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RED MUD APPLICATION AS A FILLER IN ASPHALT MIXTURES PRODUCTION

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ABSTRACT

Red mud is the solid waste from bauxite processing during aluminium production. Its inadequate disposal causes social, economic and environmental prejudices. The industrial solid waste insertion evaluation in the production chain is beneficial and necessary. This work aims to evaluate the mechanical performance of asphalt mixtures produced with red mud as filling material. Asphalt mixtures with 5% and 7% red mud were produced, and permanent deformation and moisture-induced damage tests were carried out. A mixture without red mud addition (control) was produced for comparison. The results showed that the mixtures with red mud presented permanent deformation resistance greater than the control one, with more than 40% reduction in rutting deformation. The moisture damage did not significantly affect the mixtures tested. The red mud application as a filler in asphalt mixtures is viable and can be an alternative to reduce the damage such a waste can cause to the environment.

KEYWORDS: Red mud, Asphalt mixture, Filler, Permanent deformation.

APLICAÇÃO DA LAMA VERMELHA COMO FÍLER NA PRODUÇÃO DE MISTURAS ASFÁLTICAS

RESUMO

A lama vermelha é o resíduo do beneficiamento da bauxita na produção do alumínio. A disposição inadequada gera prejuízos sociais, econômicos e ambientais. A avaliação da inserção de resíduos industriais na cadeia produtiva é benéfica e necessária. Este trabalho objetiva avaliar o desempenho mecânico de misturas asfálticas produzidas com lama vermelha como material de enchimento. Foram produzidas misturas asfálticas com 5% e 7% de lama vermelha e realizados ensaios de deformação permanente e de dano por umidade induzida. Uma mistura sem adição de lama vermelha (controle) foi confeccionada para comparação. Os resultados mostraram que as misturas com lama vermelha apresentaram resistência à deformação permanente superior à mistura controle, com redução de afundamento maior que 40%. O dano por umidade induzida não afetou significativamente as misturas testadas. A aplicação de lama vermelha como fíler em misturas asfálticas é viável e pode ser uma alternativa para reduzir os danos que este resíduo pode causar ao meio ambiente.

Palavras chave: Lama vermelha, Mistura asfáltica, Fíler, Deformação permanente.

1 INTRODUCTION

Aluminium, aluminium alloys and aluminium-based composites are light, have excellent thermal and electrical conductivity, low operating costs and adequate corrosion resistance. Due to their properties, these materials are widely used by diverse industrial sectors (Penkova & Miteva, 2022). However, as aluminium does not occur in the metallic form in nature, it is produced by refining bauxite ore into aluminium oxide (alumina), which generates hazardous solid waste (IAI, 2021).

Brazil is one of the world's largest bauxite producers, accounting for 13% of production and 9% of world reserves (USGS, 2019), which demonstrates this ore's economic importance to the country. In 2021, the leading Brazilian producing state (Pará) was responsible for approximately 89.4% of raw, processed and commercialised bauxite (BRASIL, 2023). Based on the percentage of alumina, silica and iron, bauxite is classified as metallurgical and used in alumina production, representing 98% of national production, while non-metallurgical (refractory) is used in the chemical industry, production of abrasives and cement (Sampaio, Andrade & Dutra, 2008; Xavier, 2014).

Red mud is the residue generated during bauxite processing into alumina, the raw material for aluminium production by the Bayer process. In the Bayer process, the bauxite ore is first heated under pressure at high temperatures (280°C). Caustic soda is used to dissolve alumina selectively, and most of the undissolved minerals constitute the red mud (IAI, 2021). Due to the process used, besides the alkaline nature, this industrial waste is composed of heavy metals and toxic substances (Wang & Liu, 2012).

The amount of red mud generated often depends on the production method and bauxite composition. Studies showed that for each ton of alumina produced, between 0.3 and 2.5 tons of red mud can be generated (Ribeiro, Labrincha & Morelli, 2012; Hildebrando, Sousa, Angélica & Neves, 2013). It is estimated that the amount of red mud generated annually worldwide is more than 130 million tons (Chen, Wang & Liu, 2023).

Red mud's high alkalinity hinders its applicability, and its storage requires large areas and causes environmental problems such as salinisation and pollution of the surrounding soil. Generally, its main disposal methods are sea disposal (by immersion), lagoons, dry disposal, dams, dykes and landfill. Red mud has the potential to generate highly alkaline leachate, leading to groundwater pollution when it permeates the soil. Moreover, wind can transport minute particles of red mud, leading to air pollution. Furthermore, depending on the bauxite's composition, red mud may encompass radioactive elements, contributing to physical pollution (Lima & Thives, 2020).

Serious environmental accidents occurred all over the world due to the red mud's inadequate disposal. One of the most severe accidents was registered in 2010 in Ajka, Hungary. Around 1.1 million cubic metres of red mud leaked from an aluminium industry storage, affecting an area of 40 square kilometres, resulting in seven fatalities and chemical burns in over a hundred individuals (Matos, 2010).

In Brazil, there were incidents of red mud spills in 2003, 2009, and 2018, which impacted several rivers, affecting communities living within a two-kilometre radius of the spill site (Brabo, Lima & Santos, 2003; Santos, Jesus & Lima, 2009).

The most recent incident in Brazil was in 2018, where heavy rainfall led to flooding in the area, causing the red mud deposits to overflow, polluting the rivers and affecting the local population. In response, the government imposed an environmental fine and ordered the refinery to reduce production by 50% of its capacity at the red mud deposit (HYDRO, 2018).

Litovchenko and Shumakova (2022) emphasised the importance of taking action to reduce the red mud accumulation around the refineries. The authors highlighted that the risks associated with red mud disposal and its impact on the environment and human health are often underestimated.

Considering the severe impacts of red mud disposal on the environment, developing research for its reuse and recycling is necessary. Previous studies proved the viability of red mud reuse. The most wide-ranging applications comprised the construction materials production such as particleboards (Wang *et al.*, 2017); glass (Zhao *et al.*, 2019); concrete (Liu & Poon, 2016; Tang, Wang, Donne, Forghani & Liu, 2019); aggregates based on geopolymers (Uysal, Aygörmez, Canpolat, Cosgun & Kuranlı, 2022); ceramic materials (Kavas, 2006; Macêdo, Costa, Trindade, Souza & Carneiro, 2011); asphalt and asphalt mixtures (Zhang *et al.*, 2018; Zhang *et al.*, 2020; Lima & Thives, 2020).

One of the primary challenges to applying this residue is the transport distance between the local where the residue is stored to the recycling or recovery and application site. However, given the abundance of red mud in the northern region of Brazil, its use as an alternative material in asphalt mixture composition is favourable.

In Brazil, the road mode is prevailing and responsible for 61% of cargo and 91% of passenger transportation. In 2022, the National Transport Confederation (CNT) evaluated the conditions of state and federal paved roads in Pará in an extension of 4,164 kilometres. The results showed that in 74.9%, the pavement condition presented distress, 25.1% was satisfactory, and 1.0% was severely degraded. The precarious pavement conditions affected the operational transport cost in Pará, which increased by 45.9%, leading to damage to society and the country's economy (CNT, 2023).

The large volumes of red mud available and the inadequate quality of the paved roads in northern Brazil motivated the development of this research. Finding alternative and cheaper materials for paving purposes can contribute to sustainable management and improve road pavement conditions. In that sense, this work aims to evaluate the feasibility of red mud as filler in asphalt mixture composition and evaluate its mechanical performance.

2 MATERIALS AND METHOD

2.1 Red mud origin – study area

The red mud samples were provided by the Hydro Alunorte refinery, located in Barcarena, Pará, 113 km from the capital state, Belém. Figure 1 shows (a) Barcarena's location in Brazil and (b) the company's facilities and the red mud storage.

a) b)

Figure 1: Location of the red mud origin - a) Barcarena city area; b) red mud storage in Hydro Alunorte refinery.

2.2 Materials

The materials used in the study were red mud, granite aggregates and conventional asphalt PEN 50/70. Red mud was characterised through the following tests: (i) X-ray diffraction (XRD) with the RIGAKU X-ray diffractometer equipment model Miniflex II; (ii) X-ray fluorescence by the Shimadzu Energy Dispersive X-ray fluorescence spectrometer (EDX), model 700HS; (iii) density according to the DNER-ME 084/95 standard (DNIT, 2023); (iv) laser granulometry on a MICROTRAC particle analyser, model S3500; (v) potential hydrogen (pH) in the PHTEK equipment, model PHS-3B. For the red mud mineralogical analysis, the test was performed between angles 2θ of 5° to 90°, with a pitch of 0.05 and 1 second in counting time. In order to identify the phases present, the International Center for Diffraction Data – Powder Diffraction File (ICDD-PDF) and Crystallography Open Database (COD) databases were used.

The granitic origin aggregates came from a quarry in Palhoça city, Santa Catarina state. According to the maximum nominal size, the aggregates were classified as crushed stone n. 1 (3/4”), zero crushed stone - n. 0 (3/8”) and stone powder (4.75 mm). The aggregates characterisation was performed through the tests: (i) granulometry according to DNER-ME 083/98 standard (DNIT, 2023); (ii) specific gravity, following the standards DNER-ME 081/98 and DNER-ME 084/95 (DNIT, 2023); (iii) Los Angeles abrasion in conformity with DNER-ME 035/98 standard (DNIT, 2023).

The asphalt PEN 50/70, classified by penetration grade and specified according to DNIT 095/2006 standard (DNIT, 2023), was supplied by an asphalt distributor company in Curitiba (Paraná state). For characterisation, tests such as softening point (DNIT-ME 131/10 standard; DNIT, 2023), penetration (DNIT-ME 155/10 standard; DNIT, 2023) and apparent viscosity (NBR 15184 standard; ABNT 2004) were carried out. The materials characterisation tests corresponded to Phase 1 of the Method (Figure 2).

2.3 Method

Figure 2 presents the flowchart of the method, composed of three phases. In Phase 1, the materials (aggregates and asphalt – PEN 50/70) were characterised to verify specifications compliance for asphalt mixture productions. Also, the red mud was evaluated for its physical-chemical characteristics identification in this phase.

In Phase 2, dense graded asphalt mixtures were produced according to the DNIT 031/2006 standard, range “C” (DNIT, 2023), established by the National Department of Transport

Infrastructure (DNIT). In granulometric composition, red mud was used as a filler with 5% and 7% incorporation percentages. A control mixture, without the red mud addition, was produced for comparison in which the filler was the stone powder.

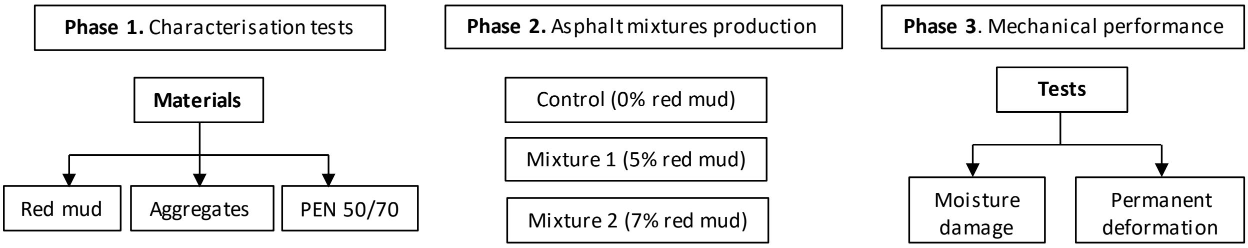


Figure 2: Flowchart of the method.

The total filler content was set at 7% for all mixtures to meet the requirements of DNIT 031/2006 standard, range "C" (DNIT, 2023). Hence, depending on the amount of red mud incorporated, stone powder was added to compose the granulometric curve. The mixture design was performed according to the Superior Performing Asphalt Pavements (SUPERPAVE) method, in which the project gyration number (N) used to establish the compaction efforts during the dosage process corresponded to a high traffic volume. Compaction was carried out in the SUPERPAVE gyratory compactor at a gyration angle of 1.25 ± 0.02°, a rate of 30 revolutions per minute and vertical tension of 600 kPa. For each mixture, four asphalt contents were tested (4.0%, 4.5%, 5.0% and 5.5%), and for each content, five samples were produced, resulting in a total of 60 samples.

After the volumetric parameters and asphalt content establishment in the mixtures design, samples were produced to perform the mechanical performance tests in Phase 3. For the permanent deformation test, per mixture, two samples (slabs with 18 cm wide, 5 cm long, and 5 cm thick) were compacted in the French tire compactor following standard NFP 98-250-2 (AFNOR, 1997). The samples were compacted until reaching the apparent specific gravity established at the design.

The test was carried out in a French traffic simulator equipment (wheel tracker) following the NFP 98-253-1 standard (AFNOR, 1993). The equipment has two wheels, allowing the slabs (two) to be tested simultaneously. The test was performed by applying a 5 kN load onto a 400 x 8 Treb Smooth pneumatic tire inflated to 0.6 MPa at 60°C. In the test, slabs were exposed to longitudinal loads up to 30,000 cycles at a frequency of 1 Hz (each cycle is equivalent to the back-and-forth movement of the tire). Throughout the test, rutting depth measurements were carried out in the following cycles: 0, 100, 300, 1,000, 3,000, 10,000 and 30,000 at 15 different points of the slabs.

The asphalt mixtures water resistance was assessed through the moisture-induced damage test following the NBR 15617 standard (ABNT, 2011). In the SUPERPAVE gyratory compactor, six samples (100 mm diameter) were compacted with 7 ± 1% of void content per mixture. The samples were divided into two groups of three, in which one group submitted a conditioning process. The sample conditioning procedure consisted of saturating in water of 55% to 80%, cooling for 16 hours at -18 ± 3°C, and then immersion in water at 60°C for 24 hours. The conditioned samples were submitted to the tensile strength test by diametral compression. The same test was conducted in the no-conditioned samples group. The test result is the ratio between the arithmetic mean tensile strength by diametrical compression of the two groups, expressed in percentage.

An environmental assessment was performed in the water in which the samples were conditioned in the moisture-induced damage test. The water pH was measured, and the concentrations of iron and aluminium were evaluated using a photocolourimeter. A visual comparison system with a colour chart and specific reagents for each parameter evaluated was used in the colourimetric analysis.

3 RESULTS AND DISCUSSION

3.1 Red mud characterisation

Red mud is composed of fine particles, and therefore, in the presence of moisture (air), *in nature*, it tends to clump together (Figure 3a). In order to avoid clumps formation during the mixtures production, prior to the tests, the red mud was dried in an oven (25ºC for 12 hours) and pulverised using a ginder (Figure 3b).

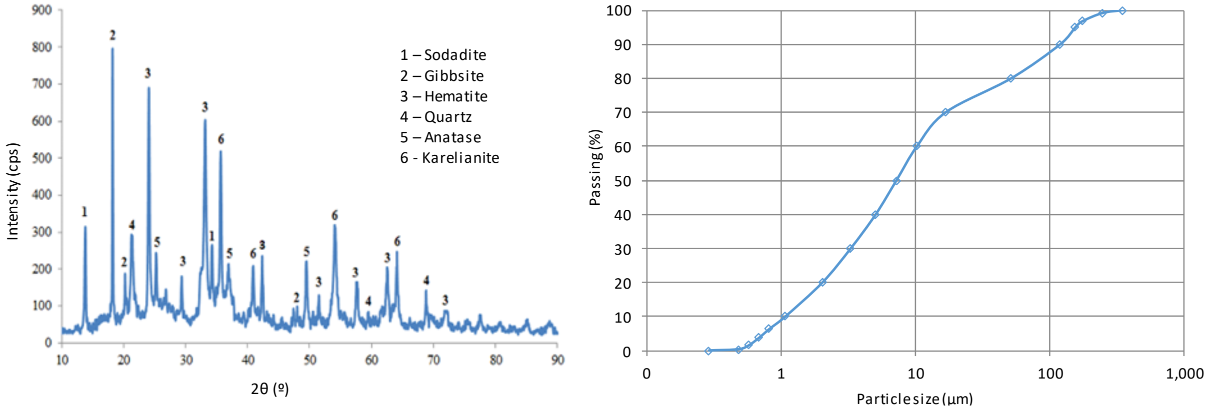

a) b)

Figure 3: Red mud aspect - a) *in nature*; b) pulverised.

Figure 4(a) shows the diffractogram, in which phases of hematite, anatase, quartz, karelianite, gibbsite (from bauxite) and sodalite (formed in the Bayer process) were detected. At concentrations lower than those established in the standard NBR 10004 (ABNT, 2004), the hematite, anatase, quartz, gibbsite and sodalite presence do not represent risks to human health. On the other hand, karelianite (vanadium trioxide), in the moisture presence, may oxidise and transform into vanadium pentoxide, which in high concentrations is a hazardous contaminant (ABNT, 1995).

According to the Brazilian standard NBR 10004 (ABNT, 2004) classification, red mud is an inert Class II-B solid waste (Lima, 2015). However, the presence of vanadium pentoxide characterises it as a toxic substance, classified as Class I - Hazardous waste. When a residue is available, it is essential to evaluate the contaminant's presence before reuse, for which the diffractogram analysis showed a suitable tool for analysis. On the other hand, in the presence of contaminants concentrations that pose risks to human health or the environment, providing means to become inert or neutralise is essential. In this study, red mud was used as a filler to produce asphalt mixtures, and it is expected that the residue particles are involved by asphalt film in the same way as the mixture aggregates, minimising the possibility of any contaminant's leaching.

The granulometric curve (Figure 4(b)) obtained in a laser particle analyser showed that 100% of the red mud particles have a diameter less than 0.29 mm. Around 85% of particles have a diameter 0.0004 mm to 0.06 mm, whose classification according to NBR 6502 (ABNT, 1995), 20% corresponds to clay fraction (< 0.002 mm), 65% to silt fraction (0.002 mm to 0.06 mm) and 15% (0.06 mm to 0.2 mm) to fine sand fraction. The filler is the asphalt mixture component in which, at least 65% of the material passes through the 75 µm sieve (0.075 mm). As for the granulometry, red mud can be used as filler in asphalt mixtures.



a) b)

Figure 4: Red mud characterisation - a) diffractogram; b) granulometric curve.

The fluorescence test results showed the presence of higher proportions of aluminium (35.47%), iron (31.45%), silicon (12.68%), carbon dioxide (12.40%), titanium oxide (5.84%), and minor proportions of calcium oxide (1.81%), vanadium pentoxide (0.22%) and manganese oxide (0.13%). The red mud density measured in the test was 2.609. In order to measure the pH, the red mud was mixed with water in a 1:1 ratio (by weight) and resulted in 10.25 ± 0.05, not being classified as corrosive residue, according to the NBR 10004 standard (ABNT, 2004). On the other hand, a pH greater than seven gives the residue a basic character and thus can influence the aggregate to the asphalt adhesion.

Pinheiro, Fernandez, Costa, Valente & Carvalho (2017) evaluated red mud from the same refinery and obtained results similar of this study. The authors concluded that the pH value was between 10.6 and 11.7, and the particle size of the material was in the range of 0.0001 mm to 0.1 mm grain size diameter.

3.2 Aggregates characterisation

Table 1 shows the particle size distribution, and Table 2 presents the test results of specific gravity (apparent and bulk) and absorption of the aggregates.

Table 1: Aggregates granulometry.

Sieve size (mm)	19.10	12.7	9.50	4.80	2.00	0.42	0.18	0.075
Aggregates	Passing (%)							
N. 1 (3/4”)	98.7	30.1	4.7	1.1	0.9	0.6	0.5	0.1
N. (3/8”)	100.0	99.9	96.4	22.4	1.0	0.9	0.8	0.4
Stone powder	100.0	100.0	100.0	99.8	67.9	29.8	15.1	5.0

Table 2: Specific gravity and absorption test results.

Aggregates	Specific gravity		Absorption (%)
	Apparent (G_{sa})	Bulk (G_{sb})	
N. 1 (3/4”)	2.774	2.748	0.351
N. 2 (3/8”)	2.740	2.701	0.521
Stone powder	2.717	-	-

The Los Angeles abrasion test was carried out on aggregates with nominal sizes of 3/4” (N. 1) and 3/8” (N. 2), resulting in 20.68% and 21.73%, respectively. According to the DNIT 095/2006 standard (DNIT, 2023), the results were satisfactory (less than 50%), and the aggregates are adequate for asphalt mixtures production.

3.3 Asphalt characterisation

Table 3 presents the PEN 50/70 characterisation tests for which the results showed that the asphalt met the DNIT 095/2006 standard (DNIT, 2023) specifications. The apparent viscosity test was performed on a Brookfield viscometer at three temperatures to establish mixing and compaction temperature ranges. The temperatures for mixing resulted from 145°C to 151°C and for compaction, from 135°C to 140°C.

Table 3: Asphalt characterisation results.

Test	Unit	Specification	Results
Penetration (100 g, 5s, 25°C)	0.01 mm	50 to 70	64
Softening point	°C	46 (min.)	49.5
Apparent viscosity			
135°C, sp 21, 50 rpm	cP	274 (min.)	308
150°C, sp 21, 60 rpm	cP	112 (min.)	157
177°C, sp 21, 100 rpm	cP	57 to 285 (min.)	63

3.4 Asphalt mixtures design

Figure 5 shows the granulometric curve of the mixtures and the limits established in DNIT 031/2006 standard for range "C" (DNIT, 2023).

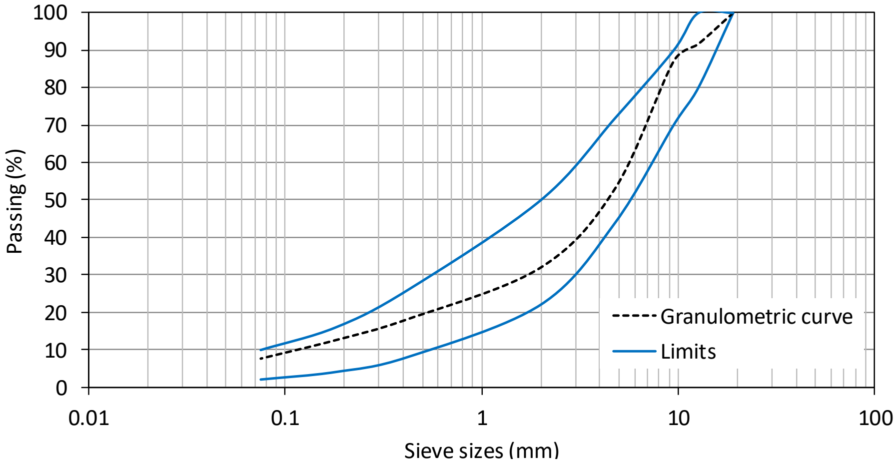


Figure 5: Granulometric curve of the mixtures and limits.

From the mixture design, the asphalt content resulted in 4.7% for the control mixture (filler with 7% stone powder), 4.5% for mixture 1 (filler with 5% red mud and 2% stone powder) and 4.4% for mixture 2 (filler with 7% red mud). It was observed that with the replacement of red mud as a filler, there was a reduction in the asphalt content percentage. Table 4 shows the mixture's volumetric parameters produced with the designed asphalt content, which met the specifications of DNIT 031/2006 standard (DNIT, 2023).

Table 4: Volumetric parameters of the mixtures.

Mixture	Asphalt content (%)	Voids content (%)	G_{mm}[1] (g/cm^3)	G_{mb}[2] (g/cm^3)	VMA[3] (%)	RBV[4] (%)
Control	4.7	4.91	2.552	2.427	14.13	70.9
1 (5% red mud)	4.5	4.96	2.560	2.421	12.7	67.6
2 (7% red mud)	4.4	5.51	2.558	2.443	12.4	67.8
Limits[5]	-	4 to 6	-	-	> 15	65 to 82

[1]G_{mm} – Maximum specific mass measured; [2]G_{mb} – Apparent specific mass; [3]VMA – Voids in the mineral aggregate; [4]RBV – Bitumen-void ratio; [5]DNIT 031/2006 standard (DNIT, 2023).

Lima, Amorim, Oliveira & Moura (2021) stated that for flexible pavement surface layers, for range "C" (DNIT, 2023), asphalt contents generally vary from 4.5% to 6.0 %, corroborating the percentages obtained in this study (Table 4).

3.5 Permanent deformation resistance

A wheel tracker French traffic simulator was used for asphalt mixtures permanent deformation resistance assessment. In the test, the final result is expressed in rutting depth (percentage) after 30,000 cycles. Figure 6 shows (a) the equipment wheel tracker, (b) samples before the test and (c) samples after the test. Moreover, measurements were evaluated during the test to monitor the deformation evolutions along the cycles.

a) b) c)

Figure 6: Permanent deformation test - a) equipment; b) samples before the test; c) samples after the test.

Table 5 presents the test results, and it could be observed that compared to the control mixture, at 30,000 cycles, the rutting depth reduction was, on average, 42.63% for mixture 1 (5% red mud) and 42.30% for mixture 2 (7% red mud).

There is no specific standard for rutting depth limitation in Brazil related to this test. The French guidelines limit the rutting depth by 10% (LCPC, 2007). However, in France, the standard axis is 130 kN, while in Brazil, it is 80 kN. Other European guidelines limit the rutting depth to 5% in surface layers composed of dense graded asphalt mixtures (as DNIT "C" range) for heavy traffic roads (COST 333, 1999). The rutting depth for all mixtures was lower than 10% at 30,000 cycles (Table 5). Nevertheless, only red mud mixtures complied with the European guidelines with a rutting depth of less than 5% at 30,000 cycles.

Asphalt and void content are volumetric parameters that influence the permanent deformation behaviour of the asphalt mixture. Generally, a higher content leads to lower resistance, while smaller void content tends to increase resistance to permanent deformation. For the mixtures studied herein, it was observed that, even with higher void content (Table 4), mixtures produced with red mud as a filler performed better in comparison with the control mixture. In this way, the red mud contributed to permanent deformation resistance improvement. Considering that mixture 1 (5% red mud) and mixture 2 (7% red mud) achieved similar performance (Table 5), the advantage of using mixture 2 is the possibility of inserting a higher percentage of residue as filler in the asphalt mixture.

Table 5: Permanent deformation test results.

Cycles	Mixtures		
	Control	1 (5% red mud)	2 (7% red mud)
	Rutting depht (%)		
100	1.09	0.51	0.51
300	1.52	0.73	0.74
1,000	2.19	1.10	1.11
3,000	3.05	1.60	1.62
10,000	4.38	2.41	2.46
30,000	6.10	3.60	3.58
Reduction (%)	-	42.63	41.30

The granulometric curve requirements limit the amount of filler, but as a component, it influences the asphalt mixture's mechanical behaviour. The filler tends to increase the asphalt viscosity and the softening, reducing the thermal susceptibility and contributing to permanent deformation resistance. Bernucci, Motta, Ceratti and Soares (2022) asserted that, during the mixing process, the filler tends to incorporate into the asphalt, forming the asphalt mortar, which contributes to increasing the stiffness of the asphalt mixture.

Considering that in this study, 7% of filler content was introduced in all mixtures, varying proportions of red mud and stone powder and that 20% of the red mud comprised particles with dimensions smaller than 0.02 mm (Figure 4b), it was important to evaluate the asphalt mortar stiffness. The asphalt mortar stiffness was evaluated through the penetration and softening point tests. The asphalt mortar samples were produced by incorporating red mud in 5% and 7% into the asphalt (PEN 50/70). Table 6 presents the test results, and it was proved that red mud incorporation promoted a slight increase in the softening point and reduced penetration (Table 5), indicating higher stiffness concerning PEN 50/70 (Table 3).

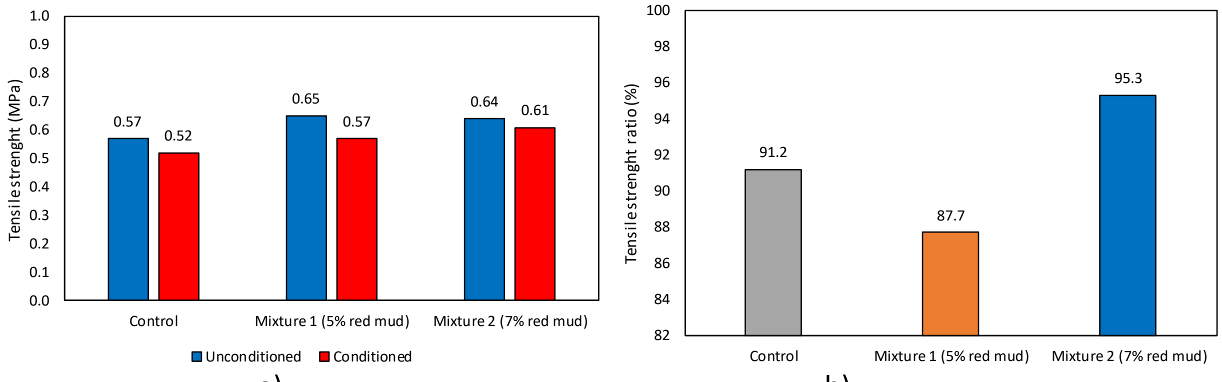
Table 6: Influence of red mud incorporation on asphalt stiffness.

Test	Unit	PEN¹	PEN¹ + 5% RM²	PEN¹ + 7% RM²
Penetration (100 g, 5s, 25°C)	0.01 mm	64	60	59
Softening point	°C	49.5	50.0	50.0

¹PEN refers to asphalt PEN 50/70; ²RM – Red mud.

3.6 Moisture-induce damage results

Figure 7(a) presents the tensile strength test results by diametral compression of the conditioned and unconditioned samples. The results correspond to the average obtained for each group (three samples). For unconditioned samples, mixtures with red mud (5% and 7%) obtained the highest average (0.65 MPa and 0.64 MPa, respectively) relative to the control mixture (0.57 MPa). As expected, the conditioning promoted a tensile strength reduction observed in all samples, independent of the asphalt mixture type. However, the tensile strength ratio (Figure 7b), represented by the tensile strength quotient average of conditioned and unconditioned, was insignificant since it was less than 30%, as required by the Brazilian standard. From Figure 7(b), it can be affirmed that mixture 1 (7% red mud) obtained higher resistance to moisture-induced damage with a tensile strength ratio of 95.3%.



a) b)

Figure 7: Moisture-induced damage test results - a) tensile strength; b) tensile strength ratio

Figure 8 shows examples of the pavement conditions on two sections of the federal roads in the Pará state. Figure 8(a) shows the pavement of BR - 163 (Altamira region) with structural defects as permanent deformation. Figure 8(b) shows the pavement of BR - 222 (Bom Jesus do Tocantins region), where many potholes can be observed.

a) b)

Figure 8: Pavement conditions in Pará federal roads - a) BR - 163; b) BR - 222.

Source: CNT (2023).

The mechanical performance results obtained by asphalt mixtures with red mud as a filler can contribute to the Brazilian highway pavement surfaces achieving the project life with adequate traffic conditions and without early defects appearance. Moreover, the feasibility of using an industrial residue in asphalt mixtures composition was proved, minimising environmental problems, especially for the disposal of red mud.

3.7 Environmental assessment

The Brazilian NBR 10004 standard (ABNT, 2004) provides a classification of residues, encompassing details about their flammability, corrosivity, reactivity, pathogenicity, and toxicity. Under this classification, red mud is categorised as an inert Class II-B solid waste. However, it is important to note that the composition of red mud can vary based on factors such as the source of bauxite ore, the specific aluminium extraction process employed, and the chemicals used in industrial operations. These factors significantly influence the characteristics and concentrations of hazardous substances that may be present in red mud.

For this reason, this study also comprised the red mud evaluation concerning corrosivity and toxicity criteria through pH analysis and chemical characterisation. The pH resulted in 10.25 ± 0.05, which, according to the NBR 10004 standard (ABNT, 2004), does not characterise it as a corrosive substance. However, the chemical characterisation analysis revealed the presence of vanadium pentoxide, a substance listed in the NBR 10004 standard, Annex “C”, as a “substance that indicates hazardous characteristics of a residue”, and in Annex “D” as “acutely toxic substances”.

Despite the small proportion (0.22%), the vanadium pentoxide offers to the red mud characteristics as a hazardous waste. Thus, red mud can be classified as a toxic substance and Class I – Hazardous waste. This finding alerts the scientific community to the need for a comprehensive evaluation of chemical compounds when a residue is reused or recycled for any applications. In previous studies conducted by Silva, Alves, & Motta (2007) and Macêdo *et al.* (2011), the researchers did not detect vanadium pentoxide in the red mud from the same source as this study.

According to Cooper (2007), the lungs are the principal route through which vanadium pentoxide affects human's bronchial airways, causing lung injury, pulmonary oedema and acute tracheobronchitis. Thus, the red mud's inadequate disposal and storage in the environment are conducive to vanadium pentoxide contamination. On the other hand, potential impacts due to leakage could be mitigated if the red mud is fully incorporated into the asphalt mixtures.

In the field, asphalt mixtures in pavement surface layers are frequently subjected to precipitation and traffic abrasion in real-world conditions. Consequently, some components of red mud may be transported into the environment, potentially contaminating rivers and water sources. Considering this concern, an analysis of the water used in the moisture-induced damage test for the conditioned asphalt mixture samples was conducted. This analysis encompassed the measurement of aluminium and iron concentrations, as well as the pH of the water.

The main route of non-occupational human exposure to aluminium is through ingestion of food and water; however, there is no indication that aluminium presents acute toxicity orally, despite its widespread occurrence in food, potable water and medicines. Like aluminium, iron is not considered toxic, but it can cause problems in public supply, giving colour and flavour to water. Ordinance 2,914 (BRASIL, 2011) of the Ministry of Health establishes maximum permitted limits for concentrations of aluminium, iron and pH of water for human consumption.

The selected parameters were measured in the potable water for human consumption supplied by the water company and in the water from the test. In civil construction, depending on the water table level, it is sometimes necessary to promote the terrain drainage for water table lowering. The water from terrain drainage is commonly discharged into pluvial networks. The average collected data in the water pipe proceeding from terrain drainage are available in ANA (2005). The result parameters obtained in the water from the test were compared to the potable water limits (BRASIL, 2011) and with the parameters measured from drainage terrain water (ANA, 2005), presented in Table 7.

Table 7: Water from conditioned samples analysis.

Parameters	Unit	Potable water	Limits[1]	Data[2]	Water from the test
Aluminium	mg/L	0.42	0.20	-	1.44
Iron	mg/L	0.09	0.30	0.01 to 1.65	0.29
pH	-	7	6 to 9	5.8 to 7.6	8

[1]BRASIL (2011); [2]ANA (2005).

From Table 7, according to potable water limits requirements (BRASIL, 2011), it was possible to verify that the water from the public supply network) presented an aluminium concentration (0.42 mg/L) higher than the allowed limit (0.20 mg/L). As expected, the water test samples from asphalt mixtures with red mud presented a high aluminium concentration (1.44 mg/L). In both cases, the aluminium concentration exceeded the limit. This parameter was not measured in the water from drainage terrains.

As for iron, concentrations remained below the limits (BRASIL, 2011), and the concentration of the water (samples conditioned) was next to the maximum limit. Water from different evaluated sources is presented within the limits established by the Ministry of Health for pH. It is essential to emphasise that the conditioned water samples have no potable purposes uses, and the mixture void content demanded to perform the moisture damage test (7 ± 1%) is higher than that obtained in the mixtures design (Table 4), condition not verified in the field.

The environmental analysis (Table 7) highlights the necessity of performing environmental tests, such as leaching, to assess the potential contamination by applying residues, particularly when red mud is used as a component in pavement layers without a binder or stabilizing agent, such as asphalt, Portland cement, or lime. In this condition, red mud is just added in a certain percentage, and the particles are not fully involved by a binder or stabilising agent. Hence, the effects of possible contaminants when alternative residues are used in road pavement layers may be mitigated by mixed-in with binder materials, which can adhere and involve the residue particles.

Further studies may comprise other alternatives, such as incorporating red mud into the asphalt before mixture production. In this alternative, the red mud role will not be a filler but be part of the asphalt mortar. The asphalt film could encapsulate the red mud particles, thus reducing environmental contamination probability.

Based on this study, using red mud as a filler in asphalt mixture production proved to be an alternative to reduce the amount of this residue, minimising the risks of environmental contamination and disasters around the aluminium refineries. Moreover, as a filler in asphalt mixture production, red mud led to mechanical behaviour improvement related to permanent deformation. This study was based on laboratory test results, and the asphalt mixture field application is recommended for findings validation.

4 CONCLUSIONS

This study evaluated the feasibility of using red mud as filler in asphalt mixture production. Initially, the physical-chemical characterisation of the red mud was carried out. The asphalt and the aggregates were also characterised to comply with the Brazilian specifications. Dense graded mixtures, DNIT range "C" with a total filler of 7%, were produced with red mud percentage variations (5% and 7% of red mud, complemented by 2% and 0% of stone powder). A control mixture with 7% stone dust filler was produced for comparison. The asphalt mixture's mechanical performance concerning permanent deformation resistance and moisture-induced damage was evaluated.

The pH of the red mud was within the limits set by Brazilian standards. However, the chemical analysis revealed the presence of vanadium pentoxide, which classifies the residue as a toxic substance and places it in the category of Class I waste - Hazardous. This contrasted with the classification of red mud as an inert Class II-B solid waste according to Brazilian standard NBR 10004. This finding underscores the importance of conducting a more thorough evaluation of the chemical components of the residue for accurate classification.

The use of red mud as a filler in the asphalt mixtures significantly enhanced the resistance to permanent deformation, reducing rutting depth compared to the control mixture. After 30,000 cycles, the control mixture showed a rutting depth of 6.1%, whereas the mixtures containing red mud as a filler achieved results of 3.50% (5% red mud) and 3.58% (7% red mud). The results represented a rutting depth reduction of over 40% compared to the control mixture. All asphalt mixtures showed favourable outcomes regarding moisture-induced damage, surpassing the 70% threshold for acceptability. Notably, the mixture containing 7% red mud demonstrated better performance.

In addition, the north region of Brazil is characterised by high temperatures, a factor that contributes to permanent deformation occurrence in the surface layers of flexible pavements. Given the proximity of red mud deposits in the region, the utilisation of this waste material is particularly advantageous. Its incorporation as an asphalt mixture filler has the potential to enhance pavement performance significantly.

The combination of heavy traffic loads and high temperatures can remove components of the asphalt mixture, especially during precipitation events. Depending on the contaminant concentrations, groundwater or rivers could be polluted. In this study, we conducted a simplified environmental assessment. As expected, the aluminium concentration was high. The iron concentration remained within permissible limits, and the pH was within an acceptable range. In order to mitigate the risk of contamination, a comprehensive assessment of pollutant concentrations of red mud is recommended, employing standardised tests like leaching studies.

In conclusion, using red mud as a filler in asphalt mixture composition has demonstrated technical feasibility and potential suitability as an environmentally responsible alternative for recycling. However, further research about incorporating red mud in road pavements should be pursued. Furthermore, other mechanical performance tests, including fatigue and crack propagation, should be conducted, along with assessing the potential use of red mud as a modifier agent in asphalt. It is imperative to emphasise that the feasibility of reintegrating red mud into the production chain must be considered due to environmental aspects, such as evaluating the concentration of leachable elements from the residue into the environment.

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