Layman’s Report

LIFE PROJECT NAME
Rehabilitation of abandoned bauxite surface mines using alumina red mud as filler (REFILL)

Reporting Date
30-11-2006
Layman’s Report

The large open pit areas of surface mining as well as the huge amounts of wastes produced from mining and metallurgical activities are considered as the two most important environmental problems associated with the mining and metallurgical industry. While many mine operators have taken precautions to fill in and restore surface mine sites, most of them were left abandoned after ore extraction was completed (Fig. 1). Furthermore, a common practice of mine operators was the stockpiling of waste rock around the mining open pit sites resulting in the devegetation of the surrounding surface.

![Figure 1. The Kleisoura abandoned surface bauxite mine](image)

A number of abandoned sites from surface exploitation of metalliferrous ores exist in Greece. Most of them are located in the wider Parnassos area and associated with the surface exploitation of bauxite ores. The main objective of this project was to develop and demonstrate an innovative, cost-effective and generic methodology for restoring abandoned surface mines by disposing mining and metallurgical wastes in an environmentally safe matter. By doing so, both environmental problems associated with the mining industry, i.e. the abandoned open pits and the disposal of mining and metallurgical wastes, will be eliminated.

Red mud (also called bauxite residue) was proposed as a filler for the remediation of abandoned surface mines. It is a by-product of bauxite treatment by the Bayer process, which is universally applied for the production of alumina, and then, aluminium, from bauxites (aluminium bearing ores) The solid residue produced by this process is mainly
composed of fine particles of silica, aluminium, iron, calcium and titanium oxides and hydroxides. The amount of bauxite residues produced during the refining process is significant and depends on the quality of the bauxite mineral used. In general, each tonne of alumina results in the production of approximately 0.5-2 tonnes (dry wt.) of bauxite residue. Bauxite residues exit the process stream as a highly alkaline slurry (pH 10-12.5) with 15-30% solids which has to be appropriately disposed off in the environment. The disposal of this residue forms an integral part of the alumina refining process and contributes significantly to the overall cost of alumina production. Aluminium of Greece is the only aluminium refinery in Greece. It produces almost 680,000 tonnes of bauxite residues annually. This residue is pumped through pipes from the refinery to the sea bed of Gulf of Corinth. The end of the pipes is located at a distance of 2800 m from the coastline and in a depth of 120 m from the sea level.

The disposal of bauxite residues in the sea currently applied by Aluminium of Greece is not a widely applied method. In order to avoid any kind of environmental problems related with this method, it is necessary to find alternative, environmentally friendly, technologically feasible and cost effective land disposal methods. The REFILL project focused on the development and field application of an innovative and cost-effective method for restoring abandoned surface mines using bauxite residues and other mine wastes.

Bauxite residue is a very fine red-coloured material (Fig. 2). Although it is an alkaline waste, the potential environmental risk associated with the containing alkalinity from such a disposal option is low. This low risk is due to the very low hydraulic conductivity coefficient of bauxite residues, which is slightly higher than the limit posed for low permeability layers in the landfill directive by the European Commission, i.e. $1 \times 10^{-7}$ cm/sec. However, in order bauxite residues to act as a low permeability layer, their prior proper moisture reduction to optimum value is required. By acting as a low permeability layer and taking into account the low precipitation rates at the sites into consideration, it is estimated that water percolation through bauxite residue layers will be minimal. In order to prove this statement pilot field tests were performed and field demonstration tests have been designed to be implemented.

Figure 2. Dried bauxite residues
The main objectives of the project were:

(a) The development and demonstrative application of a rehabilitation scheme for abandoned bauxite surface mines using bauxite residues as filler.

(b) The utilisation of dried bauxite residues and waste rock for the rehabilitation of abandoned bauxite surface mines located in the Parnassos area.

(c) The elimination of environmental problems arising from the disposal of bauxite residues in the sea.

(d) The utilization of other wastes such as sewage sludge for the vegetation of rehabilitated site.

The remediation scheme investigated includes controlled disposal of dried bauxite residue and compaction to obtain certain bulk density value, capping with waste rock or treated bauxite residues and, finally, development of a vegetation cover. The methodology followed within the project involves several tasks and activities including characterisation of bauxite residues, design and application of a methodology for bauxite residues moisture reduction using press filters, vegetation of treated bauxite residues and waste rock, and design, simulation, construction and monitoring of pilot and demonstrative field tests.

Dewatering of bauxite residues is required mainly for two reasons: a) to allow transportation, and b) only dried material can be safely disposed off in surface mining open pits. Dewatering to low moisture content at high rates can be only performed with press filters. Given the bauxite residues properties and the requirement for the production of large quantities of material with significantly reduced moisture content, an innovative press filter was required to be purchased. Furthermore, it is very important to find the operational details of a press filter to obtain the required huge quantities of material dried at certain moisture content.

Before the implementation of the demonstration test, field pilot test were constructed in order to obtain technical and economical information required for the design and construction of the demonstration test, as well as the data required for the environmental impact study and application for permits to construct the demonstration test.

Pilot test was constructed in the abandoned mine in the location Prosorema, close to Desfina, Fokida. It covers an area of 580m$^2$ which was divided with geomembrane into two equal sections (test pads). Lysimeters were installed beneath each test pad to collect and monitor the drainage water, in the central part of each test pad to avoid edge effects. PVC pipes were used to transfer drainage water out of the lysimeters and collect it in the respective vessels. Water collection pipes and vessels were also installed at the side of each test pad to collect and monitor the run-off water quantity and quality. In the first test pad a 1.6m thick bauxite residues layer was applied, whereas in the second a 0.6m thick layer of waste rock was placed above a 1m thick bauxite residues layer. The first test pad simulates conditions of the disposal site during operation, whereas the second one simulates conditions at the disposal site after capping and establishing a vegetation cover. The field tests have a 10×10m base, 1.6m height and 3:1 side slopes to improve the physical stability of the material and decrease wind and water erosion rate (Fig. 3, 4).
A final view of the field tests is presented in Fig. 5. Field tests were monitored for 2 years. Although total precipitation in the area during the first year was 570 mm, only 15 and 17 mm of water percolated through the material in test pads 1 and 2 respectively and received in the drainage collection vessels in early April 2005 (Fig. 6). The amount of drainage water collected corresponds to less than 3% (2.7 and 2.9 % for test pads 1 and 2.
respectively) of the total annual precipitation on the test pads. As it was expected, the drainage from test pad 2 was slightly higher than that of test pad 1.

![Final view of the field pilot tests](image)

**Figure 5: Final view of the field pilot tests**

![Graph showing variation of temperature, precipitation, and drainage from TP 1 and 2](image)

**Figure 6. Variation of temperature, precipitation and drainage from TP 1 and 2**

The demonstration test was planned to be implemented in the Kleisoura mine, an abandoned bauxite surface mine which is located approximately 4 km from the metallurgical plant. The Kleisoura mine covering an area of 14,150 m² was planned to be filled with dried bauxite residues up to height of 28 m. Due to the size of the test, Aluminium of Greece has co-operated with an experienced geotechnical consulting company, in order to investigate the geotechnical stability of the test even at the worst case (i.e. seismic) conditions. Apart from the geotechnical stability issue, several other issues were studied and included in the report on design of demonstration field test at
Kleisoura mine, including the construction procedure (transportation, disposal, compaction, the phases of the construction, etc.), the monitoring equipment needs, procedures and monitoring frequency during construction, the description of equipment required for the construction of the demonstration test etc.

The initial design also involved the installation of lysimeters beneath bauxite residues to collect and monitor any leachates that may infiltrate through the bauxite residues mass. However, based on the meteorological conditions at the field site and the geotechnical properties of bauxite residues (low hydraulic conductivity) it is believed that the drainage water will be minimal. The final design of the Kleisoura mine rehabilitation involves almost flat areas (2% slope, grey areas in Fig. 12) and areas with slope of 1:3 (vertical to horizontal, dark grey areas in Fig. 12).

![Figure 7. Demonstration test design (Kleisoura mine)](image)

Geotechnical analysis indicated that slope of 1:3 or less is required to ensure the stability of the impoundment. It has to be noted that, as in the case of almost all the surface mines of this type, there is a significant altitude difference between the points B (Fig. 12 - North-West part of the pit) and A’ (Fig. 12 - South part of the pit). The design also included a methodology for disposal starting from the lower part (South part) of the open pit. It also took advantage of existing roads of exploitation to transfer and dispose off bauxite residues. Furthermore, water deviation works have been proposed and included in the design, in order to avoid any access of surface water to the disposal site. Trenches were also proposed to be installed at the periphery of the disposal site and at the lower
part of the slopes, to collect and remove run-off water from the disposal area. A 3-D view representation of the Kleisoura rehabilitation design is illustrated in Fig. 8

![Figure 8. A 3-D representation of the Kleisoura mine rehabilitation design](image)

The scheme investigated for the final capping of dried bauxite residues is presented in Fig. 9.

![Figure 9. Final covering scheme](image)

The main functions of the different layers of this cover are:

**Bauxite Residues Layer.** It is expected to act as a low permeability layer. For this purpose this layer has to be compacted to the maximum dry density at the optimum moisture content in order to obtain the lowest possible hydraulic conductivity value.
Gravel Layer. Considering that the gravel layer overlies a low permeability layer, this layer is necessary for removing the water that penetrates the upper layer.

Vegetation Layer. The vegetation layer will prevent wind and water erosion, enhance evapotranspiration and improve aesthetics.

Due to the absence of topsoil in most of the bauxite mining open pit areas, two alternatives were examined for the formation of protective and topsoil layers: (a) the use of waste rock, and (b) the use of bauxite residues. Both materials need to be properly modified in order to act as a substrate for the development of a vegetation cover. Sewage sludge and organic material were found efficient ameliorants of waste rock, whereas, a mixture of gypsum, sewage sludge and calcium oxyphosphate is needed to ameliorate bauxite residues so that they can support vegetation. Laboratory chemical and vegetation tests were performed in order to demonstrate the efficiency of these additives on improving waste properties. It is noted that based on the results obtained from three years monitor of the pilot vegetation experiments previously conducted (Fig. 10) on mixtures of bauxite residue and sewage sludge, gypsum and calcium oxyphosphate, it was indicated that bauxite residue with properly modified properties can support vegetation. Furthermore, it was indicated that waste rock properly modified with sewage sludge is an effective substrate for the development of a vegetation cover.

Figure 10. Vegetation experiments that were monitored in the framework of REFILL project

Based on laboratory and field pilot test results, it is estimated that the annual infiltration rate of water will be minimal, approximately 3% of the annual precipitation. However, these results are valid only for the conditions of field pilot tests applied. Simulation provides a useful and reliable when properly applied tool for the assessment of a system response under a variety of input parameters. In order to determine a detailed hydrological balance in the surface mines to be rehabilitated using bauxite residues as a filling material two models were used: the finite difference code "Visual ModFlow" and the “Visual HELP” model, both of them developed by Waterloo Hydrogeologic, Inc.

The simulation using Visual ModFlow was applied on both the demonstration test based on its design characteristics and field data, and the field pilot tests as they were implemented in the Prosorema mine. A reference scenario was developed based on the
most probable parameters levels, and based on this scenario, 5 more were developed by varying one at a time parameter. The parameters investigated include the hydraulic conductivity coefficient of all the layers (bauxite residues, gravel, vegetation layer), their specific porosity and water retention capacity, the annual precipitation, the percentage of vegetation coverage, the layer thickness etc. In all the cases, at least 3 levels of each parameter were examined. For the demonstration test, the reference scenario resulted in total annual percolation rate corresponding to 3.1% of the annual precipitation. The respective value for all the other scenarios was between 2.3 - 4.6 %. Even at the worst case scenario, in which the values resulting in high infiltration rates were given to all the parameters simultaneously, the infiltration through the dump remains still low (29.96mm or 6.3% of the annual precipitation).

The results obtained from laboratory tests, field pilot tests, design of demonstration test and simulation confirmed the hypothesis that the amount of water infiltrating through bauxite residues and released to the environment will be minimal, i.e. approximately 3% of the annual precipitation. Therefore, the risk of groundwater contamination due to bauxite residues disposal in abandoned mines will be very low. The alkalinity as well as Na and Al concentration in the initial leachates was high, but it progressively became lower due to the depletion of these elements. The modification of waste rock with sewage sludge, and the bauxite residues with gypsum, sewage sludge and phosphates, has been proven effective on supporting vegetation. Plants and grasses were developed well on both substrates some times even better than on clean soil. The metal uptake values were found very low, ensuring that the risk on wildlife is low, and thus, rendering the technique applicable to any region. Conclusively, based on the results obtained mainly from field pilot tests and simulation, it was indicated that the proposed rehabilitation scheme is effective.