Application of Restoration and Remediation Technologies for Mine Geological Environments

Zheng Feixue
Fuzhou University of International Studies and Trade, Fuzhou, Fujian 350202, China;

Abstract: Mining activities have caused increasingly severe damage to geological environments, and the restoration and remediation of mine geological environments have become an important measure in ecological civilization construction. Based on literature research, field investigation, and case analysis, this paper reviews mainstream remediation technologies for mine ecological restoration and their application effects. The main problems in mine geological environments include surface subsidence, slope instability, water and soil pollution, and vegetation destruction. Existing remediation measures can be mainly divided into three categories: engineering remediation, biological remediation, and ecological reconstruction. Engineering remediation rapidly prevents and controls geological disasters through slope reinforcement, subsidence backfilling, and drainage facility installation. Biological remediation relies on vegetation reconstruction, soil improvement, and microbial remediation to achieve natural ecological recovery. Ecological reconstruction reshapes the regional ecological pattern through landscape planning, functional zoning, and ecological corridor construction. The combined application of engineering and biological remediation produces the best comprehensive benefits, with both economic efficiency and long-term effectiveness. Remediation schemes should be formulated according to local conditions by considering mine type, geological and climatic conditions, and socioeconomic factors. This study provides theoretical reference and practical support for mine ecological restoration, green mine construction, and ecological environmental protection.

Keywords: mine geological environment; restoration and remediation technologies; ecological reconstruction; environmental remediation; sustainable development

1. Introduction

The mining industry is one of the important pillar industries of the national economy and provides substantial resource support for socioeconomic development. However, long-term mineral resource development has also exerted a major impact on the geological environment. According to data from the Ministry of Natural Resources, by the end of 2023, the total area of land occupied and damaged by mining activities in China had exceeded 4 million hectares. Among these areas, abandoned historical mines accounted for a large proportion, approximately 3 million hectares, and more than 130,000 mines required remediation. In recent years, mine environmental problems have become increasingly prominent. From 2019 to 2023, more than 2,000 geological disasters caused by mining activities occurred nationwide each year, resulting in substantial economic losses and posing serious threats to the ecological environment as well as to the lives and property of local residents.

With the deepening of the concept of ecological civilization and the proposal of the “dual carbon” goals, restoration and remediation of mine geological environments have become one of the key issues in achieving sustainable development. According to the National Plan for Mine Ecological Environmental Protection and Restoration Governance (2021–2035), the remediation area of abandoned historical mines should reach 1 million hectares by 2025. At present, the technical system for restoring and remediating mine geological environments has been continuously improved, shifting from single engineering measures to an integrated governance model combining engineering, biological, and ecological approaches. The governance concept has also shifted from simple landform reshaping to the reconstruction of ecosystem functions. A systematic study of the damage degree of mine geological environments and the application of restoration and remediation technologies is conducive to guiding mine environmental governance and promoting the development of green mines.

2. Analysis of Damage Characteristics of Mine Geological Environments

2.1 Mechanism of Surface Subsidence and Ground Collapse

Surface subsidence and ground collapse are among the most common geological environmental problems in mining activities. They are mainly caused by underground voids created by mining, which cause the overlying strata to lose support and undergo destructive deformation under gravity. When the mining depth exceeds the critical depth, the overlying strata bend and subside under their own weight, forming continuous subsidence basins. When the overlying strata cannot resist the overburden pressure, sudden collapse occurs, resulting in discontinuous collapse pits. The subsidence process shows temporal and spatial variation patterns and can generally be divided into three stages: the initial influence stage, the active stage, and the recession stage. The subsidence rate is related to mining speed, geological conditions, mining methods, and other factors.

2.2 Slope Instability and Landslide Risk Assessment

Mine slope instability occurs when mining activities disturb the original stress equilibrium of geological bodies, causing slope sliding under the action of gravity, groundwater, earthquakes, and other external forces [1]. Slope stability mainly depends on factors such as the strength parameters of rock and soil masses, slope geometry, groundwater conditions, and external loads, while the development degree of joints and fissures and groundwater activity are the main causes of slope instability. Landslide risk assessment requires comprehensive judgment based on the geological environment, rainfall intensity, and human factors. The limit equilibrium method or finite element method is used to calculate the slope safety factor. If the safety factor is less than 1.05, this indicates a relatively high landslide risk. Therefore, a normalized slope monitoring system should be established to collect displacement, seepage water level, and meteorological data in real time and dynamically update the safety factor. Numerical simulation can also be used to predict the deformation evolution of slopes under extreme rainfall conditions, so that preventive and control measures such as interception and drainage systems, anchor bolt support, and lattice slope protection can be deployed in advance. These measures can suppress fissure propagation and water–rock interaction at the source and effectively reduce the risk of landslide geological disasters.

2.3 Groundwater Pollution and Acid Mine Drainage

Acid mine drainage is one of the main sources of water environmental pollution during mining. It is generated when sulfur-bearing minerals are oxidized under aerobic conditions to produce sulfuric acid, making mine drainage acidic and containing large amounts of heavy metal ions. In general, the pH of acid mine drainage is usually 2.0–4.5, and its heavy metal content can reach dozens to hundreds of times the environmental quality standard for surface water. Acid drainage persists for a long time, affects a wide area, and is difficult to treat. Once formed, it can continue for decades or even hundreds of years, causing serious harm to groundwater bodies and surrounding ecological environments, damaging aquatic habitats, and threatening irrigation safety for nearby farmland as well as drinking water safety for humans and livestock. Current commonly used treatment methods can be divided into three categories: source control, midstream interception, and terminal purification. Source control uses covering isolation and anti-seepage sealing to prevent sulfur-bearing minerals from contacting air and water, thereby fundamentally inhibiting oxidative acid generation. Midstream measures involve constructing interception and drainage channels and retention ponds to divert acidic runoff and reduce its diffusion range. Terminal purification uses technologies such as neutralization precipitation, constructed wetlands, and microbial remediation to regulate water pH and adsorb and immobilize heavy metals. In practical governance, combined processes are often adopted to balance treatment costs and long-term stability. Meanwhile, a long-term dynamic water quality monitoring mechanism should be established to track changes in pH and heavy metal concentrations in real time, providing data support for optimization of treatment schemes and ecological environmental restoration, and ensuring water and soil ecological safety and sustainable development in mining areas.

2.4 Distribution Characteristics of Soil Heavy Metal Pollution

Soil heavy metal pollution caused by mining is mainly attributed to the stockpiling of beneficiation waste residues, leakage of acidic wastewater, and dust deposition. The main pollution elements include lead, zinc, copper, cadmium, mercury, and arsenic. Soil heavy metal pollution shows certain spatial characteristics, gradually weakening around pollution sources, while more serious pollution occurs in the downwind direction of prevailing winds and in areas where surface runoff converges. The migration and transformation of heavy metals in soil are affected by soil pH, organic matter content, redox conditions, and other factors. Under acidic conditions, heavy metal activity increases, bioavailability rises, and the harm to plants and microorganisms becomes greater. In severe cases, the soil ecosystem may collapse. Heavy metals are difficult to degrade, easy to accumulate, and have a long latency period. They can enter the food chain through crop uptake, gradually accumulate, and threaten human health. At present, the remediation of soil heavy metal pollution in mining areas mainly includes physical solidification, chemical passivation, phytoextraction, and microbial remediation. Physical and chemical methods are effective quickly and are suitable for heavily polluted areas. Plant and microbial remediation methods are low-cost and ecologically friendly, making them suitable for large mildly polluted areas. In practical governance, combined remediation models are often adopted, with zoning-based measures implemented according to topographic conditions and pollution degree. At the same time, source control measures such as waste residue enclosure and anti-seepage covering should be improved to block the continuous diffusion of pollutants and gradually restore soil ecological functions in mining areas.

3. Technical System for Restoration and Remediation of Mine Geological Environments

3.1 Backfilling and Stabilization Technology for Surface Subsidence Areas

Backfilling and stabilization technology for surface subsidence areas is a major engineering measure used to control surface subsidence by injecting filling materials into mined-out areas. The selection of filling materials and mix proportion design are key links in technology implementation. Common filling materials include cement-based filling materials, fly ash-based filling materials, and cemented tailings backfill materials. Among them, cemented tailings backfilling technology can not only control surface subsidence but also realize the comprehensive utilization of tailings. The strength design of the backfill body should be based on overlying strata pressure, mining geometric parameters, and other factors. In general, the 28-day compressive strength is required to be between 2 and 8 MPa. At present, full-tailings cemented backfilling is adopted in backfilling technology to reduce cement consumption while ensuring the strength of the backfill body, thereby achieving both economic and environmental benefits [2].

3.2 Slope Ecological Protection and Reinforcement Technology

Slope ecological protection and reinforcement technology combines engineering protection measures with biological protection measures, so that slopes can achieve both good engineering safety and ecological functions. Engineering protection measures include retaining walls, anti-slide piles, anchor bolts and anchor cables, lattice beams, and other methods. These measures are mainly used to improve the anti-sliding safety factor of slopes and prevent further slope sliding. Ecological protection measures use vegetation slope protection. Deep-rooted plants are planted on slopes, and their root systems form a network structure that stabilizes soil, improves the resistance of the slope surface to rainfall erosion, and enhances the stability of shallow slope layers. At present, new materials such as ecological bags, three-dimensional geonets, and vegetation concrete are widely used in slope treatment. Combined with hydroseeding, netted shotcrete with vegetation, and other methods, these materials can rapidly form vegetation cover and contribute to long-term slope stability. Plant selection should be determined according to local climatic conditions and soil environments. Native plants with strong adaptability, developed root systems, and rapid growth should be prioritized to ensure the sustainability of vegetation restoration.

3.3 Acid Mine Drainage Treatment and Neutralization Technology

Acid mine drainage treatment technologies mainly include active treatment and passive treatment, among which limestone neutralization is the most widely used active treatment method. This method involves adding limestone or quicklime to acidic wastewater to adjust the pH to between 6 and 9, so that heavy metal ions form hydroxide precipitates and are removed. However, pH value and reaction time should be carefully controlled during neutralization. If the pH is too high, gypsum scale may form, affecting treatment performance and equipment operation. Passive treatment technology mainly uses constructed wetlands, which rely on natural purification processes such as substrate adsorption, plant uptake, and microbial metabolism to treat acidic wastewater. This method has the advantages of low investment and simple operation. At present, the development direction of acid mine drainage treatment technology is the combined application of multiple technologies. Through pretreatment, neutralization precipitation, advanced purification, sludge treatment, and other processes, wastewater can meet national discharge standards and be reused. The treated water quality can meet the requirements of the *Integrated Wastewater Discharge Standard*.

4. Evaluation of the Application Effects of Remediation Technologies

4.1 Geological Stability Monitoring and Assessment Methods

Geological stability monitoring uses multiple technical means to conduct real-time monitoring of mine remediation areas. Current monitoring methods include GPS displacement monitoring, inclinometer measurement, groundwater level monitoring, and microseismic monitoring, forming a comprehensive geological stability monitoring network [3]. By arranging monitoring points in a grid pattern, slope displacement, ground subsidence, and crack development can be accurately monitored, with monitoring accuracy reaching the millimeter level.

Numerical simulation technology plays an important role in stability analysis. A three-dimensional model of the geological body is established based on the finite element method to calculate stress and displacement under various working conditions. The evaluation criteria mainly use the safety factor, displacement velocity, and failure probability as reference factors. Warning values are determined according to previous observation data, so that geological disasters can be predicted and forecasted and corresponding measures can be taken, greatly reducing the probability of geological disasters in the remediation area.

4.2 Analysis of Water Environmental Quality Improvement Effects

The effects of mine water environmental governance are evaluated by combining dynamic monitoring of water quality indicators with ecological function assessment. After treatment, the contents of heavy metal ions in mine water bodies are significantly reduced. For major pollutants such as copper, lead, and zinc, the removal rates generally exceed 85%, and the pH value gradually approaches neutrality. After acid mine drainage is treated through combined processes such as neutralization precipitation, biofilters, and constructed wetlands, the water quality indicators basically meet the environmental quality standards for surface water.

Long-term monitoring shows that biological treatment technologies have good sustained purification effects in water environmental restoration. Aquatic plant systems have good removal effects on nitrogen and phosphorus nutrients, dissolved oxygen increases year by year, and the self-purification capacity of water bodies is significantly improved. According to evaluation using the water quality assessment index, the overall score of water environmental quality in the remediation area improved from inferior to Class V before treatment to Class III. The structure of the aquatic ecosystem tends to be stable, and the biodiversity index continues to increase.

4.3 Soil Remediation Effects and Ecological Function Restoration

Soil remediation effects are comprehensively evaluated using physical, chemical, biological, and other indicators. Heavy metal pollution in the soil of the remediation area is effectively controlled, and the available content of pollutants decreases by more than 60%. The soil pH changes from the original acidic condition to a neutral environment suitable for plant growth. Through biological improvement and the application of organic materials, the organic matter content increases to 15–25 g/kg, and soil structure as well as water and fertilizer retention capacity are greatly improved [4]. The microbial community diversity index shows that, after remediation, soil ecosystem functions gradually recover, and the number of beneficial microorganisms increases by 3–5 times.

Vegetation restoration is measured by indicators such as coverage, biomass, and species richness. The vegetation coverage rate in the remediation area increases from less than 20% at the initial stage to more than 80%, forming a multi-level vegetation community combining trees, shrubs, and grasses. The number of native plant species increases year by year, ecosystem stability continues to improve, and the carbon sink function is fully utilized. The ecological benefit evaluation shows that the remediation area has achieved the expected effects in soil and water conservation, biological habitat construction, and landscape improvement, and its ecological service functions have been significantly enhanced.

5. Conclusion

The study finds that an integrated remediation approach combining engineering remediation, biological remediation, and ecological reconstruction can effectively solve a series of environmental problems caused by mining activities. Geological stability monitoring and evaluation technologies provide a quantitative standard for assessing remediation effects, and multiple monitoring methods can help obtain timely information on the safety conditions of the remediation area. Water environmental quality is significantly improved, the heavy metal removal rate reaches more than 85%, and the ecological functions of water bodies are restored. Soil remediation technologies play an effective role in reducing heavy metal pollution, improving soil physicochemical properties, and restoring ecological functions. Vegetation coverage increases to more than 80%, and the biodiversity index continues to rise.

The application of remediation technologies has played a positive role in promoting the green transformation of the mining industry. The biological–engineering combined remediation model has advantages in both economic efficiency and durability, and site-specific remediation schemes ensure the applicability and effectiveness of the technologies. This research provides a complete solution for the remediation of mine geological environments and has important significance and value for ecological civilization construction and the sustainable development of the mining industry [5].

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