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# ENVIRONMENTAL VIABILITY FOR MATERIAL DEVELOPED FROM COAL BOTTOM ASH FOR HIGHWAYS UNDER CONSTRUCTION

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## ABSTRACT

The increase of the quality of life of the contemporary Man also leads to the increase of the generation of energy. Many alternative sources of energy have been explored, but coal is still an important input, contributing around 29% of the world's energy matrix, despite environmental controversies about its use. Its burning in thermal plants generates the solid bottom ash residue, a material with little application and with potential to generate environmental damages in the places where they accumulate. The Southern Region of Brazil is a region producing coal and the bottom ash generated in its burning is not being used, generating a large environmental liability in the courtyard of the companies producing the input. The present study developed with the cited residue had as objective to define a technological product for its application in the construction of highways and to find a way for the economic and environmental use of the bottom ash. As the authors consider that the goal was achieved, they understand that the importance of the present study is centered in this fact. A product with 87% bottom ash, 5% fly ash and 8% Portland cement was developed, with adequate mechanical resistance to its application on base and sub-base of road pavement, proving itself a commercial and environmentally sustainable alternative for the use of the residue. Leaching and solubilization tests indicated that the product is chemically inert according to Brazilian environmental standards.

**Keywords:** Bottom Ash for Road; Coal Ash Uses; Coal Residue; Residue Inertization.

## RESUMO

**Viabilidade ambiental para material desenvolvido a partir de cinzas de fundo de carvão para rodovias em construção.** O aumento da qualidade de vida do Homem contemporâneo também leva ao aumento da geração de energia. Muitas fontes alternativas de energia têm sido exploradas, mas o carvão mineral ainda é um importante material, contribuindo com cerca de 29% da matriz energética mundial, apesar das controvérsias ambientais sobre o seu uso. Sua queima em usinas térmicas gera o resíduo sólido cinzas de fundo, um material com pouca aplicação e com potencial para gerar danos ambientais nos locais onde se acumulam. O Sul do Brasil é uma região produtora de carvão mineral e a cinza de fundo gerada em sua queima não está sendo utilizada, constituindo responsabilidade ambiental no pátio das empresas produtoras do insumo. O presente estudo desenvolvido com o resíduo teve como objetivo definir um produto tecnológico para sua aplicação na construção de rodovias e encontrar um caminho para o uso econômico e ambiental das cinzas de fundo. Os autores consideram que o objetivo foi alcançado e entendem que a importância do presente estudo está centrada neste fato. Um produto com 87% de cinzas de fundo, 5% de cinzas volantes

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e 8% de cimento Portland foi desenvolvido, com resistência mecânica adequada à sua aplicação na base e sub-base do pavimento rodoviário, caracterizando-se como uma alternativa comercial e ambientalmente sustentável para o uso do resíduo. Os testes de lixiviação e solubilização indicaram que o produto é quimicamente inerte de acordo com as normas ambientais brasileiras.

**Palavras-chave:** Cinzas de Fundo para a Estrada; Usos para Cinzas de Carvão; Resíduo de Carvão; Inertização de Resíduos.

## INTRODUCTION

The twentieth century was marked by a great development of mankind, a consequence of the industrial growth that influenced the increase of the quality of life of man. Modern society demands, more and more, material comfort and all actions converge for generation in an equally increasing quantity of energy.

Currently, coal is an important source of energy, accounting for about 29% of the world energy matrix (BP, 2016). Although it is plentiful in many countries, its use tends to decline in the coming decades due to strong pressure from international leaders who attribute to the fossil fuel direct cause relationship with rising atmospheric temperatures on the planet. Although this issue is controversial, the pressure of society on governments is great, and they are proving to be sensitive to the anti-coal mines as an energy source, as new alternative sources are becoming more environmentally and economically viable and without apparent negative environmental impacts. In the view of the World Energy Outlook (IEA, 2014), the use of coal for power generation will grow 0.5% per year by 2040, a value well below 2.5% in the last 30 years.

In Brazil, the South Region has coal reserves that correspond to 0.7% of the world total (BP, 2016), but only part of it has been exploited for burning in thermal plants, representing 3.2% of domestic electricity supply, and adopted only as a complementary source. Non-producing regions are importing coal from Colombia, especially for self-generation of energy (EPE, 2015; Tolmasquim, 2016).

The burning of coal in thermal plants generates solid waste known as coal combustion products (CCP). Bottom ash and fly ash are the main wastes, which have been used mainly in the industry of construction materials, in civil engineering and in the construction of highways, among other applications (Sajwan et al., 2006; Aggarwal and Siddique, 2014). Ashes are used instead of natural resources and their demand in addition to saving natural resources they reduce energy demand and greenhouse gas emissions to the atmosphere caused by mining and generation of products that are replaced by CCP (Bajare et al., 2013).

The American Coal Ash Association (ACAA) (ACAA, 2016) states that fly ash used in concrete makes this material stronger and more durable than cement-only concrete, and that bottom ash has been used as an aggregate instead of sand and gravel in many construction products, because it is a material with a thicker grain size. Due to these characteristics, many studies have been carried out with both wastes to make them more useful and sustainable in various industrial segments, to avoid negative environmental impacts to the environment and to generate financial resources.

In Brazil, a significant portion of fly ash is being applied as a concrete additive in the construction industry. Many companies that produce concrete also have their own collection and transport facilities for waste near the thermal plants. However, the bottom ash has had no application and return to the mining companies when coal is produced in the country, or accumulate in the yards of the thermal plants that burn the imported fossil fuel. In both situations, the waste generates potential for environmental damage (Sundstron, 2012).

There are studies in several countries dealing with the application of coal ash on road pavements. This practice is not recent in the United States of America (USA) nor in Europe. Shuler (1976) and Colonna et al. (2012) indicate that there are records of application of fly ash in the construction of American highways since the year 1930, and that in 1949 the residue was applied in large scale on a highway in the State of Montana, and that between 1971 and 1976 the application of bottom ash occurred on more than 200 miles of rural roads in the State of West Virginia. The ACAA (ACAA, 2016) reports that in 2015 about 312,000 tons of bottom ash were used as the base and sub-base for the construction of American highways. Rohde et al. (2006) indicate that in Europe the use of coal ash stabilized as binders in bases and sub-bases of road pavements became widespread from 1960 onwards, and that in England, France, Sweden and Russia, among other countries, the use of coal ash in paving is part of conventional solutions.

Bottom ash has been used as waste in many applications in the construction of road pavements. Byung-Soo et al. (2016) report the application of coal ashes as by-product in hot mix asphalt (HMA) mixtures, replacing up to 30% of fine aggregates. Stability, flow value, and mixture volumetric properties were compared to verify the applicability of bottom ash as fine aggregate in HMA. The moisture susceptibility and fatigue cracking resistance of asphalt mixture containing bottom ash and fly ash was investigated. The authors concluded that coal ash can be efficiently used as fine aggregates in asphalt mixture.

Pasetto and Baldo (2016) conducted experiments with mixtures of cement and coal ashes, among other wastes, to design studies for road construction. Cement bound mixtures with natural aggregate were used in road foundations. Physical-mechanical and leaching properties of the materials were investigated. Satisfactory results were obtained, compression and indirect tensile strength at 7 days being up to 7.56 MPa and 0.78 MPa respectively, depending on the composition of the mixtures.

Some researchers highlight the technological advantages with the use of cement mixtures and coal ashes in road construction, such as base, sub-base and landfills. Significant reductions in global $CO_2$ emissions and a high supply of accumulated raw material, which could be used in substitution of mineral aggregates, avoiding new mineral extractions, are the main environmental benefits reported by the researchers (Edil and Benson, 2006; Eskioglou and Oikonomou, 2008; Sear, 2008; Benson et al., 2009; An et al., 2014).

The subject is not new in Brazil either. Silva et al. (1997) reported that in the 1980s the first fly ash geotechnical studies were carried out in landfills, which served as the basis for the experimental paving of 1,000 meters on BR 101 Highway, in the State of Santa Catarina. Rohde et al. (2006) point out that in the 1980s, the Autonomous Highway Department (DAER), an autonomous government agency of the State of Rio Grande do Sul (RS), responsible for the management of the state intermodal transportation system of the State, in cooperation with the Science and Technology Foundation of RS (CIENTEC), have developed constructive techniques appropriate for landfills using bottom ash and slag from coal burning. According to the same authors, in 1986 an experimental landfill was built on the highway in the municipality of São Jerônimo, RS, near the Porteirinha stream, about 200 meters long and four meters high, with the use of slag from the Thermal Power Plant (TPP) São Jerônimo, RS. In the 1990s, in the landfills of the highway and at the abutments of the bridge over the Jacuí River, which connects the municipalities of São Jerônimo and General Câmara, bottom ash and slag were used for an extension of four kilometers of road, which represents one of the largest works with the use of these residues in Brazil. Inspection of the construction activities confirmed the expectations of the good stability of the landfills, indicating the appropriate characteristics of the residue for this application. Recently, the subject has been used for research in some postgraduate courses in Brazilian universities, such as studies by Farias (2005), Lopes (2011) and Santarem (2015), among others. However, in addition to these scientific records, there are no records of official entities regarding the use of coal ash in the construction of Brazilian highways.

According to the Brazilian standard ABNT NBR 10004:2004 (ABNT, 2004a), the ashes generated in the burning of coal are classified as Class II A, or as, non-hazardous and non-inert waste. Waste included in this category when exposed to environmental conditions is subject to leaching or solubilization by percolation water and may promote the release of pollutants into the environment.

In order to evaluate this condition, this standard indicates the need to submit samples to laboratory solubilization and leaching tests to evaluate its potential of releasing components, respectively, for pure water, compared to the potability standard, and for the environment, indicating, thus, if it may impact soils and surface water and groundwater. And the standard also indicates maximum limits of substances allowed in the leached and solubilized extracts to indicate if the sample is inert or not.

Hill et al. (2001) concluded that leaching and solubilization rates cannot be determined by the composition of the material but that leaching rates are affected by material conditions such as grain size, compaction, chemical stabilization and pH of the environment. They also concluded that compacted materials have lower leaching rates than non-compacted materials and that under simulated laboratory compaction conditions many waste materials meet the environmental protection agency's quality specifications. Querol et al. (2000) and Ward et al. (2009) indicate that the pH of a gray-water coal system is important in determining the mobility of chemical elements in the environment.

Santarem (2015) developed an experimental study in the laboratory evaluating the mechanical behavior of 16 blends containing bottom ash as load and varying proportions of fly ash and composite Portland cement, with the objective of identifying blends suitable for base and sub-base application in the construction of road pavements. The results indicated an ideal blend composed of 87% of bottom ash, 5% of fly ash and 8% of cement, meeting the resistance specifications for soil-cement, according to the Brazilian standard DNIT 143/2010-ES (DNIT, 2010). The author also performed particle size distributions and Atterberg limits (Limit of Liquidity and Limit of Plasticity) in bottom ash, the main component of the blend, to classify it according to the Transportation Research Board (TRB) method. The results indicated a material of group A-4, characterized by a blend of non-plastic silt soil with 52% grains of sand and gravel retained in the 200-mesh sieve. According to Pinto and Preussler (2010), the TRB method is widely used in road engineering in many countries and is standardized through the American standard AASHTO M 145 (AASHTO, 1991).

The present study was developed with bottom ash generated in the combustion of coal in a thermal power plant in the State of Rio Grande do Sul, Southern Region of Brazil. The State is a producer of low quality coal because, despite being beneficiated after extraction, it still contains a high concentration of inorganic materials, which give rise to bottom ash. According to most developed countries, Brazilian environmental legislation requires that industries that generate waste promote their collection and management.

The fly ash, also generated in the combustion of coal, has been used especially in the cement industry. On the contrary, bottom ash has been accumulating in the yards of the coal producing companies in the State of Rio Grande do Sul, with no prospect for their use and, at the same time, configuring environmental liabilities and potential risks to the environment, because they are exposed to processes of physical-chemical weathering conditions.

In Brazil, the agency Departamento Nacional de Infraestrutura de Transportes (DNIT) is the executing agency of the Ministry of Transport with the functions to build, maintain and operate the infrastructure of the mode of road transportation. This agency reports that only 12% of the Brazilian highways are paved, a little expressive percentage for a country that has in the road modal its base of transport logistics, both for the flow of loads of the production, as for the movement of people. It also reports that about 50% of the paved roads have some deficiency in the pavement, with poor sections and classified as in regular, bad, or worse situation.

Two authors of the present study are civil engineers and work at DNIT. The authors investigated that several countries have applied coal bottom ash in the construction of bases and sub-bases of road pavements and decided to develop some experiments in the laboratory with objectives to prove technical, economic and environmental feasibility for the use of bottom ash for the same purpose, in the Brazil. Geotechnical and chemical experiments were carried out with mixtures of coal bottom ash, coal fly ash and composite Portland cement, which led to the identification of an ideal mixture among the three materials that allowed the technical, economic and environmental feasibility of its application in road pavements.

In this context, possibilities are created for the solution of two critical problems in the Southern Region of Brazil. One of them relates to the sustainable use of coal bottom ash, avoiding the formation of tailings piles and generating environmental liabilities, with a risk of contamination of soil and surface water and groundwater. The other is related to the supply of mineral raw material, avoiding that new areas are degraded with the extraction of inputs necessary for the highway construction industry. In Brazil, there are few studies on the use of coal ashes in the construction of highways, as a means of taking advantage of the waste in a sustainable way. The present study also aims to contribute data and information to fill the existing gap on this topic.

The experiments indicated that the materials fly ash and composite Portland cement acted as chemical and granulometric stabilizers in the ideal blend, which was subjected to leaching and solubilization tests. The results indicated that the ideal blend presented a characteristic of non-hazardous and inert material, according to the Brazilian standard ABNT NBR 10004:2004 (ABNT, 2004a), which gives it environmental feasibility to be applied to road pavements, subject to be approached in the present paper.

In the present study, as an element of cleaner production is highlighted the possibility of the use of coal bottom ash in the construction of highways, which nowadays in Brazil, as in several other countries, the residue has been accumulated in the environment and generating high potential to promote negative environmental impacts.

## MATERIALS AND METHODS

The product called ideal blend in the present study was obtained by mixing three materials: coal bottom ash, coal fly ash and composite Portland cement. The bottom ash constituted the main charge of the mixture. The other two materials constituted, respectively, the artificial pozzolanic material and the chemical binder, which acted as chemical stabilizers for bottom ash.

Both ashes were generated at the Charqueadas TPP, a thermoelectric power plant that operates in the State of Rio Grande do Sul, Brazil. This TPP burns coal extracted from Recreio Mine, located in the same State, and benefited by the Copelmi Mining company, an industry that extracts coal. The cement applied was a commercial product (CP II-Z-32), of the Votoran brand, a type of cement widely used in Brazil, in which it has 6 to 14% of pozzolana and up to 10% of carbonaceous material.

The bottom ash collection process consisted of 581 simple samples taken from the same amount of trucks that transported the waste to Copelmi Mining, during a period of three months. The collections complied with the Brazilian standard ABNT NBR 10007:2004 (ABNT, 2004b). Homogenized, they were a composite sample of 720 kg used in the tests. The fly ash was a simple 50 kg sample taken from the waste transportation and storage circuit at the Charqueadas TPP. And the Portland cement used in the tests was taken from samples of a 50 kg bag purchased locally.

Farias (2005) developed a similar research, but using blends between soil, bottom ash and lime, aiming, among others, to assess the hazard of using residual materials in situations similar to those submitted to a pavement structure. The author reports that his research was based on international experiences, adapted to the particular situation, citing the works of Moulton (1973), Dawson and Nunes (1993), Schroeder (1994) and Nunes et al. (1996). Regarding the last citation, the studies considered the mechanical performance aspects of the blends in pavements and the environmental interactions, based on the methods developed at the Wastewater Technology Center, Canada, which evaluated the performance of the inertization of solid waste by adding cementitious materials to them.

According to Farias (2005), the environmental risk assessments presented by Nunes et al. (1996) can be reproduced in actions segmented in three stages: i) physical-chemical characterization of the materials; ii) two tests for the leaching of the materials in their natural state, the first in a conventional test and the second in a low pH solution. These tests are similar to those of Brazilian standards ABNT NBR 10005:2004 (ABNT, 2004c) for solid waste leaching and ABNT NBR 1006:2004 (ABNT, 2004d) for solid waste solubilization; iii) leaching tests with the materials under the specific conditions of application in the pavement structure. These latter tests, in the evaluation of Sloot (1991), are more representative than the conventional leaching tests.

The present study followed the three-step method presented by Nunes et al. (1996) and carried out by Farias (2005), mentioned above. As for the tests carried out, concerning the physical characterization of stage "i", the particle size distribution of fly ash and bottom ash was determined, and as regards the chemical characterization of step "i", the Hydrogenionic potential of bottom ash, fly ash, composite Portland cement, the ideal blend of Santarem (2015) not compacted and of the same compacted blend and with curing times of three and 28 days was determined. As for step "ii", bottom ash was processed to leaching and solubilization tests. And as for step "iii", the compacted ideal blend of Santarem (2015) was processed to leaching and solubilization tests too.

The particle size distribution tests were performed in the laboratory of the Department of Geotechnics (DEPGEO), the Science and Technology Foundation (CIENTEC), the research institution linked to the Secretariat of Economic Development, Science and Technology of the State of Rio Grande do Sul, Brazil according to the Brazilian standard ABNT NBR 7181:1984 Corrected Version 1988 (ABNT, 1988).

The Hydrogenionic potential tests were carried out in the laboratory of the private Pró-Ambiente Análise Químicas e Toxicológicas Ltda. Company, authorized by the environmental public agency of the city of Porto Alegre, Brazil, to carry out environmental laboratory tests, according to the procedures of ASTM D4980-89 (ASTM, 2003).

The leaching and solubilization tests and the corresponding extracts were also performed and analyzed in the laboratory Pró-Ambiente Análise Químicas e Toxicológicas Ltda., according to procedures, respectively, of the ABNT NBR 10005:2004 (ABNT, 2004c) and ABNT NBR 1006:2004 (ABNT, 2004d) standards. As these standards specify that the particles should be smaller than 9.5 mm, the compacted ideal blend has been carefully fragmented into 9.4 and 4.8 mm maximum and minimum grain sizes, respectively, in order to obtain an adequate representation of the ideal blend in the pavement. Fragments with dimensions smaller than 4.8 mm generated in fragmentation were discarded because they could distort results.

## RESULTS AND DISCUSSION

### Particle Size Distribution

Figure 1 shows the particle size distribution curves of bottom ash and fly ash. Studies by Chies et al. (2003) and Sundstron (2012) with bottom ash from the same Charqueadas TPP indicated $D_{50}$, respectively, around 0.074 mm and 0.25 mm. The indicator $D_{50}$ is the diameter corresponding to the average grain size of a sample, that is, the diameter through which 50% of the sample particles pass through a screen. In the present study, the $D_{50}$ for bottom ash was around 0.08 mm, similar to the value of Chies et al. (2003) and different from the value of Sundstron (2012). Studies by Rosa (2009) and Sundstron (2012) indicated $D_{50}$ for the fly ash of Charqueadas TPP, respectively, around 0.018 mm and 0.02 mm, very close to the value around 0.017 mm in the present study.

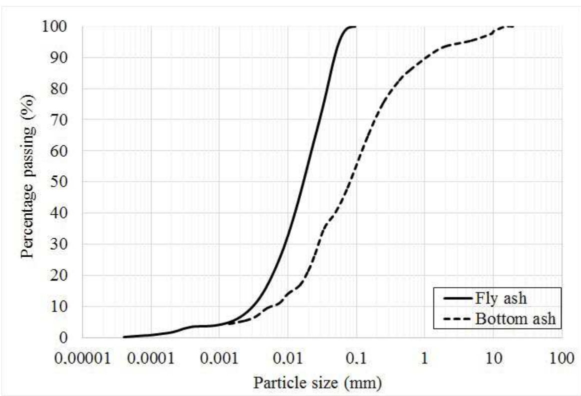


**Figure 1.** Particle size distribution curves of bottom ash and fly ash.

The physic-chemical properties of the coal ash may vary depending on the composition and the calorific value of the coal, the degree of beneficiation and grinding of the coal, the operation of the boiler, the system of extraction and handling of the ashes, the mineralogical composition of the deposit and the sampling process to compose a sample for studies. Thus, it is possible to expect, especially as to the particle size distribution of bottom ash, different results in different boilers inside a TPP and even at different times and situations of burning inside the same boiler (Goethe, 1990; Lovell et al., 1991; Sabedot et al., 2015).

**Hydrogenionic Potential**

Table 1 presents results for pH of the materials evaluated in the present study. It also shows published results for fly ash and bottom ash from other studies conducted in the same Charqueadas TPP.

**Table 1.** Hydrogenionic potential of the various materials.

| Material | Present study | Rohde et al. (2006) | Sundstron (2012) | ABCP (2002) |
|---|---|---|---|---|
| Bottom ash | 7.5 | 9.4 | 9.1 | - |
| Fly ash | 8.8 | 10.9 | 11.1 | - |
| Cement CP II-Z-32 | 12.1 | - | - | 12.0 - 12.5 |
| Non-compacted ideal blend | 11.6 | - | - | - |
| Compacted ideal blend and 3 days cure time | 12.1 | - | - | - |
| Compacted ideal blend and 28 days cure time | 11.4 | - | - | - |

Hydrogenionic potential is an important environmental indicator and, in general, it is the first variable to be analyzed as acting on an aqueous system of a given medium. Knowing the pH of the materials composing the blend to be applied to the pavement helps to evaluate the potential of harmful chemical elements present to be leached and solubilized by percolation water. Oliveira et al. (2002) indicate that pH conditions above 6 favor the dissociation of $H^+$ from OH groups of Fe and Al oxides, increasing the adsorption of the metals and subsequent precipitation.

The results for pH of the bottom ash and fly ash were, respectively, 7.5 and 8.8. These values are much lower when compared to the values obtained by Rohde et al. (2006) and Sundstron (2012) for ashes from the same TPP under study (Table 1). According to Ferret (2004), the pH of the coal ashes can vary from 4.5 to 12.0 depending on the geochemical characteristics of the coal and of the precursor deposit. It is assumed that the different values in the three studies are associated with this fact or those mentioned above by Goethe (1990), Lovell et al. (1991) and Sabedot et al. (2015).

**Environmental Stabilization**

Base or sub-base of road pavement consisting only of bottom ash does not reach the minimum mechanical resistance required by the Brazilian standard DNIT 143/2010-ES (DNIT, 2010). However, the addition of fly ash and Portland cement enabled a compound that made it possible to meet the requirement of the standard, according to studies by Santarem (2015). Besides the mechanical resistance, the additives acted as chemical stabilizers and promoted the environmental stabilization of the compound, verified in the leaching and solubilization tests.

Tables 2 and 3 present the results of the leaching and solubilization extracts of the bottom ash and the compacted ideal blend with cure times of three and 28 days, respectively. They also present results of leaching and solubilization tests performed in the bottom ash of the same TPP in two other studies, as well as the permissible values in the concentrations of substances in the leaching and solubilization extracts so that the material be considered inert according to the Brazilian standard ABNT NBR 10004:2004 (ABNT, 2004a).

**Table 2.** Results of chemical analyzes ($mgL^{-1}$) in leaching extracts. nd = not detected

| Substance | ABNT NBR 10004:2004 | Bottom ash | | | Compacted ideal blend | |
|---|---|---|---|---|---|---|
| | | Present study | Rohde et al. (2006) | Sundstron (2012) | 3 days | 28 days |
| $F^-$ | 150.0 | 15.5 | 1.9 | 0.66 | 12.5 | 1.0 |
| As | 1.0 | Nd | < 0.03 | 0,012 | nd | nd |
| Ba | 70.0 | Nd | < 0.6 | 0.645 | 0.5 | nd |
| Cd | 0.5 | Nd | < 0.007 | nd | nd | nd |
| Pb | 1.0 | Nd | < 0.2 | 0.199 | nd | nd |
| Cr | 5.0 | Nd | < 0.07 | nd | 0.1 | nd |
| Hg | 0.1 | Nd | < 0.0007 | nd | nd | nd |
| Ag | 5.0 | nd | < 0.03 | 0.021 | nd | nd |
| Se | 1.0 | nd | < 0.03 | 0.011 | nd | nd |

The bottom ash is classified as non-hazardous and non-inert material, according to the Brazilian standard ABNT NBR 10004:2004 (ABNT, 2004a). The results of Table 2 showed in the present study, as well as in the studies of Rohde et al. (2006) and Sundstron (2012), that in the extract leached from the residue all substances have values well below the limits defined in the cited standard in its Annexes F and G. In Table 3, the results of the present study showed that only the $F^-$ and $SO_4^{-2}$ substances presented values above the limits of the cited standard, in the solubilized extract; in the study by Sundstron (2012), $SO_4^{-2}$ and Al were the substances that presented values above the standard; and in the study by Rohde et al. (2006) several substances presented values incompatible with the standard in the solubilized extract. However, as for the last study, Table 3 shows that the values for most substances are not absolute, probably due to the less improved analytical method or equipment at the time. These values, above those allowed by the Brazilian standard, confer the classification "not inert" for the bottom ash generated in the combustion of Brazilian coal in TPPs, especially due to its alkaline condition, which promotes higher leaching and solubilization of some substances present in the residue. Farias (2005) corroborates this statement, pointing out that the leaching and solubilization rates are very influenced by the pH of the medium and therefore the high alkalinity obtained for fly ash and bottom ash tends to potentiate the solubilization of heavy metals by the percolation water.

Table 3. Results of chemical analyzes ($mgL^{-1}$) in the solubility extracts. (*) Surfactant alkylbenzene sulfonates; nd = not detected; na = not accessible

| Substance | ABNT NBR 10004:2004 | Bottom ash | | | Compacted ideal blend | |
|---|---|---|---|---|---|---|
| | | Present study | Rohde et al. (2006) | Sundstron (2012) | 3 days | 28 days |
| $Cl^-$ | 250.0 | 1.5 | 0.95 | 2.81 | 3.0 | 0.5 |
| $CaCO_3$ | 500.0 | na | 133.9 | na | na | na |
| $F^-$ | 1.5 | 5.8 | 0.84 | 1.31 | 1.8 | 0.9 |
| $SO_4^{-2}$ | 250.0 | 1,842.5 | 117.3 | 496.0 | 26.5 | 158.5 |
| NO3- | 10.0 | 0.1 | 0.5 | 0.2 | nd | 0.1 |
| $C_6H_5OH$ | 0.01 | 0.002 | nd | nd | nd | nd |
| ABS(*) | 0.5 | nd | nd | 0.03 | nd | nd |
| $CN^-$ | 0.07 | nd | < 0.02 | nd | nd | nd |
| Al | 0.2 | nd | < 0.5 | 1.1 | 2.1 | nd |
| As | 0.01 | nd | < 0.02 | nd | nd | nd |
| Ba | 0.7 | nd | < 0.6 | 0.06 | nd | nd |
| Cd | 0.005 | nd | < 0.007 | nd | nd | nd |
| Pb | 0.01 | nd | < 0.2 | nd | nd | nd |
| Cu | 2.0 | nd | < 0.03 | nd | nd | nd |
| Cr | 0.05 | nd | < 0.07 | nd | nd | nd |
| Fe | 0.3 | 0.1 | < 0.05 | 0.075 | nd | nd |
| Mn | 0.1 | nd | < 0.06 | 0.012 | nd | 0.1 |
| Hg | 0.001 | nd | < 0.0007 | nd | nd | nd |
| Ag | 0.05 | nd | < 0.03 | nd | nd | nd |
| Se | 0.01 | nd | < 0.03 | nd | nd | nd |
| Na | 200.0 | 5.0 | 1.06 | 20.0 | 20.6 | 16.3 |
| Zn | 5.0 | nd | < 0.008 | 0.03 | nd | nd |

The additives fly ash and Portland cement have higher pH than bottom ash. The blending between the three materials increases the alkalinity in the compound and so, in the short time the leaching and solubilization rates will tend to be higher. However, after this time the additives stabilize the compound and cause its inertization. The evolution of the process of inertization occurs more by the action of the chemical stabilization of the blend than by its compaction. It is observed that the blend has high pH, even compacted. Curing time is another important factor. The results of Tables 2 and 3 for the compacted ideal blend prove this. Comparing the values of the $F^-$, $Cl^-$ and Al substances of said blend, it is observed that in both processes, the values of these substances are higher in the extracts with curing time of three days, decreasing markedly in the extracts with curing time of 28 days. Exception occurred with $SO_4^{-2}$, but, as for the other substances, its value was below those values determined by the ABNT NBR 10004:2004 (ABNT, 2004a) standard. Thus, it was considered that the compaction of the blended compound is not determinant for its environmental stabilization, but the additives and the curing time are fundamental for its chemical inertization, allowing it to be applied as a base or sub-base in road pavements, without the risks arising from the action of percolation water. In this context, Schreiber et al. (2005) state that chemical forms and types of binders can increase or decrease the mobility of heavy metals in soils. In the present study, fly ash and Portland cement acted as binders that, besides producing mechanical resistance to the blend, acted as chemical stabilizers and decreased the mobility of the metals in simulated processes in the laboratory.

## CONCLUSIONS

The blending of bottom ash with 5% fly ash and 8% Portland composite cement generates a product that has adequate mechanical strength for application to bases and sub-bases of semi-rigid road pavements. In addition to binders, these additives also act as chemical stabilizers and promote the environmental stabilization of the compound, which can be applied to road construction without the risk of chemical environmental contamination. Its use as a base and sub-base on highways makes it possible to eliminate or reduce the potential that the coal ashes have to cause environmental contamination in water and soil, as well as to prevent new areas from being degraded in the exploitation of raw materials necessary for the construction of highways.

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