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Abstract: The increasing world steel production has contributed to the generation of million tons of mining residues. But, the huge demand of aggregates for the execution of pavements and the lack of raw material for this purpose, the research for new materials to be used in this area has become vital. The sandy residue that was studied was collected at Mariana– MG county, which was the result of the iron ore processing of the company Samarco S.A. This research has as objective the evaluation of the mechanical behaviour of asphalt mixtures utilizing residue from the processing of iron ore in substitution of the fine aggregate in the asphalt mixtures of the Asphaltic Concrete type, aiming its use in the rolling layer of a road pavement. To do so, the Marshall dosage of three asphalt mixtures and the mechanical tests characterized by the resilient modulus and fatigue life at a controlled tension were performed. It was also performed the determination of the optimum content by the Superpave dosage method conducted in two of these mixtures to obtain the Compaction Index and the mechanical behaviour by the Flow Number value. Concluded that the residue is compatible with all current standards for the use in asphalt mixtures, being able to be used in the CBUQ rolling layer, showing an improvement in the behaviour compared to the standard mixture.

Keywords: residues; Marshall dosage; mixtures; pavements

1. Introduction

Changes in nature are directly associated with the evolution of the society. The natural resources used to be uncontrollably used without worrying about a possible scarcity of natural sources. The concept of sustainability was considered contrary to the development. However, this scenario quickly brought harm, culminating in the adoption of criteria and guidelines to limit the extraction and use of raw materials (Hood, 2006)[1].

It is also known that societies, for their better progress, require industries to provide energy and goods that maintain their life style. However, the industrial activities generate the most diverse types of waste, in high proportions and with different characteristics, which are originated from the most distinct activities of the industrial branches, such as metallurgical, chemical, petrochemical, mining, food, among others (IPEA, 2012)[2].

The environmental issue brings big concern and, in principle, a waste is not something harmful. One of the viable alternatives to mitigate the environmental damages caused by mismanagement of the residue is to turn them into by-products or raw materials for other production lines, creating a new market opportunity to be explored, and also environmentally friendly (Cardoso et al, 2016)[3].

In this regard, the search for a useful purpose to the residues from industrial production has been a constant concern for the companies that dedicate themselves to these activities,

environmentalists, as well as control agencies and research institutions, interested in the preservation of the environment (Costa et al, 2014)[4]. Thus, finding a solution for the destination and utilization of the residue, as well as verifying in practice their real applicability as a reusable material, is a more desirable way than the disposal in landfills, an area that can be used for other nobles purposes and to avoid possible major catastrophes, as occurred in November 2015, with the rupture of the Samarco mining dam in Mariana-MG, characterizing the largest environmental disaster occurred in Brazil.

With the high and growing volume of residues generated by iron ore production in Brazil, many mining companies are researching more sustainable ways to dispose it. Thus, one option to mitigate the environmental impacts caused by mining is its use as alternative aggregates for asphalt paving, that is, an ecologically correct way of applying it in the transport infrastructures.

Sustainability is a current theme for pavement management in the whole world (Magnoni, 2016)[5]. In this regard, the main objective of this work was to evaluate the mechanical behaviour of asphalt mixtures utilizing residue from the processing of iron ore in substitution of the thin aggregate in the asphalt mixtures of the Asphalt Concrete (AC) type, aiming its use in the rolling layer of a road pavement.

To do so, it was performed a Marshall dosage of three asphalt mixtures, as well as mechanical tests that were characterized by the resilient modulus and fatigue life at controlled voltage. In addition, the optimum content was determined by the Superpave dosage method, which was conducted in two of these mixtures to obtain the Compaction Index and the mechanical behaviour by the Flow Number value.

1.1. Mining waste

The construction of roads and concrete structures consumes millions of tons of aggregates (Qarawi et al, 2016)[6]. Therefore, highway engineering has been the target of large research projects that point to the technical viability of using recycled aggregates and waste, which may come from civil construction, steel industry, mining, among others.

Thus, a considerable number of innovative materials and technologies are being explored to determine their adequacy for the conception, construction and maintenance of pavements (Beale, 2009)[7]. Due to that, it is extremely important the development of techniques that are effective in building pavements with lower transport costs, while keeping quality properly.

Recently, environment-related technologies are gaining momentum in all industries, and the more they combine cost, quality, and performance with environmental awareness, the better their market acceptance and the higher the profit earned by developers will be. In this context, the development of cheaper technologies and lower environmental impact for pavements and the use of possible wastes from mining can be handled together.

The determination of the type of asphalt coating to be used on a road is a function of technical, economic, financial and environmental criteria. Therefore, research involving the use of non-traditional materials, such as the steel aggregate (SA) in substitution of the mineral aggregate (MA), among other materials, are being developed in the academic environment and by companies, aiming at its application in the paving department. Conducted studies, such as those of Castelo Branco (2004)[8], Loiola (2009)[9], Pereira (2010)[10], Rocha (2011)[11], Vasconcelos (2013)[12], Apaza et al (2021)[13], Sá et al (2022) [14]and Shamsi and Zakerinejad (2023)[15], have proven the applicability of the SA in the layers of the asphaltic coating, either on asphaltic mixtures or on surface treatments by penetration.

The volume of generated solid residues, including wastes from mineral processing activities, is one of the major pollution concerns in the mining industry (Yellishetty et al, 2008)[16]. The Brazilian mineral industry, for example, has been engaged in the execution of environmental management programs that prioritize the reduction of waste volume, adequate disposal and better maintenance and monitoring of dams (Fontes et al, 2016)[17]. However, in Brazil, there is still a lack of research and published works that address the use of iron ore waste in paving, in comparison to industrial waste. In this regard, the Military Engineering Institute is one of the pioneering institutions in relation

to the development of projects that address this theme, acting strongly in the progress for the purpose of these materials.

2. Materials and Methods

The residue used in this research comes from Samarco Mineração S.A. company, located at Mariana – MG country, in the Quadrilátero Ferrífero region. This material is generated in the flotation stage of the iron ore beneficiation at the Mariana Mine and deposited at the Germano dam and its collection was performed on October 24, 2014. The samples were removed at a distance of 50 meters from the barrage crest, with spacing between collection points of 100 meters, in a total of three holes.

Due to the proximity of the water table, a depth of 2.0 meters was determined for sample collection. This material was packed in plastic drums and then transported and stored at the IME Soil Laboratory.

Figure 1. Sample of iron ore residue used in this work.

In order to perform the mixtures, coarse aggregates from crushed gneiss-granitic origin (gravel 1 and gravel 0), fine aggregate (sand) both from the state of Rio de Janeiro - RJ were used. All the materials were submitted to a complete evaluation of their physical, chemical and mechanical properties, aiming their application in paving.

The tests of characterization of the residues and aggregates were carried out according to the current DNER-ME standardization and includes the following tests: granulometric analysis, Los Angeles abrasion loss, impact loss using Treton device, absorption and density determination of the coarse aggregate, thin aggregate actual density, adhesiveness to bituminous binder, durability, sand equivalent and AIMS tests and thin and large angularity that followed the AASHTO international standards.

After the material characterization process, with the purpose of dosing and performing mechanical tests, three asphalt mixtures were selected. All three mixtures were dosed according to the Marshall method and two of them (M1 and M2) were also used in the dosage by the Superpave method for comparative purposes. As for the aggregates, their temperatures were taken as 10 ° C above the temperatures of the binders, determined in the characterization tests. The following Table 1 presents the nomenclature of the asphalt mixtures used in this research.

Table 1. Nomenclature of the asphalt mixtures used in this research.

Material	Mass percentage		
	M1	M2	M3
Gravel 1	20	15	20
Gravel 0	40	65	55
Sand	40	-	8
Residue	-	20	17

The chosen granulometric range for the mixtures was the C range of the DNIT, according to the DNIT 031/2006 – ES[18] specification, regardless of the method used to measure them. The granulometric curves were plotted on graphs with logarithmic scale for the sieves aperture on the

Marshall method. In addition to the design range, the range corresponding to the lower and upper limits of the C range, were also plotted as reference. For the Superpave method the granulometric curve was made with the apertures of the sieves elevated to the power 0.45. Thus, it was possible to visualize the maximum densification line and the control points predicted by the AASHTO M323-13 [19] standard. For the accomplishment of all the described steps, it was necessary to mold 185 specimens, distributed according to Table 2.

Table 2. Final parameters of the Marshall dosage of this research.

Tests	Specimen (diameter x hight)	Specimen Quantity	
		Marshall	Superpave
Optimum Level Definition	10cm x 6cm	80	20
Stability	10cm x 6cm	9	-
Resilient Modulus (25ºC)	10cm x 6cm	15	-
Indirect Tensil Strength (25ºC)	10cm x 6cm	9	-
Fatigue Life (FL)	10cm x 6cm	30	-
Flow Number (60º C) - Specimen with VV 7%	10cm x 15cm	-	10
Induced Moisture Loss - Specimen with VV 7%	10cm x 6cm	-	12
TOTAL		185	

Regarding the binders, it was chosen to use a CAP 50/70, supplied directly by BR Distribuidora S.A. The samples were submitted to the characterization tests provided by the ANP (2005)[20] and DNIT 095/2006[21] standard. All the tests were carried out at the Binders and Bituminous Mixtures Laboratory from IME.

3. Results

3.1. Marshall Dosage

After the determination of the granulometry of the mixtures and binder, the Marshall Dosage Method of asphalt mixtures M1, M2, M3 was carried out. For each mixture, it was chosen to vary the binder content in 0.5%, where M1 contents would range from 4% to 6.5%, M2 and M3 contents from 4.5% to 6.5%. Once the design contents for each mixture were defined, 5 specimens from each of them were executed. For each one of the mixtures, stability and indirect tensile strength tests were carried out, totaling 15 specimens. Table 3 presents the tests results with the optimum contents of each one:

Table 3. Final parameters of the Marshall dosage of this research.

Mixtures	Parameters					
	% Binder Project	VV (%)	RBV (%)	Stability (kgf)	TS(MPa)	VMA(%)
Reference DNIT-ES 031/2006	4,5 - 9,0	3 to 5	75 to 82	> 500	> 0,65	> 15
M 1	5,9	3,1	81,4	1710	1,4	16,3
M 2	5,6	3,9	76,7	1361	1,5	16,7
M 3	5,5	3,1	80,7	1442	1,6	15,7

All mixtures met the criteria established in the DNIT-ES 031/2006[18] standard, regarding the percentage of volume of voids (VV), percentage of bitumen/voids (RBV), stability, indirect tensile

strength and percentage of voids of the mineral aggregate (VMA). From the analysis of Table 3, it can be noticed that there was an increase of TS in the mixtures with residue if the residue was used and the M3 mixture showed a higher tensile strength value than the other mixtures.

The results of the resilient modulus (RM) tests and their respective statistical parameters are shown on Table 4. The mean RM was obtained by the arithmetic average of all the results from the tests, after the Grubbs Test was applied, which verifies the existence of abnormal values within a sample space.

Table 4. Statistical treatment of the RM results.

Mixture	Reliability interval (95%) (Mpa)	Standard deviation (Mpa)	Coefficient of variation	Mean rm (Mpa)
M1	5347 to 5883	140	2,5%	5640
M2	4927 to 5421	163	3,2%	5137
M3	5062 to 5773	127	2,4%	5244

From the results found on Table 4, it can be noticed a reduction in both RM and coefficient of variation values. It can be concluded that there was a decrease of about 9% of the RM value of the mixture M1 (5640 MPa) in relation to M2 (5137 MPa), and in relation to M3 (5244 MPa) the reduction was 7%. Therefore, the M2 mixture is a little less rigid than the others.

In the literature it is not very common to find references on the use of this specific type of residue in asphalt mixtures, however there is record of usage of other residues that are not very common.

Paulsen (1987) [22], performed RM tests on asphalt concrete containing 20% of roofing residue (roofing waste), obtaining values between 2873 MPa and 3000 MPa, with binder content varying between 4% and 6%.

Oluwasola et al (2015) [23], studied asphalt mixtures containing electric arc furnace steel slag and copper mine tailings. Four blends were prepared, where the first with 100% of granite aggregate - reference mixtures, the second with 80% of granite and 20% of copper mine tailings, the third with 80% of slag and 20% of tailings and the fourth with 40% of granite, 40% of slag and 20% of copper mine tailings. Two types of binders and three aging situations were used: without any type, short and long term aging.

The closest situation used in this work - similar binder and without aging - presented a resilient modulus varying between 3,800 MPa (mixture 1) and 5,000 MPa (mixtures 3), where these values are similar to those observed in the this study - between 5.137 MPa and 5.640 MPa.

Shafabakhsh et al (2014)[24], investigated the mechanical behavior of asphaltic mixtures containing glass cullet as a substitute for the conventional fine aggregate, showing an improvement of performance. In this case, the material used was the one that came closest in terms of granulometry of the sandy residue of this research, though there was a little less material passing through the nº 200 sieve: glass cullet only 2% and sandy residue 22.7%, both with 100% passing through the nº 4 sieve.

However, considering the same order of magnitude of asphaltic binder content (5.5%) adopted for mixtures containing sandy residue, the resilient modulus was observed between 300 and 900 MPa, considering a variation in the content of glass cullet between 0 and 20 % only, that is, well below those obtained in the present study.

The Fatigue Test was performed with 5 strength levels, adjusted at 10%, 20%, 30%, 40% and 45% of the indirect tensile strength (TS). From these results it was possible to trace the curves of the strength difference ($\Delta\sigma$) x number of cycles required at break (Nf). Table 5 shows the regression and correlation coefficients, derived from the regression of the fatigue life curve points on exponential scale.

Table 5. Regression parameters of the mixtures fatigue life curves.

Mixture	Nf = a1 (Δσ) b1			Nf = k1 (εr) k2		
	a1	b1	R2	K1	K2	R2
M1	3573	-2,676	0,9894	8E-09	-2,676	0,9894
M2	3514	-2,909	0,9650	1E-09	-2,909	0,9650
M3	4370	-2,802	0,9857	3E-09	-2,802	0,9851

Through the analysis of the results from Table 5, it can be observed that the mixtures presented results with small dispersion in the log-log space, since the linear regression curves presented coefficient of determination values higher than 90%.

3.2. Superpave Method

From the design contents of each mixture, two specimens were compacted at 160 turns for each of them, using the Superpave rotary compactor and the average design parameters were obtained, which will be presented and compared next. Table 6 presents the final values of the design traits with the optimum content of each mixture for the Superpave methodology.

Table 6. Summary of the mixtures characteristics.

Mixture	Esals (x106)	Type	% material				
			Binding content	Grave l 1	Grave l 0	San d	Residu e
M1	0,3 to 3	Medium	5,2	19,0	37,9	37,9	-
M2	3 to 10	Medium to high (main roads and rurals)	4,9	14,3	61,8	-	19,0

For the uniaxial repeated load tests to obtain the Flow Number value, 3 specimens were compacted for each mixture. After modelling of the deformation curves, the values of FN and the permanent deformation in the FN (εp (FN)) were extracted, according to the results presented in Table 7.

Table 7. Uniaxial repeated load test (FN) results.

Mixture	FN (cycles)			B (microns/mm)		
	Average	Standard deviation	CV	Average	Standard deviation	CV
M1	327	136	42%	28,6	5,0	17%
M2	350	78	22%	34,6	1,4	4%

It can be observed (Table 7) that the M2 mixture presented resistance to damage due to the accumulation of permanent deformations, with a higher Flow Number value. In addition, it obtained a higher accumulation rate of deformations in the secondary zone, characterizing a small improvement over the base mixture. Table 8 shows the values of this test as well as the acceptable limit for this type of pavement.

Table 8. Test values summary.

Mixture	RT (MPa)	RTu (MPa)	RRT (%)	Criterea AASHTO MP 8-01
M 1	1,47	1,19	81%	> 70%
M 2	1,50	1,12	74%	

It can be observed that both mixtures have met a limit value for this test, therefore both have little sensitivity to the deleterious action of water.

5. Conclusions

Based on what was presented, it can be concluded that the use of the residue of the iron ore beneficiation in asphalt mixtures of the Asphalt Concrete type is technically viable and brings technical, economic and mainly environmental benefits.

The mixture M2 made with a 20% residue content showed physical and mechanical characteristics compatible with the standard asphaltic mixture (M1), and suitable to be used in medium to light traffic and is therefore approved for practical application. The resilient modules of the mixtures made with iron mining residue showed to be superior or similar to mixture modules containing similar residues.

As for Superpave, in the Uniaxial Repeated Loads test, the mixture with residue presented a greater resistance to damage due to the accumulation of permanent deformations, with a higher value of Flow Number, characterizing a small improvement over the base mixture.

Regarding the tests made by the Marshall method, it was noticed a decrease in the cap content on the physical and mechanical characteristics with the application of the residue, besides the improvement of the percentage of voids. As it was also seen, the reduction of the RM values was low, linked to this, the presence of the residue is not indicative of this loss, but a set of factors, such as the change in grain size. Having said that, it is concluded that the substitution of the sand by the residue is perfectly acceptable.

Conflicts of Interest: The authors declare no conflicts of interest.

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