Evaluation of permanent deformation in asphalt mixtures composed with red mud as filler

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ABSTRACT

Red mud is a solid waste originating from the production of aluminum during bauxite processing. Currently in Brazil this sub-product does not receive appropriate destination in nature and is stored in deforested areas. Annually, approximately 11 million tons of red mud are generated just in Brazil and represent a great imminent risk of pollution and contamination. The large amount of red mud generated by the aluminum industry has motivated researchers to develop residue insert methods in the production cycle. Studies shows the possibility of using red mud to compose ceramic materials, however, there is a lack of research in other areas, such as applied to pavements. On the other hand, Brazilian highways are, in more than 50%, in poor condition, especially in the north, where high temperatures favor the spread of permanent deformation in the pavement. In this scenario, this paper describes the evaluation of the introduction of red mud as filler in asphalt mixtures, in order to apply it in the production cycle and mitigate the environmental damage caused by improper disposal. Waste characterization tests and evaluation of asphalt mixture with red mud permanent deformation were performed. The possibility of red mud introduction as a component in asphalt mixture and this ability to improve the mechanical strength was evaluated. The results showed that it is possible to use the red mud on asphalt mixtures without problems of the environment contamination.

Keywords: Environment, Permanent Deformation, Waste

1. INTRODUCTION

The red mud is a waste originated in the beneficiation process of aluminum bauxite. For each ton of aluminum produced are generated from 0.3 to 1.5 tons of red mud [1, 2, 3].
The amounts related to disposal of red mud change according to the production methods and components of bauxite. Thus, those with low aluminum content are able to produce up to 2.5 tons of red mud [4].
In northern Brazil, are produced between 4.40 million and 6.26 million tons of red mud [2]. It is estimated that about 10.6 million tons of waste are discarded annually in the country, while in the world, this figure reaches more than 117 million tons / year [1].
In the State of Pará are located the largest bauxite deposits in Brazil, with a production of approximately 30 million tons only in 2013, which makes it more red mud generator in Latin America [5, 6]. Only in Barcarena (State of Pará, Brazil), the generation of waste is around 4.5 million tons / year, occupying an area of about 4 km^2 [7].
The red mud is produced in large quantities and, although there are studies that prove the feasibility of using residue in the formation of ceramic materials [8, 9, 10], and also technology capable of neutralizing it [11, 12]. However, in Brazil, reuse policies are not adopted or no prospect of doing so on a large scale. Thus, the red mud is cumulatively stored, occupying increasingly larger areas.
Some researches classify the red mud as a non-inert waste [13, 14, 15]. However, the properties of high alkalinity [10, 16] give some danger properties to this residue, and even stored efficiently, pose a threat to biodiversity and might cause serious environmental damages such as contamination of surface effluent and underground, affecting thus the health of closest populations [10].
Despite being developed research aiming at the use of red mud in the constitution of bricks, tiles and cement [10, 17, 18], there are few references that assess the use of waste applied in other contexts.
Taking into account that in Brazil, most of the roads evaluated by the National Confederation of Transport (CNT) are classified as fair, poor or very poor, as the existing trafficability conditions, and that the most common defects found on the highways is the permanent deformation, caused not only by the high volume of traffic, as well as the high temperatures [34] region, this work aims to expand the technical library for the use of waste, evaluating the red mud properties and analyzing the possibility to apply on asphalt mixtures, compound highways.
The prospect of introduction of red mud in the pavements constitution reduces the possibility of contamination of nature, contributes to the enhancement of waste as an alternative material and reduces costs related to the management and disposal of the same. In northern Brazil, in particular the costs of deployment and maintenance of highways would be reduced due to the proximity and availability of waste.

1.1 Objective

- Analyze the performance to permanent deformation of bitumen mixture;
- Evaluate bitumen mixtures composed by red mud as filler;
- Compare results of permanent deformation with mixture composed by 7% red mud and the reference mixture consisting of 7% stone dust as filler.

2 MATERIALS AND METHODS

In this study, it is compared the performance to permanent deformation of two types of bitumen mixtures, differentiated only by the type of filler used. Under Brazilian legislation, filler corresponds to the material with 65% or more passing the 0.075 mm sieve.
Thus, bitumen mixtures fabricated is comprised of bitumen CAP-50/70, granite origin aggregates stone and filler red mud dust. The bitumen mixture consisting of 7% of red mud filler was compared to the reference mixture consisting of 7% stone dust filler, both adopted a theoretical grading curve corresponding to the average of the range "C" of the National Department Brazilian Transport Infrastructure (DNIT).
The dosage of the bitumen content was performed with the aid of Servopac gyratory compactor. The number of turns (N) design used to establish compaction efforts during the dosage process was 125, corresponding to a high traffic volume. The “N” maximum was 205 turns was used, corresponding to the end of the service life of the mixtures.
Prior to carrying out the tests, the characterization of materials was carried out. Red mud was evaluated by testing diffraction X-ray (XRD) and size laser, the aggregates were evaluated for particle size and adhesion, and bitumen by softening point test, penetration and apparent viscosity, using Brookfield equipment.
The specific surface of red mud and stone dust filler were calculated by Vogt formula.
The performance to permanent deformation was evaluated with the aid of French traffic simulator Orniéreur.

2.1 Red mud

The red mud used in this work is originally from Hydro Alunorte company, located in Barcarena, State of Pará, Brazil. Available from the Institute of Technology of the Federal University of Pará (UFPA).
The mineralogical analysis of the red mud was performed using X-ray diffractometer RIGAKU, model Miniflex II

with copper Ka radiation from the tube and wavelength of 1.540562, parafocal geometry endowed with Bragg-Brentano system.
The test was performed between 2θ angles of 5 ° to 90 °, with step of 0.05 and 1 second in the time counts and identification of the phases present was conducted using a database of the International Center for Diffraction Data - Powder Diffraction File (ICDD-PDF) and Crystallography Open Database (COD).
The particle size of the red mud was observed in laser particle analyzer Microtrac the brand, model S3500, with a detection range of 0.02 to 2,800 micrometers (µm) using Microtrac Flex software version 10.5.4. This methodology was chosen for convenience and precision of results compared to other forms of particle size measurement.
With the particle size was possible to calculate the specific surface area of the red mud. The same was done for the stone dust filler used for the composition of the bitumen mixture reference.
In Brazil, the specific surface area of the aggregates has been measured [19, 20, 21] using an adaptation of Duriez formula, known as formula Vogt, according to Equation 1, the result being expressed in m^2 / kg.

$$1000\,\Sigma = 0{,}07P4 + 0{,}14P3 + 0{,}33P2 + 0{,}81P1 + 2{,}7S3 + 9{,}15S2 + 21{,}9S1 + 135F \qquad (1)$$

At where:
P4 - fraction retained between the sieves 50-25 mm;
P3 - fraction retained between the sieves 25 and 12.5 mm;
P2 - fraction retained between the sieves from 12.5 to 4.76 mm;
P1 - fraction retained between the sieves from 4.76 to 2.00 mm;
S3 - fraction retained between the sieves from 2.00 to 0.42 mm;
S2 - fraction retained between the sieves from 0.42 to 0.177 mm;
S1 - fraction retained between the sieves 0.177 to 0.075 mm;
F - fraction passing the sieve 0.075 mm;

Prior to the tests, the red mud was dried at 100 ° C and crushed in a mortar. In order that the residue still showed signs of agglomeration, the drying and crushing process were performed again, which provided to the residue a granulometric regularity.

2.2 Agregates

The aggregates used in this work are of granitic origin and were provided by mining company Santa Barbara, in the municipality of Palhoça, state of Santa Catarina. For composition of bitumen mixtures were used gravel one with a maximum of 3/4 "gravel zero with a maximum of 3/8" and rock dust with a maximum of 4.75 mm. The adhesiveness test regulated by DNER ME 078 / 94 [22], it is an assay based on visual comparison grains, where it is checked the occurrence of detachment of the bitumen-aggregate film after immersion in distilled water for a period of 72 hours.
Thus, there was the trial of CAP-50/70 and granite coarse aggregate, later used to make the mixtures. Having observed the detachment of the bonding film, three samples were made, among which contained 0.2%, 0.6% and 1% adhesion improving agent (DOPE) mixed with the bitumen, relative to the total weight of same.
In the end, only the sample with 1% enhancer tackifying agent was considered suitable for use in bitumen mixtures.
Thus, the adhesion of the bitumen used in the composition of bitumen mixtures with red mud and stone powder has previously been improved with the addition of 1% DOPE.

2.3 Bitumen

The bitumen used was the CAP-50/70, provided by the company CBB Bitumen, based in the city of Curitiba, State of Parana.
The characterization of bitumen was performed by softening point tests - ring and ball method, regulated by rules DNIT ME 131/10 [35], penetration, regulated by rules DNIT ME-155/10 [36] that allows measuring consistency of the bitumen through the depth to which a standard needle (100g) penetrates into the sample during the time of 5 seconds at 25 ° C, and apparent viscosity held in a Brookfield viscometer. The results are shown in Table 1.

Table 1: Results of characterization of bitumen

Assay	CAP-50/70
Softening Point (°C)	49,5
Penetration (0,1 mm)	64
Viscosity (cP) 135°C, SP 21, 50 rpm	308,67

The appropriate mixing temperature for asphalt binders unmodified in SUPERPAVE methodology is one in which the binder has an apparent viscosity corresponding to 170 ± 20 cP. While adequate compaction temperature corresponding to viscosity of 280 ± 30 cP. These values are traditionally applied to asphalt mixes dosed using the

Marshall methodology with pure binders, and have also been used in determining the machining temperatures and compression modified mixtures. According to the DNER ME 043/95, binder temperature in both procedures should not be less than 107 ° C or exceed 177 ° C.
With the viscosity results could be set temperatures 148° C and 137° C for mixing and compaction procedures, respectively. The heating temperature of aggregates was 15° C above the mixing temperature of the bitumen, which is 160° C.

2.4 Dosage

Dosage procedures performed followed the recommendations of the standards AASHTO M 323 - Standard Specification for Superpave Volumetric Mix Design and AASHTO R 35 - Standard Practice for Superpave Volumetric Design for Hot-Mix Bitumen (HMA) [29,30]
Prior to the compaction process, the bitumen mixtures were conditioned for 2 hours in an oven at a temperature of 137 ° C (compaction temperature), in order to simulate the aging of the bitumen [27].
Compaction was performed in rotating the Servopac gyratory compactor mark, using rotation angle of 1.25 ° ± 0.02, a rate of 30 revolutions per minute and 600 kPa vertical stress.
After compaction, it was determined the specific apparent mass measurement (Gmb) of compacted samples, conducting weighing the specimens under the conditions of dry surface, saturated dry and submerged, according to ASTM D 2726 standard - Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures [28] to then perform the correction of the corresponding empty volume.
At first, the mixtures were compressed to 125 spins, corresponding to the project N. After setting the bitumen content on a void volume of 4%, the mixtures were compacted at 205 revolutions (Nmáximo) in order to achieve a maximum degree of compaction of 98%.
To perform the mixtures used a theoretical curve corresponding to the average range C DNIT [31] according to Table 2.

Table 2: Granulometric composition used

Pol/nº	mm	Range C (%)		Passing (%)	Retained (%)
		Minimum	Maximum		
3/4"	19,10	100	100	100	0
1/2"	12,70	80	100	90	10
3/8"	9,50	70	90	80	10
Nº 4	4,80	44	72	58	22
Nº10	2,00	22	50	36	22
Nº 40	0,42	8	26	17	19
Nº 80	0,18	4	16	10	7
Nº 200	0,075	2	10	7	3
Fundo	< 0,075	-	-	-	7

The content design adopted for the mixes with 7% stone powder and 7% red mud was 4.7% and 4.4% bitumen, respectively.

2.5 Permanent deformation

For realization of the permanent deformation test, the bitumen mixtures were compacted into slab form, according to the criteria of the standard NFP 98-250-2 [32], in dimensions of 50 cm length, 18 cm width and 5 cm thick . For this, it used the screed developed by Institut Francais current des Sciences et Technologies des Transports, L'aménagement et des Reseaux (IFSTTAR).
The amount of bitumen mixtures to be compressed is defined by calculating the apparent density refers to a void volume of 4%. In all, they molded four plates, two for each type of bitumen mix. The plates were tested for performance to permanent deformation 15 days after compaction.
The permanent deformation test is regulated by the French standard NFP 98-253-1: Essais relatifs Aux Chaussées, Permanent Deformation des Mélanges Hydrocarbonés [33] and performed in French traffic simulator called Orniéreur.
The equipment is provided by smooth pneumatic wheels of a solo axle, applying a load of 5.0 kN, and the inflation pressure of 0.6 MPa tires. The machine allows two are tested specimens simultaneously at a temperature of 60 ° C, exposed to longitudinal loads up to 30,000 cycles with a frequency of 1 Hz, and the cycle equivalent to the outward and return movement of the tire.
Before the start of the test, there was the accommodation of the plates in the mold, subjecting them to pass 1,000 cycles. Then the plates were conditioned at 60 ° C. However, until this temperature was reached and stabilized required is approximately 8 to 12 hours.
Readings were taken at 0, 100, 300, 1,000, 3,000, 10,000 and 30,000 cycles at 15 different points of the plate, using a digital caliper.
The depth of permanent deformation in each cycle was calculated by averaging the depths measured in 15 points

against the benchmark of zero cycle.

3 RESULTS E DISCUSSION

3.1 Red mud caracterization

The diffraction of X-rays detected phase of hematite (Fe_2O_3), anatase (TiO_2), quartz (SiO_2), karelianita (V_2O_3), gibbsite (Al (OH) $_3$), from the same bauxite and sodalite ($Na_8Mg_3Si_9O_{24}$ $(OH)_2$), formed during the Bayer process.
Hematite, the anatase, quartz, gibbsite and sodalite are substances that do not pose health risks, except as noted in concentrations higher than those allowed by standard (Appendix 'G') of the rules NBR 10.004 / 2004 [37].
The karelianita (V_2O_3), or vanadium trioxide in the presence of moisture can come to oxidize and turn into vanadium pentoxide (V_2O_5), in the list of 'substances which give hazardous waste', on Annex 'C' the rules NBR 10.004 / 2004.
Thus, the red mud can be classified as Class I with a residue - Dangerous.
With the laser granulometric testing can be seen that the red mud is a fine grained material with 100% of its particles less than 290 µm, 80% less than 50 µm in diameter and 40% less than 5 micrometers.
Approximately 85% of the red mud particles have a diameter in the range of 0.4 µm to 60 µm, and 20% corresponding to the clay fraction (<2 µm) and 65% to silt fraction (2 µm to 60 µm), as soil classification based on grain size criteria of the Brazilian Association of Technical Standards [40]. Only 15% of the residue of the particles have a particle size in the range from 60 µm to 200 µm, characteristic of fine sand.
According to granulometric results similar to those obtained in this work, Antunes, Conception and Navarro (2011) classified the red mud as a sandy-clay-silty material, according to the textural classification proposed soil by United States Department of Agriculture [38] characterizing it as a cohesive material low porosity, with intense phenomena of capillarity, some plasticity and existence of adsorption phenomena [39].
The particle size of the red mud is an important factor to be considered when used to make bitumen mixtures, since particles larger 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, point and thermal softening of the same susceptibility [41, 42, 43, 44].
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 CAP, changing its rheological properties.
Knowing that 85% of red mud grains have a diameter less than 0,075 mm and the remaining 15% are corresponding to the variable range S1, and that the specific gravity of the residue is 2.609 g / cm^3, the correction factor used was 1,008 obtained by interpolation. Thus, it obtained a specific surface value corresponding to red mud 119.003 m^2 / kg.
For comparison, it carried out the calculation of the specific surface of the stone dust filler used in the composition of the mixtures employing Vogt formula. Given that 100% of its particle size is passing the No. 200 sieve and that its density corresponds to 2.717 g/cm^3, used a correction factor of 0.98. Thus, the specific surface of the stone powder was found to be 132.287 m^2 / kg.

3.2 Permanent deformation

The performance of bitumen mixtures as the permanent deformation was observed in French traffic simulator Orniéreur.
Although the bitumen mixtures were dosed at a volume of 4% voids, this index none of them achieved during the compaction process, with values between 4.91% and 5.51% of voids for mixtures with crushed stone and red mud, respectively. This is due to small variations in the final thickness of the plate, resulting in large changes in the volume of voids of the compacted mixture.
It is noteworthy that bitumen mixtures compacted in the field also present volume variation, the allowed service specifications DNIT provided they have between 3% and 6% of empty [31].
Thus, boards produced were considered appropriate for evaluation of susceptibility to permanent deformation.
Table 3 presents the data from sinking bitumen mixtures produced with 7% stone powder and 7% red mud, as well as, reducing the permanent deformation compared to the reference mixture at 30,000 cycles. In Figure 1 the graphical aspect of the data is presented.
It is important to say that the percent deformation is equivalent to strains, and that the X-axis of Figure 1 begins with 100, because on 0 it doesn't have any deformation.

Table 3: Values of sag of bitumen mixtures comprised of stone powder (PP) and red mud (RM)

Numbers of cycles	Decrease (%)	
	7%PP	7%RM
100	1,09	0,51
300	1,52	0,74
1000	2,19	1,11
3000	3,05	1,62
10000	4,38	2,46

30000	6,10	3,58
Decreasing reduction (%)	**-**	**41,30**

The French guidelines limit by 10% the acceptable amount of deformation of bitumen mixtures used for coating purposes. [45] There are also other European guidelines that limit the permanent deformation at 5% for dense bitumen mixtures used as a coating on heavy traffic roads. [46]
Thus, both mixtures obtained a permanent deformation lower than the 10% specified by the French rules. However, only mixing with 7% red mud comply with European directives, having deflection values of less than 5%.
Even with a higher voids volume of the mixture with 7% red mud obtained satisfactory results, showing a sink 40% lower than that of the reference mixture consisting of 7% stone dust filler.
The permanent deformation provided by the mixtures decreased with the incorporation of the residue thus obtained mixture that the worst performance among those tested was the reference, with 7% stone dust filler.

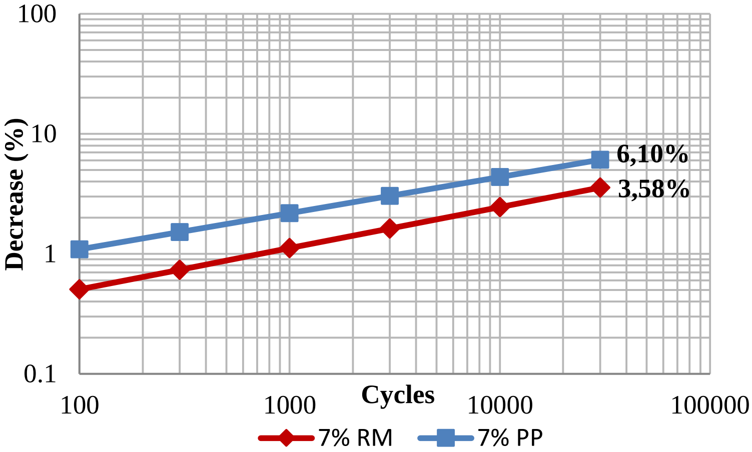

Figura 1: Performance to permanent deformation of compacted mixtures

Several factors can influence performance to permanent deformation of bitumen mixtures, among them are the volume of empty, bitumen content, percentage of filler, particle size composition and type of aggregate used in the composition of mixtures. In general, as both compounds in this work have the same particle size composition and the same type of granite aggregate, the differences obtained in outcomes can be attributed, the variables related to the volume of voids, the bitumen content, the percentage and the type of employee filler.
Like all manufactured specimens obtained voids within the specification established by the DNIT it can not be said that this variable has contributed significantly in resistance to permanent deformation of the test plates.
The stone dust filler had a higher specific surface area of the red mud thus established a direct equivalence between the design content and the amount of stone dust filler used, that is, the higher the percentage of filler stone powder, the higher the bitumen consumption.
The bitumen content has a large influence on thermal susceptibility bitumen mixtures, being able to promote lubrication between particles, to promote the most efficient accommodation aggregates, increase the workability of the bitumen mixture and possibly reducing the resistance to permanent deformation.

4 CONCLUSION

This study evaluated the possibility of applying the waste from processing bauxite in dense bitumen mixtures. Thus, they performed tests permanent deformation in bitumen mixtures composed of 7% red mud and filler 7% stone powder, considered as reference mixture.
With the waste characterization results was possible to classify red mud as environmental aspects, according to rules of NBR 10,004 / 2004. The finding of vanadium pentoxide (V_2O_5) classify the red mud like residue Class I - Dangerous.
As for the behavior to permanent deformation, both mixtures obeyed made to the French guidelines deformation, with sag values of less than 10%. However, only the mixture with 7% of red mud complies with European standards to be less than 5%, with 3.58% sinking value.
A mixture consisting of 7% red mud showed a reduction of 40% in respect of the sinking to the reference mixture.
In general, the performance improvement to permanent deformation of the bitumen mixture can be attributed to the use of red mud, thus their smaller specific surface area compared to stone dust filler, reduced the amount of required bitumen, restricting the thermal susceptibility of mixture.
It is also possible that part of the red mud grain particle size less than 20 µm, has been incorporated into the bitumen, changing the properties of the bitumen, and thereby assisting in promoting resistance to permanent deformation.
Although there is the same amount filler used in both mixtures, that consists of red mud obtained best results with

regard to the performance of the permanent deformation, therefore, it is understood that as important as determining the amount of filler to be inserted, knowing chemical and physical properties of the material applied it is too.
Despite the good results for the actual realization of viability reinsertion of red mud applied to highways, the realization of further testing with regard to the environmental aspect it is necessary, evaluating the concentration of other leachate elements can pollute or affect the environment.
Given the scarcity of works produced on this issue, this paper hopes to contribute to mitigation of problems related to disposal of red mud and, above all, expand waste reuse possibilities, transforming it into an alternative material that can be used in industry construction.

5 REFERENCES

[1] RIBEIRO, D. V.; LABRINCHA, J. A.; MORELLI, M. R. Efeito da adição da lama vermelha na corrosibilidade do concreto armado avaliado por meio de técnicas eletroquímicas. RIEM - Revista IBRACON de Estruturas e Materiais , v. 5, n. 4, p. 451-467, Agosto 2012. ISSN 1983-4195.
[2] HILDEBRANDO, E. A. et al. Application of Bauxite Waste from Amazon Region in the Heavy Clay Industry. Materials Research, v. XVI, n. 6, p. 1418-1422, Nov/Dez 2013. ISSN 1516-1439.
[3] HYDRO. Como a alumina é extraída da bauxita. A Hydro no Brasil, 2013 B. Disponivel em: <http://www.hydro.com/pt/A-Hydro-no-Brasil/Sobre-o-aluminio/Ciclo-de-vida-do-aluminio/Refino-da-alumina/>. Acesso em: 25.abril. 2014.
[4] KOMNITSAS, K.; BARTZAS, G.; PASPALIARIS, I. Efficiency of limestone and red mud barriers: laboratory column studies Miner. Minerals Engineering, v. 17, p. 183–194, 2004. ISSN 0892-6875.
[5] ABAL. Fluxo da cadeia de produção do alumínio primário. Associação Brasileira do Alumínio, 2013 A. Disponivel em: <www.abal.org.br/aluminio/producao>. Acesso em: 20 Dez 2013.
[6] ABAL. Associação Brasileira do Alumínio. Associação Brasileira do Alumínio, 2015. Disponivel em: <http://www.abal.org.br/estatisticas/nacionais/bauxita/>. Acesso em: 26 abr. 2015.
[7] BEZERRA, W. S.; MACÊCO, E. N.; SOUZA, J. A. D. S. Utilização da lama vermelha proveniente do processo produtivo da alumina como filler em Concreto Betuminoso Usinado a Quente (CBUQ). 40ª RAPv - Reunião Anual de Pavimentação. Rio de Janeiro/RJ: [s.n.]. 2010.
[8] KAVAS, T. Use of boron waste as a fluxing agent in production of red mud brick. Building and Environment, v. 41, p. 1779-1783, 2006. ISSN 0360-1323.
[9] YANG, J.; XIAO, B. Development of unsintered construction materials red mud wastes produced in the sintering alumina process. Construction and Building Materials, n. 22, p. 2299-2307, 19 Novembro 2008. ISSN 0950-0618.
[10] ANTUNES, M. L. P.; CONCEIÇÃO, F. T. D.; NAVARRO, G. R. B. Caracterização da Lama Vermelha Brasileira (Resíduo do Refino da Bauxita) e Avaliação de suas Propriedades para Futuras Aplicações. 3rd International Workshop Advances in Cleaner Production. São Paulo, Brazil: 2011. p. 10.
[11] PALMER, S. J. et al. Thermally activated seawater neutralised red mud used for the removal of arsenate, vanadate and molybdate from aqueous solution. Journal of Colloid and Interface Science , v. 342, n. 1, p. 147-154, 2010. ISSN 0021-9797.
[12] COOLING, D. J. Improving the sustainability of residue management practices-Alcoa World Alumina Australia. Australian Centre of Geomechanics, Perth, Australia, 2007
[13] EPA. Environmental Protection Agency. U. S. Government Printing Office. Electronic code of federal regulations, 2014. Disponivel em: <http://ecfr.gpoaccess.gov.>. Acesso em: 12 abril 2014. Title 40, Part 261, Sect 4 (b) (7) (ii) (c).
[14] NUNN, R. F. Advances in red mud dewatering and disposal technologies. J. Light Metals - The Minerals, Metals & Materials Society, Warrendale, 1998. p. 107-114
[15] LIMA, F. S. S. Utilização da Lama Vermelha e do Resíduo Caulinítico na Produção de Pigmento Pozolânico para Argamassas e Concretos de Cimento Portland. Dissertação de Mestrado. Universidade Federal do Pará - UFPA. Belém/PA. 2006.
[16] COLLAZO, A. et al. Evaluation of red mud as surface treatment for carbon steel painting. Process in Organic Coating, v. 52, p. 351-358, 2005. ISSN 0300-9440.
[17] MANFROI, E. P. Avaliação da lama vermelha como material pozolânico em substituição ao cimento para produção de argamassa. Dissertação de Mestrado. Universidade Federal de Santa Catarina - UFSC. Florianópolis/SC, p. 151 p. 2009.
[18] MACÊDO, A. N. et al. Comportamento de blocos cerâmicos estruturais produzidos a partir da mistura de lama vermelha e argila. Revista Ambiente Construído, Porto Alegre, v. XI, n. 4, p. 25-36, outubro/dezembro 2011. ISSN 1678-8621.
[19] SILVEIRA, M. A. Estudo sobre adição de polímero em areia-asfalto a frio. Dissertação de Mestrado. Universidade de São Paulo. São Carlos/SP. 1999.
[20] MOREIRA, H. S. Comportamento mecânico de misturas asfálticas a frio com diferentes teores de agregado fresado incorporado e diferentes modos de compactação. UNIVERSIDADE FEDERAL DO CEARÁ.Dissertação de Mestrado. Fortaleza/CE. 2005.
[21] BERNUCCI, L. B. et al. Pavimentação asfáltica: formação básica para engenheiros. 3ª. ed. Rio de Janeiro:

PETROBRAS: ABEDA, 2010
[22] BRASIL. DNER ME 078/94: Agregado graúdo – adesividade a ligante betuminoso. Departamento Nacional de Estradas de Rodagem. [S.l.], p. 3. 1994 A
[23] ASTM. D2493-09: Standard Viscosity-Temperature Chart for Bitumens. American Society for Testing and Materials. West Conshohocken. 2009.
[24] NCHRP. Mixing and Compaction Temperatures of Bitumens in Hot-Mix Bitumen: REPORT 648. National Cooperative Highway Research Program. Washington, D.C. 2010.
[25] BITUMEN INSTITUTE. Superpave mix designs, superpave series no.2. USA. 2003.
[26] ZEGARRA, J. R. E. Avaliação de misturas produzidas com ligantes asfálticos peruanos convencional PEN 60/70 e modificados por polímero SBS tipo I 60/60 e PG 76-22. Dissertação. Escola de engenharia de São Carlos, Universidade de São Paulo. São Carlos, SP. 2007.
[27] SHRP-A-698. Development and Use of the Repeated Shear Test (Constant Height): An Optional Superpave Mix Design Tool. Strategic Highway Research Program. National Research Council. Washington, D.C. 1994 A.
[28] ASTM. D 2726-00: Standard Test Method for Bulk Specific Gravity and Density of NonAbsorptive Compacted Bituminous Mixtures. American Society for Testing and Materials. USA. 2000.
[29] AASHTO. M 323 - Standard specification for SUPERPAVE Volumetric mix Design. American Association of State Highway and Transportation. Washington, DC. 2011.
[30] AASHTO. R 35-12: Standard Practice for SUPERPAVE Volumetric Design for Hot-Mix Bitumen (HMA). American Association of State Highway and Transportation Officials. Washington, D. C. 2012.
[31] BRASIL. DNIT 031/06-ES: Pavimentos flexíveis - Concreto asfáltico - Especificação de serviço. Departamento Nacional de Infra-estrutura de Transporte. Rio de Janeiro, RJ. 2006 A
[32] AFNOR. NF-P-98-250-2: Essais relatifs aux chaussées - préparation des mélanges hydrocarbonés, Partie 2: Compactage des Plaques. Association Française de Normalisation. France. 1997.
[33] AFNOR. NF P 98-253-1: Préparation des Mélanges Hydrocarbonés, Partie 1: Essai d'Orniérage. Association Française de Normalisation, AFNOR. France, p. 11. 1993.
[34] CNT. Pesquisa CNT de rodovias 2014: Relatório Gerencial. Confederação Nacional do Transporte. Brasília/DF:CNT,SEST,SENAT, p. 389. 2014
[35] BRASIL. DNIT 131/2010-ME: Materiais asfálticos-Determinação do ponto de amolecimento-Método do Anel e Bola. Departamento Nacional de Infraestrutura de Transportes. [S.l.], p. 6. 2010 A.
[36] BRASIL. DNIT 155/2010-ME: Material asfáltico-Determinação da penetração-Método de ensaio. Departamento Nacional de Infraestrutura de Transportes. [S.l.], p. 7. 2010 B.
[37] ABNT. NBR 10.004: Resíduos sólidos - Classificação. Associação Brasileira de Normas Ténicas. Rio de Janeiro, p. 71. 2004 A.
[38] USDA. Soil survey laboratory methods and procedures for collecting soil samples. Department of Agriculture. Washington, USA, p. 50. 1967.
[39] CAMARGO, O. A. et al. Métodos de Análise Química, Mineralógica e Física de Solos do Instituto Agronômico de Campinas. Campinas, SP, p. 77. 2009.
[40] ABNT NBR 6502/95: Rochas e solos. Associação Brasileira de Normas Técnicas. Brasil, 1995.
[41] CAVALCANTE, V. T. F.; SOARES, J. B. O efeito do tipo e do teor de fíler nas propriedades mecânicas das misturas asfálticas. 33a Reunião anual de pavimentação. Florianópolis/SC, p. 13. 2001.
[42] PINILLA, A. O sistema fíler-betume, algumas considerações sobre sua importância nas misturas densas. Instituto de Pesquisas Rodoviárias. 1965.
[43] SANTANA, H. Considerações sobre os nebulosos conceitos e definições de fíler em misturas asfáltica. 29ª Reunião Anual de Pavimentação. Associação Brasileira de Pavimentação. Cuiabá. 1995.
[44] MOTTA, L. M. G.; LEITE, L. M. F. Efeito do fíler nas características mecânicas das misturas asfálticas. XI PANAM. Brasil, p. 09-19. 2000.
[45] LCPC. Manuel LPC d'aide à la formulation des enrobés à chaud. Groupe de travail RST Formulation des enrobés à chaud. Laboratoire Central des Ponts et Chaussées. France. 2007.
[46] COST 333. Development of New Bituminous Pavement Design Method: Final Report of the Action. European Cooperation in the field of Scientific and Technical Research.European Commission Directorate General Transport. Belgium. 1999.