Construction of an unpaved road using industrial by-products (bauxite residue)

FOTINI KEHAGIA
Assistant Professor of Civil Engineering Department
Aristotle University of Thessaloniki
University Campus of Thessaloniki
GREECE
fkehagia@civil.auth.gr

Abstract: - Utilisation of bauxite residue, the secondary material of alumina production, has been the object of numerous research efforts striving to introduce the by-product in useful applications. In fact, bauxite residue is used today in fabrication of ceramics, in cement production as a colouring agent and in abandoned quarries as a filling material. On the contrary, rare are the research initiatives to date aiming to a potential application of the by-product in highway engineering, a sector capable of absorbing large quantities in earthwork contraction. The Highway Engineering Laboratory of the Aristotle University of Thessaloniki (AUTH) focused on the potential use of this by-product in road construction. This paper details the construction of a gravel road using bauxite residue in the vicinity of the "Aluminium of Greece" industrial plant. The aim of this pilot project was to construct a pavement made of the by-product, trafficable for trucks and other vehicles, resistant to heavy traffic loads and durable to variable climatic conditions and especially to erosion. The layer of bauxite residue applied was processed by fly-ash (3%) and reinforced by bauxite aggregates to provide additional bearing capacity. The success of the project, acknowledged three years after construction, unveils the right balance achieved between technically excellent result and environmentally beneficial solution.

Key-Words: by-product; bauxite residue; gravel road; environment

1 Introduction

In developed and developing countries, a major concern about recycling industrial by-products is recorded and relevant interest in the use of recycled materials in road construction projects is increasing. The main challenge is to develop procedures introducing these recyclable materials to sustainable initiatives within the highway sector, namely to achieve technically feasible, cost-effective and environment-friendly solutions. Following systematic research on alternative materials for construction purposes, the use of industrial by-products in highway engineering, such as fly ash, metallurgical slags and other, is nowadays common practice in many countries. These materials bearing adequate engineering features proved to be suitable substitutes to natural aggregates or binding materials in highway construction [1].

On the contrary, relative research in potential use of bauxite residue in highway engineering through respective pilot or full-scale projects is rare. The highway construction sector, capable of absorbing large quantities of recycled materials has not been totally explored to date. In this regard, a full-scale utilisation of bauxite residue in the highway construction sector would be highly beneficial to the environment, since, actually, the greatest part of the by-product is disposed to the sea floor.

The Highway Engineering Laboratory of the AUTH has made research efforts over many years on the potential application of this by-product in engineering projects. Results from these research activities have demonstrated the applicability of the material in construction of unbound pavement layers and the positive effect to the serviceability of local roads. In this paper, the construction process of a gravel road using bauxite residue in Beotia by the premises of the "Aluminium of Greece" is presented. The scope of this pilot project was to build an unpaved road using bauxite residue and industrial by-products and to appraise the results in short and long term. The road structure was meant to suitably serve light vehicles and heavy trucks and to resist adverse climate effects.

2 Bauxite Residue

2.1 Production and use

Aluminium is a material with global annual production of some 45 million tonnes in 2011 and an estimate of nearly 50 million tonnes in 2013. Aluminium is a constituent of many rocks, minerals and ores and has to be extracted and converted to metal through a combination of chemical and electrolytic processes. The normal precursor to aluminium metal is aluminium oxide (alumina) although routes based on aluminium chlorides have also been developed and employed on a very small scale. Over 95% of the alumina manufactured globally is derived from bauxite by the Bayer process.

Bauxite ore is readily available and contains aluminium oxides and hydroxides in levels between 45 and 65% (measured as aluminium oxide). Current estimates of known world reserves are some 30 billion tonnes with indications of unproven reserves being much higher. It is mined in many countries including Australia, Brazil, China, Ghana, Greece, Guinea, Guyana, Hungary, India, Indonesia, Jamaica, Sierra Leone, Suriname, Venezuela and Vietnam. In the Bayer process, bauxite is heated under high temperature and pressure conditions in caustic soda to form a solution of sodium aluminate leaving behind an insoluble residue. The sodium aluminate is then filtered and aluminium hydroxide crystals are encouraged to precipitate. The aluminium hydroxide is sometimes sold as is or can be calcined to form aluminium oxide (alumina).

The amount of bauxite residue produced by an alumina plant or refinery is primarily dependent on the sources of the bauxite and secondarily on the extraction conditions used by the plant. In the extreme, this can vary from 0.3 to as high as 2.5 tonnes of residue per tonne of alumina produced, though typically it lies between 0.7 and 2 tonnes of residue per tonne of alumina produced. The most important factors are aluminium content of the bauxite, the type of aluminium oxide/hydroxide present (e.g. gibbsite, boehmite or diaspore), and the temperature and pressure conditions used for the extraction. The last two factors are dictated by the nature and form of the alumina present, the local cost for energy, and the cost and distance the bauxite needs to be transported.

It is estimated that the annual generation of bauxite residue from all these plants is of the order of 120 million tonnes a year. [2]

Processing and disposal of this residue produced in large quantities constitute an integral part of the alumina refining process and raise significantly the overall cost of alumina production. Enormous efforts have been directed worldwide toward the potential re-use of the material, including utilization, storage and disposal based on economic and environment- friendly aspects [3].

During the last two decades, significant research has been undertaken to suggest potential and effective use of the bauxite residue. Numerous fields of effective use of the material have been reported in the literature, namely:

- building material production as an additive to cement [4]
- producing a coloring agent for paint works for ground floors of industrial and other buildings [5]
- use in the making of ceramic glazes such as porcelain, vitreous, tile and glazes [6]
- filling material for mines and quarries after neutralization of residue [7]
- improving the soil structure and as a micro-fertilizer and a neutralizer of pesticides in agriculture [8]
- extracting rare earth metals and alumo-ferric coagulants as a technogenic raw material [9]

More specifically, in the following Table, different exploitation possibilities of bauxite residue and the respectively required processes are presented [10].

Table 1. Exploitation possibilities of bauxite residue

Areas of treatment	Processes	Product
metallurgical industry	drying, reduction	production of steel and other metals melting agent
construction industry	drying, sintering	production of Al_2O_3 and cements
	addition	production of concrete fillers
	drying, pressing	bricks production
	drying, granulation	aggregates of special concretes
glass and ceramic industry	addition	glass manufacturing
	drying, pelletisation	Ceramic manufacturing
chemical industry	Chemical treatment	Catalyst
	Drying and chemical treatment	production of adsorbents, pigments, resin contents, filler for plastics
agriculture	addition to soil	improvement of soil physicochemical properties
	neutralization, adsorption	remediation of soil, revegetation
water supply	adsorption	removing of moisture and other undesirable components, treatment of

		liquid wastes
	coagulation	coagulant
other	drying and chemical treatment	filtration material
	adsorption	neutralization of acid mine drainage

It must be stated that any particular use of application of bauxite residue should be high volume and be competitive in terms of quality, costs and risks. Also, a minimum pre-treatment of the residue is desirable.

However, potential use of this by-product in highway engineering projects, engaging big volumes of earthwork, is far from being fully investigated. Considering these aspects, the beneficial use of bauxite residue in engineering applications is especially attractive. Bauxite residue, when dewatered, compacted and mixed with a suitable binder, makes a good road building material and has been used to construct haul roads on bauxite residue areas for very many years. Among the few research efforts and engineering applications recorded worldwide, relative construction projects in France [11], Greece [12],[13] and Australia [14] are the most known.

2.2 Bauxite residue in Greece

"Aluminium of Greece" is the only existing aluminum refinery in Greece. It produces 680.000 tons of bauxite residue annually, mostly discharged through pipelines to the sea bed of the Gulf of Corinth. The residue is discharged in liquid state at a distance of 2800m from the coastline and in a depth of 120m under the sea surface. Former research reports no serious ecological impact inflicted to the surrounding marine environment [15], although the validity of these research findings is questionable at present. The company exhibited strong commitment to sustainable management of bauxite residue by investigating perspectives of reducing the quantities of the by-product disposal. Through ongoing research and field trials, a range of significant improvements to re-use methods of the residue have been developed and implemented. Various domains of application have been investigated through pilot and demonstration projects, converging to the effective re-use of the by-product.

The Highway Engineering Laboratory of the AUTH started investigating the material and, especially, its physical and strength properties in 1993. These research efforts concluded to the construction of an experimental embankment (2003), a fully successful experience and, more recently, to the construction of a gravel road at a length of 1200m (2009) hereafter presented.

2.3 Bauxite residue as a soil stabilizing material

During more than fifteen years (1993-2009), the Highway Engineering Laboratory of the AUTH has undertaken research tasks to fully evaluate engineering properties of this by-product and to establish procedures of potential utilization in road construction.

During the first period of investigation (1993-96), the physico-chemical analysis of the material itself and the strength properties introduced into different mixtures were examined. The research aimed at defining a soil stabilization pattern by use of bauxite residue as a stabilizing material. For this purpose, soil types with poor characteristics, inadequate for the construction of road embankments, were chosen and their mixtures with bauxite residue were studied in laboratory. The study revealed some strengthening properties of the by-product namely the increasing bearing capacity of the soil structure after proper laying and compaction [12], [16].

2.4 An experimental embankment

During the second period of investigation (2001-2004), an experimental embankment was designed and constructed on a site adjacent to the alumina plant (2003). The project was conceived after a long-time exploration of the material properties and the forecast of performance of the earthwork. The pilot project consisted of building up a 100 m long earth structure by use of the by-product and studying its performance under real loading conditions. After a rough evaluation of the whole experimental and site monitoring research (Figure 1), it seems that the material exhibits excellent performance in earthwork construction and constitutes an effective solution in projects where borrow-pits are rare and other local materials may prove inapplicable [17], [18].

a. Shortly after construction (2004)

b. Five years later (2009)

Fig. 1: The bauxite-residue embankment

3 Construction of a gravel road

3.1 The project

The perspective of the construction of a gravel road in the vicinity of the "Aluminium of Greece" production plant was the main idea of this project. The pilot project was planned to study the performance of the road structure and the rolling adequacy under real traffic conditions. The key focus of this project was to develop technology and practices for the alternative use of bauxite residue, economically viable and environmentally acceptable, reducing, at the same time, the reliance of stockpiling and storage. The aim of the project was to construct an unbound pavement bearing a smooth rolling surface for vehicles, resistant to heavy traffic loads and durable under adverse climatic conditions.

3.2 Materials

Materials utilized in the construction were a) processed bauxite residue, b) bauxite aggregates, c) fly ash. Processing of bauxite residue takes place in a specific filter press nearby the main industrial plant. Preliminary processing aims at producing a homogeneous material, reducing, at the same time, its water content from 100-200% down to 25%. Bauxite aggregates are introduced into the material to increase resistance to heavy loads. Fly ash, a well-known industrial by-product, is added to control humidity under adverse climatic conditions (heavy rain, etc).

3.3 Laboratory investigation

Bauxite residue is a complex material liquid in its original state, following the bauxite ore processing and soil-like after special treatment. Physical and chemical properties vary widely worldwide, mainly on the bauxite origin and, to a lesser extent, on the Bayer process applied. It is highly alkaline in nature that is a result of a complex mixture of solid-state and solution phase interactions. It contains six major oxides: Fe_2O_3 is the principal constituent of bauxite residue, which also contains Al_2O_3, SiO_2, TiO_2, Na_2O and CaO. Small quantities of numerous trace elements are often encountered. In Table 2, a representative chemical composition of the examined bauxite residue is presented and also the range of typical values encountered worldwide. Alkalinity tests yielded a pH value of 11.

Table 2. Chemical composition of bauxite residue

Chemical composition	Bauxite residue (%) (Greece)	Typical values worldwide (%)
Fe_2O_3	51	30-60
Al_2O_3	15	10-20
CaO	13	2-8
SiO_2	10	3-50
TiO_2	5	trace-25
Na_2O	0.20	2-10

Bauxite residue is a very fine red-colored material, having an average particle size of < 10μm. Physical properties were evaluated by laboratory analyses according to European Standards. Sieve-size analysis on dry samples confirmed the conventional gradation of the material presenting a fraction passing the No200 sieve greater than 80% (Table 3).

The material presents low to negligible plasticity (Table 4). This is mainly due to the uniformity of the particles which impedes plastic performance of the residue. Bearing capacity tests on specimens consisting of bauxite residue and bauxite aggregates unexpectedly satisfactory performance (CBR=85-103, Table 4). This may be attributed to some cementing properties of the by-product creating inextricable bounds into its inner structure.

Table 3. Sieve-size analysis of bauxite residue

Sieve	No 10	No 16	No 25	No 40	No 80	No 100	No 200	45μm
%passing	98	97	96	95	91	90	84	80

Table 4. Physical properties of bauxite residue

Atterberg Limits			Sand Equivalent	Specific Gravity
WL	WP	PI	SE	γ_c (t/m^3)
37-39	33-NA(*)	4-NP(*)	0	3,8-4,0
NA=Non Applicable	NP=Non Plastic			

3.4 Mix design

Four different compositions of bauxite residue were investigated introducing 10% or 20% of bauxite aggregates into the mix and a supplement of fly-ash 3% (Table 5). The material made from fly ash reaches comparable parameters such as cement paste made from Portland cement [19].

Table 5. Strength properties of bauxite residue

α/α	Material mixtures	W_{OPM} (%)	γ_{OPM} (t/m^3)	CBR 90% γ_{OPM}	CBR 95% γ_{OPM}
1	BR/BA = 90/10 (%)	25	1,76	67	85
2	BR/BA = 90/10 (%) + FA(3%)	25	1,76	82	110
3	BR/BA = 80/20 (%)	23	1,81	80	103
4	BR/BA = 80/20 (%) + FA(3%)	23	1,81	82	108
where: BR=bauxite residue, BA=bauxite aggregates, FA=fly ash					

Laboratory tests were conducted to determine compaction characteristics and the bearing capacity of the mixtures (Figure 2a,b). The mix design concluded to the optimum composition of the material to be utilized in construction:

a) bauxite residue = 90%
b) bauxite aggregates (d<1" = 2.5 cm) = 10%
c) fly ash = 3%

This formula yielded high CBR values (Fig.3), predicting a sound and resisting construction.

a. Fly-ash

b. Bauxite residue

Fig. 2: Construction materials

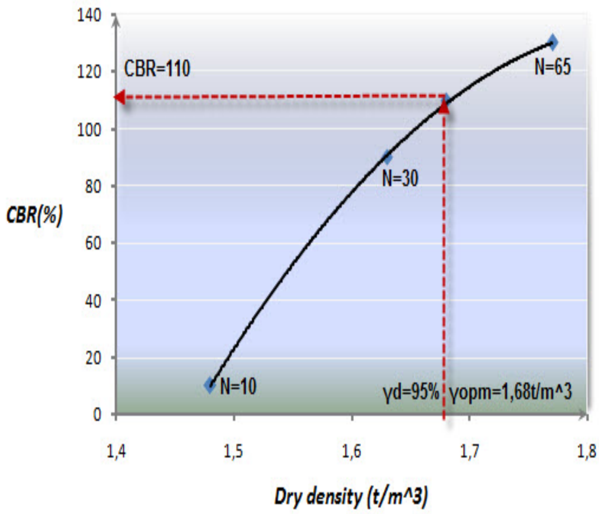

Fig. 3: CBR evaluation curve

3.5 Environmental risks

The main environmental risks associated with bauxite residue are related to high pH and alkalinity, and minor and trace amounts of heavy metals and radionuclides. In Layman's Report, it is referred that although it is an alkaline waste, the potential environmental risk associated with the containing alkalinity is low [20]. This low risk is due to the very low hydraulic conductivity coefficient of bauxite residues. Permeability measurements indicate that bauxite residues posses low hydraulic conductivity (k) values ranging from $3x10^{-5}$ to $4.6x10^{-7}$ cm/s depending on the compaction conditions. The lower k value was obtained when bauxite residues were compacted at optimum moisture content. Moreover, dewatering to low moisture of the material is required mainly using press filters. This k value is slightly higher than the limit posed in the European landfill directive for low permability layers ($1x10^{-7}$). By acting as a low permeability layer and taken into account the low precipitation rates at the sites into consideration, water percolation through bauxite residues layers is estimated to be minimal.

Standard leaching tests (TCLP, Italian leaching test) applied to bauxite residue have reported leached concentrations of trace metals well below the threshold concentrations. The absence of severe eco-toxicological or genotoxic effects of this material has been also reported. All these studies suggest that the use of bauxite residue is safe in terms of metal leachability and toxicity [20], [21].

4 Construction process

The project consisted of laying a 12 cm-layer of bauxite residue mixture with aggregates and fly-ash over the existing surface of a local earth road presenting serious surface defects: potholes, irregularities, transverse distortion.

The main components of the mixture (bauxite residue and bauxite aggregates) were obtained from deposits in the vicinity of the industrial area. Fly ash was transported to the construction site from an electrical power station. The issue of provision and transportation of fly ash is a practical impediment and a costly option. Nevertheless, this issue must be properly addressed in favor of the success of the project. Addition of fly ash was judged necessary to effectively control moisture of the mix under rainy conditions. The proposed percentage was the minimum required to achieve a satisfactory engineering outcome and, at the same time, a cost-effective project.

Throughout this experience, materials had to be clean and free of contaminants such as soil, clay and organics. The mixing process was scheduled to take place by the site just before the laying of the material. This condition must be respected to avoid binding effects between constituents before laying the material. Homogenous distribution of fly-ash in the mixture is very important. Suitable equipment, such as loaders, can be used to achieve satisfactory mixing. Moisture content must be very low ($w<5\%$) while mixing the materials, otherwise there is a risk of chemical reaction before laying and potential failure during construction. Since the by-product is retrieved from the processing plant at a water content of 25%, it is necessary to spread and dehydrate it before mixing.

The first stage of construction operations consisted of grubbing and clearing the existing surface of the local road, followed by water spreading to achieve adhesion of the new layer. Main earthwork operations were carried out by a grader and a loader (Figure 4), laying the material at a thickness of 12 cm and a length of 1200m. Before compaction, additional bauxite chippings at a rate of 20 kg/m^2 were applied on the gravel surface to improve bearing capacity. The compaction was carried out by a light non-vibrating roller of 8t.

The large quantity of bauxite residue laid, the satisfactory workability and the resistance to erosion were the main advantages of the construction experience introducing the adopted formula of bauxite residue mixture.

Fig. 4: Spreading the material (2009)

5 Conditions for effective construction

There are some conditions to respect in order to achieve a satisfactory outcome:

a) Although the optimum water content of the mixture (modified Proctor) is equal to the one of the material after processing (w=25%), the mixing and laying of the mixture must be carried out at dry state (w<5%). Otherwise, drying shrinkage may start before laying the mixture and the construction risks to fail.

b) Bauxite chippings must be spread and rolled on top of the layer before water spreading and compaction.

c) If the aforesaid layer constitutes the rolling surface, a superelevation (2-3%) must be foreseen to facilitate surface drainage.

d) Vibration during compaction risks to disintegrate the inner structure of the mixture and must be absolutely avoided.

6 Road condition assessment

The final outcome was very satisfactory, the road rolling surface being even and resistant. Traffic loads, moving after construction, did not cause rutting or surface deformation. Evenness of the road surface proved more than satisfactory. No erosion traces appeared after 3 years exposure to precipitation aggressiveness. Locally, excessive dust on the pavement surface created some problems. This functional defect vanished after some time, especially after some rainfall. The local road has been under traffic for 36 months. The overall performance is very good and this proves that this secondary material can be used successfully in road construction (Figure 5).

Fig. 5: Construction completed (2009)

This experience is the first and the only one known worldwide, utilizing bauxite residue and other by-products to construct an unbound pavement of a local road. This is a full-scale pilot construction experience under real loading conditions. It is worth mentioning that, three years after construction, the gravel road presents a satisfactory riding surface bearing no sign of significant distress due to traffic or to aggressive climatic conditions (Figure 6 a,b).

Fig. 6a,b: Road condition following three years under traffic (2012)

7 Conclusion-Discussion

Due to shortage of natural resources and increasing waste disposal costs, the re-use of waste and recycled materials is increasing worldwide in civil engineering, especially for road construction. However, full understanding of the engineering behaviour of these materials is essential so that they can be used safely in civil engineering applications. So, recycled materials that have suitable engineering, environmental and economic properties can be used as substitutes for natural aggregates or traditional materials in highway construction.

Large-scale storage of bauxite residue has continued to be the preferred solution for its management on balance of economic, environmental and social considerations. However, the residue provides the opportunity to create value through utilisation of it as a resource, either as a feedstock for the production of other materials, or as a product in its own right. In order to have a significant impact on the rapidly growing global amount of bauxite residue, large tonnage utilisation challenges are needed to be implemented.

The most important barrier to remediation and re-use of bauxite residue management is its high alkalinity. Better understanding of these interactions is required to support progress in the development of the sustainable bauxite residue management.

A research engineering project by the Laboratory of Highway Engineering of AUTH introducing the use of bauxite residue in road construction, confirmed he suitability of this by-product for construction purposes. The project suggests a technically sound solution for unbound pavements on the secondary network. High strength and resistance to external factors are obtained through a special engineering process. The objective of this full-scale construction project was to demonstrate the applicability of bauxite residue in a real engineering experience. This experience proved absolutely successful and contributed in the establishment of basic rules to handle properly the by-product in construction. Following the proposed construction process and the conditions for a suitable application, a large-scale use of bauxite residue in highway engineering projects seems feasible, presenting technical advantages all by contributing to the preservation of the environment.

References:

[1] FHWA, Recycled materials in European Highway Environments. Uses, Technologies and Policies, *International Technology Exchange Program*, ReportPL-00-025, 2000

[2] International Aluminium Institute (IAI), Bauxite Residue Management: Best Practice, 2013

[3] Layman's Report, Rehabilitation of abandoned bauxite surface mines using alumina red mud as filler, LIFE03 ENV/GR/000213, 2006

[4] Pilurzu S., Cucca L., Tore G., and Ullu F., New research proposals for utilization and disposal of bauxite red mud from Bayer process, *Global Symposium on Recycling, Waste Treatment and Clean Technology*, 1999, pp. 471-480

[5] Martinent-Catalot V., Lamerant J-M., Tilmant G., Bacou M-S, Ambrosi J.P., Bauxaline: A new product for various applications of Bayer Process red mud, *Light Metals*, 2002, pp. 125-131

[6] Yalcin N., Sevinc V., Utilization of bauxite waste in ceramic glass, *Ceramics Int*. 26(5), 2000, pp.485-493

[7] Brown S.O., Kirkpatrick D.B., Red mud product development, *Light Metals*, 1999, pp.5-6

[8] Koulikourdis A., Paspatis E., Grigoropoulou H., Red mud residue application to soil: phytotoxicity assessment," *9th International Conference on Environmental Science and Technology*, 2005, Rhodes.

[9] Nikolaev I., Zakharova V.I., Khajrullina R.T., Acid methods of red mud processing: Problems and prospects, *Izvestiya Vysshikh Uchebnykh Zavedenii, Tsvetnaya Metallurgia*, 2, 2000, pp.19-26

[10] Schwarz M.,Lalik V., Possibilities of exploitation of bauxite residue from alumina production, Recent Researches in Metallurgical Engineering-From Extraction to Forming, InTech, 2012

[11] LRPC d'Aix-en Provence, Utilisation des Bauxites Inertes en Technique Routiere, Rapport Technique, 1997, 10p.

[12] Mouratidis A., Tsohos G, Investigation of red mud properties for use in road construction, *4th International Congress on Environmental Geotechnics*, Rio de Janeiro, 2002, pp.493-496.

[13] Mouratidis A., Construction d'un remblai routier en boue rouge," *Symposium International sur l' Amélioration des sols en place*. Dhouid, Magnan et Mestat (ed.) Presses de l'ENPC/LCPC, 2004, pp.457-464

[14] Nikraz, H. R., and P. Jitsangiam, Evaluation of Sustainable use of a Residue Sand as a Highway Embankment Material, *International Conference on the Role of Universities in Hands-On Education*, 2009, Bangkok, Thailand.

[15] Varnavas S., Achilleopoulos P., Factors controlling the vertical and partial transport of metal-rich particulate matter in seawater at the outfall of bauxite red mud toxic waste, *The Science of the Total Environment* 175, 1995, 199-205

[16] Kehagia F., An innovative geotechnical application of bauxite residue, *The Electronic Journal of Geotechnical Engineering*, Vol. 13, 2008

[17] Mouratidis A. Construction d'un remblai routier expérimental, *Revue Francaise de Géotechnique*, No.125, 2008, pp.41-46
[18] Kehagia F. A successful pilot project demonstrating the re-use potential of bauxite residue in embankment construction, *Resources, Conservation and Recycling*, Vol.54, 2010, pp. 417-421
[19] Padevet P., Lovichova R., The changes of material properties on the cement paste with fly ash exposed to high temperatures, WSEAS Transactions on Applied and Theoretical mechanics, Issue 4, Vol.8, 2013
[20] Layman’s Report, Rehabilitation of abandoned bauxite surface mines using alumina red mud as filler (REFILL), LIFE03 ENV/GR/000213, 2006
[21] Rubinos D., et al., Assessment of bauxite refining residue (red mud) as a liner for waste disposal facilities, International Journal of Mining, Reclamation and Environment, 2013