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INFLUENCE OF THE USE OF WASTE GENERATED BY THERMOELECTRIC POWER PLANT ON SUSTAINABLE ASPHALT MIXES

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ABSTRACT

The main objective of this research is to evaluate the influence of using waste generated by a coal-burning thermoelectric power plant in asphalt mixes. The matrices called fly ash, bottom ash and a composition with 50 % of each type were analyzed, and compared to conventional crushed gneissic rock particles, all used as filling material (filler) at 6.0 % passing through the mesh opening 0.075 mm, in the granulometric curves of asphalt mixes. The matrices studied are technically viable for use in asphalt mixes, creating the potential for large-scale market use of bottom ash, especially in the southern region of the State of Santa Catarina. Thus, to benefit more directly from the proximity to the source producing these inputs, the South region can explore the use of power plant waste, given the easy access and shorter transport distances.

KEYWORDS: Mineral coal ash; Dense asphalt mixes; French formulation methodology.

INFLUÊNCIA DA UTILIZAÇÃO DE RESÍDUOS GERADOS POR USINA TERMELÉTRICA EM MISTURAS ASFÁLTICAS SUSTENTÁVEIS

RESUMO

O objetivo principal desta pesquisa é avaliar a influência da utilização de resíduos gerados por uma usina termelétrica movida a carvão mineral em misturas asfálticas. Foram analisadas as matrizes denominadas cinzas volantes, cinzas pesadas e uma composição com 50 % de ambas as ocorrências, que foram comparadas com frações convencionais de granulares gnáissicos britados, todos utilizados como material de enchimento (fíler) a 6,0 % passante na malha de abertura 0,075 mm, nas curvas granulométricas das misturas asfálticas. As matrizes estudadas são viáveis tecnicamente para utilização em misturas asfálticas, abrindo inclusive a possibilidade de um mercado para a utilização em larga escala da cinza de fundo, especialmente na região sul do Estado de Santa Catarina. Assim, de forma a se beneficiar mais diretamente pela proximidade com a fonte produtora destes insumos, a região Sul pode explorar a utilização destes resíduos, visto o acesso fácil e as menores distâncias de transporte.

Palavras chave: Cinzas de carvão mineral; Misturas asfálticas densas; Metodologia francesa de formulação.

1 INTRODUCTION

Expansions of road infrastructure often cause several adverse environmental problems, representing a risk to the environment and to human beings. Road construction utilizes various types of raw materials, such as aggregates, bituminous binders, and chemical additives, which consume large amounts of natural resources and energy for their extraction, production, and processing. Thus, road construction results in energy consumption, dust and gas emissions, soil depletion and deterioration, consumption of non-renewable natural resources, noise pollution and generation of solid waste (YUE et al., 2022; LU et al., 2011).

Although the need to build and maintain roads and other road infrastructure is a key factor in the socioeconomic development of a society, over time road construction has come to cause negative impacts to the environment. The construction of road pavements often involves the exploitation of large volumes of materials, mainly aggregates, and mass transport, which results in increased greenhouse gas emissions (BAMIGBOYE et al., 2021; MAJER AND BUDZIŃSKI, 2018).

The extraction of natural aggregates raises serious environmental concerns, such as deforestation, loss of natural landscape and dust production. In many areas, the availability of high-quality natural aggregates is limited, leading to a shortage of aggregates and an overall increase in the cost of road projects (ZIARI et al., 2022; PATTANAIK et al., 2021; LIMA et al., 2021).

Replacing natural aggregates with waste and by-products is one of the most widespread techniques for achieving sustainable pavements, as it provides a double benefit. On the one hand, the extraction and production of raw materials is reduced, which results in a reduction in the consumption of water, electricity, and diesel, in addition to reducing the production of noise and dust. Furthermore, the deposit of waste in landfills is avoided, extending the useful life of the landfill, and reducing emissions (ESTHER et al., 2020; BARRETO E AMORIM, 2020).

Coal is an important source of energy, but it has a harmful influence on the environment due to the waste that is generated when coal is burned to produce power. In general, coal waste deposits are considered a long-term source of land and water contamination (KUMAR et al., 2022).

Statistical projections estimate that, even with clean energy production being massively encouraged, coal will maintain its current global role at least through 2040, being slightly overtaken by natural gas and photovoltaic solar panels. The primary origins of this coal usage stem from its large global availability, exceeding 1 trillion tons, i.e., coal is capable of meeting world energy demands for the next 130 years. The coal usage is enhanced by extensive geographic distribution of reserves, and the low cost and price stability when compared to other fuel sources (IEA, 2022).

Concerns surrounding global warming, climate change and environmental pollution caused by the combustion of fossil fuels have led governments around the world to take measures and implement stricter regulations to mitigate these effects (CUAN et al., 2023; SHAKIBI et al., 2023, SHAKIBI et al., 2022).

Current methods for road construction necessitate innovations to identify sustainable and economical alternatives to replace natural aggregates with mining waste, processing waste and industrial waste (fly ash, residual ash, steel slag, among others), and in order to use these waste products in the formulation of asphalt for construction of pavements (MOHANTY et al., 2023).

Researchers around the world have studied the use of various waste products as fillers in asphalt mixes. Results highlight the importance of developing new materials, with ongoing research seeking solutions for the disposal of certain waste products on large scales. The use of coal ash as an asphalt filler has been described by several groups (AKINWUMI et al., 2023; MOHANTY et al., 2023; KUMAR et al., 2022; ZIARI et al., 2022; BAMIGBOYE et al., 2021; WANG et al., 2019; LI et al., 2019; WOSZUK et al., 2019; OMRANI and MODARRES, 2018 and LE et al., 2018).

The use of waste products for asphalt fillers can mitigate environmental concerns that result from road construction. Specifically, use of ash from coal burning shows significant promise, with the aim of reducing environmental problems and promoting the production of more efficient and sustainable materials. Research presented in this paper highlights fly ash, which has already been widely studied in paving research and used by the cement industry, and bottom ash, which currently lacks known applications or markets for its large-scale use.

In the context of utilizing ash as an asphalt filler, the main objective of this work is to promote the extension of scientific discussions and perspectives related to the use of waste generated by thermoelectric plants in sustainable asphalt mixes, with the aim of contributing in a viable way to the reduction of environmental impacts. To achieve this objective, the physical-chemical and mineralogical characteristics of fly and bottom ash are analyzed, and compared with solid gneissic rock particles, aiming to evaluate the efficiency of a well-formulated dosage of asphalt mix to ultimately obtain paving of higher quality.

2 MATERIALS AND METHODS

2.1 Materials

The current research began with the selection of deposits for collecting samples of study materials. Next, characterization tests for these materials were carried out and the respective geological, mineralogical, chemical, and physical classifications of their occurrences were defined.

The gneissic crushed rock particles were supplied by a quarry located in the district of Pirabeiraba, nearby the city of Joinville, Santa Catarina. The criteria for selecting this location for this research was based on the availability of material occurrences and the partnership existent with Paving Development and Technology Laboratory, hereinafter called as LDTPav.

Fly and bottom ash samples were obtained from the Jorge Lacerda Thermoelectric Complex, located in the city of Capivari de Baixo/SC.

The bituminous binder used in the formulation has a penetration of 30/45 (0.1 mm). The temperatures adopted for the mixing and compaction procedures were 155 °C and 145 °C, respectively, determined based on Brookfield viscosity test (ASTM D4402M-15, 2015).

2.2 Methods

Crushed gneissic rock particles are within the limits imposed by regulations for asphalt mixes: Abrasion wear Los Angeles (DNER-ME 035/1998 and DNER-ME 037/1997); Shape index (ABNT NBR 7809/2006); Resistance to chemical attack (Durability) (DNER-ME 089/1994 and DNER-ME 037/1997); Sand equivalence (DNER-ME 54/1997); Powdery material content (DNER-ME 266/1997 and DNER-ME 37/1997) and Absorption. Therefore, the proposed rock particles can be used in asphalt mixes, except for the adhesion parameter to the bituminous binder (DNER-ME 078/1994), which must be corrected in practical construction situations with the insertion of adhesion improving additives in the bituminous binder dosage, or by replacing granular additions with an electropositive nature, which allow the formation of a chemical attraction dipole with the electronegative matrix of hydrocarbon materials.

However, it is important to highlight that in this research no additives or adhesion improvement additions were used, so that the true effect of incorporating ash from the burning of mineral coal in asphalt mixes could be verified.

To analyze the characteristics of the ash, a technical partnership was carried out between the SATC Technological Center (CT-SATC), belonging to the Charitable Association of the Carboniferous Industry of Santa Catarina (SATC), and the Postgraduate Program in Engineering and Mechanical Sciences (Post-ECM) from the Federal University of Santa Catarina (UFSC). This partnership was based on studies already developed by SATC related to applications of ash.

Particularly, the ash from the burning of coal was analyzed considering aspects such as: Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), X-ray Fluorescence (XRF), texturing, in addition to a theoretical estimate of the hardness of its components.

The choice of the French methodology for the formulation of the asphalt mixes studied was motivated by the rigorous evaluation criteria and the testing techniques and technologies available in this approach. The French methodology makes it possible to simulate the efforts applied to materials in a more realistic way, approaching the conditions found in the field. Furthermore, there is a close relationship between field and laboratory practices, which guarantees greater confidence in the results obtained. This approach aims to ensure the quality and performance of asphalt mixes, considering the specific requirements of the application environment.

The compaction ability of asphalt mixes was evaluated by the PCG test, using the Compaction Shear Press (PCG) (AFNOR NF P 98-252, 1999), imposing a slow and isothermal compaction under static compression, performed by a rotating (shearing) movement of a face around the axis of symmetry applied at an angle α. Tests were carried out with the PCG-3 series equipment, made available by LTP-EPUSP.

The evaluation of the harmful action of water on asphalt mixes was carried out by Duriez test at 18 °C (AFNOR NF P 12697-12, 2018), consisting of a rigorous compression test.

Resistance to the formation of wheel tracks was evaluated by the rutting test standard (AFNOR NF P 12697-22, 2020), which aims to evaluate the resistance of asphalt mixes to wheel track subsidence at 60 °C. The test consists of subjecting the asphalt mix to repeated loading, using a wheel equipped with a tire that performs back and forth movements, called cycles, under load and pressure conditions close to the tensions generated by heavy vehicles, which produces permanent deformations.

3 RESULTS AND DISCUSSIONS

Before performing the gneissic crushed rock particles and coal ash characterization tests, the ash samples used in this study were sieved, seeking to know their representative fractions. The sieve process was executed with the aim of achieving more efficient reuse of this solid waste in paving. Figure 1 demonstrates the representative fractions of fly and bottom ash in the study samples.

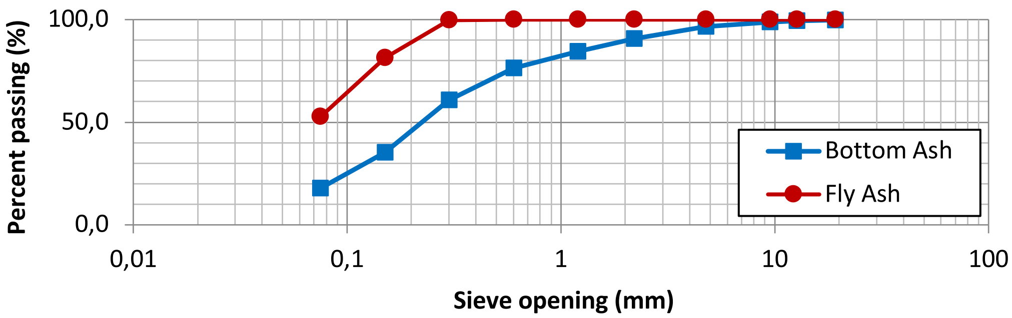

Figure 1: Granulometric distribution of the coal ashes.

Figure 1 illustrates that the representative fractions of bottom ash are those retained between the sieves with an opening of 0.60 mm to the material passing through 0.075 mm, while the most representative fractions corresponding to fly ash are those retained between the sieves with an opening of 0.15 mm until that passing through 0.075 mm.

Due to the morphology of the grains, where the molten clay minerals generated glassy particles which are rich in gaseous inclusions, a spongy appearance or vesicular structure can be observed, as demonstrated by Clara (2020). In addition to morphology, the fragility of larger grains is observed, in fractions located between the sieves with openings of 0.60 mm to 0.15 mm.

Due to the observed fragility, and to the percentages of fines generally used in the formulation of asphalt mixes, the limit for the use of ash fractions was established at 6.0 %. This value is also in line with other studies on the formulation of asphalt mixes using ash fillers, in which the maximum addition to avoid risks of loss of resistance was close to the adopted value.

It is important to justify the adopted replacement fraction. When analyzing the most representative fractions for both ashes, together with the maximum percentage for use in the formulation, it was decided to replace the bottom fraction (< 0.075mm), since in bottom ash the percentage of this fraction is 17.8 %, while in fly ash it is approximately 52.6 %.

The shape and texture of the filler particles under study (gneissic powder, fly ash and bottom ash) were verified by analyzing the images produced by scanning electron microscopy (SEM), as illustrated in Figure 2.

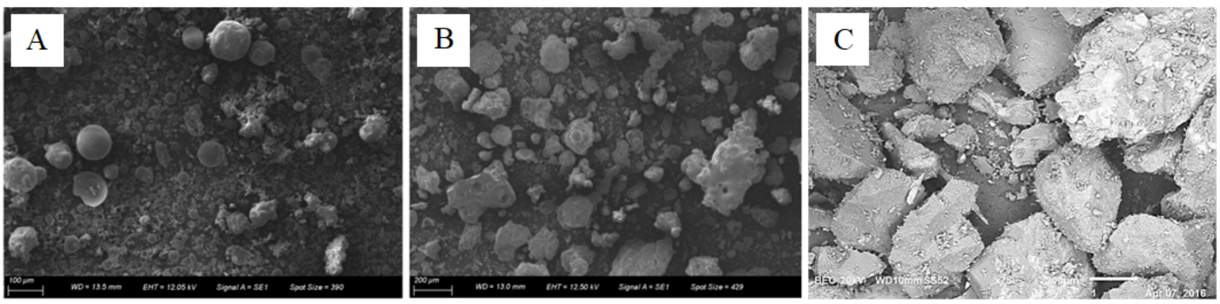

Figure 2: Scanning electron microscopy (A) Fly ash, (B) Bottom ash, and (C) Gneissic rock particles. Source: A-B: Aquino et al. (2017). C: Siroma (2018).

From the analysis of the images in Figure 2, it is possible to observe that coal ash has spherical shapes of varying diameters, as well as irregular particles of varying sizes. As noted by

Sarbak et al. (2004), this occurs due to the different physical states of silica present in coal ash samples, which are responsible for the formation of irregularly sized particles.

The morphology of the gneissic powder can be observed in Figure 2c, which presents the scanning electron micrograph of gneissic particles from the company so-called Vogelsanger Britagem, although the granular materials used in this research were supplied by the company Rudnick Minérios S.A. The intention of including this analysis is to demonstrate some characteristics related to the composition, macrotexture and microtexture of fine rock particles. Both deposits come from the Joinville/SC region and have the same classification in petrographic slide analysis, as demonstrated by Meurer (2015), in addition to presenting very similar results in characterization tests, which indicates a good proximity between the samples of the two companies.

When analyzing the microscopy image (Figure 2c), it is possible to verify that the predominant grain shape is subangular and the texture appears rough. These characteristics tend to favor granular interlocking, resulting in more stable asphalt mixes.

X-ray Diffraction (XRD) analyses were carried out at the SATC Technological Center (CT-SATC). Figure 3 presents the results of the mineralogical analyzes of the fillers.

The percentage quantities shown in Figure 3 are estimated by the software, based on the relative heights of the peaks of the standard charts. Furthermore, a 100 % basis is presented, excluding materials in amorphous form. In the graph legends, “pp” means possible presence.

The presence of Mullite in the ash is the result of reactions that occur during the combustion of coal. Quartz, in turn, is present in precursor coal and does not melt under burning conditions in thermoelectric plants. The presence of hematite and magnetite in the ashes is due to the oxidation of iron sulfides in the form of pyrite, normally present in Marcasite and Pyrrhotite present in burned coal (RHODE et al., 2006).

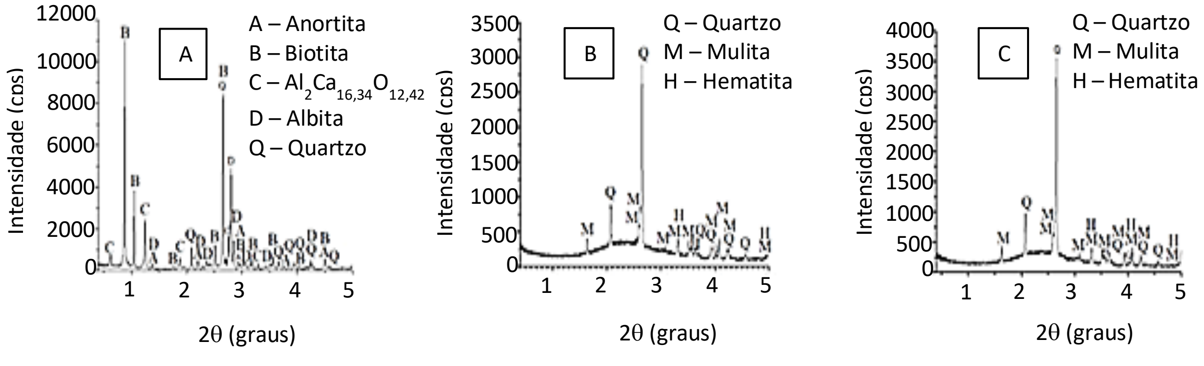

Figure 3: XRD mineralogical analysis (A) Stone dust, (B) Fly ash, and (C) Bottom ash.

The chemical composition related to the majority elements present in the samples was carried out at the SATC Technological Center (CT-SATC). Initially, the samples were subjected to fire loss (PF) testing in accordance with ASTM D7348-07. This test aims to eliminate organic materials and water in the composition present in the material.

The percentage values obtained for fire loss were 1.63 % (fly ash), 4.74 % (bottom ash), 3.21 % (50 % fly ash + 50 % bottom ash) and 2.51 % (gneissic particles). In addition to the elements indicated in Table 1, the elements Rb_2O, Y_2O_3 and PbO were detected in the ash, but in quantities below 0.03 %.

Results of the X-ray Fluorescence tests, as shown in Table 1, indicate that the crushed gneissic powder presented 53.60 % SiO_2, which justifies the poor adhesion observed in the stone aggregates characterization tests.

Table 1: Major chemical elements of the fillers.

Fillers (%Mass)	Elements														
	SiO_2	Fe_2O_3	Al_2O_3	Cao	MgO	K_2O	TiO_2	SO_3	MnO	ZrO_2	V_2O_5	SrO	ZnO	Cr_2O_3	Na_2O
Bottom Ash	58.91	6.99	19.62	1.79	0.61	4.29	1.54	0.22	0.04	0.13	0.09	0.03	0.04	0.04	0.86
Fly Ash	60.26	7.21	19.87	2.87	-	4.60	1.60	0.81	0.04	0.10	0.09	0.03	0.07	0.08	0.67
50 % Fly Ash + 50 % Bottom Ash	58.48	7.38	20.13	2.60	0.62	4.24	1.48	0.78	0.03	0.11	0.10	0.03	0.06	0.05	0.64
Gneissic Powder	53.60	14.51	10.93	8.08	3.26	2.58	1.23	0.44	0.25	0.10	0.07	0.06	0.04	0.03	2.31

The main differences in the composition of ash, without any treatment, are in the contents of Al, Si, Fe and fire loss (PF). Among these elements, the biggest difference is in the concentration of unburned material contained in the bottom ash, determined by the fire loss (PF).

The elements that were present in abundance are: Silica (SiO_2), Alumina (Al_2O_3), Iron Oxide (Fe_2O_3), Calcium Oxide (CaO) and Carbon (C). However, other trace elements were present, such as Zinc, Copper, Chromium, Lead, Mercury, Phosphorus, among others, which are responsible for the toxic potential of ash. The predominance of silicon and aluminum oxide is what gives ash its pozzolanic character, while the amorphous structure of the ash facilitates the solubilization of silica and aluminum so that it can react with free calcium oxide. The chemical characteristics of the ash are linked to the type of carbon from which it originated, and the transformations that occur depending on the burning temperature, therefore, it is a very heterogeneous product (MALLMANN, 1996).

The leaching and solubilization tests were carried out with the same coal ash from the Jorge Lacerda Thermoelectric Complex (OLIVEIRA et al., 2012) and with gneissic particles (GONÇALVES, 2000), both classified as non-hazardous Type II, according to Brazilian environmental standards (ABNT NBR 10004, 2004).

It is worth noting that Carnin et al. (2005) carried out leaching tests on asphalt mix formulations with reuse of foundry sand containing similar chemical and mineralogical compositions in relation to the coal ash and gneissic loads of this research. As a result, it was found that the coating generated by the bituminous binder encapsulates the aggregate particles, preventing them from being carried by water or other fluids, thus preventing infiltration through soil structures, and coming into direct contact with groundwater.

Similarly, the use of the same binders infers that coal ash and gneissic particles would also be encapsulated and thereby become impervious to the leaching of elements.

Textural analyzes of the samples were carried out at CT-SATC, in the CO_2 Capture Laboratory. The nitrogen (N_2) adsorption technique was used. The gas adsorption techniques used to determine these structures consist of determining the amount of adsorbate necessary to form a monomolecular layer (monolayer) on the surface to be measured. For textural analyses, isotherms developed by BET (BRUNAUEER et al., 1938) are generally used. From the equation of this isotherm, the necessary number of molecules to form a monolayer can be evaluated and, as the area occupied by the molecule is known (or estimated), the specific area of the material can then be calculated. This method also allows an assessment of the porosity of the material.

The results presented in Table 2 demonstrate that gneissic powder has a larger pore diameter and larger pore volume. Porosity has a great effect on the mechanical properties of the material, such as: resistance, hardness, and deformation.

Furthermore, porosity also influences physicochemical properties, such as dissolution characteristics and water retention capacity. Regarding transport properties, porosity affects thermal conductivity, diffusion of aromas and low molecular weight components.

As confirmed by Barra (2009), porous solids have an excellent adsorption capacity. Therefore, fillers that have high porosity will have the capacity to adsorb a greater amount of bituminous binder, which theoretically results in a firmer anchoring of the particles and, consequently, an increase in the stiffness of the overall material.

Table 2: Surface textural characteristics.

Sample	Surface Area (m^2/g)	Pore volume (cm^3/g)	Average pore diameter (Å)
Bottom Ash	1.454	0.013950	88.44
Fly Ash	6.311	0.003170	87.24
50 % Fly Ash + 50 % Bottom Ash	3.933	0.009819	99.84
Gneissic Powder	3.052	0.012850	168.40

It is important to note that during the production of asphalt mixes, the drying process is not always completely effective, which can result in the presence of a small amount of water lodged in the pores, making complete adhesion difficult. Furthermore, a significant amount of bituminous binder is mobilized to cover the developed surface and which then no longer contributes to adhesion to the aggregates, which increases the porosity of the mix. In the context of asphalt binders, the presence of water can accentuate the disintegration process.

The determination of the hardness of the fillers was necessary to justify the behaviors observed during the experimental campaign of the present research. The procedure for determining hardness was carried out through a literature search, given the great difficulty of obtaining the hardness through conventional methods due to their grains being fragile as mentioned previously. The results obtained through this estimation are presented in Table 3.

When analyzing the estimated hardness, it is observed that the estimated value for gneissic powder presents a small variability compared to the ash hardness. Among the ashes, fly ash has the highest estimated hardness. This greater hardness can be justified by the fact that its predominant composition is Al_2O_3 and SiO_2, with hardness values around 9 and 7 Mohs, respectively.

Table 3: Estimation of filler hardness.

Sample	Estimated hardness
Bottom Ash	7.13
Fly Ash	7.17
50 % Fly Ash + 50 % Bottom Ash	7.15

Gneissic Powder	6.08

The definition of the binder contents used in the research was initially based on the work of Eing (2018), which established the levels of 4.54 %, 4.70 % and 4.86 %. However, during the experimental campaign of the present research, using the PCG (Compacting Shear Press), promising results were observed indicating the possibility of working with lower binder contents, in order to improve the results already obtained, as well as to reduce the binder consumption, with a content of 4.22 % being incorporated into the series.

The compaction ability of an asphalt mix is quantified considering the average result of three specimens for each formulation. The results were then compared with the normative prerogatives that establish the measurement of void content at 80 turns, which must fall within the range between 4.0 % and 9.0 % for BBSG type asphalt mixes.

The normative limits are represented by the alignments called upper limit and lower limit BBSG. Thirty (30) specimens were produced, with 3 specimens for each content studied. The average results obtained in the tests are shown in Figure 4.

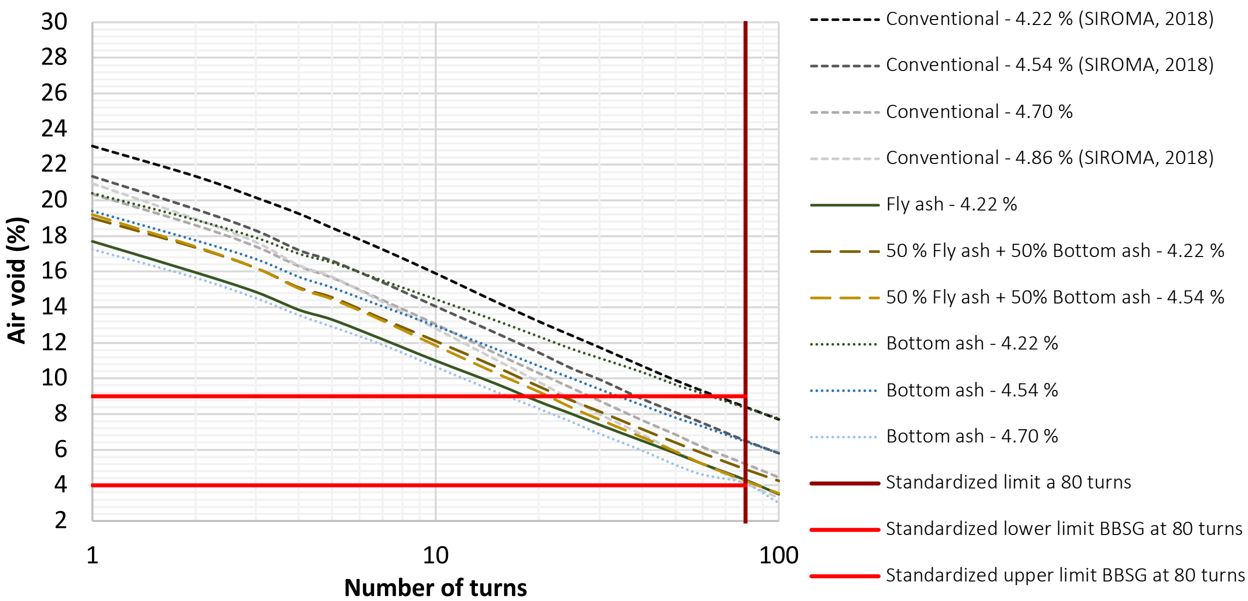

Figure 4: PCG test results.

It is also possible to observe that, in this research, conventional mixes were made with a single binder content of 4.70 %. This choice was made based on the previous research carried out by Siroma (2018), who carried out experimental tests for the same type of mixes with formulations containing binder levels of 4.22 %, 4.54 % and 4.86 %.

If the regulatory limits are observed, mixes that do not meet this limit, presenting levels lower than the minimum value determined by the standard by 4.0 %, are considered failed. These results prove that asphalt mixes would demonstrate, in the field, an undesirable compaction ability, that is, with an excessively early reduction of voids, a situation that could result in the potential for rutting appearance and even exudation in the field.

It is possible to verify that both the morphology and texture of the granular materials have a strong influence on the compaction ability of asphalt mixes. Noting that gneissic particles have characteristics inherited from the parent rock and can be somewhat modified by crushing techniques, they have a predominantly subangular shape and a rough surface, favoring granular interlocking and resulting in more stable asphalt mixes.

Analyzing the mineralogical characteristics of the ash tested, it is generally observed that the fly ash is predominantly made up of vitreous material of a silico-aluminous nature and to a lesser extent crystallized compounds. This particle morphology, as mentioned by Rhode et al. (2006), varies according to the burning conditions. Therefore, fly ash from the combustion of pulverized coal predominantly contains spherical particles, with small amounts of cenospheres and irregular particles, as already observed in the characterization of the ash, giving these mixes greater densification potential.

As for the bottom ash, these are made up of a silico-aluminous glassy phases associated with Carbon in the amorphous phase. Morphological features are presented as rounded and irregular transparent particles, angular to subangular opaque particles, and finally spherical shapes. These characteristics, when compared to the morphology of fly ash, justify the behavior of these mixes, presenting better granular interlocking and resulting in a greater volume of voids.

The high sensitivity demonstrates the importance that the interaction between the particles has on the behavior of asphalt mixes. When analyzing the same addition of binder content between samples with ash addition and conventional mixes, less void formation is noted in the former, corroborating the results of the morphological characterization already presented. Furthermore, results in Figure 4 indicate that increasing the binder content causes greater compactness of asphalt mixes. The result is due to the increase in lubrication generated between the particles due to the addition of binder, resulting in greater accommodation of the particles.

After completing the PCG tests, the water sensitivity resistance of the asphalt mixes was evaluated by carrying out the Duriez test. The results obtained in these tests are presented in Figure 5.

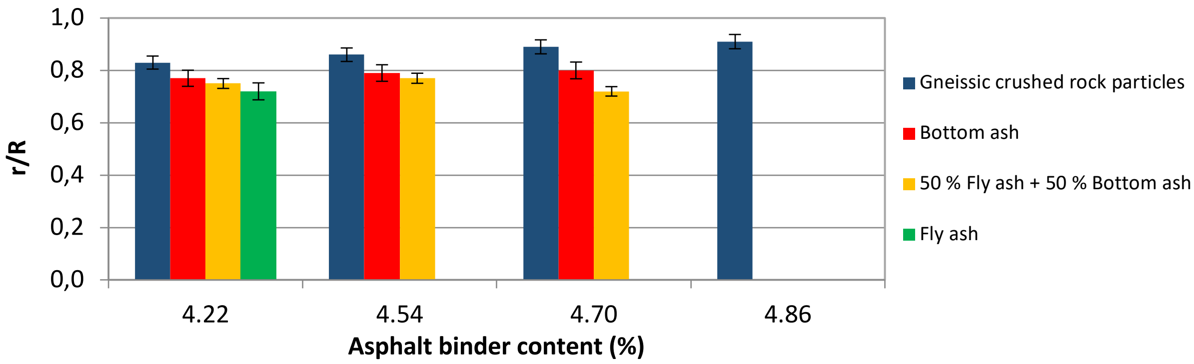

Figure 5: Results of Duriez tests.

Results shown in Figure 5 indicate that all the levels of the mixes studied were approved, presenting an average higher than the minimum value established by the standard. It is concluded, therefore, that the mixes studied did not present a reduction of more than 30 % in mechanical resistance during axial compression tests.

However, it is important to highlight that again the morphology of the granular fractions played a decisive role in the results obtained, this time in the r/R ratio of the water-conditioned (r) and dry-conditioned (R) specimens. Both gneissic matrices and ash have chemically electronegative characteristics, with a predominant presence of silica, which does not contribute to good resistance to the harmful action of water in both cases. Thus, the predominance of the rough surface texture and subangular shape of the gneissic granular particles provides better resistance to the shear stresses generated during the rupture process of the specimens, compared to the partially smooth and rounded macro-textural condition of the ash particles studied. It is worth mentioning that the hardness observed for ash grains is equivalent to that of Gneiss grains.

Therefore, the need to include adhesive-improving agents in the composition of the traces of the mixes studied under practical conditions of use is reiterated.

On the rutting test, it consists of evaluating the resistance of asphalt mixes to the formation of wheel tracks, totaling 20 molded plates for this research, two for each mix studied. All mixes analyzed presented results within regulatory compliance in tests prior to level 2 of the French methodology for formulating asphalt mixes. Figure 6 illustrates a general overview of the asphalt mixes analyzed.

The BBSG 0/14 mm mix has three possible classifications, determined according to the rutting percent after 30.000 cycles (AFNOR, 2007). According to Barra et al. (2010), classes 2 and 3 are those that most resemble the Brazilian context, depending on the region.

When analyzing the mixes dosed with a binder content of 4.22 %, they all fell into class 3, which indicates the best conditions of resistance to rutting for the BBSG category, that is, below 5.0 %. Furthermore, based on the results shown in Figure 6, it can be observed that the higher the asphalt binder content used, the greater the rutting percent found in the asphalt mix.

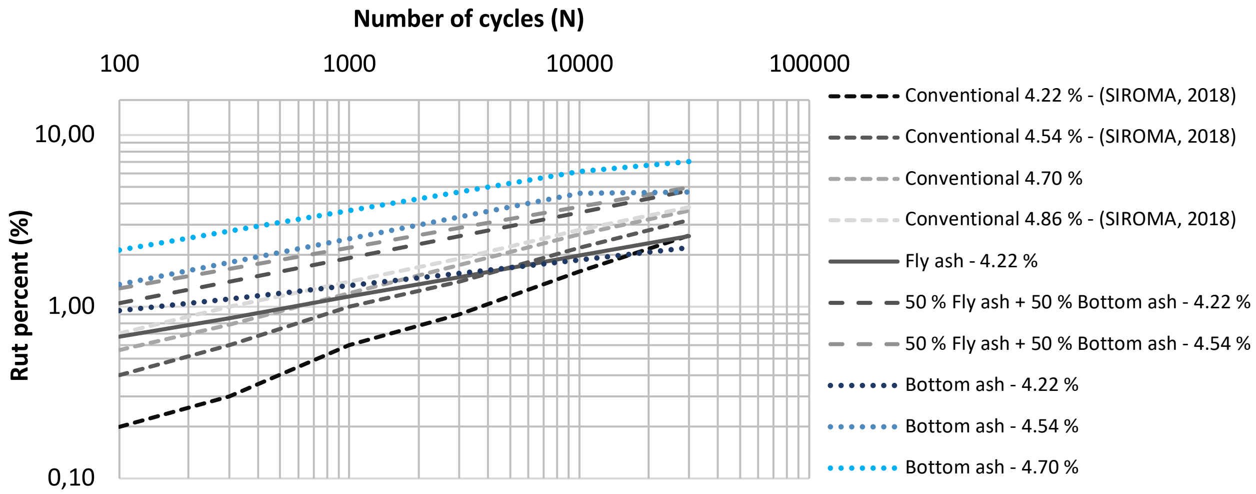

Figure 6: Rutting test results.

The graphs presented, in general, verify the stated results in a similar way to the explanations for the results of the PCG and Duriez tests. The morphology and roughness of the ash particles used in this study indicate that this material is not capable of providing the same degree of interlocking between particles compared to crushed Gneiss grains. This means that, in most of the situations presented, mixes with ash are less resistant to shear stresses caused by the constant dynamic load applied at low frequency during the test.

In the case of mixes containing 100 % fly ash and 100 % bottom ash, values close to those of the conventional mix were obtained. This occurs because the binder content used is low, which indicates less lubrication of the ash particles, especially the more rounded ones. In this case, the interlocking provided by particles with subangular macrotexture and rough microtexture prevailed, taking into account the composite morphology of these materials, according to the microscopic analyzes presented.

On the other hand, in the case of the mix containing 50 % fly ash + 50 % bottom ash, with the same binder content analyzed (4.22 %), a higher rutting percent was obtained than the other mixes. Increased deformation occurs due to the higher concentration of rounded particles, since this mix accumulates contributions from the fly ash and bottom ash fractions in the same sample. Reducing the interlocking effectiveness of the composition, increasing rutting levels.

The fact that mixes composed of ash present slightly lower ruts than the conventional mix is due to the greater porosity of the ash fractions in relation to the gneissic crushed fractions. The greater porosity allows greater absorption of binder, reducing its lubricating effect on the mix, especially on rounded ash particles. Reduced lubrication contributes to greater stability of the mix and less rutting percents.

All mixes fell into class 3, except the mix with the addition of 100 % bottom ash at a binder content of 4.70%. Therefore, all mixes were suitable for use in the most severe traffic conditions in practical situations. The same comparative considerations apply to dosages with 4.70 % binder content. It is worth mentioning that the rutting percent obtained of 7.01 % for the 100 % bottom ash mix classifies it in class 2, according to the French methodology. This means that the value is in the range between 5.00 % and 7.50 %, lower than class 3, but suitable for use in traffic situations in a climatic environment with a high thermal gradient.

4 CONCLUSIONS

Based on the results presented by the experimental campaign, objectives set for the research were achieved.

With regards to the characterizations of the materials in the electrochemical context, it was demonstrated that the predominantly electronegative condition of the gneissic matrices and siliceous ash did not contribute to the formation of a strong electrical attraction with the hydrocarbon asphalt binder. This occurred due to the formation of an intense amorphous phase, which not only prevented good adhesion of the granular-bitumen set, culminating in poor resistance to the harmful action of water, but also confirmed the inert character of these inputs in asphalt mixes, without any significant contribution in the rigidification parameters of the mastics formed.

From another perspective, it is important to highlight that the physical characteristics were decisive in the contribution of the aforementioned matrices to the mechanical behavior of asphalt mixes. It was observed that the aggregate gradation curves composed entirely of crushed gneissic particles presented superior results in general. Better performance was due to the fact that these particles had a rough surface texture and a regular, subangular macrotexture. On the other hand, the ash tested found variability in its composition, with partial presence of smooth surfaces, cenospheric elements and rounded macrotexture. Variable composition impaired the formation of friction angles for the global interlocking of the particles, which hindered effective resistance to shear stresses caused by applied loads. It is important to highlight that, even if the estimated hardness of both occurrences was equivalent, the morphological characteristics of the particles had a significant impact on the performance of asphalt mixes.

Thus, it is possible to infer that the good mechanical behavior of a material, notably asphalt mixes, is not related only to the physical resistance itself, but also to the shape variables of its granular matrices.

Furthermore, to achieve this success with the ash matrices used, essential care prior to the formulation of asphalt mixes must be taken in each case, such as: thorough analysis of the granulometric distribution, accurate assessment of the morphology of the particles and, above all, use of a moderate percentage of the material in the granulometric composition of the mixes, that is, below 10 %, in this case 6.0 %, in order to reduce the potential for the occurrence of the rutting phenomenon. Otherwise, the assumed risks of failure are very high, due to the morphological characteristics of their occurrences.

Given the results obtained and the analyzes carried out, it is possible to conclude that the studied ash matrices from the burning of mineral coal are technically viable for use in asphalt mixes, even opening up the possibility of a market for the large-scale use of bottom ash, currently not intended for input processing services, notably in the southern region of the State of Santa Catarina, where it can benefit more directly from the proximity to the source producing these inputs, including easy access and shorter transport distances, as long as the due technical precautions already mentioned are taken.

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