Measures to restore metallurgical mine wasteland using ecological restoration technologies: A case study at Longnan Rare Earth Mine

Yunzhang Rao 1, 2, 3, Ruizhi Gu 1, Ruikai Guo 1 and Xueyan Zhang 1

1School of Resources and Environmental Engineering, Jiangxi University of Science and Technology, Ganzhou, Jiangxi 341000, China
2Jiangxi Key Laboratory of Mining Engineering, Jiangxi University of Science and Technology, Ganzhou, Jiangxi 341000, China

Email: raoyunzhang@sohu.com

Abstract: Whereas mining activities produce the raw materials that are crucial to economic growth, such activities leave extensive scarring on the land, contributing to the waste of valuable land resources and upsetting the ecological environment. The aim of this study is therefore to investigate various ecological technologies to restore metallurgical mine wastelands. These technologies include measures such as soil amelioration, vegetation restoration, different vegetation planting patterns, and engineering technologies. The Longnan Rare Earth Mine in the Jiangxi Province of China is used as the case study. The ecological restoration process provides a favourable reference for the restoration of a metallurgical mine wasteland.

1. Introduction

The abandoned mine land in China totaled 3 x 106hm² at the end of twentieth century, with no recovery measures being in place for 80% of this wasteland [1-2]. Furthermore, the scale of the effects of abandoned mines expands rapidly as the demand for resources increases. Moreover, the damage to the environment is exacerbated by associated activities such as road building, strip mining, and constructing of waste-rock yards and tailings ponds, as these occupy large tracts of land and lead to the destruction of vegetation. Toxic heavy metals such as Pb, Zn, As, Cr, Cu, and others that remain in the waste-rock yards and tailings ponds of sulfide mines can potentially pollute the surface water and groundwater through surface runoff and leakage. The destruction of normal vegetation detrimentally affects soil fertility, leading to mud-rock flows, soil erosion, and landslides down mountains. In addition, abandoned mining areas pose other geologic hazards, for instance, exposed mining pits that are dangerous to humans and animals. In view of the extensive damage to the environment in the mining areas of China, this study discusses several ecological restoration methods. Furthermore, by employing the area surrounding the Longnan Rare Earth Mine as case study, the general process of restoration is explored, with a focus on the restoration of the ecosystem. Finally, concerns for the future are discussed.
2. Repair Methods

2.1. Principle of adjusting restoration measures to suit local conditions
Mining activities can have disastrous effects on the surrounding geochemical environment and ecosystem, such as soil disturbance, surface collapse, acid mine drainage, heavy metal pollution of the soil, atmospheric pollution, upsetting of the ecological environmental balance, and others. The source of such problems has to be determined and special technologies have to be employed to solve them. In addition, the local climate and soil conditions have to be considered, when selecting appropriate plants for vegetation remediation.

2.2. Methods of synchronization
Ideally, the ecological restoration plan should be applied throughout the entire period of the mining activity, rather than simply focusing on the recovery of the land after the end of the exploitation. According to Dai [3], the different development stages of mining areas can have crucial effects on the ecological remediation of such sites. Therefore, the reclamation of the site has to be considered at the start of the exploitation; for instance, in the construction and management of tailings ponds and the slopes of waste-rock yards and steps. After closing of the mining activities, the retention, or the dismantlement of the remaining structures mainly depends on an assessment of their value. In addition, the reclamation of each mining tunnel should be done in consideration of its characteristic in order that ecological restoration of each site can be effected.

2.3. Combination with landscape study
Another method, based on the original landform, is available for appropriately planning the reclamation efforts for mine environments. This method combines the knowledge of the geography of the sites, landscape study, ecology, and the aesthetics of the particular sites in the remediation efforts. Since the 1990s, landscape design practices have been utilized often to transform the mine environments[4]. A case in point is Nanhu Park, the former site of the Kailuan Coal mine, which is part of the heavily industrialized Tangshan City, a coal mining in Hebei Province. The environment was restored by utilizing the principles of bionics in the design of wetlands to purify the area, and, subsequently, wetland ecosystems have formed that contain aquatic and terrestrial plants[5].

3. Remediation Measures

3.1. Restoration and improvement of the soil matrix

3.1.1. Soil replacement method. The crucial problem in restoring the soil matrix is the lack of soil; consequently, searching for replacement soil is of vital importance in remediating abandoned mine lands. However, a new layer of soil can be formed artificially to solve the problem. As regards topsoil contaminated with heavy metals, a layer of impervious paving is essential to separate the heavy metals from the soil layer. So for mine wastelands, the main problems in applying this measure are finding a suitable soil source and confirming the thickness of the soil layer[6].

3.1.2. Improvement of soil matrix nutrients. This measure includes two main actions, namely, decreasing the toxicity, and enhancing the nutrients of the soil. As an example, toxic metals from sulfide mining can affect the groundwater and soil adversely by surface runoff and infiltration, causing environmental pollution, such as acid mine drainage and the like. In such an instance, the toxicity should first be reduced by utilizing the chemical reaction technique, i.e., mainly adding sulfate, sulfur, and other acidic modifiers to alkaline mining areas, and lime, fly ash, and the like to acidic mining areas. This technique is often employed to modify the pH level of the soil in order to reduce the toxicity of the metals. Generally, low pH conditions can potentially increase the solubility of heavy metals, which increases toxicity, whereas high pH conditions can potentially reduce solubility and
reduce toxicity. This is because heavy metals precipitate as metal hydroxide or exist in carbonate and phosphate forms, which, accordingly, reduces toxicity\[7\]. Basically, pH can control the bioavailability of Zn and Cd[8]. The biological method is utilized mainly to enable vegetation to adsorb metals from the soil, which facilitates soil remediation while being free from secondary pollution, but leaves a long life cycle of plants.

On the other hand, the selection of appropriate fertilizer is crucial for soil that lacks nutrients in order to encourage vegetation cover. Moreover, the role of soil organisms, e.g., earthworms and microbial fungi in maintaining soil fertility should not be overlooked. Various studies have tested the inoculation efficiency of the arbuscular mycorrhizal fungus (AMF) on plants growing in mine areas. The results indicate that the fungi could promote the growth of the root system, enhance the absorption ability of the roots, and increase the soil organic content. Furthermore, the inoculated fungi accelerate the degree of aging of the matrix, which enhances the nitrogen fixation ability and the absorption of the available potassium[9]. Furthermore, the action of earthworms increases the speed of soil turn over, accelerates the ripening process of humus, and encourages the aeration and hydration of the soil. One study has pointed out that the waste of organisms, such as the compost sludge of resources-based cities, could be used for soil modification, as the nutrients contained in the sludge, such as nitrogen, phosphorus, and potassium, could supplement the soil nutrients[10]. Although this technique has various advantages, the sewage sludge could contain pathogenic microorganisms, parasitic ova, and trace metal elements, which are harmful to plant growth. Consequently, using sewage sludge has to be considered carefully[11].

3.2. Phytoremediation technology
Phytoremediation has recently emerged as a restoration technology because of its slight secondary pollution and low cost[12]. The purpose of using phytoremediation is to decrease the toxic metals content and the degree of toxicity through adsorption, transformation, and the deposition of heavy metals in the soil by using hyperaccumulator vegetation. This technique includes three main mechanisms, namely, phytoextraction, phytostabilization, and phytovolatilization[7]. It is interesting to note that there is no definite criterion for every hyperaccumulator plants; different plants have different criteria. For instance, as regards Zn, it could be appropriate to regard Zn levels exceeding 3000 µg/g as remarkable, and the particular plant deserving of being described as a hyperaccumulator of Zn[13].

It has been reported that Pb metal hyperaccumulator plants, such as Sedum Tatarinowii, Ailanthus Desf., rosebush, and Gold Vein Forsythia could accumulate levels of Pb metals as high as 11.87–164.502 mg/kg in their aboveground biomass[14]. Plants such as Sedum spectabile Brilliant have been proven to remediate mine areas highly contaminated (up to 3 000 mg/kg) by Zn²⁺. As Sedum spectabile Brilliant has high tolerance for ZnCl₂, as well as phytostability, it should be the primary choice as hyperaccumulator plant[15].

3.3. Compound planting patterns
A technique that combines various planting patterns could increase the nutrients in soils, improve the soil physicochemical character, and accelerate the speed of remediation. In addition, employing this technique could establish a stable ecological structure. Chen[16] conducted a comparison between six planting patterns and unplanted (bare) land, finding that after planting the soil moisture capacity and the soil organic matter content had increased, the soil structure had become more stable, and the soil physical and chemical properties were superior in comparison with those of the bare land. Peng et al.[17] have investigated the effects of different vegetation restoration patterns on the physicochemical properties of and the heavy metals in soil. For this purpose, they employed six different vegetation patterns in the abandoned lands containing tailings of the Fujian Gold Mine, comparing the land under a natural vegetation community and the bare tailings without vegetation restoration. Compared with the soil properties and soil bulk density of the bare tailings, the results showed the soil porosity and
water retention capacity significantly increased, and the soil organic matter increased 12.23–27.74 times.

3.4. Engineering technologies

The loose soils on the slopes of mine dumps could cause geologic hazards such as landslides, mud-rock flows, and collapse; therefore, it is essential to reduce the slope gradient.

Steep slopes have little ability to retain soil and water. Combining an adequate drainage system with a technique to convert the slope into ladder-type topography, or to lower the gradient of the slope is crucial to enhancing such ability. The technique for blocking stonewall in mine slopes is building a stonewall in the root of the mine areas. The principle is to rely on the self-weight capacity of the wall to resist the lateral thrust of the soil mass in order to maintain the stability of the soil and to prevent the slope from falling down. At the same time, drainage ditches should be arranged sensibly to ensure that the water flows away easily in order to decrease the possibility of landslides and debris flow disasters and to reduce the surface water erosion to the soil of the slope.

Subsequently, ecological repair measures can be employed, such as integrating engineering technologies with the planting of vegetation to stabilize the slope and retain soil and water. Additional methods include:

• The vegetation carpet restoration technique, which is a carpet of mixed straw and wheat straw, a water retention agent, nutrient soil layer, adhesive, and water together to make it be a whole. Then put it on the mines slope. This technique is suitable for stable mines with a slope percentage lower than 1:1.5[18].

• The ecological vegetation bags method. The vegetation bags are made of special degradable fiber material and have nutrient soils containing proper seeds. The bags are placed on the slope, and are watered regularly and maintained. Over time, the bags degrade completely and the vegetation and soil layer could cover the entire area[18].

• The hydraulic seeding method (hydroseeding), in which anchor stock is used to fix wire netting on the slope, after which a high-voltage machine is used to attach the mixture of soil, grass seeds, adhesive, and a water retention agent to the rock face of the slope[4]. It is important to employ the principle of adjusting the measures to suit the local climatic conditions in the different mining areas. The most important aspect is the selection of plants, as choosing local plant varieties increases the possibility of the plants growing successfully.

4. Ecological restoration of the Longnan Rare Earth Mine

The Longnan Rare Earth Mine is located in Ganzhou city, Jiangxi Province, and has been mined for the past 40 years. Since 1994–1995[19], in conformance with government requirements, the mine started using the in-situ leaching method. However, this has caused various environmental problems, such as vegetation destruction (Figure 1) and soil erosion (Figure 2). In addition, pollution of the water and soil has occurred, including tailings effluent containing Pb up to 14 mg/L and Cd up to 0.024 mg/L. This pollution has affected the drinking water of more than 30 000 people, with more than 400 acres (161.874 ha) of farmland being destroyed[20].

In consideration of these conditions, the Longnan Rare Earth Mine has implemented various remediation schemes.

4.1. Environmental and geological exploration of the Longnan Mine

Remote Sensing (RS) technology was employed to survey the situation of the mine rare earth resources in the vegetation pollution and destruction of land [21]. Subsequently, with the help of the Ganzhou government, access to relevant information was gained and accurate topographic maps were drafted. The physical and chemical properties of water and soil samples were determined to establish the mechanical stability of the rock and the weathering crust in the mining area, providing the basic data required for the subsequent activities[21].
4.2. Cutting slope and smoothing the mining area
In the rare earth mining area, in accordance with the principle of local conditions and, therefore, based on the terrain and landforms, measures should be employed to convert the abandoned mine land into small plain or artificial terraces. At the same time, for flat mining areas, the first step of restoration is sourcing soil, subsequently adding organic fertilizer, and sprinkling grass seeds directly in the matrix. In the instance of a larger slope, other suitable engineering measures should be employed, such as laying down an ecological vegetation blanket or ecological vegetation bags, and the like. Subsequently, suitable ditches and drainage systems can be constructed to ensure that each part of the regional drainage system is able to remove the water without difficulty.

4.3. Selection of vegetation species
The soil of rare earth mining waste mainly comprises loose rocks and hardened tailings, which have poor water conservation ability, and contain low levels of organic matter, phosphorus, and potassium, but high levels of ammonium ions. Therefore, it is preferable to choose tall plants for vegetation restoration that have a developed root system and rapid growth ability[22]. In the restoration of the Longnan Rare Earth Mine, in accordance with the soil and climatic conditions, suitable biological measures and various planting patterns were employed. Elephant grass, economic forestry, and sericulture were established in three planting bases at the Zudong mining area. In this area, the planting layout is pine trees at the top of the mountain, grass on the slopes, mulberry trees on the terrace, and bamboo in the valley[20]. Plants such as paspalum notatum and green bristlegrass are used in the tailings area to reduce surface runoff erosion. Cash crops, such as pine and fir trees, and bamboo, and fruit trees, such as pear and navel orange (Figure 3) complete the restoration project, with considerable economic benefits (Figure 4). The so-called "Longnan model" successfully established a large area of green coverage, improved the soil, and facilitated water conservation. Moreover, it established the unity of the economy, society, and the environment.
4.4. Strengthening policy management

A sewage disposal plant for mine wastewater has been set up in the downstream of the river that runs through the Longnan Mine area and the water quality has been improved to discharge standard. At the same time, the government has established a rare earth ceramic factory to make full use of the mine tailings. In addition, the government of Longnan County has implemented various legal measures, such as requiring the mine to take environmental responsibility for the mine and paying environmental governance fees [20].

Although the “Longnan model” has achieved a certain degree of success, and has increased the vegetation reclamation rate, achieving complete success is difficult because of the poor natural conditions. Nonetheless, this model is worth employing [19].

5. Conclusion

Based on the knowledge acquired from the Longnan project, more research is needed on the following aspects:

- The selection of plants and the application of compound planting patterns.
- Enhancing the exploration of the survival environment and the limiting factors of hyperaccumulator plants, and increasing the research on new materials, especially a new soil matrix. For example, adding biological bacteria that are suitable to the soil environment and are able to live in mine areas in an effort to increase the fertility of the soil.
- Finding new technologies suitable to the mine environment, for example, the application of nanotechnology and transgenic technology in mine areas could be worth the effort and cost of extensive research. The nanotechnology technique is often applied for metal remediation in wastewater treatment because of its special adsorption and mechanical properties and high chemical stability. However, there has been little progress in the study on reducing metal contamination in the soil and research on improving soil fertility [23]. However, Groza [24] has used ionic phosphate nanoparticles (vivianite) to immobilize Pb$^{2+}$ in soils by in-situ remediation. The results of the study indicated that the nanoparticles could reduce the leachability and bioaccessibility of Pb$^{2+}$ of soils effectively. In conclusion, more attention should be paid to the application of nanotechnology in mine areas. At the same time, transgenic technology can be employed in plant cultivation to improve the absorption rate of plants and the extraction rate of heavy metals of the plants.
- Enhancing government supervision and management. Mines should accept responsibility for the "who pollutes, who controls" mining model, whereas the government should introduce appropriate policies to regulate mining models and mining methods, including post mining management.

Acknowledgements

Fund project: The National High Technology Research and Development Program of China (863 Program). (Number: 2012AA061901)

References

[1] Shu W S, Zhang Z Q and Lan C Y 2000 The countermeasure of reclaiming of Chinese Mining Industry abandoned land Ecologic Science 19 24-29 (in Chinese)
[2] Lin G C S and Ho S P S 2003 China’s resources and land-use change: insights from the 1996 land survey Land Use Policy 20 87-107
[3] Dai H W 2010 The techniques of ecological remediation and rehabilitation for derelict mine land Chinese Mining magazine 19 58-61 (in Chinese)
[4] Liu G 2008 Ecological rapid recovery technology of abandoned mine SHANGHAI LAND&RESOURCE 16-19 (in Chinese)
[5] Xu J R, Wu J M, Dong R Y and Xu X S 2016 A Primary Research of Mining Wasteland Landscape Regeneration in the View of Bionic Design---A Case Study of Huolinhe
Opencast Coal Mine *Jour of Fujian Forestry Sci and Tech* **43** 182-188 (in Chinese)

[6] Wu W Y 2004 Ecological Restoration Research Progress of Mining Area *Guangdong Chemical Industry* **41** 82-83 (in Chinese)

[7] Guo S C and Yang W Q 2015 Research Progress of Phytoremediation Technology to Remediate Heavy Metal Contaminated Soil *Journal of Northwest Forestry University* **30** 81-87 (in Chinese)

[8] Farrag K, Senesi N, Rovira P S and Brunetti G 2012 Effects of selected soil properties on phytoremediation applicability for heavy-metal-contaminated soils in the Apulia region Southern Italy *Environmental Monitoring & Assessment* **184** 6593-606

[9] Qian K M, Wang L P, Li J, Zhang J and Jia L F 2010 Inoculation Effect of AMF in Reclamation of Abandoned Mining Area *Environmental Science and Technology* **23** 5-9 (in Chinese)

[10] Zhong T, Shen G, Wang W and Yang H J 2015 Prospect analysis of resource based on urban compost sludge for ecological restoration of abandoned mine in mine *Resources Economization & Environmental Protection* 147-48 (in Chinese)

[11] Zhao M H 2008 The Research on Amelioration of Soil in the Mining Wasteland *Chinese Agricultural Science Bulletin* **24** 128-31 (in Chinese)

[12] Guo B, Li W D, Ding N F, Fu Q L, Liu C and Li N Y 2013 Problems and Countermeasures of phytoremediation of heavy metal contaminated soil *Acta Agriculturae Zhejiangensis* **25** 852-57 (in Chinese)

[13] Ent A V D, Baker A J M, Reeves R D, Pollard A J and Schat H 2013 Hyperaccumulators of metal and metalloid trace elements: facts and fiction *Plant and Soil* **362** 319-34

[14] Gao H Z, Guo W Z and Bi J 2014 Study on the Accumulation and Tolerance of 20 Plants to Heavy Metal Pb in soil *Chinese Agricultural Science Bulletin* **30** 19-24 (in Chinese)

[15] Wang C, Bi J, Song X L and You H Z 2014 Study on the Accumulation and Tolerance of 6 Plants to Heavy Metal ZN in soil *Environmental Science & Technology* **37** 62-65 (in Chinese)

[16] Chen J H 2016 Effect of Mine Wastelands Vegetation on Soil Properties *METAL MINE* **45** 147-50 (in Chinese)

[17] Peng D H, Hou X L, He Z M, Liu L Q, Cai L P, Lin J W, Huang F C and Zhong J H 2015 Effects of Different Vegetation Restoration Patterns on Soil Physical and Chemical Properties in Wasteland of Gold Tailings *Journal of Soil and Water Conservation* **29** 137-42 (in Chinese)

[18] Zhao F T and Sun B P 2009 Technique of mine ecological vegetation restoration (Beijing: China Forestry Publishing House) pp 80-93 (in Chinese)

[19] Liu F 2013 Eco-environment Status and its Comprehensive Countermeasures of Longnan Ionic Rare-earth Mine *METAL MINE* **42** 135-38 (in Chinese)

[20] Chen J G and Li Z M 2010 Rare earth mine environmental governance and land reclamation—Gannan "Longnan model" as an example Proceedings of the annual conference of the 2010 China Environmental Science Society (Shanghai,China) vol 4 (in Chinese)

[21] Lei G J, Liu S F and Cheng S Y 2006 Application of RS in the extraction of vegetation on pollution information in rare earth mining area *Nonferrous Metals Science and Engineering* **20** 1-5 (in Chinese)

[22] Rao Y Z, Deng Y W, Li G Q and Hu W etc 2015 Study on comprehensive treatment technology of waste rare earth mine environment in Ganzhou City (Changsha: central South University Press) pp 46,29-30 (in Chinese)

[23] Singh A and Prasad S M 2015 Remediation of heavy metal contaminated ecosystem: an overview on technology advancement *International Journal of Environmental Science &Technology* **12** 353-66

[24] Groza N 2008 Ecological Solutions of Contaminated Environment Remediation from Uranium Mining Activities in Romania// Uranium, Mining and Hydrogeology (Springer Berlin Heidelberg) pp 333-334.