Red mud application in construction industry: review of benefits and possibilities

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Abstract. Red mud is a waste originated in the processing of bauxite into aluminium, which properties of high alkalinity make it cumulatively stored, occupying increasing deforested areas. Annually, it is estimated that approximately 117 million tons of red mud are generated in the world, with no prospect of use, what represents an imminent risk of pollution prone to contamination. Nevertheless, environmental liabilities caused by red mud affect not only the environment, but also the companies responsible for the waste, which will be subject to highest fee payments. Although there are studies that prove the feasibility of using this solid waste in the constitution of ceramic materials, there are no large-scale applications. This study seeks to evaluate the possibilities of red mud application in construction industry, focusing into two main areas: cement production/ceramic material and road construction. Backgrounds from other researchers were taken into consideration and analysed according environmental, economic and technical feasibilities.

Keywords: Red mud. Road sublayers. Materials construction. Cement constitution.

1. Introduction

The red mud is a solid waste originated in the beneficiation of bauxite into aluminum. The process is named as 'Bayer process' and it has four main steps: digestion, clarification, precipitation and calcination [1, 2, 3]. Digestion consists on granulometry reduction of bauxite. At clarification stage, the bauxite is immersed in a sodium hydroxide solution to separate the alumina and impurities (red mud). Precipitation allows taking out the alumina and introducing it to the calcination, when it is exposed to temperatures higher than 960°C [2]. The next stage is the reduction process (Hall-Héroult), where the alumina is transformed into aluminum through electrolytic procedures [3].

Because of the sodium hydroxide, the red mud has alkalinity properties and some heavy metals in the constitution [4, 5]. This characteristic made most part of the researchers classify the red mud as a hazardous waste for the environment. However, there are some studies that classify the red mud as a non-inert waste [6, 7, 8].

The disagreements between red mud classifications it happens due different standards and legislations adopted, also, because of the varied places where the bauxite is extracted, once this can change composition and chemical components. Even amounts of red mud generated at the same industry can changes according the production methods.

The International Aluminum Institute [13] estimated that 2.274.271 metric tons of alumina were produced between January 1973 and November 2016, which suggests the red mud generation is twice this value.

There are studies that prove the feasibility of using this residue for construction materials [4, 14, 15, 16, 17], compounding roofs, tiles, bricks, road sublayers, cement and bituminous mixtures. Most part of the researches showed improvement of properties, specially increasing the resistance. Even having technologies capable of neutralizing the red mud [18, 19] there are no policies to reuse this waste in large scale. Thus, the red mud is cumulatively stored, occupying increasingly larger areas.
Even being stored efficiently, the red mud it is a hazardous material and might cause serious environmental damages such as contamination of surface effluent and underground, affecting the population health [4]. Therefore, the ideal situation should be find a practicable and safe way to use this solid waste taking it out of the industrial landfills and applying into the production cycle.

The construction industry has been considered as an ideal field to reusing solid wastes, once it consumes bigger quantities of material and most part of the residues can be incorporated, considering the chemical similarities.

In this context, this work aims to review the possibilities of using the red mud, evaluating physical and chemical properties for applying it on construction industry.

2. Statistics of generation

The International Aluminum Institute [13] declared that just in 2016, China was responsible for 55% of world’s alumina production, followed for Australia and Brazil with 17% and 9%, respectively. Therefore, those countries are the biggest source of red mud in the entire world.

In north of Brazil, are produced between 4.40 million and 6.26 million tons of red mud [4]. It is estimated that about 10.6 million tons of waste are discarded annually in the country, while in the world reaches more than 117 million tons/year [15].

It is estimated that are more than 85 refineries located around 32 countries, responsible for the alumina production and red mud generation in all world [13, 20].

In the Figure 1 it is shown the quantities of red mud, alumina and aluminum produced worldly between 2010 and 2015.

![Figure 1. Values of alumina, aluminium and red mud produced in the world.](image)

All data were based in the International Aluminium Institute [13] and according estimates that say for each ton of alumina produced can be generated 0.3 till 2.5 tons of red mud [9, 10, 11, 12]. Therefore, as the red mud it is not used for any kind of application, this solid waste it is stored in deforest areas accumulating year by year.

In the north of Brazil is located the largest deposit of red mud in Latin America [5, 6], where it is added every year around 4.5 million tons of waste, occupying an area around 5 km² [7]

3. Red mud characterization

3.1. Chemical properties

Usually, the red mud has in the constitution alumina (Al₂O₃), iron oxide (Fe₂O₃), quartz (SiO₂), titanium dioxide (TiO₂), calcium oxide (CaO), vanadium pentoxide (V₂O₅) e manganese oxide (MnO). Some red mud compositions from different companies in the world are exhibited in Table 1.

Manfroi [16] obtained percentages of vanadium pentoxide (V₂O₅) and manganese oxide (MnO) similar as Lima [2] for the red mud. However, as the bauxite does not have a mineralogical composition defined, the red mud can vary according to the place of bauxite extraction, processing and red mud storage methods. Therefore, there are differences of composition even for red mud generated in the same place [3].
Lima [2], Macêdo et al. [17] and Silva Filho et al. [3] for example, analyzed the residue came from the same company, and the researchers had some discrepant results. In both authors studies, the silica values (SiO₂) were lower than those obtained by Lima [2], beyond were not detected the presence of vanadium pentoxide (V₂O₅) and manganese oxide (MnO) in their work. Macêdo et al. [17] detected 8% of caustic soda (Na₂O), however, this component was not identified for Lima [2].

| Substances | ALUNORTE Brazil | ALCOA Brazil | CBA Brazil | ALCAN Canada | ALCAN Australia | ALCAN Africa |
|------------|-----------------|--------------|------------|--------------|----------------|--------------|
| Al₂O₃      | 35.5            | 35.67        | 36.7       | 37.6         | 25.45          | 26.6         |
| Fe₂O₃      | 37.16           | 33.78        | 29.89      | 32.45        | 34.5           | 48.4         |
| SiO₂       | 2.34            | 3.45         | 6.78       | 3.67         | 17.06          | 5.5          |
| TiO₂       | 6.18            | 4.56         | 5.67       | 4.12         | 4.9            | 2.8          |
| Na₂O       | 8.49            | 9.67         | 7.89       | 6.78         | 2.74           | 2.4          |
| CaO        | 1.23            | 2.34         | 1.2        | 3.45         | 3.69           | -            |

Table 1. Red mud constitution at different companies.

It is possible that Na₂O was not identified due a changing of red mud storage method by the company. Once, before were made by lagooning method and is now being gradually modified for dry stacking because it is less aggressive to the environment. In the dry stacking method the red mud is washed to extract and reuse the caustic soda and the alumina still present in the residue [21], making it less alkaline.

The chemical variability of the red mud is one of the greatest challenges for the scientific community, since it demands a greater control of the process and, consequently, increase the costs related to the reutilization.

3.2. Physical properties
The red mud has a bulk specific gravity around 2.609 g/cm³[2]. Manfroi [16] found the value 2.71 g/cm³ and Souza [22] 2.13 g/cm³. Chandra [23] declared that the red mud has the bulk specific gravity between 2.5 – 2.7 g/cm³. Although, Han et al. [24] established as 3.04 g/cm³ for Korean red mud.

The red mud specific surface area (BET) generally lies between the ranges of 20–30 m²/g [25].

Huang et al. [26] noticed the Australian red mud had a specific surface area around 22.71 m²/g, similar the value found for Han et al.: 23.53 m²/g [24].

The surface area can be lower when the red mud is calcined at high temperatures (>600°C). Thus, when this solid waste is applied as part of ceramic materials, it helps at surface finish.

At laser granulometry test made for Lima [2] it can be seen that the red mud is a fine grained material with 100% of the particles smaller than 290 µm, 80% than 50 µm in diameter and 40% than 5 µm, as Figure 2.
classification based on grain size criteria of the Brazilian Association of Technical Standards [27].

Only 15% of the particles have a size in the range from 60 µm to 200 µm, characteristic of fine sand.

According to granulometry results similar to those obtained in this work, Antunes, Conceição and Navarro (2011) [4] classified the red mud as a sandy-clay-silty material, according to the textural classification proposed soil by United States Department of Agriculture [28] characterizing it as a cohesive material with low porosity and intense phenomena of capillarity [29].

The particle size of the red mud is an important factor to be considered when it is used compound bituminous mixtures for layer highways. Since particles bigger than 40 µm tend to fill the voids of the aggregates and particles smaller than 20 µm are mixed to the bitumen, modifying the viscosity, softening point and thermal susceptibility [30, 31, 32, 33].

Therefore, since about 70% of the grains that make up the red mud have a particle size less than 20 µm, it is possible that part of the residue used in the composition of bitumen mixtures is incorporated into the binder, changing its rheological properties and improving the strength of bituminous highways to deformations.

4. Possible applications

The chemical variation it is an obstacle to apply the red mud in any situation. However, it is possible recognizing the red mud characteristics for each place where is generated and establish a template as base.

Many researches has been evaluating different applications, like: composting [34], sewage treatment [35, 36], stabilization material [37], metal recovery [39] and mainly composing building materials such as pigments, paints, aggregates, bricks, tiles, as cement additive and applied at pavements constitution [2,5,14,20,39,42-45].

According to Shinomiya [46] between 1964 and 2008, 734 patents on red mud applications were generated. Among them, it is estimated that 33% is directed to civil construction applications (Figure 3).

![Figure 3. Red mud applications: registered patents (1964-2008).](image)

Despite the good results obtained in the construction industry, the red mud still does not have a large scale application, since none of the options studied meets all the requirements for wastes valorization: environmental and budgetary feasibility beyond mechanical performance equal or better than conventional methods [40, 47]. This means it still cheaper for companies leave the red mud storage than use it somehow.

Basically, the applications can be divided into three types: construction, neutralization and metal recovery.

There are several methods of neutralization using acids [48], sea water [48], carbon dioxide [38, 41] and high temperatures (sintering) [49]. However, none of them are able to inert radioactive and toxic elements, being only for alkalinity neutralization.

Metals recovery researches have grown [50], however they do not solve the environmental problem related to storage.

In this way, the best perspective of application it is on construction industry, since it allows consuming larger amounts of red mud in the most diverse applications, being a low cost alternative material.

In his work, Shinomiya [46] evaluates the most viable applications for red mud. For this, the author took into account criteria of industries availability for tailings processing, usage in large quantities and
waste pre-treatment need. Thus, he concluded that the most appropriate applications for the Brazilian reality are: road construction, cement production and ceramic materials.

4.1. Cement production and ceramic materials
When applied in ceramic materials, He et al. [44] declares that the alkaline substances at the red mud can decrease the sintering temperatures and save energy, beyond can promote vitreous phase formation which improves the resistance of ceramic materials.

In fact, many researches described the improvement of ceramic materials resistance when the red mud is used as component. Yang e Xiao [15], for example, evaluated the performance of non-sintered structural blocks constituted by the residue. The authors observed when the percentage of red mud increase the mechanical strength improved. The results obtained were attributed to the hydration reaction due to the combination of silica and alumina with calcium hydroxide.

Some researches approach about the pozzolanic properties of the red mud [8,10,15,16]. According Brazilian Standards pozzolanic materials are siliceous or silico-aluminous materials those when mixed with calcium hydroxide and water acquires cementitious properties increasing the strength resistance [51,52]. Basically, the pozzolanic capacity are assigned by the sum quantities of Al₂O₃, Fe₂O₃ and SiO₂ that needs to be higher than 70% (as results presented at Table 2) and possess an index of pozzolanic activity greater or equal to 75% [16].

The hydration reaction promoted by mixtures of red mud and calcium hydroxide source it happens in the same way as cement with water. In fact, in both the calcium hydroxide react with silica and aluminium oxides originating calcium silicates and aluminates responsible for increasing the mechanic resistance.

The reaction with the silica only occurs when it is in the amorphous state, which means as vitreous silica, once when in the crystalline state the reactivity is reduced [53].

Factors as temperature and specific surface of materials influence the hydration reactions and formation of chemical compounds [54]. When hydration occurs in temperatures higher than 35°C, for example, compounds less soluble are formed. In general, the heat of the hydration is directly proportional to the specific area of the materials used. Therefore, the larger the specific surface, the greater the heat released [55].

As stated above, the amounts of silica and alumina present in the red mud may vary according to the origin of the bauxite and Bayer process used, thus the pozzolanic activity as well as the formation of hydrated calcium silicates and aluminates may vary. Consequently, the resistance provided by the hydrated compounds is not stable.

4.2. Road construction
When applied to road construction the red mud can be used as filler in bituminous mixtures or in pavement base layers. Red mud applied in road construction are still innovative option, but with good prospections.

Kehagia [42] made an analysis about the behavior of an unpaved road after three years, constructed with 97% red mud and 3% of fly ash. It was constructed a layer with bauxite residue reinforced by bauxite aggregates.

The author highlights that any particular application for red mud should use high volume and needs to be competitive in terms of quality, costs and risks. Also, it is necessary analyze if a minimum pre-treatment of the residue is desirable.

Therefore, using red mud in highway engineering projects is especially attractive, once needs big volumes for earthwork and when dewatered, compacted and mixed with a suitable binder, makes a good road building material and has been used to construct roads [42]. Despite, the good prospections there are only few researches and engineering applications relative to construction projects with red mud. The most known are in France [56], Greece [57] and Australia [58], however, only Brazil [2, 59] has studies applying the residue in bituminous mixtures.

According Kehagia [42] the pilot road project had really good results and after three years the construction was without rutting, surface deformation or had any erosion traces.

Jitsangian and Nikraz [58] investigated whether red mud is viable to be used as road base material. A pozzolanic stabilized mixture was created using fly ash, lime and water to improve the properties of the residue. The optimum proportion was to stablish which mixture would achieve an unconfined compressive strength (UCS) between 0.6 and 1.0 MPa requested by Australian Standards. The selected
A mix was 70% red mud, 25% fly ash and 5% lime. The results showed that the performance of stabilized residue was superior of the conventional material and provide improved performance when applied as road base material.

As happens in ceramic and cement materials the calcium hydroxide presented in the lime react with the silica and aluminium oxides promoting hydration (pozzolanic) reaction that increase the material resistance.

Other possible application for the red mud in road construction is as filler in bituminous mixtures. In Brazil, Lima [2] and Bezerra, Macêco, Souza [59] evaluated bituminous mixtures performance composed with red mud and compared the results with mixtures made with conventional materials. Both studies show that the red mud is capable to improve the resistance of bituminous layers.

Lima [2] used different red mud percentages to evaluate how this changing would affect the performance. However, the quantity of filler it is an important factor to define the consumption of bitumen. Generally, higher percentages of filler request more bitumen. As Lima’s proposal was analyze the red mud influence, the author used the same percentage of filler to all mixtures (7%) diversifying filler types. Thus, it was used red mud and stone dust as filler to compose the mixtures in different percentages. The conventional mixture had 7% stone dust and the others 3%, 5% and 7% red mud. Those composed by 3% and 5% red mud were completed with 4% and 2% stone dust to reach 7% of filler.

As much the red mud percentages increased the bitumen content decreased. This happened because the red mud specific surface is smaller than the stone dust, consequently, less bitumen would be necessary to cover the aggregate grains. The usage of a residue as the red mud instead stone dust in bituminous paving can decrease construction costs, not just for being solid waste highly available but, specially, because it needs smaller amounts of binder.

The performance evaluation was made using permanent deformation tests. Higher the amount of red mud better were the results. Thus, the worst performance was from the conventional mixture, however, all the mixtures had acceptable results according French guidelines, which mean all of them obtained values of permanent deformation lower than 10%.

The red mud results can be explained by the lower bitumen content, since higher contents increase the thermal susceptibility and reduces the performance of permanent deformation. The red mud was incorporated by the bitumen and increased the viscosity, improving the results.

5. Environmental concerns and challenges for large-scale valorisation

The main concern regarding the red mud application in the construction industry it is based in the higher alkalinity (pH around 10-13) and heavy metals presented in the residue constitution.

To be used in road layers it is important understand how this characteristics can influence and prejudice the environment, since it can promote leaching of heavy metals to underground water. However, despite these concerns there are promising studies that suggest being possible using the residue to stabilize and improve the soil quality.

The red mud has been used in agriculture to increase the phosphorus retention of sandy soil [60] and to increase the low pH [61]. According studies the combination of iron, aluminum, and silicate presented in the red mud, are capable to immobilize toxic metals from polluted soils [62], removing toxic metals from wastewaters[63] or to reduce the leaching of soil nutrients[64].

Kehagia [42] suggest that the use of bauxite residue is safe in terms of metal leachability and toxicity, also, affirm the red mud when compacted has low permeability and as the road was constructed in a local with low precipitation rates any type of pollution would be minimal.

In 2010, an industrial embankment used for red mud storage broke in Hungria and more than 800,000 m³ of toxic (highly alkaline, pH = 13) red mud slurry flooded the environment covering 1017 ha of agricultural land.

Ujaczki et al. [65] made previous microcosm studies analyzing the potential utilization of the Hungarian red mud (main components: Fe, Ti and Al oxides and hydroxides, pH = 10–12) as soil improvement. The red mud ratio mixed into the soil ranged between 0–40%. The experiments were monitored by physical-chemical, biological and eco toxicological methods. Mixing of 5% red mud into the soil significantly increased the total As, Cr, Ni, Pb and Na content of the soil, but it did not exceed the Hungarian soil quality criteria. The microcosms containing 5% red mud did not show any adverse effects on the tested organisms. Overall, 5% red mud could be mixed into the soil without any mid-term adverse effects [65].
The most common heavy metals found at contaminated sites, in order of abundance are Pb, Cr, As, Zn, Cd, Cu, and Hg [66]. The heavy metals concentration in the red mud composition is very close to the normal values found in soils, excepting total chromium content. Chromium concentration should be carefully regarded, because previous studies show the leachable parts of chromium are decreasing under the acceptable standards, as far as the pH drops toward usual values in soils [66].

Ujaczki et al. [67] investigated the applicability of red mud and soil mixture (RMSM) removed from the accident with Hungarian red mud landfill. In this paper the application of RMSM is evaluated in a field study aiming at re-utilizing waste, decreasing cost of waste disposal and providing a value-added product. The subsoil (LQS) was mixed with 5%, 10%, 20% and 50% RMSM by weight. The characteristics of the LQS + RMSM mixtures compared to the subsoil (LQS) and the RMSM were determined by physical–chemical, biological and ecotoxicological methods. RMSM addition did not change the pH during the experiment. The metal analysis of the LQS + RMSM mixtures indicated that the RMSM is applicable as landfill surface cover component at up to 20% RMSM dose because the concentration of the examined toxic metals and metalloids did not exceed the Hungarian limit value for soil. Assessing all the environmental toxicity test results we concluded that 20% RMSM application did not have any harmful effect on the subsoil (LQS), beyond increased the water holding capacity. Based on this study, the authors recommend the use of the removed RMSM as additive to the surface layer of landfill cover systems at landfill sites.

The hazardous properties of the red mud are the main difficult to apply this residue in large scale. However, if we simulate an insertion of 10% red mud as filler in bituminous mixtures and estimate that 50% leach during the road life, there is good probabilities that this would not provoke any harmful effect to the soil if we consider results obtained by Ujaczki et al. [65, 67], further yet if the road is constructed in locals with low precipitation rates.

6. Conclusion

The environmental viability for red mud application can be obtained in two ways: neutralization and inertness. However, even the neutralization is not enough to ensure a safe application, since only the alkalinity is solved. The best option is to use the residue in applications that allows it to be inert, avoiding leaching to the environment.

Several studies prove that the application of red mud to ceramic building materials such as tiles and bricks have improved performance and mechanical strength, however, despite being considered economically feasible, applications like this are considered environmentally ineffective, since there is no inertness of the residue and possibility of red mud leaching.

Undoubtedly, the construction industry is the best option to use the red mud, once permits easily mixing the residue into ceramics, cement or even polymers. Beyond, it is a great option to use residues previously stocked without defined purposes and becomes an alternative material with low costs, which allows decreasing the mineral aggregates consumption.

The best scenario for reusing solid wastes is to find a way that does not need any kind of pretreatment (which increase the costs), that makes the residue inert, presents mechanic results better than conventional ones and allows using a bigger volume of it.

Among the applications studied over the years in several parts of the world, the most suitable one is on road construction.

For road construction, it is more indicated using the red mud as filler in bituminous mixtures, once this residue has chemical similarities with other filler types already used. Bituminous mixtures allow using this residue in bigger quantities and the bitumen can cover the red mud grains making it inert, which means any leach can be avoid.

After being old, the pavement can present some scratches and roles where can possibly leach a bit of waste, however, the quantity would be substantially lower than in other applications as in ceramic materials, for example, once the bitumen it is hydrophobic and ceramic materials are hydrophilic, what makes easier red mud leaching.

Red mud into bituminous mixtures is feasible at economic aspects, since don’t need any type of special treatment or process.

There are good possibilities if the red mud is applied as filler in low percentages to compose bituminous mixtures, however, unquestionably the road construction area needs to be more investigated and be sure about environmental/budgetary feasibility.
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References
[1] Habashi F 2005 J. Hydrometallurgy 79 15-22
[2] Lima M S S 2015 Avaliação do emprego de lama vermelha no desempenho à deformação permanente de misturas asfálticas a quente. Universidade Federal de Santa Catarina, Brazil.
[3] Silva Filho E B, Alves M C M and Motta M D 2007 Lama vermelha da indústria de beneficiamento de alumina: produção, características, disposição e aplicações alternativas. Revista Matéria 12, n. 2, p. 322-338, ISSN 1517-7076.
[4] Antunes M L P, Conceição F T D and Navarro G R B 2011 Caracterização da Lama Vermelha Brasileira (Resíduo do Refino da Bauxita) e Avaliação de suas Propriedades para Faturas Aplicações. 3rd International Workshop Advances in Cleaner Production. Brazil, p. 10.
[5] Collazo A, Fernandez D, Izquierdo M, Novoa X R and Perez C. 2005 Evaluation of red mud as surface treatment for carbon steel painting. Process in Organic Coating 52, p. 351-358.
[6] EPA - Environmental Protection Agency. 2014 U. S. Government Printing Office. Electronic code of federal regulations. Available: <http://ecfr.gpoaccess.gov/>. Title 40, Part 261, Sect 4 (b) (7) (ii) (e).
[7] Nunn R F 1998 Advances in red mud dewatering and disposal technologies. J. Light Metals - The Minerals, Metals & Materials Society p. 107-114
[8] Lima F S 2006 Utilização da Lama Vermelha e do Resíduo Caulinitico na Produção de Pigmento Pozolânico para Argamassas e Concretos de Cimento Portland. UFPA, Brazil.
[9] Ribeiro D V, Labrincha J A and Morelli M R 2012 Efeito da adição da lama vermelha na corrosibilidade do concreto armado avaliado por meio de técnicas eletroquímicas. Riem - Revista IBRACON de Estruturas e Materiais 5 451-67.
[10] Hildebrando E A, Souza J A da S, Angélica R S and Neves R F 2013 Application of Bauxite Waste from Amazon Region in the Heavy Clay Industry. Materials Research 16 1418-22.
[11] HYDRO. 2013 B Como a alumina é extraída da bauxita. A Hydro no Brasil. Available: <http://www.hydro.com/pt/A-Hydro-no-Brasil/Sobre-o-aluminio/Ciclo-de-vida-do-aluminio/Refino-da-alumina/>.
[12] Komnitasas K, Bartzas G and Paspaliaros I 2004 Efficiency of limestone and red mud barriers: laboratory column studies Miner. Minerals Engineering 17 183–94.
[13] The International Aluminium Institute. 2016 Primary aluminium production. Available: <http://www.world-aluminium.org/statistics/>.
[14] Kavas T 2006 Use of boron waste as a fluxing agent in production of red mud brick. J. Building and Environment 41 1779-83.
[15] Yang J, Xiao B 2008 Development of unsintered construction materials red mud wastes produced in the sintering alumina process. Construction and Building Materials 22, 2299-2307.
[16] Manfroi E P 2009 Avaliação da lama vermelha como material pozolânico em substituição ao cimento para produção de argamassa. UFSC, Brazil.
[17] Macêdo A N, Costa D H P and Trindade S R Souza J A da S and Carneiro R J F M 2011 Comportamento de blocos cerâmicos estruturais produzidos a partir da mistura de lama vermelha e argila. Revista Ambiente Construído 11 25-36.
[18] Palmer S J 2010 Thermally activated seawater neutralised red mud used for the removal of arsenate, vanadate and molybdate from aqueous solution. Journal of Colloid and Interface Science 342 147-154.
[19] Cooling D J 2007 Improving the sustainability of residue management practices-Alcoa World Alumina Australia. Australian Centre of Geomechanics, Perth, Australia.
[20] Tsakiridis E, Agatzini-Leonardou S, Oustadakis P 2004 Red mud addition in the raw meal for the production of Portland cement clinker. Journal of Hazardous Materials B116 103-110.
[21] Grafe M, Power G, Klauber C 2011 Bauxite residue issues: III. Alkalinity and associated chemistry Hydrometallurgy 108 60–79.
[22] Souza J A D S 2010 Estudo e Avaliação do Uso de Resíduos do Processo Bayer como Matéria Prima na Produção de Agregados Sintéticos para a Construção Civil. PhD Thesis, UFPA, Brazil.
[23] Chandra S 1997 Waste materials used in concrete manufacturing. New Jersey, EUA..
[24] Han S W, Kim D K, Hwang G, Bae J H 2002 Development of pellet-type adsorbents for removal of heavy metal ions from aqueous solutions using red mud. *J. Ind. Eng. Chem.* 8 120–125.

[25] Sushil S, Batra V S 2008 Catalytic applications of red mud, an aluminium industry waste: A review. *Applied Catalysis B: Environmental* 81 64–77.

[26] Huang W, Wang S, Zhu Z, Li L, Yao X, Rudolph V, Haghseresh F 2008 Phosphate removal from wastewater using red mud. *Journal of Hazardous Materials* 158 35–42.

[27] ABNT NBR 6502/95: Rochas e solos 1995. Associação Brasileira de Normas Técnicas, Brasil.

[28] USDA 1967. Soil survey laboratory methods and procedures for collecting soil samples. Department of Agriculture. Washington, USA.

[29] Camargo O A 2009. Métodos de Análise Química, Mineralógica e Física de Solos do Instituto Agronômico de Campinas, Brazil.

[30] Cavalcante V T F, Soares J B 2001 O efeito do tipo e do teor de filer nas propriedades mecânicas das misturas asfálticas. 33a Reunião anual de pavimentação, Brazil.

[31] Pinilla A 1965 O sistema filer-betume, algumas considerações sobre sua importância nas misturas densas. Instituto de Pesquisas Rodoviárias.

[32] Santana H 1995 Considerações sobre os nebulosos conceitos e definições de filer em misturas asfálticas. 29º Reunião Anual de Pavimentação. Associação Brasileira de Pavimentação, Brazil.

[33] Motta L M G, Leite L M F 2000 Efeito do filer nas características mecânicas das misturas asfálticas. *XI PANAM* 09-19, Brazil.

[34] Lombi E, Zhao F J, Wieshammer G, Zhang G, McGrath S P 2002 In situ fixation of metals in soils using bauxite residue: biological effects, *Environ. Pollut.* 118 445–452.

[35] Gupta V K, Ali I, Saini V K 2004 Removal of chlorophenols from wastewater using red mud: an aluminium industry waste, *Environ. Sci. Technol.* 38 4012–18.

[36] Nadaroglu H, Kalkan E, Demir N 2010 Removal of copper from aqueous solution using red mud, *Desalination* 251 90–95.

[37] Kalkan E 2006 Utilization of red mud as a stabilization material for the preparation of clay liners, *Eng. Geol.* 87 220–229.

[38] Johnston M, Clark M W, Mc Mahon P, Ward N 2010 Alkalinity conversion of bauxite refinery residues by neutralization, *Journal of Hazardous Materials* 182 710–715.

[39] Liu W, Yang J, Xiao B 2009 Application of Bayer red mud for iron recovery and building material production from alumosilicate residues, *Journal of Hazardous Materials* 161 474–78.

[40] Qin S, Wu B 2011 Effect of self-glazing on reducing the radioactivity levels of red mud based ceramic materials. *Journal of Hazardous Materials* 198 269–74.

[41] Soo Han Y, Ji S, Koo Lee P, Oh C 2017 Bauxite residue neutralization with simultaneous mineral carbonation using atmospheric CO₂. *Journal of Hazardous Materials* 326 87–93.

[42] Kehagia F 2014 Construction of an unpaved road using industrial by-products (bauxite residue). WSEAS transactions on environment and development, v.10, p. 2224-3496.

[43] Pera J, Boumaza R, Ambroise J 1997 Development of a pozzolanic figment from red mud, *Cem. Concr. Res.* 27 1513–22.

[44] He H, Yue Q, Su Y, Gao B, Gao Y, Wang J, Yu H 2012 Preparation and mechanism of the sintered bricks produced from Yellow River silt and red mud. *Journal of Hazardous Materials* 203–204 53–61.

[45] Chaddha M J, Mishra R S, Mahendiran P, Mukhopadhyay J, Yoo C K, Wasewar K L. 2012 Neutralization and utilization of red mud for its better waste management, *Arch. Environ. Sci.* 6 13-33.

[46] Rath S, Lataye D H, Chaddha M J, Mishra R S, Mahendiran P, Mukhopadhyay J, Yoo C K, Wasewar K L. 2013 An Alternative to Clay in Building Materials: Red Mud Sintering Using Fly Ash via Taguchi’s Methodology. Hindawi Publishing Corporation, *Advances in Materials Science and Engineering*, Article ID 757923.

[47] Wang W, Pranolo Y, Cheng C Y 2013 Recovery of scandium from synthetic red mud leach solutions by solvent extraction with D2EHPA. *Separation and Purification Technology* 108, 96–102.

[48] NBR 5751 – 1991: Materiais pozolânicos -Determinação de atividade pozolânica - Índice de atividade pozolânica com cal. Rio de Janeiro, Associação Brasileira de Normas Técnicas (ABNT).

[49] NBR 5752 – 1992: Materiais pozolânicos – Determinação da atividade pozolânica com cimento Portland – Índice de atividade pozolânica com o cimento. Rio de Janeiro, Associação Brasileira de Normas Técnicas (ABNT).

[50] Neville A M 1997 Propriedades do concreto endurecido. 2 ed. São Paulo: PINI.
[54] Rojas M I S, Rivera J, Frias M 1999 Influence of the microsilica state on pozzolanic reaction rate. *Cement and Concrete Research* **29** 945-49.

[55] Lagier F, Kurtis K E 2007 Influence of Portland cement composition on early age reactions with metakaolin. *Cement and Concrete Research* **37** 1411-17.

[56] LRPC 1997 d’Aix-en Provence, Utilisation des Bauxites Inertes en Technique Routiere, Rapport Technique.

[57] Mouratidis A, Tsobos G 2002 Investigation of red mud properties for use in road construction, *4th International Congress on Environmental Geotechnics*, Rio de Janeiro, 493-96.

[58] Jitsangiam P, Nikraz H R 2013 Sustainable use of coarse bauxite residue for alternative roadway construction materials, *Australian Journal of Civil Engineering* **11** 1-12.

[59] Bezerra W S, Macêco E N, Souza J A D S 2010 Utilização da lama vermelha proveniente do processo produtivo da alumina como filer em Concreto Betuminoso Usinado a Quente (CBUQ). 40º RAPv - Reunião Anual de Pavimentação, Brazil.

[60] Summers R N, Pech J D 1997. Nutrient and metal content of water, sediment and soils amended with bauxite residue in the catchment of the Peel inlet and Harvey Estuary, Western Australia. *Agric. Ecosyst. Environ.* **64** 219–32.

[61] Snars K E, Gilkes R, Wong M 2004 The liming effect of bauxite processing residue (red mud) on sandy soils. *Aust. J. Soil Res.* **42** 321–328.

[62] Gadepalle V P, Ouki S K, Van Herwijnen R, Hutchings T 2007 Immobilization of heavy metals in soil using natural waste materials for vegetation establishment on contaminated sites. *Soil Sediment Contam.* **16** 233–51.

[63] Garau G, Silvetti M, Deiana S, Deiana P, Castaldi P 2011. Long-term influence of red mud on asmobility and soil physico-chemical and microbial parameters in a polluted sub-acidic soil. *J. Hazard. Mater.* **185**, 1241–1248.

[64] Phillips, I R 1998 Use of soil amendments to reduce nitrogen, phosphorus and heavy metal availability. *J. Soil Contam.* **7** 191–212.

[65] Ujaczki E, Klebcz O, Feigl V, Molnár M, Magyar Á, Uzinger N 2015. Environmental toxicity assessment of the spilled Ajka red mud in soil microcosms for its potential utilisation as soil ameliorant. *Period. Polytech., Chem. Eng*.

[66] Wuana R A, Okieimen F E 2011 Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *Ecology*, Article ID 402647, 20.

[67] Ujaczki E, Feigl V, Molnár M, Vaszita E, Uzinger N, Erdélyi A, Gruiz K 2016 The potential application of red mud and soil mixture as additive to the surface layer of a landfill cover system. *Journal of environmental sciences* **44** 189 –196.