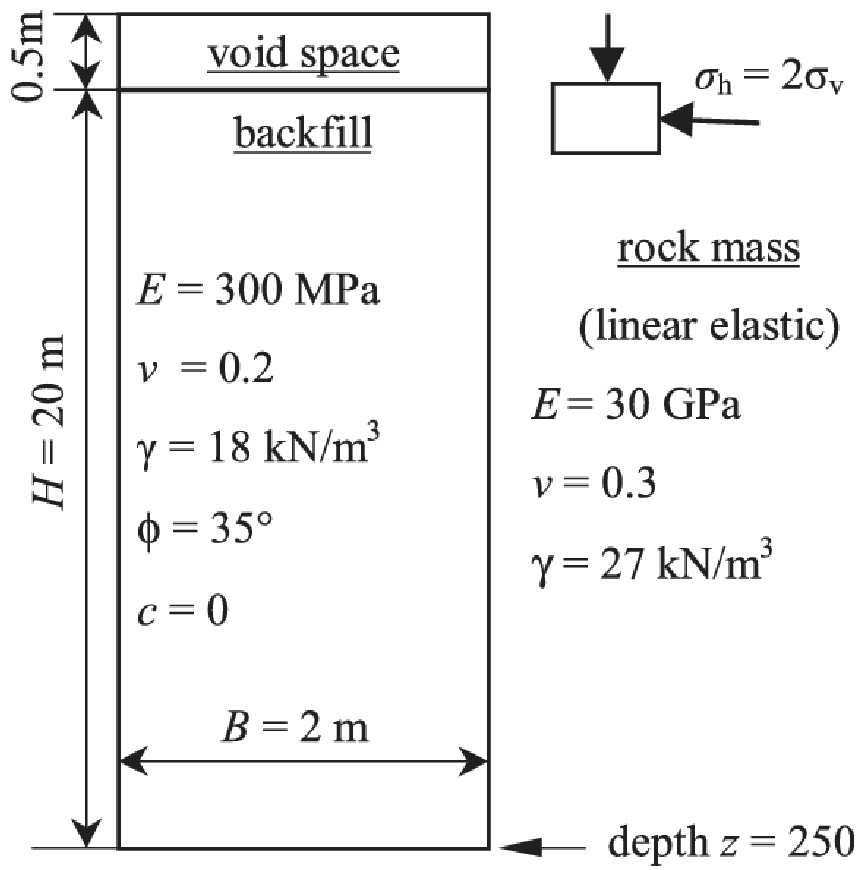
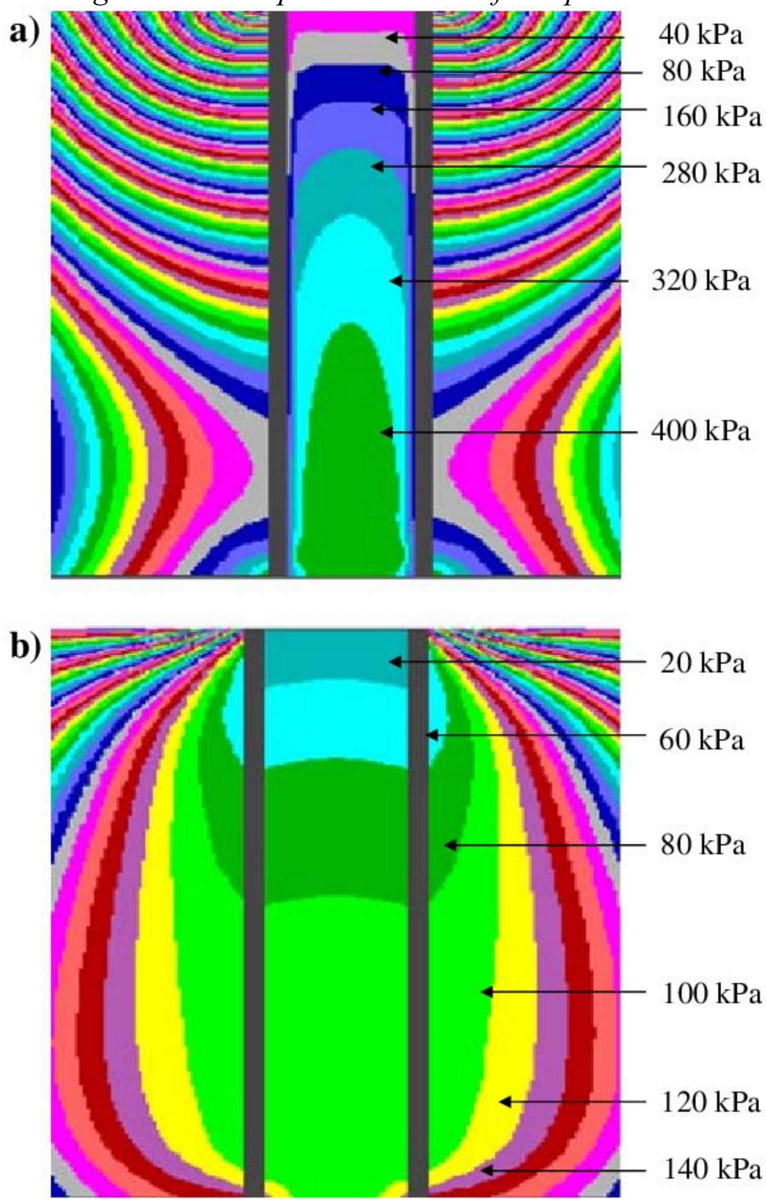


Figure 14. *Normal stress distribution contours within backfill and surroundings from FLAC. Panel (a) represents the initial stress states at various depths with pressure levels indicated in kilopascals (kPa), showing the contours of equal stress around the stope. Panel (b) illustrates the altered stress distribution after backfilling, with the corresponding pressures at different depths, highlighting the stress gradients and potential zones of compaction within the fill material.*[7]



The impact of incorporating backfill in different configurations, such as single layer, half layers, quarter layers, and 1-meter layers, on the alteration of vertical stress with depth along the centerline of the stope is shown in figure 7. A closer analysis of this figure reveals that when the stope is filled in a single layer, the vertical stress exceeds the stress caused by the overburden, especially

[7] (a) Vertical stresses (b) Horizontal stresses

in the upper third part of the stope. However, this effect is significantly reduced when the backfilling process is divided into two layers and completely eliminated when multiple layers are used. The results obtained from these simulations demonstrate a significant improvement compared to the numerical models by Li et al. (2023), where the vertical stress does not surpass the overburden pressure when more than four layers of backfill are used[1] [3]. This suggests that dividing the backfilling process into multiple layers effectively reduces the concentration of stress in the upper sections of the stope, thereby enhancing the stability and safety of the backfilling operation.

Figure 15. *A vertical backfilled opening with acting forces on an isolated layer element On the left, the dimensions of the stope are defined: height (H), width (B), and length (L), with a differential height (dh) representing the layer of backfill material. The right side of the figure details the forces acting on a differential layer element within the backfill stope, including vertical stress (V), shear stress (S), and the corresponding changes in these stresses (dS) and volume (dV), illustrating the mechanical analysis of backfill stability and stress distribution in an underground mine [21]*

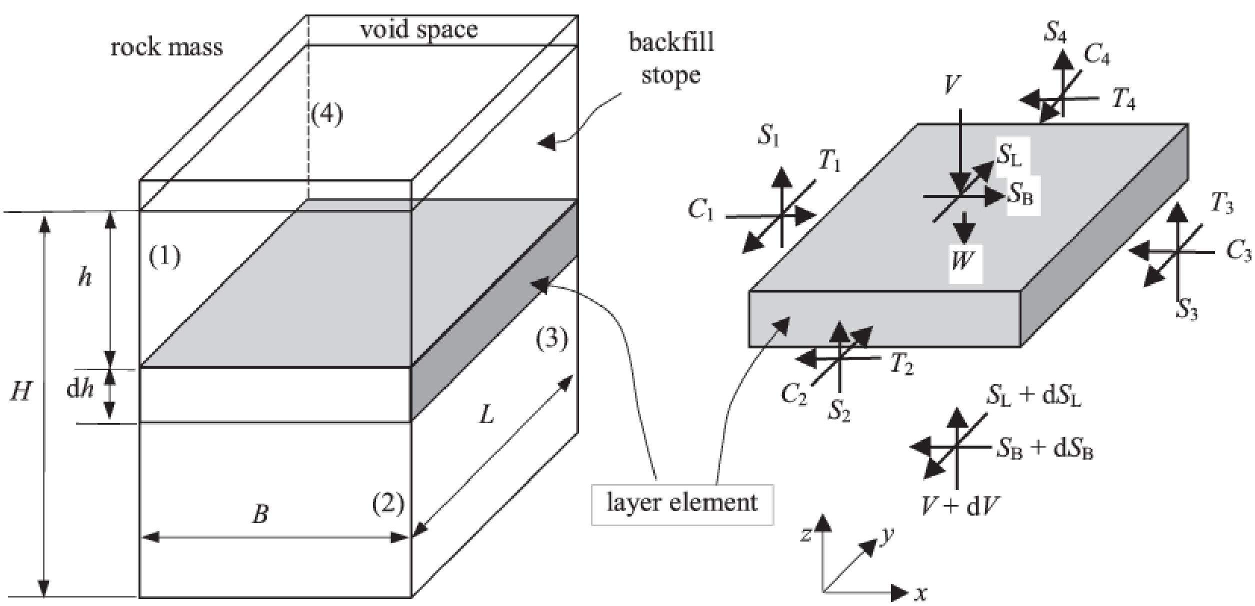
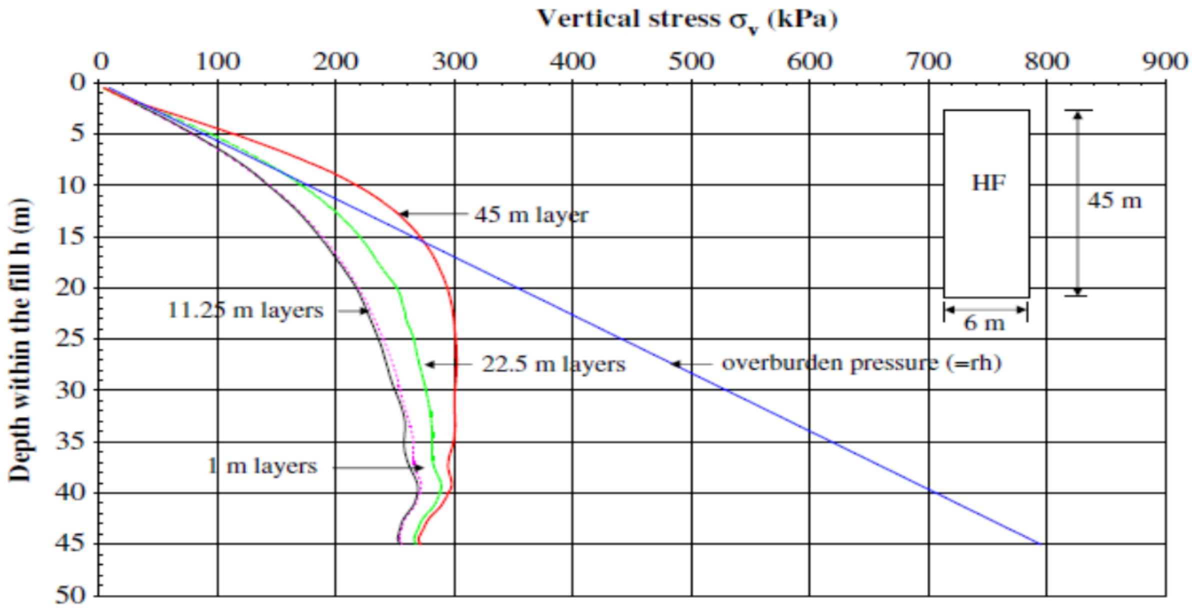


Figure 16. *Change of vertical normal stress along the center line of narrow stope in various thickness of backfill layers [13]*



The results of numerical modeling have shown that stress levels in the upper third of the stope remain consistent regardless of the friction angle of the backfill material. However, when the friction angles are 40 and 45 degrees, there is a slight decrease in stress between 1/3 and 4/5 of the stope's height. Interestingly, at the bottom level of the stope, there is a significant deviation from the expected stress changes according to analytical methods. This suggests that there is a unique behavior in this area that goes against established predictions. This finding emphasizes the importance of further investigation to fully understand the factors driving these stress changes in the lower levels of the stope. The variation in stress distribution highlights the complexity of geomechanically responses in backfilled stopes and emphasizes the need for ongoing research to enhance our understanding of backfill behavior and its impact on mine stability.

2.2.2 Pneumatic Backfilling

The use of compressed air to transport dry or slightly moistened backfill materials through pipelines in mining operations, known as pneumatic backfilling, is a highly significant method. This technique is particularly remarkable due to its limited dependence on water, making it an environmentally friendly solution. It is especially suitable for arid regions or situations where water resources are scarce or adding water to mine voids could result in environmental or structural issues.

Pneumatic backfilling is a practice that involves using compressed air to propel materials like sand, fly ash, or crushed rock, enabling the efficient filling of underground spaces. One of the key advantages of this method is its versatility, as it can handle different types of backfill materials, allowing for the selection of the most suitable, cost-effective, and environmentally friendly options. This adaptability enhances the overall performance of pneumatic backfilling, ensuring stability within the mine structure and making a significant contribution to both safety and operational efficiency [39].

Although pneumatic backfilling offers many benefits such as lower water usage and reduced risk of contaminant leaching compared to traditional backfilling methods, it does come with its fair share of challenges. One major obstacle is the significant initial investment required for the necessary equipment, including air compressors and extensive pipeline networks [15]. Furthermore, operating this equipment requires specialized skills and expertise, potentially adding to the overall cost of training and labor. Another issue is the generation of substantial dust during the transportation of dry materials, which raises concerns for worker health. To address this, effective dust management strategies must be implemented to minimize respiratory risks.

The implications for the environment when it comes to pneumatic backfilling are a combination of positive and negative effects. One positive aspect is that this technique helps to conserve water, which is particularly important in areas where water is scarce, and aligns with sustainable mining practices [37]. However, there are also negative aspects to consider, such as the energy consumption involved in operating air compressors and the potential for generating dust. It is crucial to manage these factors carefully in order to keep the overall environmental impact of this method low. This can be achieved by implementing effective measures to control dust, such as using ventilation systems and dust suppressants, as well as selecting machinery that is energy-efficient. By taking these steps, we can minimize the adverse effects on the environment.

2.2.3 Mechanical Backfilling

Mechanical backfilling plays a crucial role in contemporary mining operations as it relies on various physical mechanisms, including conveyor belts, trucks, and heavy machinery, to effectively transport and deposit backfill material into the empty spaces left behind by mining activities. Unlike other backfilling methods, mechanical backfilling offers a direct and precise approach to the distribution of materials, thereby ensuring the utmost stability and safety of mining structures.

Mechanical backfilling is characterized by its adaptability and accuracy. Unlike hydraulic or pneumatic methods that depend on the force of fluids or air to transport backfill materials, mechanical backfilling employs tangible machinery to transfer materials from one location to another[43]. This method enables the meticulous placement of backfill, guaranteeing that particular sections within a mine can be specifically targeted and filled according to precise specifications. The range of materials utilized in mechanical backfilling is extensive, encompassing everything from waste rock and tailings to specialized engineered backfills. This diversity allows for flexibility in addressing the unique environmental and structural requirements of each mining operation [27].

Mechanical backfilling offers numerous advantages due to its ability to adapt to different mining environments. Whether it is being used in open-pit or underground settings, mechanical methods can be customized to meet the specific logistical and spatial limitations of the site. Additionally, this approach significantly reduces the reliance on water, making it particularly appealing for mining operations in arid regions or where water conservation is a critical concern [34]. Moreover, the precise placement of backfill aids in maximizing ore recovery and effectively managing and controlling subsidence, ultimately enhancing the overall efficiency of mining activities.

Nevertheless, there are certain difficulties associated with mechanical backfilling. One major challenge is the considerable upfront cost involved in acquiring the required equipment. Furthermore, the ongoing expenses, such as maintenance and fuel, can be quite substantial.

Moreover, the physical characteristics of the machinery necessitate sufficient room for maneuvering and operation, which may not always be feasible in confined underground spaces. Additionally, the use of heavy machinery raises concerns regarding energy consumption and carbon emissions, which have become increasingly significant in the worldwide endeavor to mitigate and combat climate change.

2.3 Environmental and Sustainability Considerations

In the exploration of mining backfilling methods, environmental and sustainability considerations emerge as among important factors. These considerations influence the selection and application of backfilling techniques, with a keen focus on their environmental impacts and the potential for enhancing sustainability. This section investigates the comparative analysis of various backfilling methods, emphasizing their ecological footprints and the pursuit of innovations aimed at fostering sustainability.

The environmental repercussions associated with mining backfilling vary significantly across different materials and methodologies. Cementitious backfills, noted for their structural integrity, are concurrently associated with substantial carbon footprints, primarily due to the manufacturing processes of Portland cement. Conversely, silica alumina-based and rockfill backfills, especially those derived from industrial by-products or mining waste, exhibit considerably lower environmental impacts [37]. This dichotomy underscores a growing trend towards sustainable practices within the mining sector.

__Table 3.__ Environmental Impact and Sustainability of Backfilling Materials [37]

Material Type	**Environmental Impact**	**Sustainability Benefits**
Cementitious Backfill	High CO_2 emissions due to Portland cement production.	-
Silica Alumina-based	Lower environmental impact through the utilization of industrial by-products.	Minimizes landfill use, conserves resources.
Rockfill	Minimal environmental impact when utilizing mining waste.	Encourages the reuse of on-site materials, reducing external waste.

Innovations in backfilling techniques are focused on improving operational effectiveness and minimizing environmental impact. Hydraulic backfilling, for example, encourages the recycling of tailings to reduce the need for new mining sites and minimize waste generation. While pneumatic backfilling requires a lot of energy, it provides more precise material placement, improving the efficiency and sustainability of the process. Mechanical backfilling has also seen advancements in energy efficiency, further enhancing the sustainability of mining activities [42].

Figure 17. *CO_2 void space pressure variation under different initial water-binder ratio by depicting the pressure decay over 48 hours for two cementitious backfill mixtures, each with an initial pressure of 1 MPa. The solid blue line tracks a mixture containing 30 grams of cement, 15 grams of water, and 0.5 grams of aluminum, while the dashed red line follows a similar mixture with reduced water content at 10 grams. The comparison illustrates the effect of water content on the rate of pressure decrease, related to the setting and strength development of the backfill over time. [44]*

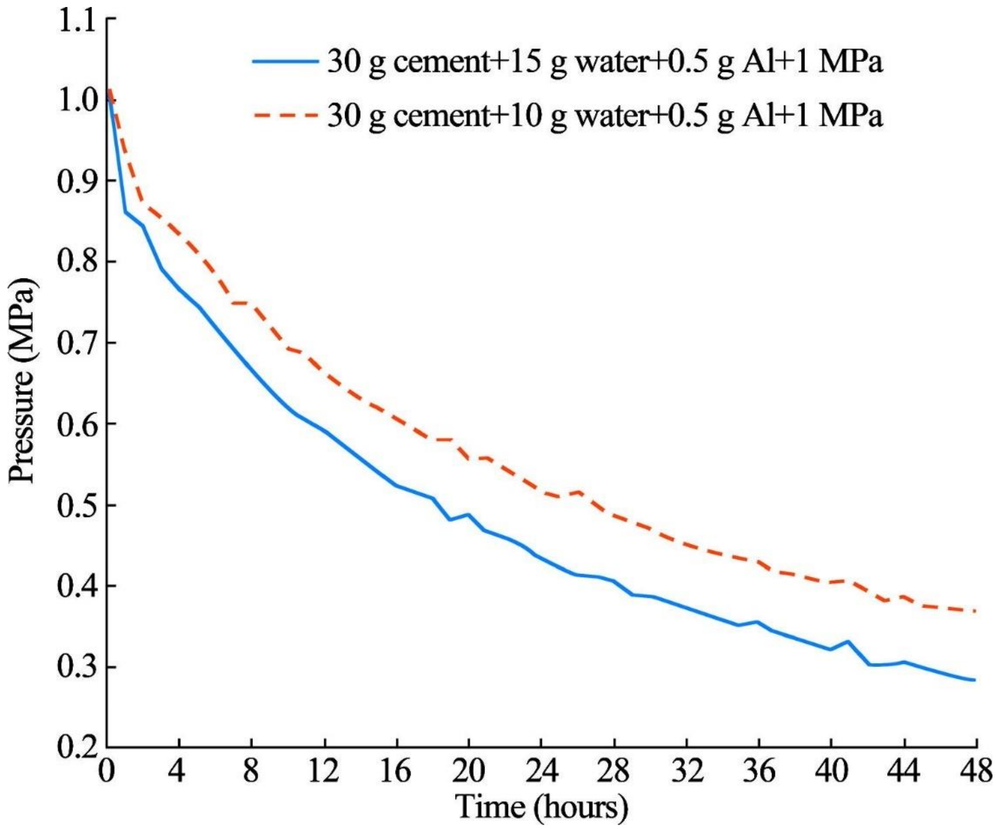
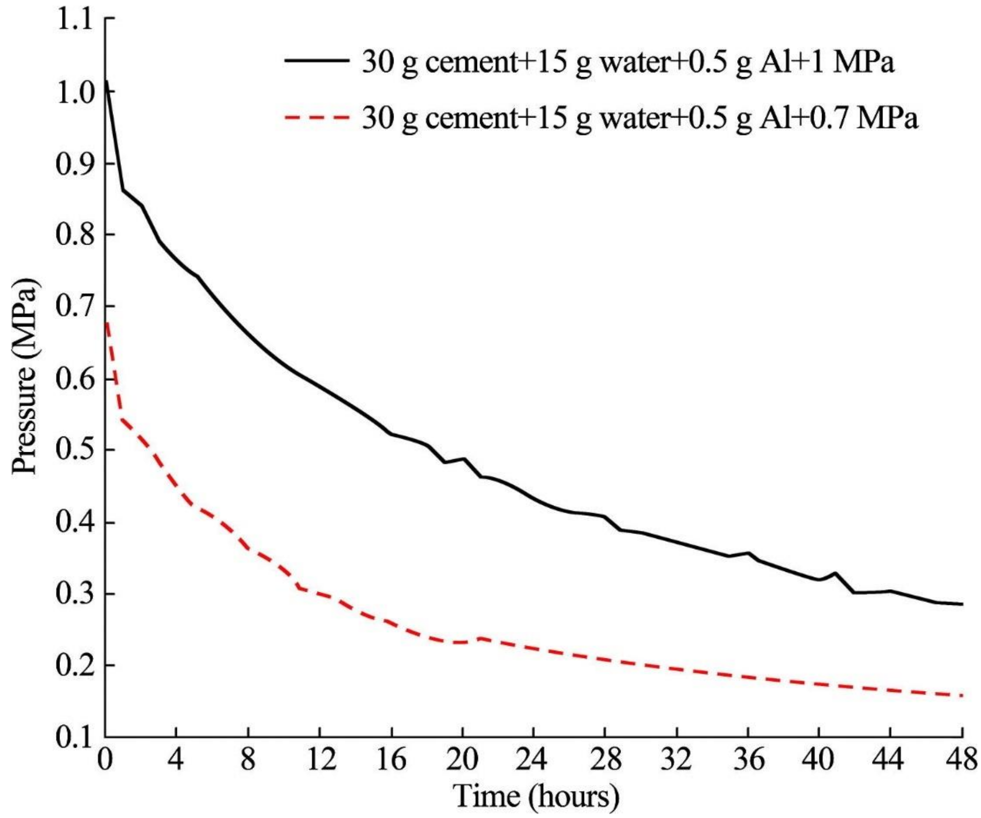


Figure 18. *CO_2 void space pressure variation under different initial CO_2 pressure. The solid black line indicates a backfill mixture with 30 grams of cement, 15 grams of water, and 0.5 grams of aluminum, while the dashed red line represents the same mixture with an increased aluminum content of 0.7 grams, both initiated at 1 MPa. This demonstrates how varying aluminum content influences the material's pressure behavior and, by implication, its setting time and strength development. [44]*



The research conducted by [44] investigated three principal factors that could significantly influence the accelerated diffusion of CO2 and carbonation in cement-based materials. Utilizing the CTPRC system along with two other analytical methods, ESEM and XRD, it was demonstrated that the initial water-to-binder ratio, porosity, and CO2 pressure are determinants in the acceleration of carbonation. The water-to-binder ratio plays a crucial role in the chemical reactions occurring throughout the experiments. Furthermore, the condition of initial pressure predominantly affects the external physical conditions during the process of mineral carbonation, whereas the initial porosity of the material facilitates alterations in the internal physical conditions of the specimen during carbonation.

In recent years, there have been significant improvements in energy recovery systems for pneumatic backfilling, which address concerns about its high energy consumption and minimize its negative impact on the environment. McCarthy's research has shed light on the latest advancements in pneumatic systems, demonstrating how these innovations contribute to more accurate and efficient material placement during backfilling operations, ultimately enhancing the sustainability of such practices. Similarly, mechanical backfilling methods have also undergone notable changes to improve energy efficiency. Lee and Kim have emphasized the integration of renewable energy sources as a particularly promising development in the pursuit of sustainable mining practices [15].

Despite the ongoing efforts to reduce the environmental impact of backfilling practices, there are still numerous challenges that need to be addressed. The energy demands of pneumatic and mechanical methods, as well as the carbon dioxide emissions resulting from the production of cement for cementitious backfills, highlight the urgency for further advancements. The future trajectory is focused on the creation of more eco-friendly substitutes for cement, improvement of backfilling techniques to maximize efficiency, and the investigation of sustainable materials that can be sourced locally for backfilling purposes.

The quantifiable potential of reducing CO2 emissions can be realized by adopting innovative backfilling materials and methods. The formula mentioned previously acts as a fundamental framework for measuring the environmental advantages that can be obtained by transitioning towards more sustainable backfilling practices.

Finally, delving into environmental and sustainability factors in mining backfilling reveals a range of obstacles and potential benefits. Despite the negative environmental effects of traditional backfilling processes, advancements in materials and techniques offer hope for mitigating these impacts. Achieving sustainability in mining requires a complex approach that involves continual research, creativity, and cooperation within the industry. Therefore, the insights and results of recent research not only demonstrate progress but also emphasize the need for ongoing dedication to this important issue.

III. ANALYSIS AND DISCUSSION

3.1 Advantages and Disadvantages of Different Backfilling Methods

The extensive examination of different backfilling techniques, such as cementitious backfill, silica alumina-based backfill, and rockfill, along with their respective application methods like hydraulic, pneumatic, and mechanical backfilling, provides a range of benefits and drawbacks that are crucial for improving underground mining processes. This analysis is important for understanding the complex nature of backfilling practices, which not only fill the empty spaces caused by mining but also contribute to environmental sustainability and the safety and structural stability of mining operations.

The use of cementitious backfill, which utilizes waste tailings, water, and cement, is a strong solution for providing structural support in underground mines. Its growth and acceptance show its effectiveness in improving safety conditions by creating columnar structures that uphold underground excavations. Nevertheless, the use of cement raises concerns regarding its impact on the environment because of the carbon emissions linked to its production. In spite of this, the creative application of cementitious backfill showcases a dedication to managing waste and protecting the environment, providing both operational safety and environmental preservation benefits.

The emergence of silica alumina-based backfill as a new alternative in the mining industry is gaining attention due to its utilization of industrial by-products like coal refuse and fly ash. This unique method not only offers environmental benefits but also contributes to the repurposing of waste materials, reducing the necessity for new mining operations and minimizing waste production. By undergoing a thermal activation process, the properties of this material are significantly enhanced, making it a feasible choice for sustainable mining practices. However, it is important to note that the thermal treatment required to optimize these characteristics may result in additional energy costs, potentially counteracting some of the environmental advantages it offers.

Rockfill, which is made from waste rocks, provides a simple and practical method for filling spaces and dealing with large amounts of waste materials. This technique has the added benefit of helping to reclaim land and reduce surface waste. However, there is a major concern about the potential release of harmful elements into the environment. While the straightforward and cost-effective nature of rockfill is appealing, it is crucial to consider the environmental consequences, such as the generation of dust and the leaching of dangerous substances, when using waste rocks for this purpose.

Hydraulic backfilling stands out for its ability to efficiently fill intricate underground areas by employing slurry mixtures. This technique is highly regarded for its contribution to the recycling of tailings and its alignment with environmental sustainability efforts. However, it is important to acknowledge the potential environmental risks associated with the release of contaminants and the proper management of surplus water, which highlights the necessity for meticulous control and the development of inventive strategies to minimize these hazards.

The utilization of compressed air in pneumatic backfilling presents a sustainable solution that reduces water consumption and provides an environmentally friendly option. This technique is especially beneficial in dry areas where water conservation is crucial. However, there are certain obstacles that need to be overcome in order to optimize the sustainability and efficiency of pneumatic backfilling, such as the significant energy consumption and the generation of dust. Therefore, it is essential to develop innovative technologies and implement effective dust management strategies to address these challenges.

Mechanical backfilling involves the utilization of advanced machinery to carefully and accurately deposit backfill materials, providing a level of adaptability and control that is unmatched. Although the method may require a substantial upfront investment and ongoing maintenance expenses, its exceptional precision and efficiency in material placement make it a practical choice for safeguarding the structural stability of mining activities. Additionally, there is a possibility of integrating renewable energy sources to power the machinery, which would further augment its environmental sustainability.

The importance of addressing environmental and sustainability concerns in mining backfilling practices highlights the need to find a delicate equilibrium between operational effectiveness, safety measures, and ecological responsibility. To promote sustainability in mining operations, it is crucial to embrace inventive materials and techniques that aim to decrease carbon emissions, preserve water resources, and recycle waste materials.

The table provided a comprehensive overview of the pros and cons associated with various backfilling techniques and materials, demonstrating the intricate balance between operational efficiency, safety measures, and environmental consequences. This detailed comparison is intended to assist mining engineers and environmental experts in making informed decisions when choosing the most suitable backfilling methods that adhere to sustainable mining principles.

Table 4. *Advantages and disadvantages of different backfilling methods and materials*[8]

Backfilling Method	**Advantages**	**Disadvantages**	**Environmental Considerations**
Cementitious Backfill	High structural support; Effective waste management	High carbon footprint of cement production	Utilizes waste materials; Requires innovations to reduce environmental impact
Silica Alumina-based Backfill	Utilizes industrial by-products; Potential for cost savings	Energy-intensive thermal activation process	Reduces waste generation; Requires energy management strategies
Rockfill	Cost-effective; Simplifies waste rock management	Potential for environmental contamination	Promotes land reclamation; Needs careful management of toxic elements
Hydraulic Backfilling	Efficient filling of complex spaces; Supports recycling of tailings	Potential release of contaminants; Water management issues	Encourages waste recycling; Demands innovative solutions for water and contaminant management
Pneumatic Backfilling	Minimizes water usage; Suitable for arid regions	High energy consumption; Dust generation	Conserves water; Requires advancements in energy efficiency and dust control

[8] Source: Own elaboration

Mechanical Backfilling	Precise material placement; Adaptable to various environments	High initial investment; Energy and maintenance costs	Potential for renewable energy use; Needs strategies for reducing carbon emissions

This analysis not only offers insights into the factors considered when choosing backfilling methods, but it also emphasizes the continuous requirement for research and development in the field of mining engineering. To achieve sustainable mining practices, a well-rounded approach is necessary, taking into account the operational, safety, and environmental aspects of backfilling. The objective is to enhance the effectiveness of mining operations while reducing their impact on the environment.

3.2 Selection Criteria for Backfilling Method

Choosing the right backfilling method for underground mining is a complex decision that depends on several important factors. These factors include the type and source of waste material, the direction of stoping, desired backfill properties, monitoring considerations, and the use of modeling techniques. All of these elements are crucial in ensuring the efficiency, safety, and environmental friendliness of backfilling operations.

The selection process takes into account the primary consideration of the origin of waste material. The physical and chemical properties of waste materials might vary, which affects their suitability for different backfilling methods. For example, waste materials produced in industrial processes, like fly ash and slag, may be appropriate for silica alumina-based backfills because of their pozzolanic properties. On the other hand, waste rocks from mining operations are commonly used in rockfill methods. The chemical composition of these materials, specifically their ability to produce acid mine drainage, is an important factor that requires thorough assessment.

The choice of backfilling method is influenced by the direction of stoping, whether it is upward or downward. Upward stoping requires backfill materials that can offer immediate structural support for sequential excavation and filling of stopes from the bottom up. Rapid setting and hardening materials like cementitious backfills are necessary for this. On the other hand, downward stoping allows for the use of backfills that may take longer to consolidate, such as hydraulic backfills, as the fill is placed after excavation is completed from the top down.

The anticipated characteristics of the backfill, including strength, permeability, and environmental stability, are crucial factors in the selection process. Backfills with high strength, like cemented paste backfills, are necessary in locations that need strong structural support. Permeability is important in hydraulic backfills to ensure proper drainage and prevent water accumulation and potential stability problems. Environmental stability refers to the backfill's ability to withstand chemical degradation and reduce the leaching of harmful substances, which is a key consideration in choosing environmentally-friendly backfill materials.

Ensuring the long-term stability and integrity of backfilled areas is a challenging task due to monitoring issues. It is crucial to have effective monitoring strategies in place to detect potential problems, such as subsidence or chemical contamination, at an early stage. This necessitates the incorporation of advanced sensor technologies and regular inspection routines to evaluate the condition of the backfill and the surrounding rock mass over a period of time.

Modeling techniques are essential in the planning and execution of backfilling operations as they offer valuable insights into the behavior of backfill materials under different conditions. These techniques, such as computational fluid dynamics for hydraulic backfills and finite element analysis for analyzing the structure of cemented backfills, assist in predicting the flow and settlement properties of backfills, optimizing material composition, and designing efficient placement strategies.

Table 5. *Types of backfill, highlighting their key characteristics and suitability for different mining scenarios*[9]

Backfill Type	**Origin of Waste Material**	**Suitable Stoping Direction**	**Desired Properties**	**Monitoring Challenges**	**Modelling Techniques**

[9] Source: Own elaboration

Cementitious Backfill	Industrial and mining waste	Upward	High strength, rapid setting	Subsidence, strength	FEA, material models
Silica Alumina-based	Industrial by-products	Both	Flowability, environmental stability	Chemical stability	CFD, chemical models
Rockfill	Mining waste rocks	Downward	Bulk strength, simplicity	Settlement, leaching	Empirical, FEA
Hydraulic Backfill	Tailings, industrial slag	Downward	Permeability, volume reduction	Water management	CFD, hydrological models
Pneumatic Backfill	Dry industrial and mining waste	Both	Low water usage, adaptability	Dust control	Fluid dynamics models
Mechanical Backfill	Varied	Both	Precision placement, versatility	Equipment maintenance	Mechanical models

This overview explains the complexities associated with choosing the most suitable backfilling method. The decision depends on the alignment between the source and properties of the waste material, the specific needs of the mining operation, and the overall objectives of environmental sustainability and operational efficiency. Additionally, the utilization of advanced monitoring and modeling techniques improves the ability to forecast and control the behavior of backfill materials, thus guaranteeing the safety and stability of underground mining activities. Finally, choosing a backfilling method is a complex process that requires a deep understanding of the materials, mining conditions, and desired results. By strategically incorporating monitoring and modeling tools, backfilling operations can be optimized, leading to safer, more efficient, and environmentally friendly mining practices.

3.3 Recent Advancements and Innovations in Backfilling Technology

The field of mining engineering has been greatly influenced by recent advancements and innovations in backfilling technology, which have opened up new opportunities for improving the efficiency, safety, and environmental sustainability of underground mining operations. These progressions are linked to changes in the types of backfill, how they are used in different mining situations (such as upward or downward stoping), the sourcing and treatment of waste materials, the desired characteristics of backfills, and the challenges of monitoring and modeling these systems.

The ongoing development of backfilling techniques demonstrates a collaborative push to tackle the inherent difficulties of underground mining, such as the necessity for enhanced structural support, environmental conservation, and resource optimization. Progress in the formulation and implementation of backfill materials has resulted in the creation of more versatile, durable, and eco-friendly backfill options. These improvements play a vital role in prolonging the lifespan of mines, minimizing the environmental impact of mining operations, and guaranteeing the safety of underground activities.

One of the noteworthy progressions in this field involves improving the characteristics of materials in cementitious backfills by incorporating innovative additives and binders. Scientists have investigated the utilization of industrial by-products like fly ash and slag as substitutes for Portland cement, with the aim of enhancing the mechanical properties of backfills and reducing the environmental consequences of cement manufacturing. This strategy not only utilizes waste materials for a beneficial purpose but also promotes a circular economy by minimizing waste.

Significant advancements in backfill placement techniques have been made, particularly in challenging mining configurations. Improvements in hydraulic and pneumatic backfilling systems have enhanced the delivery and distribution of materials, resulting in more uniform compaction and increased stability of filled voids. These developments are crucial for both upward and downward stoping operations, where the direction of mining dictates the choice of backfill material and application method. Upward stoping benefits from fast-setting backfills for immediate structural support, while downward stoping allows for slower settling backfills to gain strength over time.

There has been a shift towards more sustainable practices in the origin of waste material, with a growing focus on using locally sourced and environmentally friendly materials. The mining industry's dedication to reducing its environmental impact is evident in the exploration of alternative waste materials for backfilling, such as recycled construction debris, processed mine waste, and other unconventional materials that are suitable for backfilling purposes.

The expected qualities of backfill materials have progressed to meet more stringent performance standards, such as increased compressive strength, improved flowability, and enhanced environmental stability. These characteristics are crucial for guaranteeing the durability and sustainability of backfilling processes over time. Additionally, creating backfills with customized properties to fit particular geological and operational circumstances is a major advancement in tailoring mining solutions.

The monitoring and modeling of backfill operations have greatly improved thanks to technological advancements, which now include advanced sensors, real-time data analytics, and sophisticated computational models. These tools allow for more efficient monitoring of backfill conditions, early identification of potential problems, and more precise forecasting of backfill behavior. By incorporating these technologies, a proactive approach to managing the challenges of backfilling is enabled, leading to enhanced control over the quality and performance of backfill operations.

Modelling techniques have become more advanced, as they now include intricate physical and chemical interactions within backfills. Computational models are now capable of simulating various scenarios, such as the flow of hydraulic backfills and the structural response of cemented backfills when subjected to a load. These models are extremely valuable in optimizing the design of backfills, predicting their performance, and evaluating potential effects on mine stability and safety.

Table 6. *Advancements and innovations in backfilling technology, highlighting their impact*[10]

[10] Source: Own elaboration

Advancement/Innovation	Impact on Mining Industry
Use of industrial by-products	Reduces environmental impact; enhances backfill properties
Improved application techniques	Increases efficiency and precision of backfill placement
Exploration of alternative waste materials	Promotes sustainability; reduces reliance on traditional materials
Development of backfills with tailored properties	Enhances performance; meets specific operational needs
Advanced monitoring and modelling tools	Improves management and prediction of backfill behavior

The advancements in mining engineering discussed here signify a major advancement in the field. Finally, the significance of ongoing innovation in addressing the challenges of modern mining operations is highlighted by the ever-changing landscape of backfilling technology. The utilization of advanced materials, advanced application methods, and state-of-the-art monitoring and modeling techniques has the potential to revolutionize backfilling practices, rendering them more efficient, safer, and environmentally sustainable. As the mining industry progresses, these advancements will be vital in determining the future of underground mining, ensuring a balance between operational requirements and environmental responsibility.

3.4 Challenges and Future Trends in Backfilling Practices

The investigation of backfilling techniques in the mining industry reveals a changing landscape marked by continuous development and creativity, with the goal of tackling the many challenges faced by modern mining operations. These challenges include the need for sustainable use of materials, efficient backfilling methods, safe and structurally sound mining operations, and the environmental impact of mining activities. To address these challenges, the industry has utilized advancements in technology, material science, and engineering practices, resulting in significant advancements in backfilling. This progress not only demonstrates the industry's dedication to excellence and environmental responsibility but also highlights the complexity of incorporating different backfilling strategies into various mining situations.

The future of backfilling practices is positioned at the junction of technological advancement, environmental sustainability, and economic feasibility. Therefore, a thorough knowledge of current technology, the characteristics of backfill materials, the operational contexts of upward and downward stoping, and the wider implications of these practices on mine stability, environmental integrity, and resource management is necessary to address the upcoming trends and challenges in backfilling practices.

One major challenge that stands out in the near future is the sourcing and optimization of materials used for backfilling. The mining sector is now relying more on waste materials for backfilling purposes, not just to lessen environmental harm but also to improve the cost-effectiveness of mining activities. The source of these waste materials, which can range from industrial leftovers to treated mine waste, offers both advantages and difficulties in terms of their accessibility, processing needs, and appropriateness for different backfilling tasks.

Research and development efforts are focused on improving the strength, durability, and environmental performance of backfill materials. This includes integrating new additives and binders, developing new material formulations, and exploring alternative waste materials. These advancements aim to meet the structural needs of mining operations and also address environmental challenges related to backfilling practices.

Monitoring and modeling are now essential elements of successful backfilling strategies in the mining industry. They allow for the prediction, evaluation, and enhancement of the performance of backfill materials in real-time. Advanced monitoring systems, which come with advanced sensors and analytical tools, offer data on how backfill materials behave under different operational circumstances. Modeling methods, such as computational fluid dynamics and finite element analysis, have been crucial in simulating the intricate relationships between backfill materials, mine infrastructure, and geological formations.

Table 7. *Key frameworks that shape the future trends and challenges*

Framework Component	**Description**
Backfill Types	Diversity of materials used for backfilling, including cementitious, silica alumina-based, rockfill, hydraulic, pneumatic, and mechanical backfills.
Stoping Direction	Differences in backfilling strategies for upward and downward stoping, influencing the choice of materials and methods.
Waste Material Origin	The shift towards sustainable sourcing of backfill materials from industrial by-products and mine waste.
Expected Properties	Advances in material science aimed at enhancing the strength, durability, and environmental performance of backfill materials.
Monitoring Issues	The development of sophisticated monitoring systems to assess the performance and stability of backfilled areas.
Modelling	The use of advanced modeling techniques to simulate the behavior of backfill materials and optimize backfilling operations.

In the mining industry, the future of backfilling practices is characterized by a mix of challenges and opportunities. Advances in material science, engineering, and environmental science have led to the development of more efficient, safer, and environmentally friendly backfilling technology. As the industry faces the complexities of modern mining, the ongoing innovation and implementation of backfilling strategies will be crucial in shaping a sustainable future for mining operations.

CONCLUSIONS

Throughout this thesis, the exploration of mining backfilling methods has provided a detailed overview of the different techniques and materials used to address the physical voids created by mining activities. This comprehensive study has not only shed light on the various backfilling strategies but has also emphasized the significance of these practices in improving the safety, efficiency, and environmental sustainability of mining operations. The complex relationship between the selection of backfill types, the direction of stoping, the origin and processing of waste materials, and the desired properties of backfills has been thoroughly examined, offering valuable insights into the current state and future prospects of backfilling technology.

The thesis began by providing an introductory overview of various types of backfill, including cementitious, silica alumina-based, rockfill, hydraulic, pneumatic, and mechanical backfills. This classification laid the groundwork for understanding the complex nature of backfilling practices and how they are used in different mining situations. The conversation underscored the importance of backfill materials in offering structural support, aiding in ore extraction, and reducing environmental effects, highlighting the significant role of backfilling in the mining sector.

Examining upward and downward stoping highlights the operational differences between these mining techniques and their impact on backfilling practices. The choice of a suitable backfill method is greatly influenced by the direction of stoping, as each method presents unique advantages and challenges. Upward stoping requires fast-acting backfills for structural support, whereas downward stoping permits the use of materials that take longer to settle and harden. This underscores the importance of customizing backfilling strategies to individual mining operations.

The emergence of waste material's origin as a crucial aspect of backfilling highlights the industry's transition towards more sustainable practices. The use of industrial by-products and processed mine waste not only decreases the environmental impact of mining activities but also improves the economic efficiency of operations. This environmentally responsible approach to obtaining backfill materials demonstrates the industry's dedication to preserving the environment and conserving resources.

Key factors in the selection and optimization of backfill materials include the expected properties of strength, durability, and environmental stability. Backfill materials have been developed with enhanced performance characteristics, specifically designed to meet the structural and environmental needs of mining operations, thanks to advancements in material science. The conversation about anticipated properties highlighted the significance of material innovation in advancing the technology of backfilling.

Monitoring and modeling are emphasized as crucial elements of successful backfilling strategies. Cutting-edge monitoring systems and computational models offer valuable information on the behavior of backfill materials, allowing for the prediction, evaluation, and enhancement of backfill performance. Incorporating these technologies into backfilling procedures enables a proactive method for handling the challenges of backfilling, guaranteeing improved oversight and effectiveness of operations.

Finally, the field of mining backfilling methods is constantly evolving and improving through the use of sustainable materials, advanced techniques, and cutting-edge tools. The future of mining backfilling depends on advancements in technology, refining strategies, and a commitment to excellence in both environmental and operational aspects. Backfilling will continue to play a crucial role in ensuring the stability, safety, and sustainability of mining operations as the industry faces modern challenges. This thesis offers a thorough analysis of current practices and suggests potential innovations for future research and development in mining engineering.

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APPENDIX

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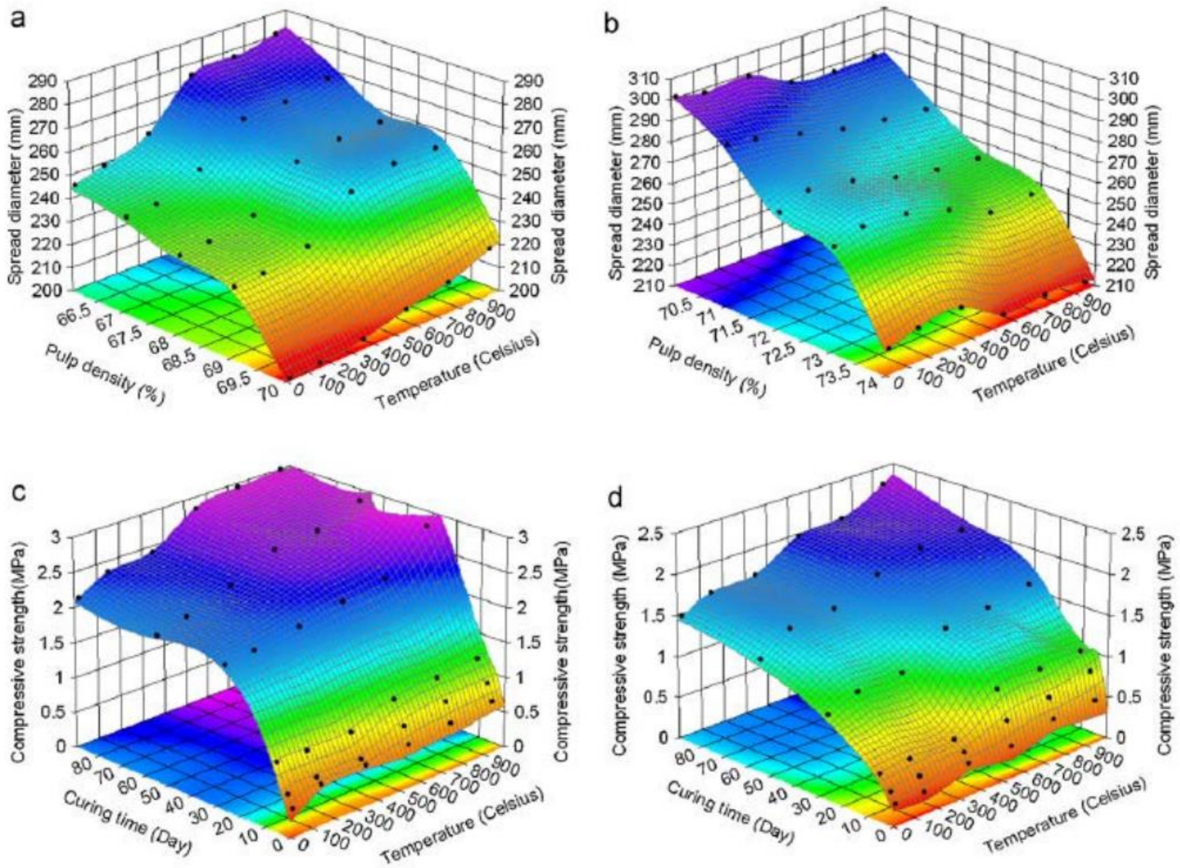

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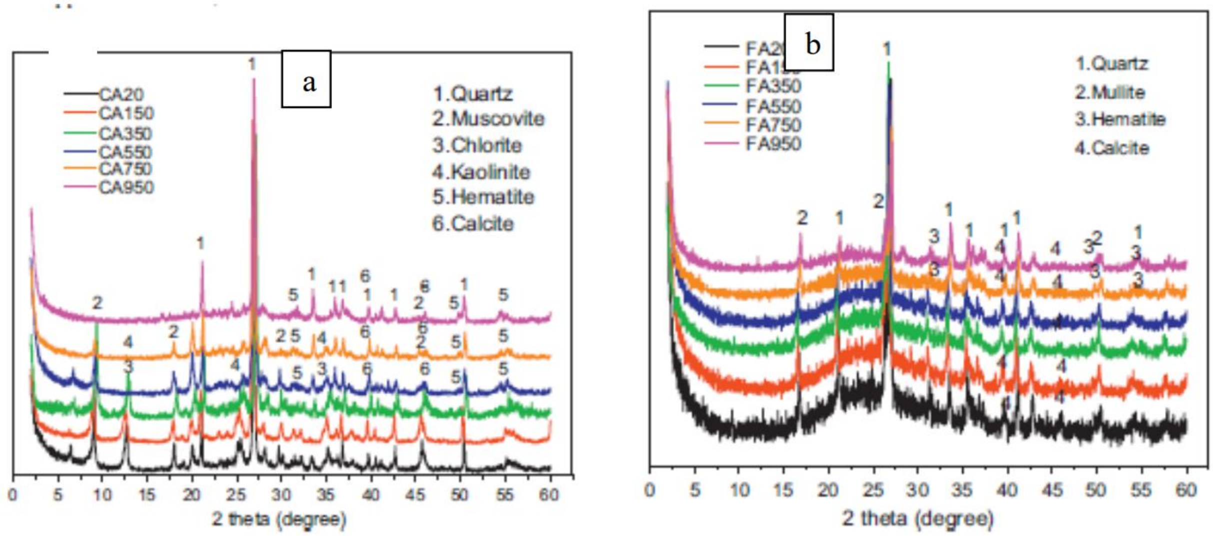

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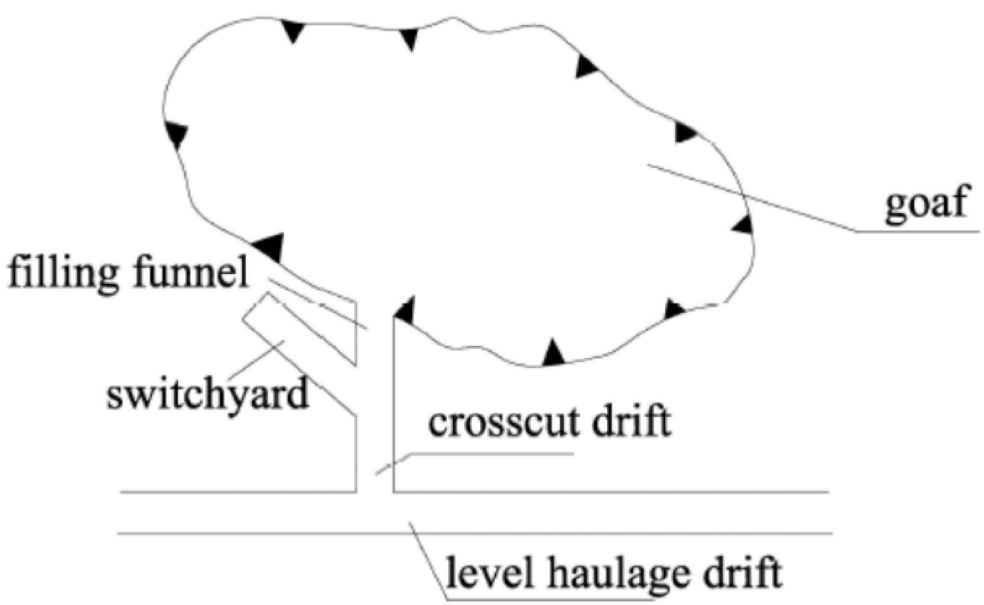

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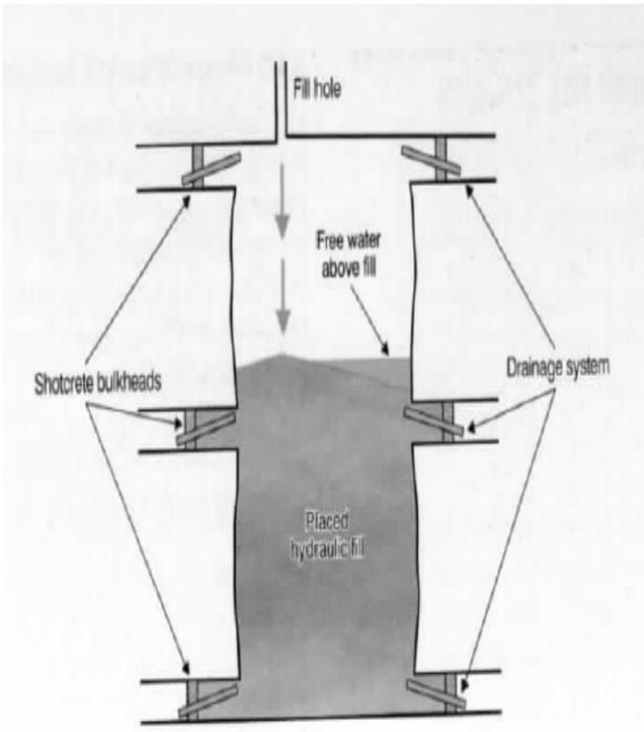

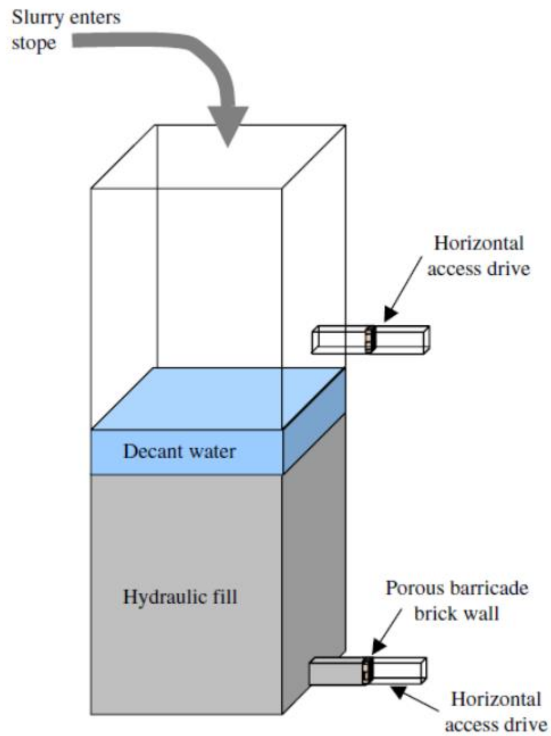

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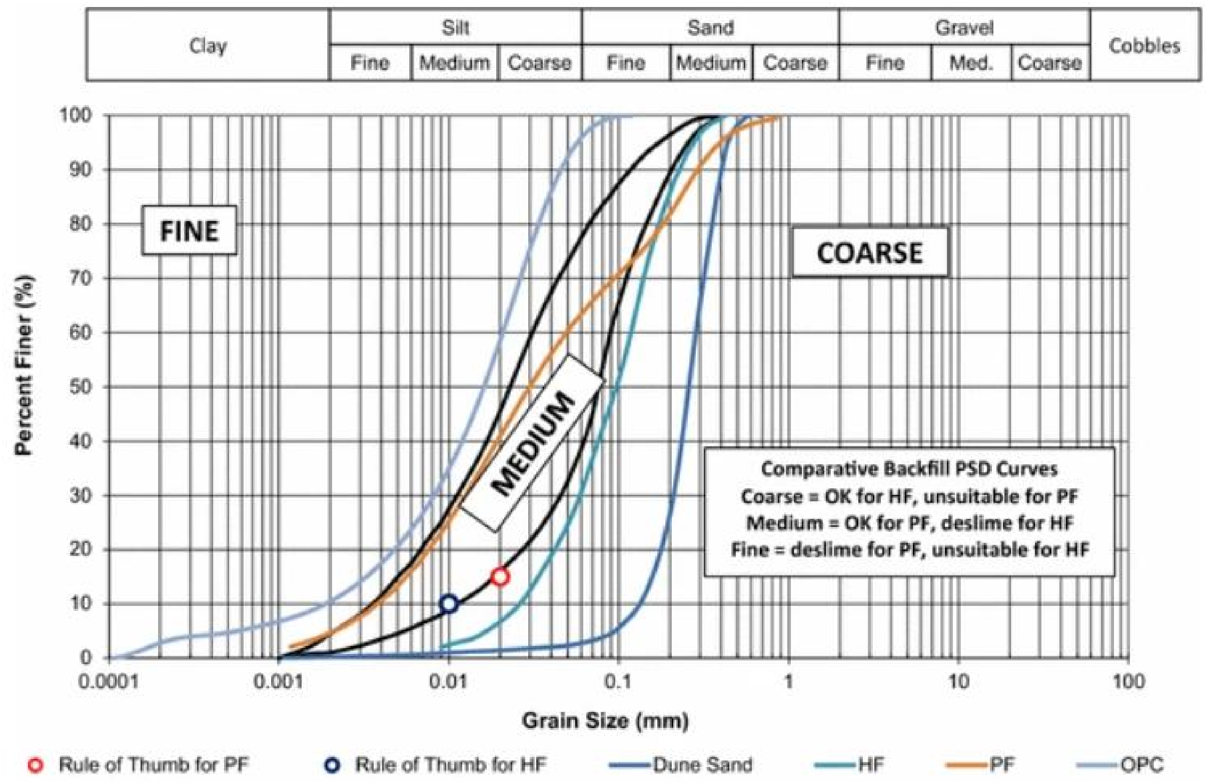

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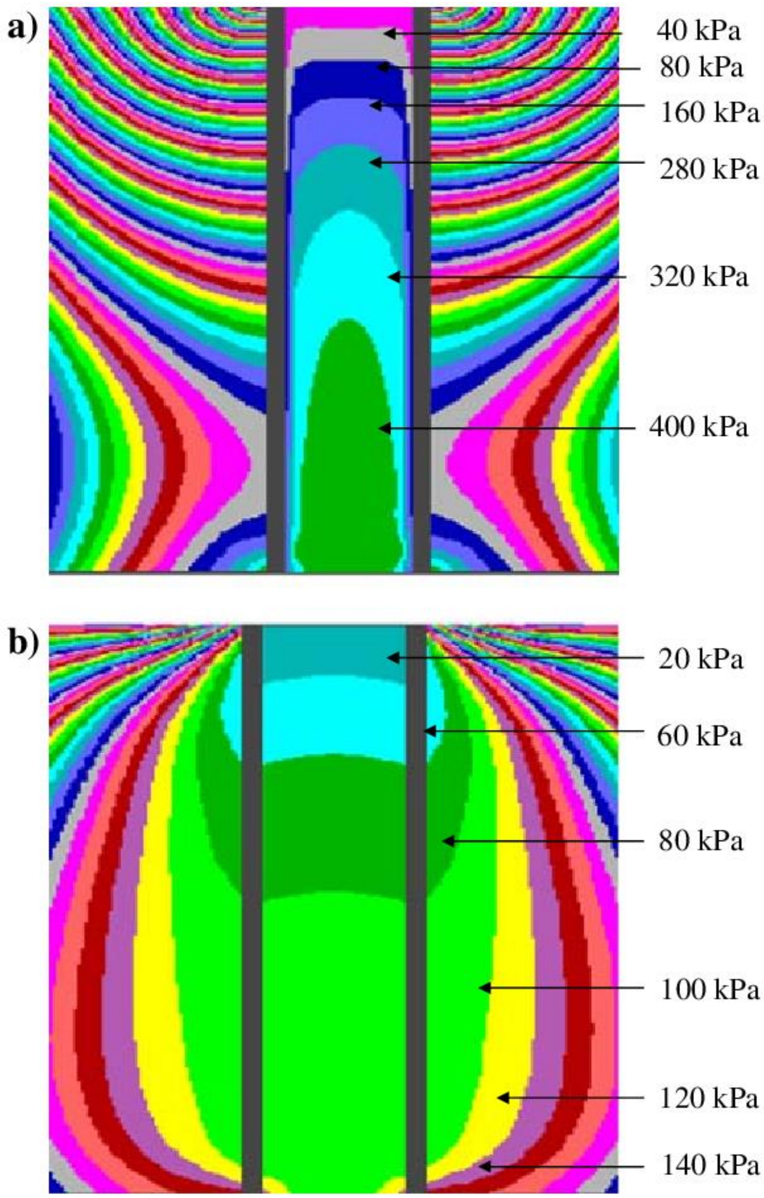

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Scheme	Applicable Areas	Advantages	Disadvantages
I	Gobs small in size with good stabilities	Easy for operation; Few devices input	High labor intensity; Low efficiency
II	Filling workface nearby hanging wall	High capacity; Flexible operation	Expensive devices; Complex structure
III	Mines with truck Transportation	High capacity; Wide application range	Critical tire wear; Gas pollution

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