Environmental Remediation of Abandoned Mines in Portugal – Balance of 15 Years of Activity and New Perspectives

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Abstract

Portugal has an important legacy of degraded former mining sites with clear environmental and public health impacts and safety problems. Since 2001 they are being subjected to environmental remediation operations by EDM- Empresa de Desenvolvimento Mineiro, S.A. under a legal regime of concession assigned by the Portuguese State and approved by the Decree-Law Nº 198-A/2001.

From an inventory of 175 abandoned mining areas, 61 of which in radioactive minerals and 114 of polymetallic massive sulphides mines, EDM had until 2015 remediated most of the old mines with more significant negative environmental and public health impacts, having concluded the remediation works in 90 mining areas and there were ongoing remediation works in 10 mining areas. An important effort has been made to achieve these results and the definition of a clear strategy for the remediation of the old mining areas as well as comprehensive set of characterization studies, plans, and detailed projects were key factors. Additionally a pre and post remediation environmental monitoring and maintenance is ongoing in the old mining areas that include the operation and maintenance of several mine water treatment plants.

This paper briefly presents EDM adopted model and strategy for the environmental remediation mission, the most representative actions concluded in Portuguese old mining sites remediation with different and adapted solutions for mining wastes confinement and mine water management, including active and passive treatment systems, and a balance of these fifteen years of intense activity, lessons learned and perspectives for the future.

Key words: Environmental remediation, abandoned mines, Portugal

Introduction

Portugal, although being a small country in the EU, has a high geological, geotectonic and geodynamic diversity which generated particular conditions concerning its geological resources and a relevant mining legacy, especially as a result of the post-industrial revolution period where mining activity grew and assumed a strong expression in Portugal. In result of this situation, a significant number of old abandoned mines can be found spread over all over Portugal, due the exploitation of basic and precious metals mainly in Alentejo (Iberian Pyrite Belt) and Trás-os-Montes, of tungsten and tin (North and Center of the country) and also of radium and uranium in the Beiras Granitic Region (Figure 1). The exploitation of radium and uranium minerals took place from the second decade until the end of the 20th century. This activity had importance at international level.

The main environmental impacts in old mines are related to polymetallic massive sulphide is acid mine drainage resulting from old mining works and wastes that generate chemical contamination in water and soil, that may also be contaminated by air dust dispersal. In the case of radioactive mines the main environmental impacts include acid mine drainage as a direct result from exploitation methods with static leaching and/or in situ and from ore concentrates production, but especially the radiological risks for public health and environment as a result of the presence of mining wastes and tailings.

Given the environmental hazards associated with many of these old legacy mines, and considering the evolution of the relevant mining and environmental legislation, namely the Environmental Framework Law (DL 11/87), the National Plan of Environment Policy (1995), the Mining Framework Law (DL 90/90) and the European Directives, the Portuguese Government has committed itself for its environmental remediation, and in 2001, entrusted to EDM – *Empresa de Desenvolvimento Mineiro*, SA, a state-owned company, the responsibility for the recovery of all degraded old mining sites under an exclusive concession contract approved by the Decree-Law nº 198-A/2001. The scope of the concession is very clear and it includes only "abandoned mines" and, considered as old and deteriorated mines that constitute a potential public health or environmental risk, requiring the State intervention, where the Polluter Pays Principle could not be applied.

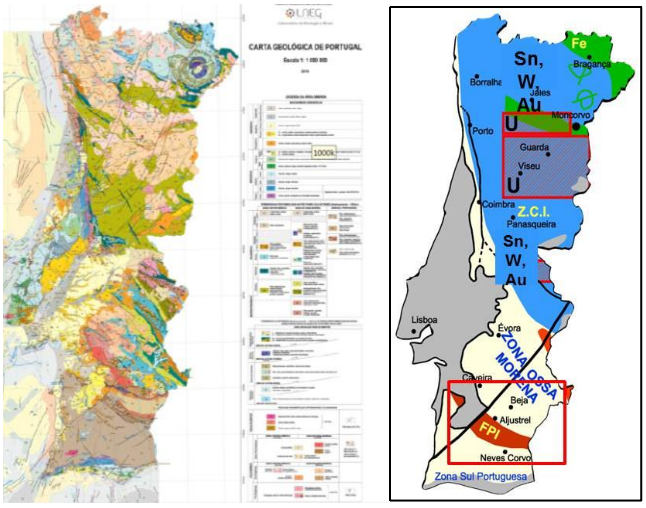

Figure 1 *Mainland Geologic Map of Portugal, 1:1000.000 (Ribeiro ML et al. 2010) and Metallogenic Portuguese Belts (EDM 2011).*

The objectives of the concession are to eliminate the risk factors for public health and safety resulting from old mining areas, rehabilitate the surrounding landscape and natural conditions of development in accordance with the previous or potential land uses in order to provide conditions for future use of reclaimed areas such as agricultural or forestry uses, tourist and cultural promotion, or another that promotes the community development, and to ensure the preservation of significant heritage of old mines, both economic and archaeological and the valorization of archaeological remains related to mining activity.

Intervention Strategy

EDM defined the strategy for the environmental remediation of the old mining areas (Figure 2), and started with the inventory and detailed characterization of abandoned and degraded old mining areas and the prioritization of environmental remediation interventions on the basis of technical and scientific analysis (Phase 1).

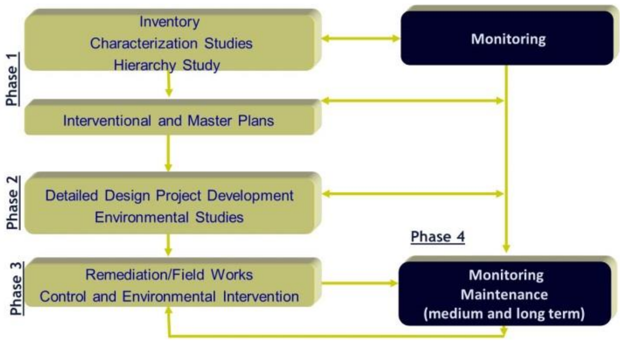

Figure 2 *EDM Strategy phasing for environmental remediation.*

Furthermore conditions were established for ensuring funding for the development of characterization studies, master plans, environmental studies and execution of projects that supported investment decisions and their priority (Phase 2). The phase 3 consisted in the realization of the remediation works and it is continuously on-going, and integrates for each area the adequate project management activities, the supervision of construction works including the health and safety, environmental and archaeological supervision. During all these phases and also after the environmental remediation works it is assured the monitoring of all relevant aspects such as soil, water, wastes, and air environments, as well as implemented a medium and long term maintenance plan.

In total EDM is responsible for the environmental rehabilitation of 175 abandoned mining areas identified in Portugal, 61 of which in radioactive minerals (more relevant are Urgeiriça, Cunha Baixa, Quinta do Bispo, Bica and Vale de Abrutiga) and 114 in polymetallic sulphides (more relevant are São Domingos, Aljustrel, Lousal, Caveira, Argozelo, Covas, Montesinho and Terramonte).

For all these mining areas EDM has performed a Base Characterization Study that included descriptive records, as location, concession date, excavation type, ore beneficiation steps, geomorfology, mining wastes, impacts and other relevant aspects.

In order to help define the priority of intervention in these mining areas EDM developed a Hierarchy Study for the Rehabilitation of Abandoned Mining Areas (Nero 2003), based in an Analytic Hierarchy Process that relied on three fundamental principles (decomposing, weighting and evaluation) of relevant aspects such as safety, environment, heritage, population and landscape.

Considering the specific risks and characteristics of radioactive ores, and also the remediation solutions, EDM classified the old mining areas in two groups: uranium and radium mining areas and polymetallic massive sulphide mining areas; for which had development Master Plans defining typified solutions in order to optimize the remediation works, subject however to further detailed design projects and adjusted solutions case by case in each mining area.

Methods / solutions

Common principles of actuation in the remediation of old mining areas consist in the elimination of risk factors associated with underground works and open pits, elimination or mitigation of the contamination source, typically through the adequate **confinement and sealing of mining wastes** *e.g.* waste rock, tailings, etc., ensuring also the physical stability of these waste deposits for the long term period, and in an adequate **mine water management** including the controlled water flooding of underground mines and open pits, the separation of clean waters from contaminated waters and ensuring the adequate treatment systems, either through passive or active treatment systems, and to guarantee a proper decommissioning and demolishing of degraded and unnecessary infrastructures and soil decontamination. In this paper we will briefly present some examples of solutions implemented with success in the environmental remediation of old abandoned mines sites by EDM in Portugal.

Confinement and sealing of mining wastes

For the confinement and sealing of radioactive mining wastes EDM designed a multilayer cover system (Figure 2) consisting of both geological and synthetic materials to be disposed over the surface of the tailings after previous geotechnical stabilization (Pereira *et al*. 2014; Pereira *et al*. 2004b; Janssens *et al*., 2006; EDM, 2008).

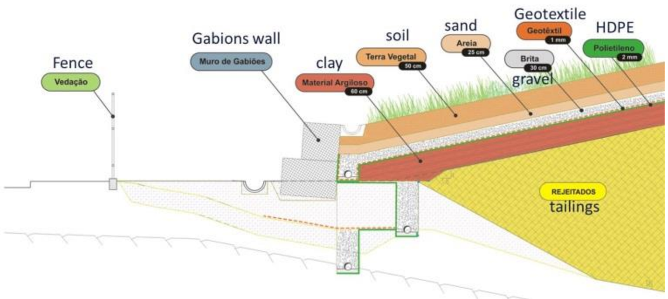

Figure 2 *Multilayer cover system for radioactive mining waste confinement.*

This solution is complemented with the construction of a peripheral concrete structure provided with surface and two deep drainage systems to separate surface run-off and contaminated seepage, and was firstly designed for Barragem Velha (Old Tailings Dam) at Urgeiriça Mining Area, where the radioactive tailings from the chemical treatment processment of the Radium and Uranium ore was disposed since 1951. This tailings dam was located over a former small valley containing a streamline with occasional water flow and occupied an area of 13 ha and with an estimated volume of 1.4 million

m^3 of tailings very heterogeneous particularly in terms of radium (226Ra) concentration which varies from 3.4 to 52 kBq/kg (Pereira *et al*. 2004a,b). The depth is also very variable, ranging from a few meters to about 70 m. The taillings material was disposed directly over hercynian granites with variable degree of rock matrix alteration and fracturation. Apart from a small proportion of the uranium remaining from the uranium dynamic lixiviation extraction (around 10%), the sludge deposited in the tailings contains all the other radionuclides of the decay chain of this chemical element that can be mobilized by natural processes thus migrating into the environment (Barbosa *et al.* 2015). This solution of *insitu* confinement was selected due to the high amount of tailings here disposed for decades, and considering all aspects including the environmental impacts and costs of transportation, and therefore it was more advantageous compared to the creation a new disposal site with bottom and top cover sealing.

The effectiveness of the cover was estimated through numerical modeling by Pereira *et al*. (2004a) based on the RESRAD code, pointing to a negligible dose (less than 1 mSv/yr) to the nearby population after remediation in contrast with an average effective dose of 39 mSv/yr before the confinement based on the external radiation measurements.

The monitoring results after the conclusion of the remediation works proved the effectiveness of the solution, with very significant reduction in the superficial radiometry (Cintilometry, SPP2) from a maximum of 15.000 cps to 300 cps, and external radiation from a maximum of 7,5 mGy/h to 0,35 mGy/h (Figure 3), being the average effective dose less than 1 mSv/yr as predicted.

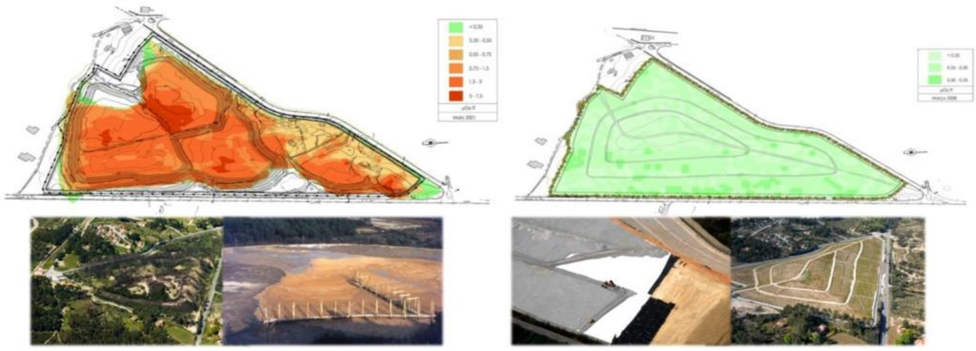

Figure 3 *External radiation results in Old Tailings Dam at Urgeiriça old mining area before and after the remediation works.*

EDM also implemented a set of radon probes at three different depths and layers namely in the tailings both below (2,4 m depth) and above the sealing cover (1,0 m depth) and also in the top-soil (0,2 m depth) for online monitoring of the radon gas concentration and emissions due to the proximity to Canas de Senhorim village. The results (Figure 4) proved that radon concentration measured at different levels of the cover of the Urgeiriça tailings is characterized by very different average values below, inside and above the multi-layer cover, showing that the sealing structure is performing as expected and effectively reducing surface radioactivity levels, although these concentrations also display very different temporal patterns and daily fluctuations (Barbosa SM *et al*. 2015).

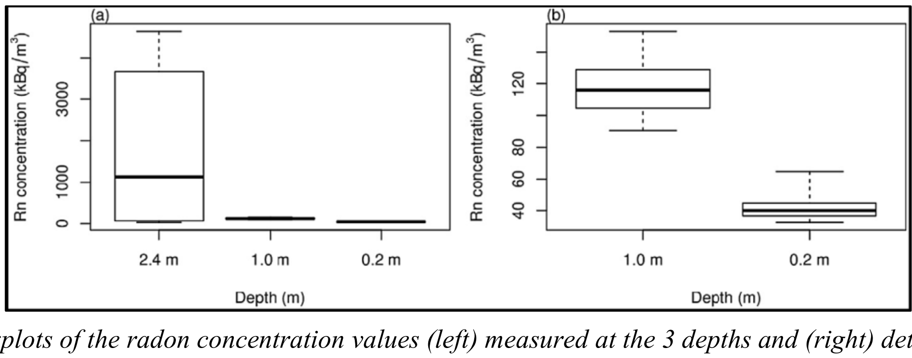

Figure 4 *Boxplots of the radon concentration values (left) measured at the 3 depths and (right) detailed view for the shallower measurements (Barbosa SM et al. 2015).*

In the case of polymetallic massive sulphide mining areas the waste confinement solutions had as main objectives to eliminate or avoid the acid mine drainage by reducing the water and air contact with the waste rock and tailings, as well as to reduce the air and water dispersion and contamination. Therefore the solutions consisted in the impermeabilization of these waste deposits with natural (clay) or artificial (HDPE Liners) layers and to ensure the adequate clean water drainage and diversion, like the old mining areas of Aljustrel which had a sealing with clay (Figure 5) and Lousal with a hybrid solution with HDPE liner and an asphalt cover to allow the future use of the area for parking of the railway station and mining museum (Figure 6). In particular, the selection of clay as solution for confinement should be used carefully as the type of clay and impermeabilization coefficient should be analyzed to ensure proper sealing, and only if this material is available near the mining area since the costs of transport of this material could easily turn this solution not feasible.

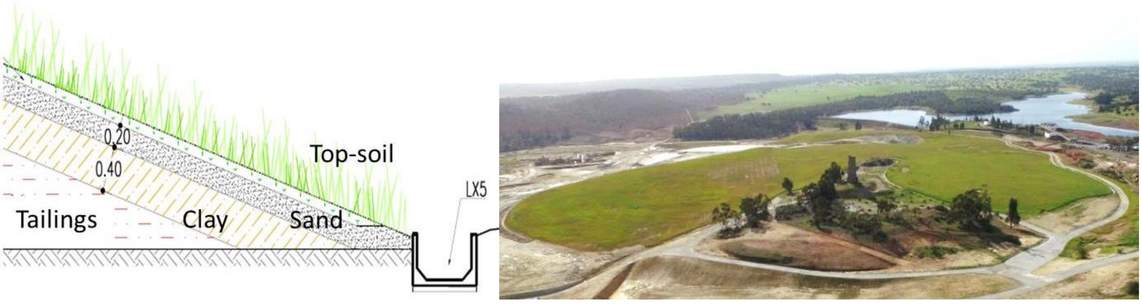

Figure 5 *Clay cover system in Aljustrel old mining area and photography after remediation works.*

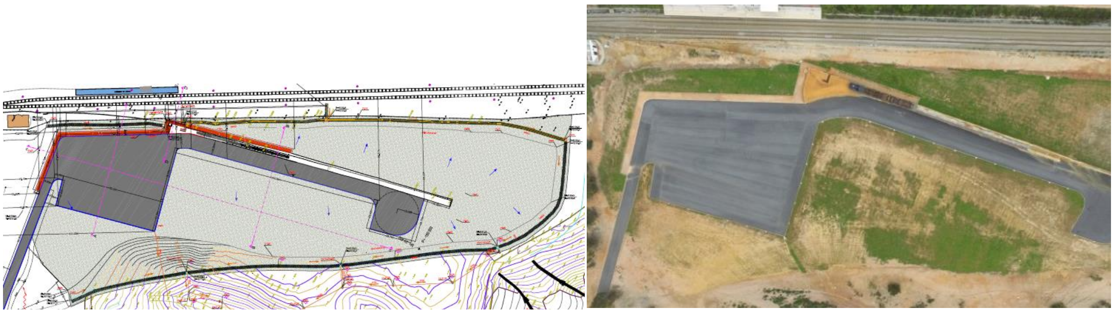

Figure 6 *HDPE and asphalt cover system in Lousal old mining area and photography after remediation works.*

These solutions are less complex than the multilayer cover system designed for the radioactive mining waste since the need to mitigate the radiological impacts, namely the gamma radiation attenuation and radon emissions is not present. However, they proved to be effective in the objective to avoid the entrance of rain water in the mining waste deposits and therefore contribute to drastically reduce the amount of acid mine water produced.

Mine water management

The mining wastes confinement has as one of the main objectives to prevent the contact of rainwater and runoff with the wastes to avoid the leachates generation. The confinement solutions should be complemented with clean water and leachate separate drainage systems, as presented in Figure 2. The clean water drainage systems have the objective to drain the rainwater and surface run-off within the mining area, and to divert the upstream hydrographic basin flows and streams to downstream the mining area avoiding the contact of the clean water with the mining wastes and the generation of high volumes of leachates and contaminated waters that will require treatment (Figure 7).

Figure 7 *Aljustrel cleanwater diversion channel and Vale d'Abrutiga surface run-off drainage system.*

The collection of leachates and other contaminated mine waters depends on the occurrence of these waters. In seepage waters or mine gallery drainage one solution is the construction of a wide barrier for collection and direct the flow towards treatment through open channel, eventually filled up with limestone (open limestone drains). However, to collect the percolated and subsurface contaminated waters it is necessary to construct subsurface drains that can also create a barrier for the propagation of the waters outside the boundaries of the mining waste area (peripheral subsurface drains). By adding limestone in these drains and ensuring the soil cap, the drain also functions as an *anoxic limestone drain* (ALS) (Figure 8).

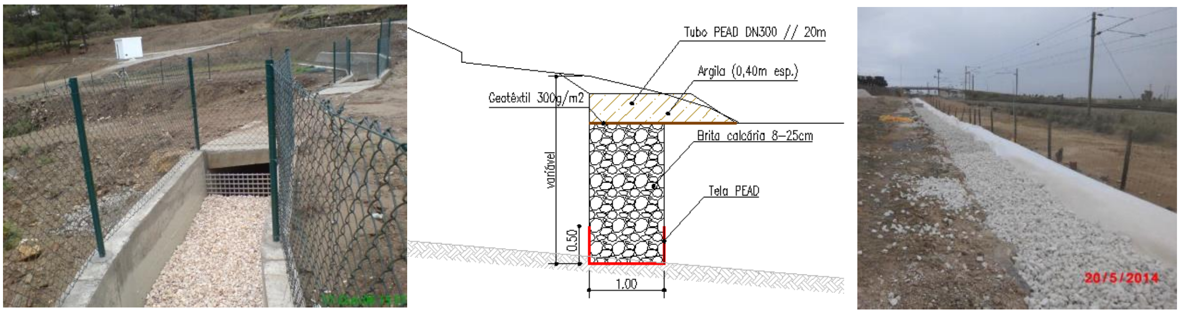

Figure 8 *Mine gallery open limestone drain (left) and anoxic limestone drain before soil cap(center and right).*

After collection, the contaminated waters are treated either recurring to active (ATS) or passive treatment systems (PTS). In 2015 EDM had treatment plants for uranium and radium contaminated water in Urgeiriça (ATS and PTS), Cunha Baixa (ATS and PTS), Quinta do Bispo, Castelejo, Bica (ATS and PTS), Vale da Abrutiga (ATS and PTS) and Prado Velho. In these cases the active treatment systems consist in adding lime milk or sodium hydroxide and barium chloride in a set of mixing tanks followed by sedimentation ponds/tanks (Figure 9).

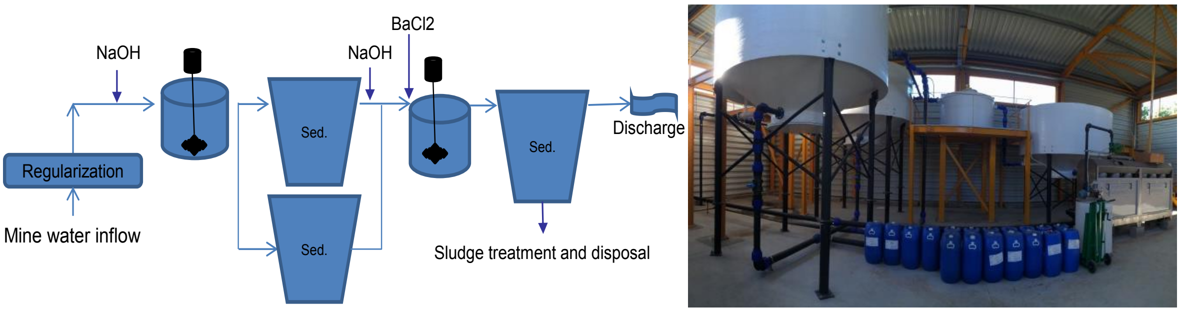

Figure 9 *Cunha Baixa active treatment process and photo.*

The discharge of treated mine water meets the regulatory standard limits for effluents discharge into watercourses, including the more restrictive limits the use for human consumption in the case of Ra-226. Manganese concentrations are still one gram per liter superior to the legal effluent discharge limit value of 2 mg/L, nevertheless this is not considered a relevant exceedance because of the mining framework of the area and background geochemical composition of groundwater's (Diamantino *et al*. 2016).

The passive treatment systems have some variations but in general include successive steps of aeration and or open limestone drains, sedimentation ponds, biological treatment (aerobic wetlands), and final filtration in limestone, barite and activated carbon, as shown in the example of Cunha Baixa passive treatment system (Figure 10).

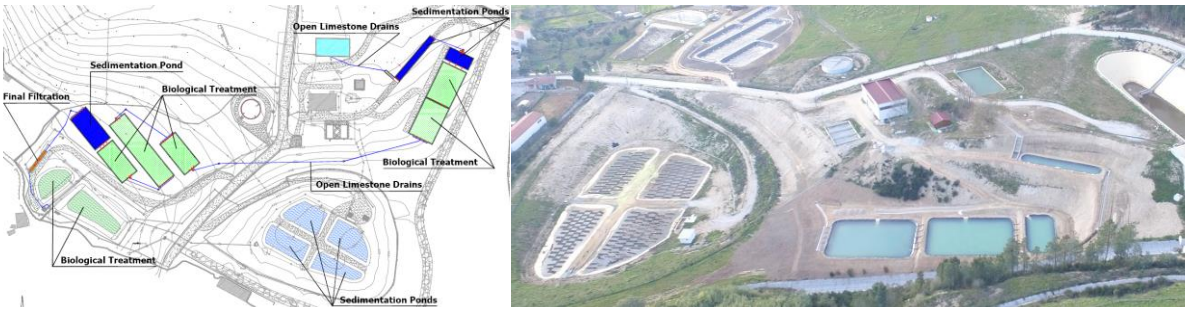

Figure 10 *Cunha Baixa passive treatment process and photo.*

In Polymetallic Massive Sulphide Old Mining Areas, affected by acid mine drainage (AMD), EDM currently has passive treatment systems in Lousal (Figure 11), Aljustrel, Jales, Terramonte and Argozelo, and backup active treatment systems in Lousal and Aljustrel. The passive treatment systems depend on the mining area and characteristics of the mine waters, however could include aeration channels, sedimentation ponds, alkaline leach beds and wetlands.

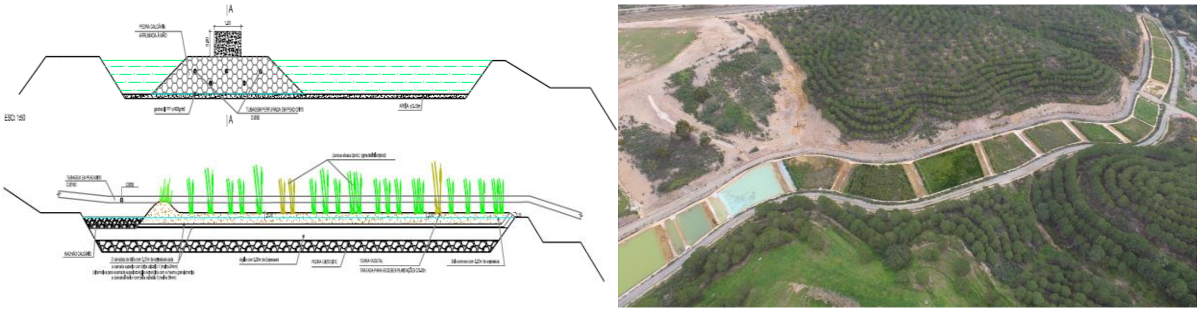

Figure 10 *Lousal passive treatment process with alkaline*

In case of passive treatment systems in general the most relevant regulatory limits is being complied, with some exceptions regarding iron and manganese. In case of Cunha Baixa and Lousal contaminants removal did not produced the excepted results and the existing passive system were recently improved and enhanced, and although the preliminary results are promising the period of operation is still not representative.

Conclusions and new perspectives

Since 2001 when the concession contract for the Environmental Remediation of Old Mining Areas was signed between the Portuguese State and EDM, 95 old mining areas were already recovered including most of the old mines with more significant negative environmental and public health impacts and the environmental liabilities.

Table 1 *Status of environmental remediation of the 175 old mining areas in Portugal in December 2015.*

Status	Polymetallic	Radioactive	Total
Concluded	61	34	95
Ongoing works	4	6	10
To be carried out	29	21	50
With constraints	20	0	20
Total	114	61	175

At the end of 2015 there were ongoing efforts to conclude the remediation of another 10 mining areas and there were 50 remaining areas with remediation works to be carried out until 2022, when the concession contract expires (Table 1). Overall, until 2015 a total of 86,4 million euros was invested in the remediation of old mining areas, 49,3 million euros in radioactive old mining areas and 37,2 in polymetallic massive sulphides old mining areas, and EDM estimates the need for around 89 million euros to conclude the remediation works in all old mining areas until 2022. Additionally, a post rehabilitation environmental monitoring and maintenance plan is ongoing in the old mining areas and should be continued after this period that could represent an annual expense of around 1,5 million euros.

The funding of this public service is ensured trough the royalties from Portuguese Mining Operators and EDM also benefited from significant co-funding from the European Cohesion Funds, which has been a critical factor for the realization of the implementation of the Old Mining Areas Remediation Plan in Portugal. Although the old mining areas represent a liability and a high cost in the environmental remediation, they can also be a source of income. In most of the 175 inventoried mining sites there are mining wastes that in light of the current rational of economic growth by the efficient use of the resources, should be regarded as secondary sources of raw materials.

A paradigm shift is needed allowing these wastes and mine waters to be considered not only as an environmental issue but mostly as possible stocks and sources of mineral raw materials. Given the current level of knowledge about the existing mining wastes in the Portuguese old mining areas, the first step to achieve this objective is the thorough characterization of the different mining waste deposits at each mine site, with particular emphasis on its particle size distribution and compositional features, and mine waters, including the demonstration that they can be reused. The mine sites already rehabilitated will have to be addressed without jeopardizing the interventions already undertaken. Only after a comprehensive analysis of the results to be obtained by such kind of approach it would be possible to separate the true wastes from residues and to search for new ways of reuse including the promotion of more powerful and environmentally friendly reprocessing technologies in order to recover additional by-products (Carvalho *et al.* 2016).

EDM is considering this new perspective not only in the on-going remediation projects, but also in the remediated mines, in order to assess the potential and feasibility for recovering value from old mining wastes and mine waters. It is also involved in international R&D projects to help new methods for extraction and exploration of secondary sources, like Project ENVIREE (ENVIronmentally friendly & efficient methods for extraction of REE from secondary sources), UNEXMIN (Autonomous Underwater Explorer for Flooded Mines) and VAMOS (Viable and Alternative Mine Operating System).

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