Mechanical feasibility of using red mud as filler in asphalt mixtures to improve permanent deformation

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ABSTRACT

Red mud is a solid residue that results when bauxite ore is processed to obtain alumina, the main material to produce aluminum. Brazil has a large reserve of bauxite in Pará State and processes this ore in large scale. However, in the country red mud is stored inadequately in the environment. Pará is situated in the north of Brazil and presents high temperature throughout the year. The elevated traffic volume and the high temperatures contributed to the early appearing of defects in the pavement asphalt surfaces. This laboratory study aims to develop a method for use this residue as filler in dense asphalt mixtures. Asphalt mixtures with 3%, 5% and 7% red mud were produced. A conventional mixture with 7% stone powder filler was used as the reference. The permanent deformation performance of the mixtures was evaluated through French Rutting Tester. The mixture with 5% red mud presented better resistance, that obtained at 30,000 cycles, 3,5% of rutting depth. The asphalt mixtures with red mud presented good performance, with reduction of the permanent deformation of 12.63 to 42.62% in relation to the reference mixture. Red mud as filler in asphalt mixtures is an option to reuse this waste, as well as being an environmentally friendly alternative.

Keywords: Red mud. Permanent deformation. Asphalt mixtures.

1. INTRODUCTION

Red mud is the solid waste residue from bauxite ores process with caustic soda for alumina (Al_2O_3) production [1]. In general, for each tonne of alumina produced, 0.3 to 1.5 tonnes of red mud can be generated [2, 3]. Currently, alumina is produced from bauxite through the Bayer process. From this process, the major by-product is converted to waste slurry named red mud tailings that contains 15-40% solids and is very alkaline (pH 11.0-12.5) [4].

Due to the alkaline nature and presence of heavy metals (arsenic, cadmium, nickel, zinc, lead, copper, chromium, vanadium, iron, gallium, phosphorus, manganese, magnesium, thorium, niobium), the red mud is considered a hazardous waste [5-7]. The red mud is usually placed off in the landfills and the presence of sodium hydroxide can contaminate the areas adjacent to the storage of the waste [6, 8]. Even when stored correctly, industrial wastes such as red mud represent a threat to the fauna and flora, being able to cause environmental damage, such as contamination of surface and groundwater effluents, and affect the health of neighboring populations [9].

Brazil has a large reserve of bauxite and is the third largest producer of this ore in the world [10]. Pará, the main Brazilian State that produces this ore, produced 90.9% of the national total (32.2 Mt of bauxite) in 2015 [11]. However, in the country, the recycling of red mud is incipient and is deposited inadequately in the environment. Several researches have studied alternatives to the usage and reinsertion of the red mud in the production chain. [12, 13, 14, 15]. Although the red mud has been studied in several researches, its application as filler in asphalt mixtures is still limited.

The asphalt mixtures applied as a flexible pavement surfaces consist of large aggregates, filler (material with at least 65% passing in the 75 µm sieve) and previously measured asphalt content. The filler incorporated into the asphalt mixture can improve rheological, thermal and water sensitivity performance, having void filling functions and increasing asphalt viscosity. Also, the presence of filler tends reduce the thermal susceptibility, the increase of the strength and the resistance to permanent deformation [16]. Thus, the interaction powder/asphalt is an important factor to be considered in asphalt mixtures characterization.

The Brazilian highways have shown early defects due to the high rate of heavy traffic along with high temperatures. One of the main defects verified is the permanent deformation on the asphalt mixture surface. In high-temperature conditions, because of the repeated effect of the wheel rolling, load stress will exceed the plastic limit of the asphalt mixture, and then flow deformation will accumulate to form ruts, named permanent deformation [17].

The State of Pará is situated in the north of Brazil and presents high temperature over the year. The elevated traffic volume and the high temperatures of the region have contributed to the early appearance of defects in the road pavement, especially in the asphalt surfaces.

The main problem of permanent deformation arises from excessive traffic consolidation on the upper layer of the pavement, plastic deformation due to insufficient mixture stability and also instability caused by stripping of asphalt binder below the riding surface of the pavement. Test procedures have been conducted to evaluate and predict permanent deformation at the laboratory. One of these consists of the wheel tracking test, which simulates conditions similar to pavement conditions in service to obtain rut depth under a specified load cycle [18-20].

In this context, this laboratory study aims the introduction of the red mud as filler in dense asphalt mixtures to improve the permanent deformation performance.

2. METHODOLOGY

In this study the use of red mud as filler in asphalt mixtures was evaluated in relation to permanent deformation at high temperatures. Figure 1 shows the flowchart of the experimental methodology.

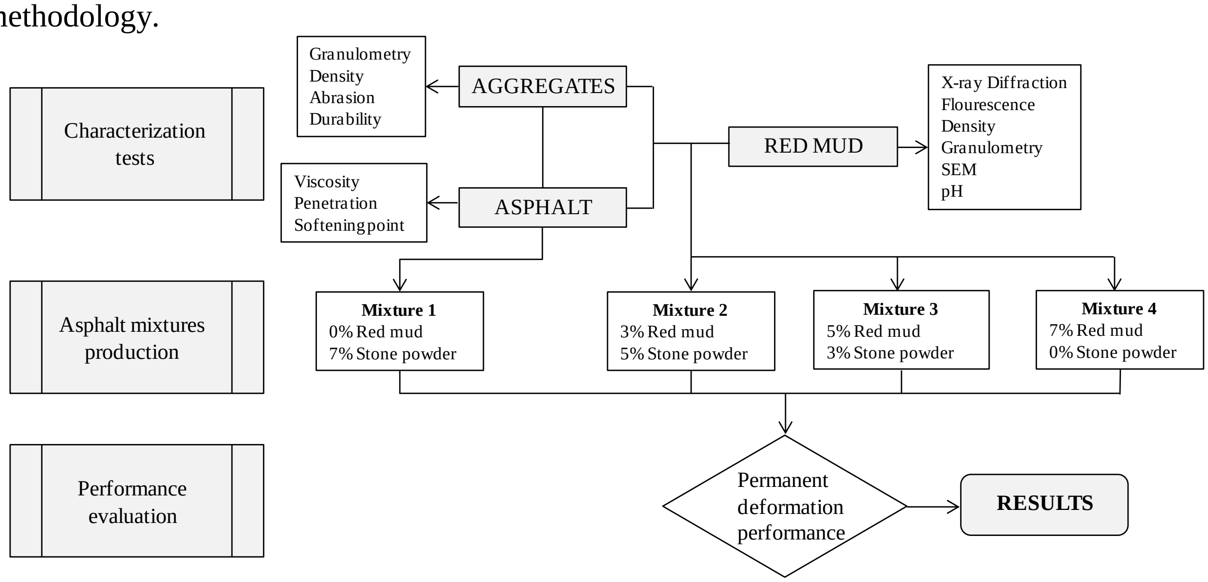

FIGURE 1 Flowchart of the experimental methodology

In the experimental methodology, dense asphalt mixtures were produced according to the Brazilian specification DNIT 031/06, Grade "C" [21]. The asphalt CAP-50/70, classified by penetration grade [22], granite aggregates, and filler (red mud stone powder) were used. Prior carrying out of the mechanical tests, material characterization tests were conducted (asphalt binder, aggregates and red mud). The asphalt mixtures were produced with a total of 7% filler, being 3%, 5% and 7% red mud. A mixture with 0% red mud and 7% stone powder was used as reference. The mixtures were design according to the Superior Performing Asphalt Pavements (Superpave) design method for high volume of traffic. The performance to permanent deformation was evaluated through the wheel tracker test, in the French Rutting Tester at 60°C.

3. RESULTS

3.1 Aggregates and asphalt

The granite aggregates come from a quarry located in the State of Santa Catarina, Brazil. ¾" (maximum diameter of 19.0 mm), ⅜" (maximum diameter of 9.5 mm) and stone powder (maximum diameter of 4.75 mm) were used for asphalt mixtures composition. Characterization tests were carried out, which showed that the aggregates are able to produce asphalt mixtures.

The asphalt used for the production of the mixtures was the Brazilian asphalt CAP-50/70, classified by penetration. The characterization was performed by following tests: softening point (49.5ºC; penetration 64 (0.01mm), and viscosity (308.7 cP at 135ºC), that fit into Brazilian specifications [22].

3.2 Red mud

The red mud comes from Barcarena (Pará State). The mineralogical analysis was carried out using an X-ray diffractometer (Figure 2). Hematite, anatase, quartz, gibbsite and sodalite are substances that do not present health hazard, except in concentrations higher than those listed in the Brazilian standard NBR 10.004/2004, [23]. Karelianite (V_2O_3), or vanadium trioxide, in presence of moisture, may oxidize and transform into vanadium pentoxide (V_2O_5), which, in high concentrations, presents hazard to the residue.

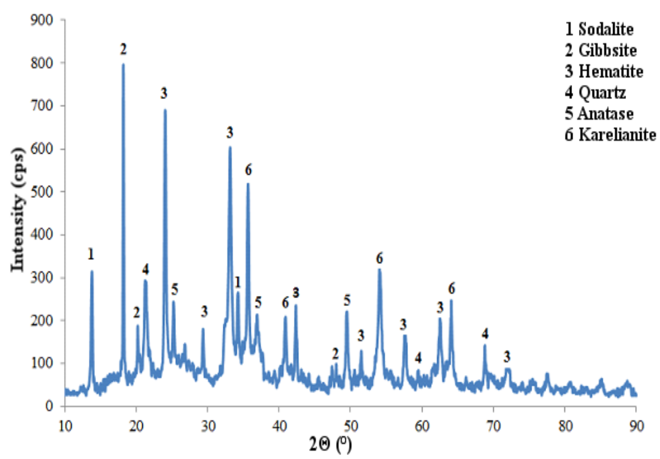

FIGURE 2 Red mud diffractogram

The morphological structure of the material was evaluated by a scanning electron microscope (SEM). In Figure 3, on (a), the micrograph with magnification of 1,000x, the red mud presented a spongious structure that characterizes the high specific surface of the material and; on (b), with a magnification of 5,000x, it was observed agglomerates of particles of size inferior to 5 µm with irregular granulometric distribution.

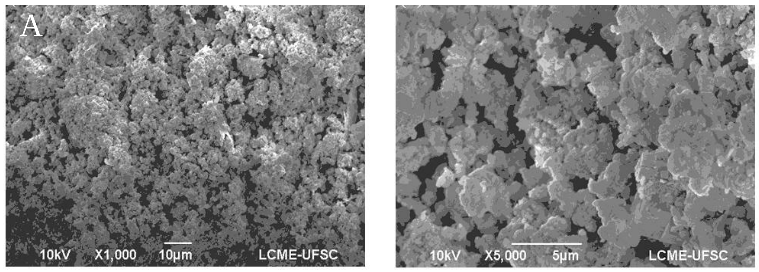

FIGURE 3 Micrographs of the red mud

The microscopic characterization of the material by energy dispersive X-ray spectrometry provided the composition of the chemical elements in the red mud, presented in Table 1. Also, Table 1 shows the compounds present in the red mud that were quantified by a Shimadzu Energy Dispersive X-ray fluorescence spectrometer (EDX).

TABLE 1 Elements and compounds measured in the red mud

Red mud elements		Red mud chemical compounds	
Elements	Percentage by weight	Compounds	Percentage
O (Oxygen)	25.94	Alumina (Al_2O_3)	35.47
Si (Silica)	22.35	Iron(III) oxide (Fe_2O_3)	31.45
Al (Aluminum)	15.83	Silica (SiO_2)	12.68
C (Carbon)	15.08	Titanium dioxide (TiO_2)	5.84
Ti (Titanium)	9.30	Lime (CaO)	1.81
Na (Sodium)	5.22	Vanadium pentoxide (V_2O_5)	0.20
Fe (Iron)	3.78	Manganese(II) oxide (MnO)	0.13
Ca (Calcium)	2.50	Carbon dioxide (CO_2)	12.40

The red mud granulometry was determined in a laser particle analyzer. From the results, around 85% of the particles had a diameter in the range of 0.4 µm to 60 µm, being 20% the clay fraction (< 2 µm) and 65% the silt fraction (2 µm - 60 µm), according to the Brazilian classification [24]. Also, 15% of the particles presented a grain size of 60 µm to 200 µm range that is characteristic of fine sand granulometry. The presence of particles larger than 40 µm tends to fill the voids of the aggregates and particles smaller than 20 µm mix with the binder, altering the viscosity, softening point and thermal susceptibility. Thus, as 70% of the grains of red mud presented a grain size of less than 20 µm, it is possible that this material is incorporated to the asphalt and altered its rheological properties.

The specific surface, calculated by the Vogt equation, resulted in 119.00 m²/kg. The red mud presented a pH of 10.25 ± 0.05. According to the Brazilian standard NBR 10.004/2004, [25], the waste is considered corrosive when the value is in the range 12.5 ≤ pH ≤ 2.0. However, a pH above 7.0 gives the residue a basic character, so that the surface of the residue becomes electrically negative, which may influence the asphalt-aggregate adhesiveness.

3.3 Asphalt mixtures

Asphalt mixtures were produced with red mud as filler (3%, 5%, and 7%). Another asphalt mixture was produced with 7% of stone powder (filler). This mixture with stone powder was the reference. The granulometric curve was established according to the Grade “C” of the Brazilian standard [21] as presented in Figure 4.

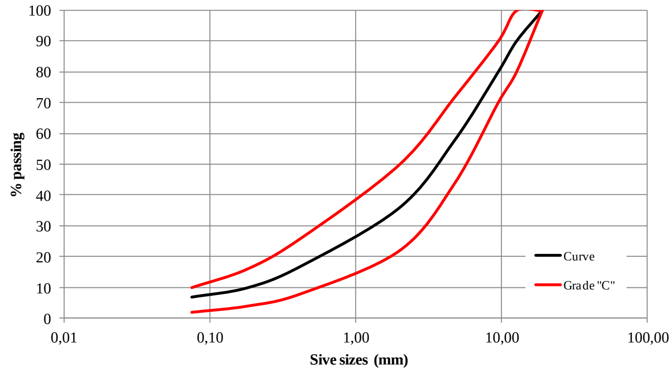

FIGURE 3 Granulometric curve and range of the asphalt mixtures

The asphalt mixtures design was performed according to the standards AASHTO M 323 [26] and AASHTO R 35-12 [27] in specimens with diameter of 150 mm. The production temperatures, established from the asphalt viscosity curve, were 148°C (for mixing) and 137°C (for compaction). The compaction was performed by a Superpave gyratory compactor ($N_{project}$ = 125 revolutions), with rotation angle of 1.25 ± 0.02°, rate of 30 revolutions per minute and vertical tension of 600 kPa. The results are shown in Table 2.

TABLE 2 Asphalt mixtures volumetric parameters

Parameters	Mixtures			
	M1	**M2**	**M3**	**M4**
Filler – stone powder (%)	7	4	2	0
Filler – red mud (%)	0	3	5	7
Asphalt content (%)	4.7	4.6	4.5	4.4
$G_{mm}^{(1)}$ (g/cm^3)	2.551	2.558	2.559	2.557
$G_{mb}^{(2)}$ (g/cm^3)	2.448	2.460	2.455	2.455
Voids content (%)	4.0	4.0	4.0	4.0
Voids in the mineral aggregate (VMA)	14.1	13.4	12.6	12.4
Asphalt-void ratio (RBV)	70.9	71.7	67.6	67.8
Powder-asphalt ratio (P/A)	1.45	1.48	1.51	1.55

$^{(1)}G_{mm}$ - maximum specific mass measured; $^{(2)}G_{mb}$ - Apparent specific mass.

3.4 Permanent deformation

The permanent deformation of asphalt mixtures was evaluated in laboratory by a French Rutting Tester (FRT). The slabs dimensions are 180 mm wide, 50 mm long, 50 mm thick. Samples are compacted with a French laboratory-tired compactor until reaching the apparent density established at the design (NF-P 98-250-2 [28]). The test follows the French standard NF-P 98-253-1 [29], in which loading of samples is accomplished by applying a 5,000N load onto a 400 x 8 Treb

Smooth pneumatic tire inflated to 600 kPa. The test temperature was 60°C. The measurement of rutting depth along the cycles is shown in Figure 4. The mixtures with red mud filler presented higher resistance to permanent deformation in relation to the reference mixture, and the mixture M3 (5% red mud filler) obtained better performance. The usage of red mud as filler for asphalt mixtures improved the performance to permanent deformation in relation to the conventional mixture, with rutting depth reduction, on average, of 12.82% to 42.63%.

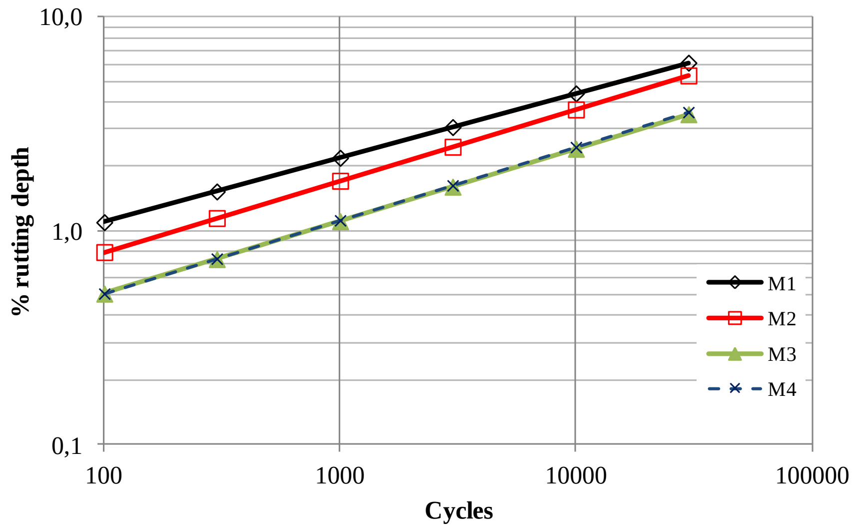

FIGURE 3 Evolution of the rutting depth along the cycles

4. CONCLUSION

This laboratory studies evaluated the application of the bauxite processing waste, the red mud, as filler in dense asphalt mixtures in relation to the increase in resistance to permanent deformation. Asphalt mixtures composed of 3% (M2), 5% (M3) and 7% (M4) red mud were produced. A mixture with 7% (M1) stone powder was used as reference for comparison. The red mud was characterized by the following tests: X-ray diffraction, fluorescence, specific mass, laser granulometry and Scanning Electron Microscopy. The granulometry test showed that the red mud can be used as filler. The pH of the waste is in accordance to standards established in the Brazilian standard regarding toxicity. However, the presence of vanadium pentoxide (V_2O_5), even in small portions (0.20%), characterizes it as toxic (Class I - hazardous waste). The evaluation of the resistance to permanent deformation showed that all the mixtures containing red mud as filler had superior performance with reduction of the rutting depth of 12.63 to 42.63 in relation to the reference mixture. The mixture with 5% red mud (M3) presented the best performance with rutting depth at 30,000 cycles of 3.50%. It is possible that the red mud has acted on the thermal susceptibility of the asphalt. As a result, this study showed the viability of reinserting the red mud in the production chain and contributed for the mitigation of its disposal and reuse problems, as alternative material of possible applied in the road infrastructure.

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