applied sciences

MDPI

Article

Resistance to Fatigue in Asphalts Used in Military Airports of the Brazilian Amazon through the Use of Nickel-Holding Ash

Carlos Navarrete [1,2], Antonio Carlos Rodrigues Guimarães [1], Maria Esther Soares Marques [1], Carmen Dias Castro [1] and Theofilos Toulkeridis [2,*]

1 Instituto Militar de Engenharia-IME, Rio de Janeiro 22290-270, Brazil
2 Departamento de Ciencias de la Tierra y Construcción, Universidad de las Fuerzas Armadas ESPE, Sangolquí 171-5-231B, Ecuador
* Correspondence: ttoulkeridis@espe.edu.ec

Abstract: The current study presents the evaluation of the mechanical behavior of an asphalt mixture using the alternative aggregate boiler coke ash, an element that originates in nickel processing. Hereby, we have focused the research on the runways for military purposes, which marks a great difference to the existing commercial runways in the Western Brazilian Amazon. This area suffers extreme heat, with temperatures oscillating up to 80 °C on the corresponding asphalts. This leads to deformations that are the main aim of the present investigation and the main consideration of fatigue damage. The main property of the alternative aggregate, whose granulometry composes the fine elements of the asphalt mix, is the pozzolanity that acts as a cement in the putty of the mix. Based on our experimental approaches, there is a significant improvement in the results of the tests standardized by DNIT, ABNT and DIRENG, allowing the technical and economic evaluation of the used mixture. Another fundamental aspect is the reduction of the volume of waste disposed of in nickel processing plants in Brazil.

Keywords: alternative aggregate; Marshall dosage methodology; asphalt mixtures; fatigue damage; nickel-holding ash

Citation: Navarrete, C.; Guimarães, A.C.R.; Marques, M.E.S.; Castro, C.D.; Toulkeridis, T. Resistance to Fatigue in Asphalts Used in Military Airports of the Brazilian Amazon through the Use of Nickel-Holding Ash. *Appl. Sci.* **2022**, *12*, 9134. https://doi.org/10.3390/app12189134

Academic Editor: Luís Picado Santos

Received: 25 June 2022
Accepted: 18 August 2022
Published: 12 September 2022

1. Introduction

The accessibility of remote sites of both old and new settlements, natural resources and the extension of social-economic activities is essential for the development and progress of each country [1–4]. Brazil is the fifth largest country worldwide, with an extension of more than 8.5 million square kilometers and a population of some 214 million citizens. It has a poorly maintained road network, a shortage of railways and a river network of scarce resources [5–9]. This scenario makes air transport a relevant alternative for travel and, on occasions, is the only one to access certain regions [10–12].

Aeronautical pavements play a prominent role in the airport complex due to their importance in the operation and safety of aircraft [13–17]. Its conditions of use and conservation are one of the main concerns of the administration in charge of its management [18–20]. The gradual degradation of these infrastructures is one of the factors that can contribute to incidents and accidents involving aircraft [21–23]. Therefore, the maintenance and rehabilitation practices of aeronautical pavements should be treated as a priority and responsibility by its administrators, given this difficult task and the financial resources involved, which in most cases are high or often insufficient [24–26].

Transportation systems are essential for the economic and social growth and development of a country [27,28]. The need to transport more in less time requires these systems to be efficient and safe. In order to guarantee these conditions, special attention must be paid to the infrastructure [29]. Among the means of transport, rail and air stand out due to their function of transporting heavy loads efficiently and safely [30]. However, with the increase in applied loads, traffic volume and practiced speeds, it became necessary to develop new methodologies to size pavements and analyze new materials. Therefore, the data points to a high demand for paving products, from equipment to construction materials. In the latter case, aggregates, which represent approximately 95% of the composition of bituminous mixtures for the production of asphalt concrete, deserve special attention [31–33]. The demand for road infrastructure materials is enormous and is often limited to deposits of raw materials. This raises concerns about the possibility of depletion of natural resources and the effects that their extraction can have on the environment. Thus, the supply of infrastructure materials associated with the demand for deposits of raw materials, generates changes in the evaluations of economic viability of the so-called residual or alternative materials [34–39].

Ashes are in the group of industrial waste that is generated annually in large volumes and that is often improperly disposed of in the environment, without any technical criteria [40,41]. Other times they demand high costs related to storage and final destination, a fact that is a problem for an industry that is beginning to worry about the adoption of disposal practices in suitable areas and the necessary protection measures [42]. The reuse of various types of ash has already aroused great interest in some branches of industry. Various investigations aimed at its use have allowed its use in civil construction, especially light ash in the manufacture of pozzolanic Portland cement [43–45]. This procedure began in the mid-1930s, when the ashes began to be available in significant quantities, occupying a large space in industries and requiring specialized infrastructure to restrict environmental legislation [46–48]

The use of alternative materials aims to improve the properties of asphalt mixtures to reduce the defects to which a pavement is subjected [49–51]. The permanent deformation in the wheel track of the support layer is one of the most important defects, since this type of defect, in addition to providing an accelerated degradation of the pavement structure, considerably reduces the comfort and safety of the user, thus increasing operating costs [52,53]. It is noteworthy that an important factor to consider in the safety of this mechanical phenomenon is that on rainy days, a layer of water forms along the entire section in the sumps of the wheel tracks. This makes water drainage difficult and provides minimal contact between the tire and the coating, which can result in hydroplaning [54,55].

Thus, the main objective of the current research is to present the study of the physical and mechanical properties of an innovative asphalt mixture in remote military airports. With the addition of boiler ash to coke and using the Marshall dosing method, with CAP 30/45 as an asphalt binder and determined by laboratory tests, the differences between this mixture and another were conducted with traditional aggregates. The tests were performed in the IME's Asphalt Mix Laboratory, with fine and coarse aggregates supplied by the quarry of the Magé municipality in the State of Rio de Janeiro, while the asphalt binder was supplied by CENPES-RJ, and the ashes from the city of Niquelândia, Goiás State in Brazil.

2. Brazilian Military Airports and Their Importance

The Brazilian National Defense Plan of Action, which belongs to the responsibility of the State, has its highest-level conditioning document in the National Defense Policy and which establishes the National Defense Objectives [56,57]. The first is the guarantee of sovereignty, national heritage and territorial integrity. Other objectives include structuring the armed forces with adequate organizational and operational capacities, creating social and economic conditions to support the National Defense in Brazil, contributing to international peace and security, and protecting Brazilian interests at different levels of external projection of the country [58–60].

The Amazon is an area of continental dimension with a fascinating flora and fauna. Understanding this region, its great distances, difficulties in terms of logistical support whether by sea or air, its vulnerabilities in terms of security and defense, permeate the actions of the armed forces and especially the Brazilian Air Force. Since the middle of the 20th century, it has acted as a factor of defense, integration, deterrence and, above all, presence, fulfilling its constitutional function [61–65]. In Brazil, the Amazon region occupies 60% of the national territory which is spread across nine states. The interconnection of the Amazon biome spans across borders. For all these reasons, it is a region that has profound difficulties from the point of view of surveillance and defense. It should be noted that borders are political, that is, they are not biological or social, despite the attempts of integration by neighboring countries.

The first great challenge in the Amazon region has to do with the environmental issue. Added to this is the great permeability of the country's borders. About a thousand rivers penetrate the Brazilian territory, and each one of them is a means of communication through which all kinds of legal and illegal trades pass [66,67]. This makes the task of defense gigantic. Currently, the army has 87 military units along the border, and another 28 platoons are being created. Therefore, local aerodromes or airports are of great importance for the economic, social and security development of the region [68–83].

3. Classification of Pavements

The pavements behave differently to the requirements imposed by traffic and the climatic variations, depending on the materials used in the different layers [84–86]. According to its constitution and its deformability, it is possible to distinguish different classes. In general, aeronautical pavements are divided into classes, namely flexible pavements and rigid pavements. There can be combinations of pavement types and stabilizing layers, bituminous or rigid reflows (overlays) that result in complex pavements. However, for the FAA, it continues to classify the floor as rigid or flexible [87]. The type of pavement that will be used in the different paved areas of an airport depends on technical and economic factors [88]. The trend is the use of flexible pavements on rails and circulation paths due to their good characteristics of friction, regularity and comfort [89]. Rigid pavements are most used in aircraft parking areas because of their greater resistance to fuel spillage, among other advantages (Figure 1) [90–92].

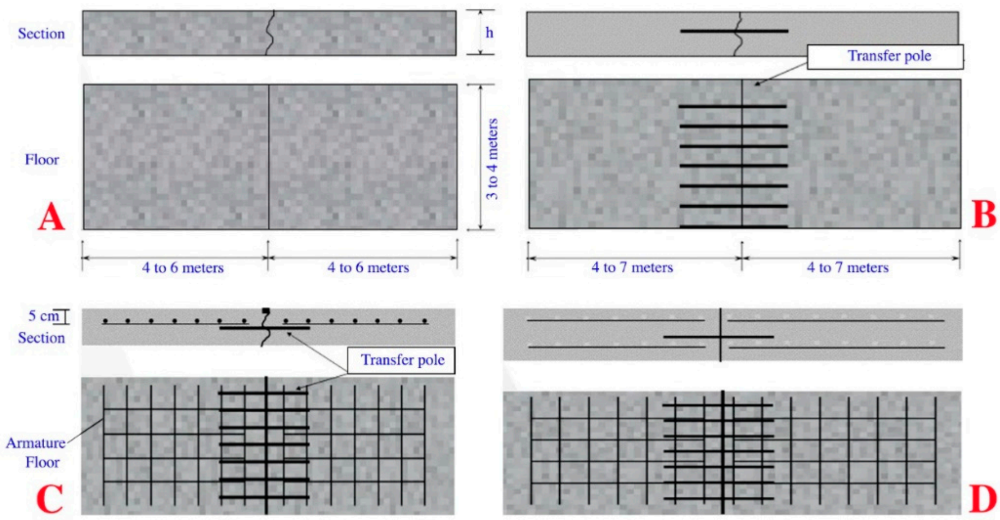

Figure 1. Types of rigid pavements: (**A**) simple concrete pavement; (**B**) simple concrete pavement with transfer pole; (**C**) reinforced concrete pavement with simple continuous distributed reinforcement; (**D**) structurally reinforced concrete pavement. Redesigned and modified from [98].

3.1. Rigid Pavements

The rigid pavement consists of a top layer of concrete with the use of Portland cement, that acts simultaneously as a wear layer and base with support functions [93–95]. The high flexural strength of concrete means that the pavement does not suffer severe deformations, even when it is subjected to high temperatures and heavy and intense traffic. It is very important that this layer guarantees the impermeability of the floor, not only through the slab but also through the joints, which must be sealed with a suitable material. As the concrete slab absorbs the loads imposed on the pavement over a large area, the maximum vertical stress reaching the foundation corresponds to a small fraction of the contact pressure between the tire and the ground. In this case, the subbase does not play as important a role in the load-bearing capacity of the pavement as in the case of a flexible pavement [96]. The base is made of homogeneous material that is not sensitive to water. If it presents heterogeneity in its physical and mechanical characteristics, as well as reduced load capacity, it must incorporate a pavement bed with improved soil. Figure 1 indicates the typical constitution of a rigid pavement. Regarding the typology, rigid pavements can be grouped into four different categories [97] depending on how they control shrinkage cracking, with reinforced concrete pavements with joints being the most common in airports.

3.2. Flexible Pavements

Flexible pavements can have a highly variable constitution depending on the characteristics of the available materials, the climatic conditions, the resistance of the foundation soil, the intensity, and the types of traffic to which they are subjected. Its composition must allow that the transmitted loads, from the surface to the foundation, do not exceed the load capacity of the successive layers; that is, the layers must be arranged in such a way that the respective modulus of elasticity or rigidity progressively decreases in depth [99–101].

In the airport zone, the important characteristics of the pavements are good adherence conditions (such as avoiding aircraft hydroplaning) and resistance to chemical attack by pollutants. Flexible porous pavements, composed of an open mix of aggregates and bitumen, improve the drainage of the pavement and consequently the visibility of the horizontal grooves that run in the coating. This improves conditions against hydroplaning in wet weather on the coating. Floors modified by the addition of resins and hardeners are less susceptible to temperature and are highly resistant to chemical attacks from fuels and oils [102–104]. The wear and leveling layer is constructed from a mixture of selected aggregates bound together by a bituminous binder. The surface of the wear layer prevents the penetration of surface water into the base layer. It is essential that it provides the free circulation of disaggregated particles so as not to endanger the safety of people and goods. It must be capable of supporting aircraft loads, with good skid resistance without compromising the integrity of aircraft tires. Being the layer most subject to atmospheric conditions, it is also the one that degrades the most. The base layer is the main structural component of the flexible pavement and distributes the loads to which it is subjected through the sub-base layer, and from there to the foundation. Sized to resist the compressive forces produced on the surface, it prevents the soil from reaching the final state of ruin and from permanently deforming [105,106].

Composed of hard aggregates, resistant to impacts, with friction between its own particles and wear caused by traffic on the pavement surface, the base layer may or may not be stabilized. Stabilized foundations typically incorporate binders such as asphalt bitumen or Portland cement, and transform the pavement into a semi-flexible or semi-rigid structure. Its quality is inevitably influenced by the composition, physical properties and compaction of the constituent materials [107–109].

The underlayer is subject to lower compressive stresses and may consist of a simply compacted granular layer. Although it has resistance characteristics, it essentially performs drainage functions. Therefore, it must be composed of granular materials with good drainage characteristics to avoid the rise of water by percolation and, if necessary, be provided with a drainage mat (geotextile) that prevents the ascent of fines to the upper layers. The foundation, which includes not only earthworks (landfill or excavation) but also the pavement bed, is composed of compacted natural soil. In flexible pavement, the foundation is subjected to much lower stresses than the surface, base or subbase. Much of the stresses dissipate along the granular layers [110–112].

3.3. Fatigue Damage to the Asphalt Pavement

The useful life of a pavement, in terms of service and performance, is related to its correct dimensioning which seeks to avoid the occurrence of structural defects such as cracking and subsidence. These two are the main defects of asphalt pavements, traditionally called flexible pavements. Cracking can be caused by phenomena such as fatigue in which intermittent loads cause cracks, which is progressive damage. Sinks are due to a mechanism called permanent deformation. These defects are caused by two different modes of mechanical demand like repeated bending (responsible for the fatigue of the material) and simple compression, in the development of the service [113–120].

In a mechanistic methodology for pavement design, the stresses and deformations required by the structure are calculated and compared with the permissible stresses and deformations of the materials to be used, which are obtained through laboratory tests or mechanistic-empirical equations [121]. Thus, by evolving from an empirical approach to a rational or mechanistic-empirical one, it becomes possible to calculate stresses and deformations that will lead to the correct functioning of pavements in the face of previously ignored or poorly understood defects. Fatigue cracking and permanent deformation are the main acceptance and/or evaluation criteria of the pavement structure. They correspond to the most common defects that most affect the usefulness of a pavement throughout its useful life [122–125].

The well-dosed and well-executed asphalt layer, at the beginning of its useful life, is subject to a small permanent deformation that is characterized more by compaction than by the viscous characteristics of the asphalt binder [126]. This initial deformation must be small or unimpressive. Even reduced, it allows for closing of the asphalt mix with a small reduction in the volume of voids. Permanent set caused by asphalt binder viscosity associated with particulate lubrication is most pronounced over the life of the asphalt mix. Obviously, in poorly dosed asphalt mixtures and with unsuitable binders for the climate and demanding traffic, the deformations caused by lubrication and viscosity can be important at the beginning of the useful life [127–129].

Asphalt coatings have high surface temperatures due to the black color of the asphalt binder [130,131]. The surface of the mixture absorbs large amounts of solar radiation that the coating stores as heat. The heat stored throughout the day is transmitted from the coating to the lower layers of the soil by conduction. During the day, soils become considerably warmer than the environment. During the night, the heat stored in the lower layers is transmitted to the coating and this radiates the excess heat to the environment. Thus, the surface temperatures of the coating are even higher than those of surfaces covered with Portland concrete or with vegetation [132].

The wheel tread sag (Automated Traffic Recorders (ATR)) observed in a pavement is the sum of the permanent deformation portions experienced by all its constituent layers, these being subgrade, subbase, base, and cladding [133,134]. This non-recoverable deformation is a function of several variables such as weather and traffic conditions, together with the level of stress supported by the layer. However, due to the proximity of the load and the high stiffness compared to other layers of pavement, the asphalt coating is usually responsible for most of the magnitude of the total permanent deformation of the structure. This is especially evident on roads with heavy traffic, featuring vehicles with high axle loads and high tire pressure. Thus, the role of each constituent of the asphalt mixture (asphalt binder, aggregates and volumetry) in the phenomenon of permanent deformation will be discussed below.

There are two main mechanisms of fatigue cracking in asphalt pavements, being top to bottom and bottom to top [135]. Cracks in the upper part of the base start at the bottom of the asphalt layer as a result of the high deformations associated with bending, and propagate to the pavement surface. This type of cracking is the most common form of fatigue damage that occurs. Top-to-bottom cracking begins at the pavement surface, just below the wheel path, and spreads downward. This type of damage is due to shear stresses due to vehicle traffic and the constant change in climatic conditions to which the asphalt mixture is subjected [136]. Currently, multiple load configurations are used for these tests such as axial traction, diametral compression and simply supported beams, among others. Traditionally, fatigue testing of asphalt mixtures is performed in the field using three- or four-point bending tests on rectangular samples of asphalt concrete [137,138].

During the fatigue process, the interpretation of the behavior of the material is complex. Fatigue is common in asphalt materials, and can be basically addressed by two theories, namely Fracture Mechanics and Continuum Mechanics. The first has phenomena that are framed on the microcrack scale to represent the behavior of the material, while the second globally represents the micro-scale phenomena through the use of state variables. Thus, the complexity of the problem and the consequent computational costs are reduced, at the cost of a less detailed analysis and the need for some tests to determine the evolutionary law of the state variables. The main models of continuous damage are based on several studies [139–142]. These studies defined the law of evolution of the internal variables through the strain energy. This is an area under the stress-strain curve in a monotonic test that leads to failure and the principle of viscoelastic correspondence [143], in order to characterize the evolution damage under monotonic loading [144].

4. Use and Classification of Ash on Pavements

Bituminous mixtures consist of asphalt binder and mineral aggregates, and their behavior is affected both by the individual properties of these components and by the relationship between them. The binders, which can be asphalt cement or modified asphalt cement (with the addition of modifiers such as polymers and rubber), act as binders for aggregates and as a waterproofing agent, encompassing the mineral particles and forming a cohesive mass. Aggregates, regardless of source, processing method or mineralogy, must be strong (tough and durable) and resist the stresses and abrasion resulting from the application of repeated loads. In this context, the study of the reuse of tailings from the steel industry in the investigation of asphalt mixtures seeks to contribute to reducing the large volumes of this material in landfills. Thus, this solution is an alternative to mitigate environmental liabilities and contribute to the study of an alternative paving material [145,146].

The demand for road and airport infrastructure materials is enormous, and is often limited to deposits of raw materials such as gravel, soil and sand, among others. Thus, it can be concluded that the supply of so-called alternative materials for the execution of the infrastructure has a great influence on the evaluations of the economic viability of a pavement [147,148]. Ashes have been used in the industry since the 1930s, when they began to be available in significant quantities. Initially, they were used as raw material incorporated in the manufacture of concrete and pozzolanic Portland cement [149,150]. However, there is a growing increase in the control criteria by environmental agencies in relation to the exploration of new deposits and the search for raw material, causing the use of waste to increase throughout the world. In general, the two factors being the scarcity of deposits of conventional materials and the availability of large quantities of waste around the world, are the driving forces of the studies that point to the use of these materials [151–153].

The use of waste in pavement construction is often economically viable, as paving works consume large amounts of material. However, the reuse of materials in this type of work must be done in such a way that the expected performance of the pavement is not compromised, since the residues and by-products differ substantially in their types and properties and, consequently, in their paving applications [154]. The pavement should not be used only as a waste disposal site, only to solve environmental problems. It is necessary to show the advantages of using waste from the point of view of improving the pavement and not only its contribution to nature conservation. Experience and knowledge of the use of waste varies by material. In order to use these materials, engineers, researchers, the generating industry, and environmental and paving agencies must be aware of the properties of the material to be used and the associated limitations in their use and application.

The use of waste in paving can be beneficial, both for the generating industry and for the civil construction industry. This use of waste leads to the reduction of costs with the extraction and transport of conventional aggregates, minimizing the environmental impact caused by the construction waste disposal deposits and the preservation of deposits of natural materials. The residues can be reused both in pavements and in the manufacture of pozzolanic Portland cement, in stabilized bases and modified soils for roads, paths and buildings, and also as fillers in bituminous mixtures. Some of the residues already used or studied in pavement layers are mentioned, such as construction, renovation and demolition residues (CRD), steel slag, rubber from waste tires, coal ash from thermoelectric plants, rice husk ash, ornamental rock residues, and petroleum exploration and production residues (drilling gravel, copper slag and oily sludge, among others) [155].

In Brazil, the generation of ash derived from coal, without counting other sources, is quite high. It is estimated at four million tons per year, and the trend is for this value to increase due to the development of the industrial sector. The production of residues from the burning of fossil coal is an inevitable consequence of the use of this non-renewable natural resource as fuel. Of the total amount of coal burned in Brazil, only 30% of the ash is sold, justifying the importance of developing research, products and techniques that seek to take advantage of this waste [156,157].

It is known that the ash has a high contaminating potential, related to its hydraulic drag and with two determining factors, being the alkaline pH present in its composition and the solubilization of its elements when it comes into contact with the drag water [158–160]. In large areas of settling basins, elements including heavy metals are leached into the environment. This can contaminate the soil and subsoil, reach the water table and adversely affect animals and plants. Considering the cumulative effects of the heavy metals, these effects can be serious [161,162]. However, when evaluating the contaminating potential of the ash, it should be considered that not all ash has the same composition. Its physical, chemical and mineralogical characteristics depend on a variety of factors, including the composition of the source material of the matter, combustion conditions, type and efficiency of the emission control system and disposal methods used.

Contrary to investigations that only consider the contaminating potential of the ashes, it is stated that the ashes can be considered an important mineral resource, due to their physicochemical and mineralogical properties (Table 1). Rarely found in other materials, they are characterized by a high reaction capacity with binders of the lime. Furthermore, its potentially dangerous or toxic elements are immobilized when it is used in a stabilized form with lime [163]. In addition, other factors must be considered. For example, the large amounts of material available ready for use after its formation, requiring no processing processes, except for occasional drying in the presence of excess moisture. The main effort to reduce the environmental impacts resulting from the disposal of ash in the environment has been aimed at evaluating the potential of ash for use in different industrial processes [164].

Table 1. Overall assessment of waste and by-products [165,166].

WASTE	CHARACTERISTICS	USE	ADVANTAGES
Background ash	By-product of coal combustion: particles with a size of 0.09 mm to 20 mm; angular shape; very porous	Cement light aggregate Sub-base	Energy saving Increased production capacity for relatively lower capital expenditure
Fly ash	By-product of coal combustion, smaller particles carried by flue gases into chimneys.	Cement Concrete light aggregate Sub-base asphalt filler Brick	Energy saving Increased production capacity for relatively lower capital expenditure Fine texture Low specific mass Ease of combination with free lime

Ash is a by-product that is classified, according to the standard, as industrial waste. That is, it originates in the activities of the different branches of industry, such as metallurgical, chemical, petrochemical, paper and food. However, according to the standard, for its classification the leaching and solubilization tests must first be carried out. These tests will indicate if the waste presents any type of danger, flammability, toxicity, reactivity or pathogenicity, all reactions that can be harmful to the environment.

Solid waste is classified as Class I Waste, which represents hazardous waste, Class II Waste, which represents non-inert waste, and Class III waste, which is inert waste [15]. This classification serves to define the procedures necessary for the treatment to be given in the disposal of solid waste resulting from industrial processes. Based on these tests, and comparing the leached and solubilized concentrations with the standards established as the norm, a solid residue is classified as inert or not inert. When the concentration of a chemical element that is considered dangerous exceeds the established limit, the waste is classified as dangerous, i.e., Class I. Characteristics such as corrosivity, flammability and violent reaction with water also classify the waste as dangerous. It can be concluded that, although there are many beneficial applications for ash, they can only be used if they meet the regulatory requirements established in the legislation on solid waste [15]. Since ash is industrial waste, it is classified according to the Brazilian standards that govern the classification of solid waste in terms of how dangerous it is.

In the case of coal ash, the ash formation process occurs by direct combustion of coal. Coal is a solid raw material, consisting of two closely mixed fractions: an organic (volatile material plus fixed carbon), and a mineral (clay, quartz, pyrites, carbonates, etc.). The action of heat causes the organic fraction to generate volatiles and coke, while the mineral turns into ash with modified mineralogy. There is loss of water from the clays, the decomposition of carbonates and the oxidation of sulfides. Broadly speaking, the ash is considered to consist of non-combustible carbon components and unburned particles due to the incomplete combustion of pulverized coal [167–169].

The combustion characteristic of pulverized coal occurs at high temperatures, between 1200 °C and 1600 °C, in an oxidizing gaseous environment. The residence time of the particles in the oxidizing flame is an average of two seconds, a sufficient condition for the total or partial fusion of mineral matter. The different temperature zones within the boilers cause the pulverized coal particles to present, after combustion, different characteristics. This results in ash fractions with different physical, chemical, mineralogical and microstructural characteristics, which allows the ashes to be classified into two different types, being light or flying (dry) and heavy (wet).

All of the physical and chemical properties of coal ash are influenced by several factors such as coal composition, degree of processing and grinding of coal, type, design and operation of the boiler, ash extraction and handling system, and transformations that occur according to the combustion temperature [170]. Due to the factors presented, the ash will present variations in its composition and physicochemical properties, not only from plant to plant, but from boiler to boiler in the same plant and even in the same boiler at different times.

Ash is generated from various organic and inorganic components of the coal feed. Due to the scale of a variety of components, they constitute one of the most complex anthropogenic materials that can be characterized. Approximately 316 individual minerals and 188 mineral groups have been identified in different ash analyzed as documented in Table 2. The ashes are classified according to the gasification or coal burning process in three different types: light ash (or fly ash), bottom ash (heavy ash or wet ash), and finally slag or coarse ash.

Light ash (or fly ash) is composed of extremely fine light particles (100% less than 0.15 mm), and which are entrained by the combustion gases of furnaces or gases generated in industrial gasifiers [171,172]. A large part of these particles is retained by a capture system such as fabric filters, cyclones, electrostatic precipitators, etc. The large units that produce this type of ash are thermoelectric plants and steam plants.

Bottom ash (heavy ash or wet ash) originates from the processes of combustion of coal in pulverized form, and from the burning or gasification of coal in a fluidized bed, which generally contain a non-carbon content that is burned from 5 to 10% [173]. They are heavier and coarser-grained, which fall to the bottom of the furnaces and gasifiers. They are extracted by the flow of water, mainly in the large boilers of thermal power plants and steam plants.

Slag (or coarse ash / boiler slag) originates in the process of combustion or gasification of coal in fixed and mobile grates [174,175]. They often occur with coarse-grained particles and synthesized blocks, with a considerable content of unburned carbon (10–20%). They are removed from the bottom of the ovens after cooling with water.

It should be noted that Brazil does not have specific legislation for the classification of ashes. Therefore, these are only classified as solid waste, and their use requires the adaptation of the relevant regulations and the approval of environmental agencies. Light or volatile ashes appear in small amounts as hollow spheres. These are called cenospheres when they are empty, and plerospheres when they are filled with many small spheres [176,177]. A large part of these particles is retained by a capture system, such as tissue filters, cyclones and electrostatic precipitators, which are listed in Table 2.

Table 2. Characteristics of Fly Ash [33].

CLASS 1	CLASS 2	CLASS 3
Blast furnace waste	Phosphate residue	Gold scraps
Fly ash	Copper residue	Copper scraps
Sulfur	Cement manufacturing fines	Lead and zinc waste
Refining residue	Quarry waste	Coke mill
Boiler and grill ash	Mine scraps	Foundry sand
Nicel residue	Slate waste	Refractory and ceramic waste
Demolition waste	Feldspar waste	Resin
Coal mine rejects	Rubber tires	Lagnina
Oil shale waste	Zinc and lead slag	Potash mine waste
Taconite waste	Mixed ash	Pyrite ash
Clay treatment sand	Incineration waste	Glass waste
Slag from the iron mines		Plastic waste
Pyrolysis residue		

This type of ash is usually gray, abrasive, mainly alkaline and refractory in nature. These materials are in the category of pozzolanic and/or cementitious materials. The main constituents of the ash are crystals of silica SiO_2, alumina Al_2O_3, oxide of iron Fe_2O_3 and lime CaO, in addition to other components in smaller amounts such as MgO, Na_2O, K_2O, SO_3, MnO and TiO_2, as well as carbon particles not consumed during combustion. The potential use of fly ash is controlled primarily by its chemical composition, although their small particle size is also an important consideration.

Fly ash has cementation characteristics that allow its use for soil stabilization without the use of activators to improve its mechanical properties, such as in soft soils for application on bases and sub-bases. This allows it to contribute to a stable work platform favorable for road construction [178,179]. Fly ash is capable of developing pozzolanic reactions and has characteristics for soil stabilization, since its composition contains the main elements responsible for pozzolanic activity such as SiO_2, Al_2O_3, Fe_2O, CaO, MgO, SO_3, Na_2O and K_2O.

The first recorded study on the use of ash in pavements in Brazil was performed in 1998 [180]. The authors evaluated the behavior of fly ash, produced in a thermoelectric plant in the country's south, as a sand stabilizing agent in order to confirm studies that had been carried out only abroad. As a conclusion of that work, the possibility of stabilizing the soil with this type of residue was evidenced, since fly ash is a precious complementary material in soil stabilization that can help correct and even replace traditional materials. Later, two other important works of great reference were developed for the study of ash in layers of pavement. Through these studies, they demonstrated the feasibility of stabilizing sand with fly ash and lime. Studies that were used in the implementation of an experimental section located on the margins of the BR-101, in the municipality of Imbituba/SC, where, on the sand subgrade, a sand subbase stabilized with lime and fly ash was placed and constructed. In this section, instrumentation sections were installed and the monitored results were quite satisfactory, approving the performance of the material. They concluded that the ashes are suitable for use in pavement bases and sub-bases. The curing conditions, the traffic requirements and the rigidity of the base layer must be evaluated, in order to promote a reduction of the vertical stresses transmitted to the subgrade and delay the effects of fatigue. Since as the strength of the material increases over time, the development of cracks in the material is also delayed [181–187].

In Brazil, there are a series of barriers to the use of ash as a raw material. Among the main ones is the lack of dialogue between the coal sector, coal mining, steel and metallurgy, thermoelectric plants and other industries with research entities and environmental control bodies. There is a lack of favorable policies, legislation and subsidies that encourage the consumption of these residues, with a potential consumption of ashes. In addition, many companies are neither interested nor prepared to invest in this field of study, classifying the ash simply as a disposable waste. However, in recent decades, studies have been carried out in Brazil that show great potential for the use of ash in pavements, both in rigid and flexible pavement structures. The potential for the use of ash in paving is enormous and these are materials are seldom used in Brazil in road works [181]. It can be noted that the studies are in the initial phase, since in countries such as the United States and other developed countries, ash is already widely used as a base and sub-base material for pavements, as aggregate for concrete, asphalt and mortar for masonry and in the construction of dikes, while in Brazil a large part of the ash is deposited in sedimentation basins.

With the growing increase in control criteria in environmental agencies regarding the search for new deposits, the use of waste has become more and more general. In view of these criteria, current experiences on the use of tailings and the geotechnical performance of materials in the pavement structure have been further explored. So far, there have been several investigations into the use of ash as a raw material. Most of these studies specifically address the pozzolanic activity of this material and how it can serve a noble purpose in engineering according to its chemical and physical characteristics. It should be noted that in recent years, several investigations have been carried out on the use of this type of waste, which studied the ashes in their different forms and contents and gave their contribution to the application of ashes in pavements [182–187].

5. Methodology

5.1. Marshall Dosing Method

The dosage of an asphalt mixture is a formulation process in which a granulometry of aggregates with specific natures is sought together with the addition of CAP, so that after mixing at the appropriate temperature and subsequent compaction, they form a material that offers conditions for proper mechanics. This supports loads that demand a specific pavement, and whose material does not show premature deterioration when subjected to climatic and traffic variations [188]. This method considers a variety of characteristics, such as granulometry, bulk density of the mix, maximum theoretical density of the mix, percentage of voids of the compacted mix (Vv), percentage of voids of mineral aggregates (VAM), bitumen-void ratio (RBV), stability and fluidity (creep).

The grain size adopted must have the maximum possible density to ensure maximum stability. The bulk density of the mixture is calculated with the samples of the compacted mixture. The maximum theoretical density of the mixture is the density of the mixture, supposedly without voids. The percentage of voids of the compacted mixture (Vv), is the volume of air existing between each particle of aggregate covered with CAP in the compacted mixture in relation to the total volume of the sample. The percentage of mineral aggregate voids (VAM) is the percentage of the volume of intergranular space of a compacted asphalt mixture, which includes the volume of air and asphalt, in relation to the total volume of the sample. The bitumen-void ratio (RBV) is the percentage of VAM that is filled with CAP. Stability is the maximum load to which the specimen is subjected until it breaks, being under semi-confined radial compression. Flowability is the total deformation of the specimen after breaking during the stability test.

The Marshall dosing method continues to be the most widely used in Brazil [51]. The dosage of a hot-machined bituminous concrete-type asphalt mix (CBUQ) has consisted until today in the choice, by means of experimental procedures, of a so-called "optimal" binder content. The definition of what is an optimal content is not simple. It is possible that this term was chosen by analogy with the optimum moisture content of a soil, which, for a given energy, is a function only of the specific mass. However, in the case of asphalt mixes, there are several aspects to consider, and the "optimal" content varies according to the evaluation criteria. In this method, five groups of three samples are cast with different binder contents. The experience of the designer may suggest a CAP content for the first group of three samples based on the range of particle size considered. The other four grades are determined in 0.5% and 1.0% increments from the first grade.

Even using the Marshall procedure for dosing, there are different methods for choosing the optimal content, all of which use the void volume of the mixture for their determination. The void volume (Vv) is the most important volumetric property of asphalt concrete. Air voids are always needed within the compacted mix to allow for thermal expansion of the binders and to resist light compaction caused by traffic. Very low void volumes (less than 3%) compromise the performance of the mixes in terms of ATR (sink on wheel track) and very high (more than 8%) compromise durability [189].

5.2. Tested Mixtures

A study of asphalt mixtures with coke boiler ash as filler was carried out for different mixtures by the binder content (CAP 30/45), with 4.0% plus 0.5% until reaching a content of 6.0% CAP. This procedure was carried out for the two main types of mixture, with and without ash, both made by the Marshall dosing method (M1 and M2) whose models are represented in Figure 2. As for the aggregates, their temperatures were taken as 10 °C above the temperatures of the binders. The diameters and heights of the Marschall tests consists of an optimal content being 10 cm × 6 cm (amount of 50), a stability of 10 cm × 6 cm (6), a modulus of resilience (at 25 °C) of 10 cm × 6 cm (15), an indirect tensile strength (at 25 °C) of 10 cm × 6 cm (9) and a fatigue life (TC) of about 10 cm × 6 cm (30), which results in a total of 110.

The range of particle size chosen for the mixtures was the DIRENG range B [190], regardless of the method used to dose them. Particle size curves were plotted on logarithmic scale graphs for sieve opening using the Marshall method. In addition to the project range, the ranges corresponding to the lower and upper limits of range B were also drawn as a reference. Table 3 describes the specimens for the corresponding tests for Marshall dosage. The tests were carried out in the asphalt laboratories of the Military Institute of Engineering (IME).

With the contents of the project of each mixture, five samples of each were executed and stability and indirect tensile strength tests were carried out, totaling 110 samples. Table 4 describes the results of the tests with the optimal contents of each mixture, and the reference parameters recommended in the DNIT-ES 031/2006 standard.

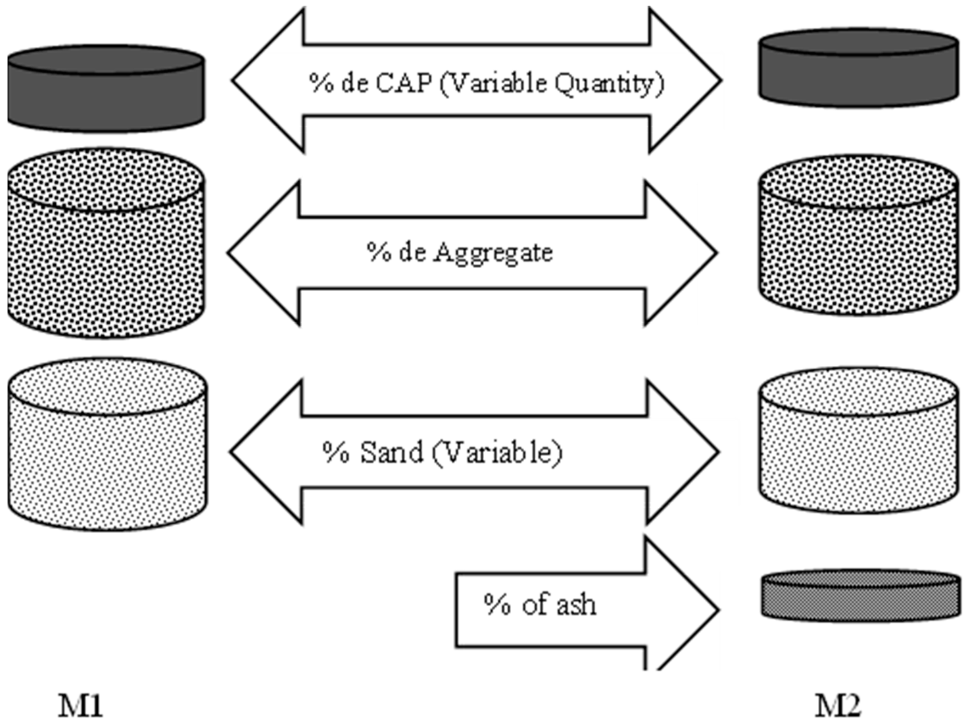

Figure 2. Schematic representation of the mixtures tested in the current study.

Table 3. Test bodies used by stage.

Trials	(Diameter × Height)	MARSHALL
(1) Definition of optimal content	10 cm × 6 cm	50
(2) Stability	10 cm × 6 cm	6
(3) Resilience Module (25 °C)	10 cm × 6 cm	15
(4) Indirect tensile strength (25 °C)	10 cm × 6 cm	9
(5) Fatigue Life (TC)	10 cm × 6 cm	30
Total		110

Table 4. Results of Marshall dosing tests. RT represents the tensile strength, while MR is the resilient modulus.

Mixtures Obtained	Amount of Binder	Apparent Density Gmb (mist.)	Effective Density Gmm (mist.)	Estability (kgf)	Creep (mm)	RT (MPa)	MR (MPa)
I	4.0	2.318	2.542	14,022	7	1.7	8013
II	4.5	2.380	2.510	12,606	7	1.9	11,399
III	5.0	2.386	2.498	13,897	8	1.9	12,844
IV	5.5	2.390	2.467	13,108	9	1.9	10,859
V	6.0	2.405	2.432	15,273	9	1.0	9177

The ideal percentages for the dosage and the necessary test tubes were determined that allowed the tests to continue until the Design Content was obtained. However, the choice through experimental methods from a predefined granulometric range is not easy. In the present study we tried to obtain the best results with the available materials, and for this, the mixtures that were tested are shown in Figure 2 (M1 without gray and M2 with gray).

6. Results and Discussion

For the ash-free mix, it was decided to start varying the content from 4.0%, varying from 0.5% to 6.0%, thus resulting in five contents. Five copies were executed for each grade chosen. Table 5 documents all the average parameters for each mix content. It shows also the results of the densities for each binder content of the M1 mixture (without ash) and the tests of creep, tensile strength and modulus of resilience, values that conform to the reference standard [190]. For the mixture with ash, the test results are presented in Table 6, also referenced by the standard [191]. There is little difference when comparing the results of the mixes with and without ash (Figures 3 and 4). However, it is important to highlight the difference in the behavior of the mixtures in the tensile strength (RT) and resilient modulus (MR) tests.

Table 5. Marshall dosing parameters obtained for mixture M1 (without ash) and results of mechanical tests.

Reference	VV(%)	RBV (%)	VAM (%)	ESTABILITY (kgf)	RT (MPa)
(DNIT-ES 031/2006)	3–5	75–82	TMN 19 mm	>500	>0.65
Results of Attempts	**I**	**II**	**III**	**IV**	**V**
CAP Amount (%)	4.00	4.50	5.00	5.50	6.00
Density Max. Theoretical	2.655	2.632	2.610	2.589	2.567
Apparent Specific Mass (Gmb)	2.365	2.387	2.388	2.383	2.394
% Voids (% V)	10.92	9.31	8.51	7.96	6.74
Vacuum with binder (VCB)	9.38	10.65	11.83	12.99	14.24
Aggregate gaps. Mineral (VAM)	20.30	19.96	20.34	20.95	20.98
Asphalt-Void Ratio (RBV)	46.21	53.36	58.16	62.00	67.87

(DNIT-ES 031/2006).

Table 6. Marshall dosing parameters obtained for mixture M2 (with ash) and results of mechanical tests.

Results of Attempts	**I**	**II**	**III**	**IV**	**V**
CAP Amount (%)	4.00	4.50	5.00	5.50	6.00
Measured Specific Mass (Gmm)	2.542	2.510	2.498	2.467	2.432
Specific Apparent Mass (Gmb)	2.318	2.380	2.386	2.390	2.405
% Voids (% V)	8.80	5.19	4.47	3.12	1.10
Voids Filled with Bitumen (VCB)	9.19	10.62	11.82	13.03	14.30
Mineral Aggregate Voids (VAM)	17.99	15.81	16.29	16.15	15.40
Bitumen-Vacuum Ratio (RBV)	51.08	67.17	72.56	80.68	92.86

(DNIT-ES 031/2006).

The test is performed to determine the modulus of resilience (Figure 4), with the purpose of determining the relationships between recoverable deformations (resilience), with the cracks that appeared in the asphalt coatings. The tests are based on the energy stored in the elastically deformed body that is returned when the stresses causing the deformations cease.

The test is standardized in Brazil by the [192] standard, and is conducted by repeatedly applying a load in the vertical diametric plane on the regular cylindrical specimen. For this test the Poisson's ratio of 0.35 was adopted (Figure 5). Analyzing the MR curves, it is observed that the ashless mixture has greater elasticity, or it can also be determined that a greater stiffness determines the amount of ash in the mixture, which in turn maintains an elastic balance in the mixture. The mean MR was taken as the arithmetic mean of all the results obtained in the tests after applying the Grubbs test. In this research, no extreme value was ruled out by the criteria adopted. The value of the average MR behavior, characteristic of each mixture, is considered as the arithmetic mean of the results that fell within the 95% confidence interval.

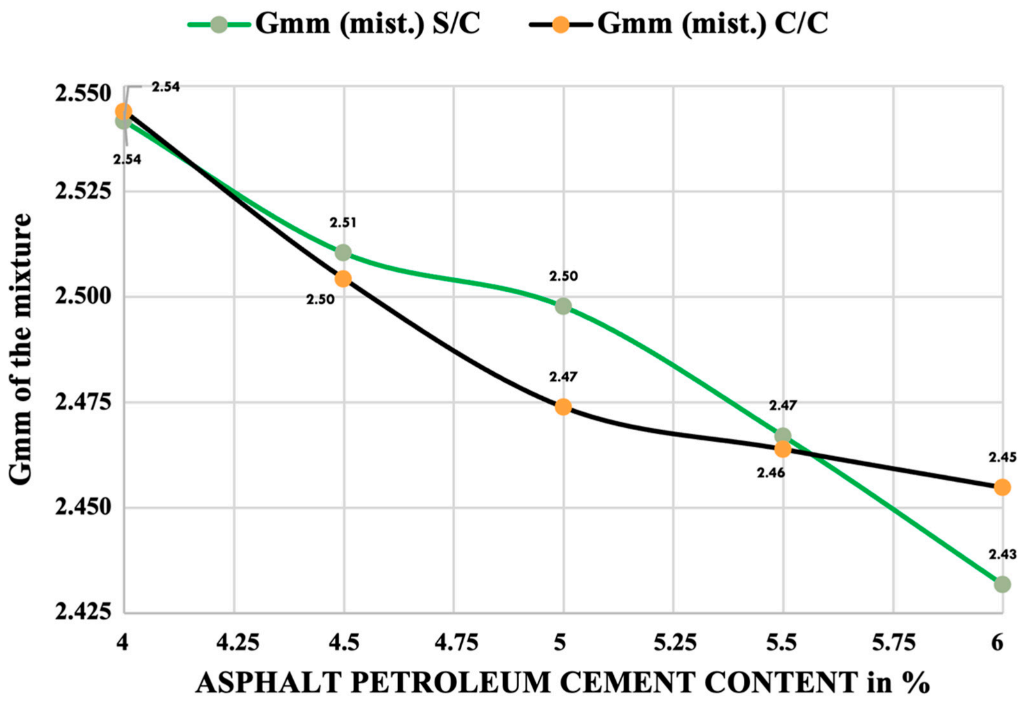

Figure 3. Maximum Specific Mass Measured (Gmm).

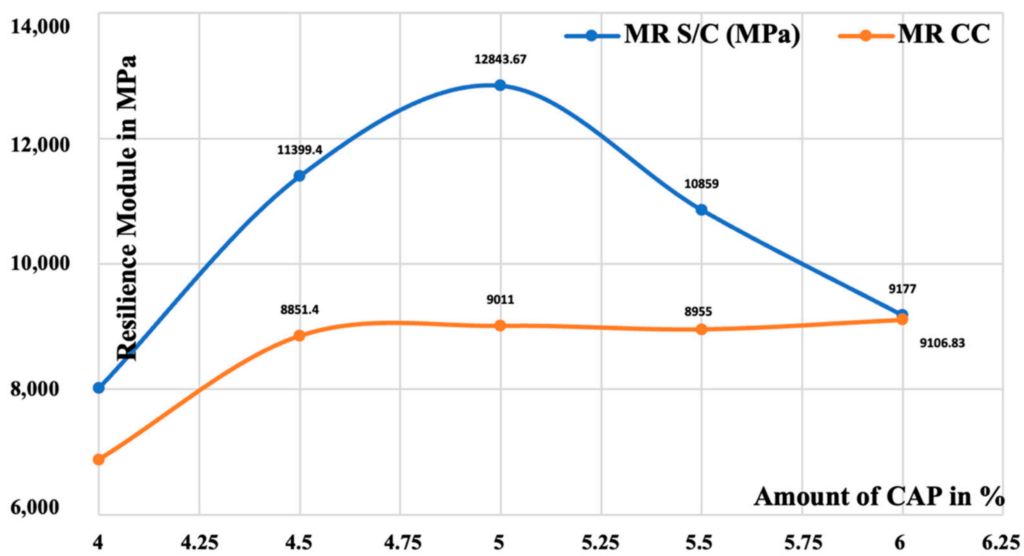

Figure 4. Resilience Module.

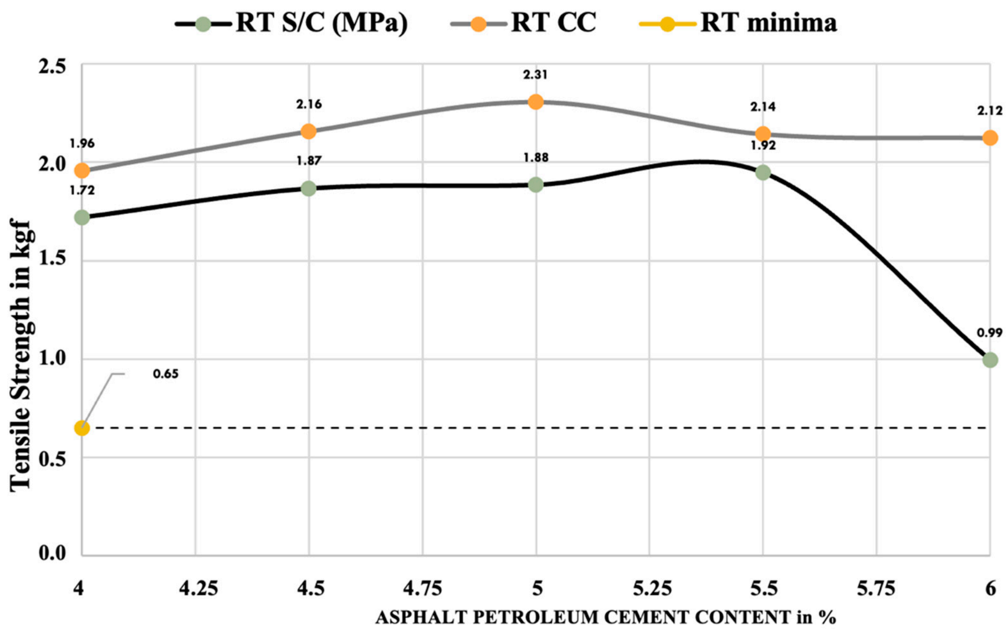

Figure 5. Tensile Strength Test.

There was a decrease of approximately 12% in the MR value of the mixture M1 (5.3%) relative to M2 (5.2%). Mix M2 is slightly less stiff than M1, despite its lower binder content. The decrease in MR is small and cannot be attributed to the residue in the mixture, but instead to factors such as the change in particle size, for example. It is concluded that the substitution of sand for ash is perfectly acceptable. In the tensile strength test as shown in Figure 6, which is one of the failure tests, an important parameter for the characterization of the material as Portland cement (and in this specific case the Coke boiler ash), the only behavior is assumed elastic due solely to the uniform tensile stresses that were generated.

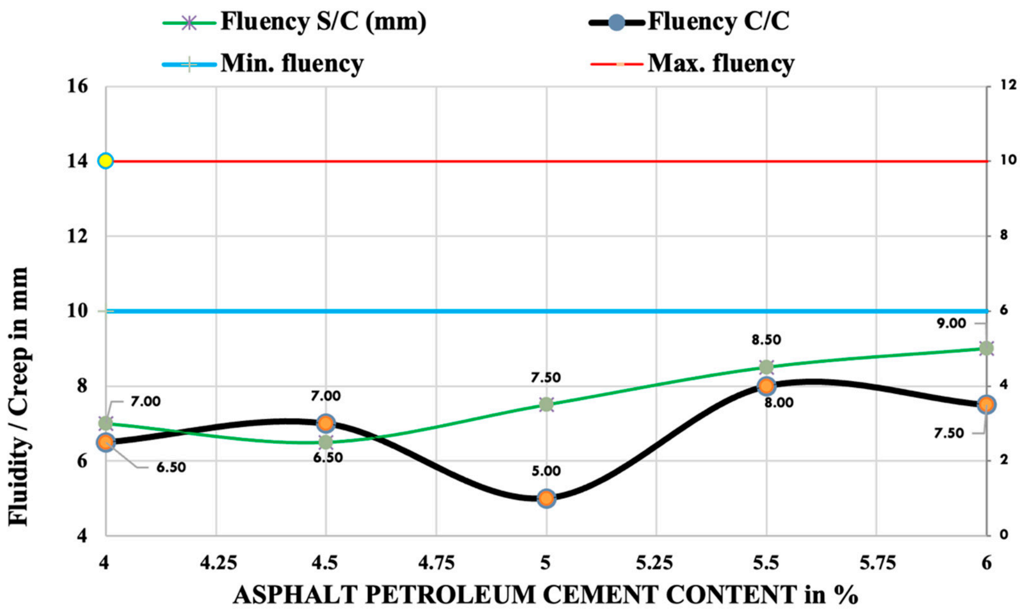

Figure 6. Creep test result.

The test makes it possible to determine the maximum support load for the specific specimen, insofar as the fluidity allows it to maintain its stability. In Figure 6 it can be observed that for the mixture with ash (M2), the creep values are lower than for the mixture without ash (M1). This fact is mainly due to the accumulation of stresses and the low elasticity in the deformation that the specimen supports. The fatigue test was performed with four stress levels, adjusted to 15%, 20%, 30%, 35% of the indirect tensile strength (RT).

From these results, it was possible to plot specific deformation curves and stress differences as a function of the number of cycles required for failure (Nf), as illustrated in Figures 7 and 8.

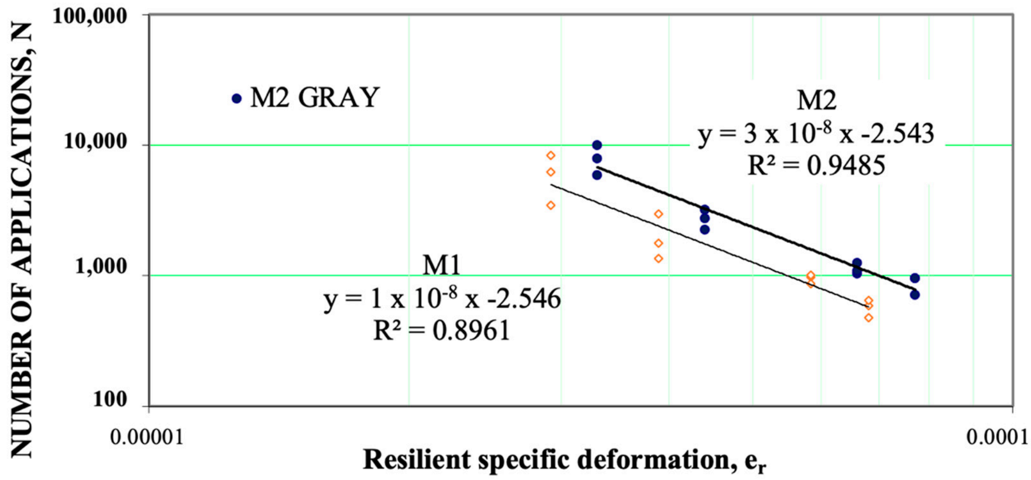

Figure 7. Fatigue life x resilient specific deformation.

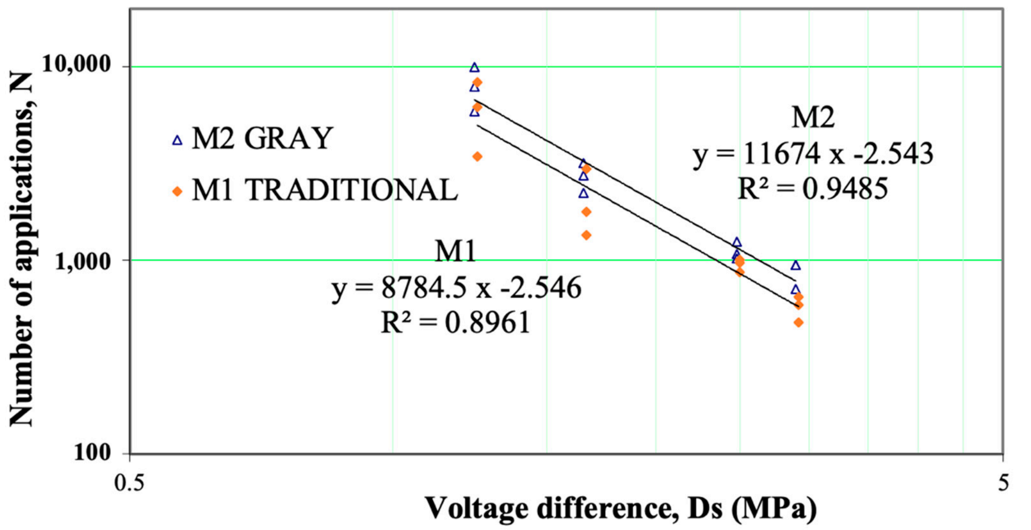

Figure 8. Fatigue life x Voltage difference.

It can be observed that the mixtures presented results with small dispersion in the log-log space, since the linear regression curves presented values of the coefficient of determination around 90%. Normally a direct comparison of the fatigue curves is not possible, but in this case as the MR values are close, it is observed that the mixture with ashes has a somewhat longer fatigue life than the other. This direct comparison was preliminarily possible by considering the similarity between the values of the modulus of resilience of the mixtures.

The ash-free asphalt mix had the shortest fatigue life for all stress differences evaluated, as indicated in Table 7. The table lists the results of the fatigue test performed on two samples (M1 and M2) related to Figure 2, where a traditional structure of the asphalt pavement stands out, and M2, which adds a percentage of the residue of the nickel mineralization (nickel-holding ash). These two mixtures have a similar mineral skeleton. The granulometric curves and the type of aggregates are similar, however they only differ by the percentage of filling M2 with 3% gray. This indicates that the addition of ash improved the resistance of the mix to fatigue damage when the test was performed under controlled stress.

Table 7. Regression parameters of the fatigue life curves of the mixtures.

Mixtures	$Nf = a_1 (\Delta\sigma)^{b1}$			$Nf = k_1 (\varepsilon_r)^{k2}$		
	a_1	b_1	R^2	K_1	K_1	R^2
M1	8784.5	−2.546	0.8961	1.00×10^{-8}	−2.546	0.8961
M2	11,674	−2.543	0.9485	3.00×10^{-8}	−2.543	0.9485

7. Conclusions

Studying the mechanical behavior of asphalt mixtures with complex modules and fatigue tests is a great contribution to transport engineering (airway paving), in addition to promoting a contribution to combat global warming. In this study it was possible to analyze the behavior of hot asphalt mixtures with the addition of boiler ash to the coke with fatigue parameter analysis. The results presented in this study are limited to a single comparison between the two mentioned mixtures, which does not allow generalizing the behavior of the material.

The difference from total to effective voids determined in asphalt mixtures is due to the use of the actual specific gravity of the aggregates in determining the theoretical maximum density of the asphalt mixture, thus generating high voids. The determination of these parameters, mainly for bituminous mixtures with very porous aggregates such as the M2 fill, increases the total percentage of Vv by approximately 10% due to the ash.

Coke furnace ash is a new element and has not been studied much in academia. Therefore, there are still no rules to guide its use. The standards used in this study led to the classification of the ash as light ash or fly ash, due to its high content of fines. However, analyzing its composition, it did not fit into any of the classes described in the standard.

The mechanical characteristics of the asphalt mixtures that include coke boiler ash by the Marshall method remained within the ranges proposed by the Brazilian DNIT and DIRENG standards. In addition, an important characteristic was the improvement in resistance to deformation under loads, compared to a traditional mix at any temperature level.

Author Contributions: Conceptualization, A.C.R.G.; Data curation, M.E.S.M., C.D.C. and T.T. Formal analysis, C.N.; Investigation, C.N. and C.D.C.; Project administration, A.C.R.G.; Resources, M.E.S.M.; Software, M.E.S.M.; Supervision, A.C.R.G.; Validation, A.C.R.G.; Visualization, C.D.C.; Writing—original draft, C.N.; Writing—review & editing, T.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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

References

1. Kenworthy, J.R. The eco-city: Ten key transport and planning dimensions for sustainable city development. *Environ. Urban.* **2006**, *18*, 67–85. [CrossRef]
2. Pichón, F.J. Colonist land-allocation decisions, land use, and deforestation in the Ecuadorian Amazon frontier. *Econ. Dev. Cult. Change* **1997**, *45*, 707–744. [CrossRef]
3. Antrop, M. Changing patterns in the urbanized countryside of Western Europe. *Landsc. Ecol.* **2000**, *15*, 257–270. [CrossRef]
4. Geist, H.J.; Lambin, E.F. Dynamic causal patterns of desertification. *Bioscience* **2004**, *54*, 817–829. [CrossRef]
5. Leff, N.H. Economic retardation in nineteenth-century Brazil. *Econ. Hist. Rev.* **1972**, *25*, 489–507. [CrossRef]
6. Reid, M. *Brazil: The Troubled Rise of a Global Power*; Yale University Press: New Haven, CT, USA, 2014.
7. Hilling, D. *Transport and Developing Countries*; Routledge: Oxfordshire, UK, 2003.
8. Onokala, P.C.; Olajide, C.J. Problems and challenges facing the Nigerian transportation system which affect their contribution to the economic development of the country in the 21st century. *Transp. Res. Procedia* **2020**, *48*, 2945–2962. [CrossRef]
9. Chibnik, M. *Risky Rivers: The Economics and Politics of Floodplain Farming in Amazonia*; University of Arizona Press: Tucson, AZ, USA, 1994.

10. Chaves, W.A.; Wilkie, D.S.; Monroe, M.C.; Sieving, K.E. Market access and wild meat consumption in the central Amazon, Brazil. *Biol. Conserv.* **2017**, *212*, 240–248. [CrossRef]
11. Cristino, J.S.; Salazar, G.M.; Machado, V.A.; Honorato, E.; Farias, A.S.; Vissoci, J.R.N.; Neto, A.V.S.; Lacerda, M.; Wen, F.H.; Monteiro, W.M.; et al. A painful journey to antivenom: The therapeutic itinerary of snakebite patients in the Brazilian Amazon (The QUALISnake Study). *PLoS Negl. Trop. Dis.* **2021**, *15*, e0009245. [CrossRef]
12. Horonjeff, R.; McKelvey, F.X.; Sproule, W.J.; Young, S.B. *Planning and Design of Airports*; McGraw-Hill Education: New York, NY, USA, 2010.
13. Ashford, N.; Stanton, H.P.; Moore, C.; Coutu, P.; Beasley, J. *Airport Operations*; McGraw-Hill Education: New York, NY, USA, 2013.
14. Humphries, E.; Lee, S.J. Evaluation of pavement preservation and maintenance activities at general aviation airports in Texas: Practices, perceived effectiveness, costs, and planning. *Transp. Res. Rec.* **2015**, *2471*, 48–57. [CrossRef]
15. Ruiz-Real, J.L.; Uribe-Toril, J.; De Pablo Valenciano, J.; Pires Manso, J.R. Ibero-American Research on Local Development. An Analysis of Its Evolution and New Trends. *Resources* **2019**, *8*, 124. [CrossRef]
16. Liu, Y.N.; Guo, Z.H.; Xiao, X.Y.; Wang, S.; Jiang, Z.C.; Zeng, P. Phytostabilisation potential of giant reed for metals contaminated soil modified with complex organic fertiliser and fly ash: A field experiment. *Sci. Total Environ.* **2017**, *576*, 292–302. [CrossRef] [PubMed]
17. Wesolowski, M.; Iwanowski, P. Evaluation of Natural Airfield Pavements Condition Based on the Airfield Pavement Condition Index (APCI). *Appl. Sci.* **2021**, *11*, 6139. [CrossRef]
18. Pittenger, D.M. Sustainable Airport Pavements. In *Climate Change, Energy, Sustainability and Pavements*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 353–371.
19. Lima, D.; Santos, B.; Almeida, P. Methodology to assess airport pavement condition using GPS, laser, video image and GIS. In *Pavement and Asset Management*; CRC Press: Boca Raton, FL, USA, 2019; pp. 301–307.
20. Di Mascio, P.; Moretti, L. Implementation of a pavement management system for maintenance and rehabilitation of airport surfaces. *Case Stud. Constr. Mater.* **2019**, *11*, e00251. [CrossRef]
21. Gannon, C.A.; Liu, Z. *Poverty and Transport (No. TWU-30)*; World Bank: Washington, DC, USA, 1997.
22. Johnson, C.W. Linate and Uberlingen-Understanding the role that public policy plays in the failure of air traffic management systems. In Proceedings of the International Workshop on Complex Network and Infrastructure Protection CNIP, Rome, Italy, 28–29 March 2006; Volume 6, pp. 508–519.
23. Netjasov, F.; Janic, M. A review of research on risk and safety modelling in civil aviation. *J. Air Transp. Manag.* **2008**, *14*, 213–220. [CrossRef]
24. Kharoufah, H.; Murray, J.; Baxter, G.; Wild, G. A review of human factors causations in commercial air transport accidents and incidents: From to 2000–2016. *Prog. Aerosp. Sci.* **2018**, *99*, 1–13. [CrossRef]
25. Babashamsi, P.; Md Yusoff, N.I.; Ceylan, H.; Md Nor, N.G.; Salarzadeh Jenatabadi, H. Sustainable development factors in pavement life-cycle: Highway/airport review. *Sustainability* **2016**, *8*, 248. [CrossRef]
26. Santa, S.L.B.; Ribeiro, J.M.P.; Mazon, G.; Schneider, J.; Barcelos, R.L.; de Andrade, J.B.S.O. A Green Airport model: Proposition based on social and environmental management systems. *Sustain. Cities Soc.* **2020**, *59*, 102160. [CrossRef]
27. World Health Organization. *Global Status Report on Road Safety*; World Health Organization: Geneva, Switzerland, 2015.
28. Forman, R.T.; Sperling, D.; Bissonette, J.A.; Clevenger, A.P.; Cutshall, C.D.; Dale, V.H.; Fahrig, L.; France, R.L.; Goldman, C.R.; Heanue, K.; et al. *Road Ecology: Science and Solutions*; Island Press: Washington, DC, USA, 2003.
29. Tapkın, S.; Çevik, A.; Uşar, Ü. Prediction of Marshall test results for polypropylene modified dense bituminous mixtures using neural networks. *Expert Syst. Appl.* **2010**, *37*, 4660–4670. [CrossRef]
30. Bonati, A.; Merusi, F.; Polacco, G.; Filippi, S.; Giuliani, F. Ignitability and thermal stability of asphalt binders and mastics for flexible pavements in highway tunnels. *Constr. Build. Mater.* **2012**, *37*, 660–668. [CrossRef]
31. Xu, J.Z.; Hao, P.W. Study of aggregate gradations in foamed bitumen mixes. *Road Mater. Pavement Des.* **2012**, *13*, 660–677. [CrossRef]
32. Kosson, D.S.; van der Sloot, H.A.; Sanchez, F.; Garrabrants, A.C. An integrated framework for evaluating leaching in waste management and utilization of secondary materials. *Environ. Eng. Sci.* **2002**, *19*, 159–204. [CrossRef]
33. Somasundaram, S.; Jeon, T.W.; Kang, Y.Y.; Kim, W.I.; Jeong, S.K.; Kim, Y.J.; Yeon, J.-M.; Shin, S.K. Characterization of wastes from construction and demolition sector. *Environ. Monit. Assess.* **2015**, *187*, 1–14. [CrossRef] [PubMed]
34. Haque, M.A. Assessment of nickel leaching phenomena from landfill waste mixed paving block for eco-friendly field application. *J. Clean. Prod.* **2016**, *139*, 99–112. [CrossRef]
35. Reuter, M.A.; van Schaik, A.; Gutzmer, J.; Bartie, N.; Abadías-Llamas, A. Challenges of the circular economy: A material, metallurgical, and product design perspective. *Annu. Rev. Mater. Res.* **2019**, *49*, 253–274. [CrossRef]
36. Spooren, J.; Binnemans, K.; Björkmalm, J.; Breemersch, K.; Dams, Y.; Folens, K.; González-Moya, M.; Horckmans, L.; Komnitsas, K.; Kurylak, W.; et al. Near-zero-waste processing of low-grade, complex primary ores and secondary raw materials in Europe: Technology development trends. *Resour. Conserv. Recycl.* **2020**, *160*, 104919. [CrossRef]
37. Blengini, G.A.; Mathieux, F.; Mancini, L.; Nyberg, M.; Viegas, H.M. *Recovery of Critical and Other Raw Materials from Mining Waste and Landfills*; JRC Science for Policy Report; Publications Office of the European Union: Luxembourg, 2019.
38. Misra, V.; Pandey, S.D. Hazardous waste, impact on health and environment for development of better waste management strategies in future in India. *Environ. Int.* **2005**, *31*, 417–431. [CrossRef]

39. Pappu, A.; Saxena, M.; Asolekar, S.R. Solid wastes generation in India and their recycling potential in building materials. *Build. Environ.* **2007**, *42*, 2311–2320. [CrossRef]
40. Freeman, H.; Harten, T.; Springer, J.; Randall, P.; Curran, M.A.; Stone, K. Industrial pollution prevention! A critical review. *J. Air Waste Manag. Assoc.* **1992**, *42*, 618–656. [CrossRef]
41. Utsev, J.T.; Taku, J.K. Coconut shell ash as partial replacement of ordinary Portland cement in concrete production. *Int. J. Sci. Technol. Res.* **2012**, *1*, 86–89.
42. Ephraim, M.E.; Akeke, G.A.; Ukpata, J.O. Compressive strength of concrete with rice husk ash as partial replacement of ordinary Portland cement. *Sch. J. Eng. Res.* **2012**, *1*, 32–36.
43. Nwankwo, C.O.; Bamigboye, G.O.; Davies, I.E.; Michaels, T.A. High volume Portland cement replacement: A review. *Constr. Build. Mater.* **2020**, *260*, 120445. [CrossRef]
44. Alhozaimy, A.M.; Soroushian, P.; Mirza, F. Mechanical properties of polypropylene fiber reinforced concrete and the effects of pozzolanic materials. *Cem. Concr. Compos.* **1996**, *18*, 85–92. [CrossRef]
45. Massazza, F. Pozzolana and pozzolanic cements. *Lea's Chem. Cem. Concr.* **1998**, *4*, 471–631.
46. Malhotra, V.M.; Mehta, P.K. *Pozzolanic and Cementitious Materials*; CRC Press: Boca Raton, FL, USA, 2004.
47. Tabaković, A.; Schlangen, E. Self-healing technology for asphalt pavements. *Self-Heal. Mater.* **2015**, *273*, 285–306.
48. Tahami, S.A.; Arabani, M.; Mirhosseini, A.F. Usage of two biomass ashes as filler in hot mix asphalt. *Constr. Build. Mater.* **2018**, *170*, 547–556. [CrossRef]
49. Milad, A.A.; Ali, A.S.B.; Yusoff, N.I.M. A review of the utilisation of recycled waste material as an alternative modifier in asphalt mixtures. *Civ. Eng. J.* **2020**, *6*, 42–60. [CrossRef]
50. Yoder, E.J.; Witczak, M.W. *Principles of Pavement Design*; John Wiley & Sons: Hoboken, NJ, USA, 1991.
51. Pasetto, M.; Baldo, N. Resistance to permanent deformation of road and airport high performance asphalt concrete base courses. In *Advanced Materials Research*; Trans Tech Publications Ltd.: Bach, Switzerland, 2013; Volume 723, pp. 494–502.
52. Cedergren, H.R.; Arman, J.A.; O'Brien, K.H. *Development of Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections (No. FHWA-RD-73-14)*; United States, Federal Highway Administration, Office of Research: McLean, VA, USA, 1973.
53. Bamigboye, G.O.; Bassey, D.E.; Olukanni, D.O.; Ngene, B.U.; Adegoke, D.; Odetoyan, A.O.; Kareem, M.A.; Enabulele, D.O.; Nworgu, A.T. Waste materials in highway applications: An overview on generation and utilization implications on sustainability. *J. Clean. Prod.* **2021**, *283*, 124581. [CrossRef]
54. Hall, A. Peopling the environment: A new agenda for research, policy and action in Brazilian Amazonia. *Rev. Eur. De Estud. Latinoam. Y Del Caribe/Eur. Rev. Lat. Am. Caribb. Stud.* **1997**, *62*, 9–31.
55. Leon, R.A.; Gomez, J.E. Colombian national defense system against large scale events. In *2011 IEEE Power and Energy Society General Meeting Detroit, MI, USA, 24–28 July 2011*; IEEE: Piscataway, NJ, USA, 2011; pp. 1–6.
56. Franko, P. The defense acquisition trilemma: The case of Brazil. In *Strategic Forum*; National Defense University Press: Washington, DC, USA, 2014; No. 284; p. 1.
57. Cepik, M.; Licks Bertol, F. Defense policy in Brazil: Bridging the gap between ends and means? *Def. Stud.* **2016**, *16*, 229–247. [CrossRef]
58. Cervo, A.L. Brazil's rise on the international scene: Brazil and the World. *Rev. Bras. Política Int.* **2010**, *53*, 7–32. [CrossRef]
59. Filho, J.R.M.; Zirker, D. Nationalism, national security, and Amazônia: Military perceptions and attitudes in contemporary Brazil. *Armed Forces Soc.* **2000**, *27*, 105–129. [CrossRef]
60. Cope, J.A.; Parks, A. *Frontier security: The case of Brazil*; National Defense University-Institute for National Strategic Studies: Washington, DC, USA, 2016.
61. Dhenin, M.; Correa, P.G.P. Brazil's grand border strategy: Challenges of a new critical thinking in a modern era. *Rev. Bras. Estud. Def.* **2017**, *4*, 199–218. [CrossRef]
62. Barros-Platiau, A.F.; Barros, J.G.D.C. Brazil's strategic diplomacy for maritime security and safety. *Contemp. Politics* **2021**, *28*, 38–54. [CrossRef]
63. Marques, A.A.; Neto, J.M. Brazil's National Defence Strategy, Defence Diplomacy and Management of Strategic Resources. In *Defence Diplomacy and National Security Strategy: Views from the Global South*; Sun Press: Cleveland, OH, USA, 2020; Volume 13.
64. Ramos, A. Illegal trade in tobacco in MERCOSUR countries. *Trends Organ. Crime* **2009**, *12*, 267–306.
65. Fearnside, P.M. Soybean cultivation as a threat to the environment in Brazil. *Environ. Conserv.* **2001**, *28*, 23–38. [CrossRef]
66. Novakoff, R. Transnational organized crime: An insidious threat to US national security interests. *Prism* **2016**, *5*, 134–149.
67. Shelley, L.I.; Picarelli, J.T. Methods and motives: Exploring links between transnational organized crime and international terrorism. *Trends Organ. Crime* **2005**, *9*, 52–67. [CrossRef]
68. Sanderson, T.M. Transnational Terror and Organized Crime. *SAIS Rev. Int. Aff.* **2004**, *24*, 49–61. [CrossRef]
69. Muggah, R.; Diniz, G. *Securing the Border*; Strategic Paper 5; Igarapé Institute: Rio de Janeiro, Brazil, 2013; pp. 1–29.
70. Francelino, J.; Urbina, L.; Soto, M.; Furtado, A.T.; Damiani, J.H.D.S. Impacts of the aircraft AM-Xs acquisition program (1982–1994) on technological management capability of the Brazilian Aeronautical Command. In Proceedings of the Congresso Latino-Iberoamericano de Gestão da Tecnologia, Porto Alegre, Brazil, 19–22 October 2015; Volume 16.
71. Toulkeridis, T.; Tamayo, E.; Simón-Baile, D.; Merizalde-Mora, M.J.; Reyes–Yunga, D.F.; Viera-Torres, M. and Heredia, M. Climate change according to Ecuadorian academics–Perceptions versus facts. *Granja* **2020**, *31*, 21–49. [CrossRef]

72. Quadros, S.G.R.; Nassi, C.D. An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil. *Transp. Policy* **2015**, *40*, 8–16. [CrossRef]
73. Santos, A.M.; Bastos-Filho, C.J.; Maciel, A.M.; Lima, E. Counting Vehicle with High-Precision in Brazilian Roads Using YOLOv3 and Deep SORT. In Proceedings of the 2020 33rd SIBGRAPI Conference on Graphics, Patterns and Images (SIBGRAPI), Virtual, 7–10 November 2020; pp. 69–76.
74. de Castro Victoria, D.; da Silva, R.F.B.; Millington, J.D.; Katerinchuk, V.; Batistella, M. Transport cost to port though Brazilian federal roads network: Dataset for years 2000, 2005, 2010 and 2017. *Data Brief* **2021**, *36*, 107070. [CrossRef] [PubMed]
75. Chagas, D.M.; Silva Filho, L.C.P. Improvement opportunity for bridge inspections in Brazil. In *Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks*; CRC Press: Boca Raton, FL, USA, 2016; p. 544.
76. Buncher, M.; Duval, J. Superpave for Airfields. In *Proceedings of the Airfield Pavements: Challenges and New Technologies Proceedings of the Specialty Conference*; Las Vegas, NV, USA, 21–24 September 2003, pp. 316–326.
77. Sousa, A.F.; E Gomes, S. *Tecnologia Aplicada à Avaliação das Estruturas dos Pavimentos Aeroportuários—Monografia de Especialização em Gestão da Aviação Civil*; Universidade de Brasília: Brasília, Brazil, 2008.
78. Westergaard, H.M. *Theory of Elasticity and Plasticity*; Harvard University Press: Cambridge, MA, USA, 2013.
79. Westergaard, H.M. *Stresses in Concrete Pavements Computed by Theoretical Analysis*; Public Roads; Federal Highway Administration: Washington, DC, USA, 1926.
80. Chou, Y.T. Reliability design procedures for flexible pavements. *J. Transp. Eng.* **1990**, *116*, 602–614. [CrossRef]
81. Wang, S.K.; Sargious, M.; Cheung, Y.K. Advanced analysis of rigid pavements. *Transp. Eng. J. ASCE* **1972**, *98*, 37–44. [CrossRef]
82. Santos, A.M.; Bastos-Filho, C.J.; Maciel, A. Counting Vehicle by Axes with High-Precision in Brazilian Roads with Deep Learning Methods. In *International Conference on Intelligent Systems Design and Applications*; Springer: Cham, Switzerland, 2021; pp. 188–198.
83. Heitzman, M. *Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier*; Transportation Research Record: Washington, DC, USA, 1992.
84. Meyer, M.D.; Weigel, B. Climate change and transportation engineering: Preparing for a sustainable future. *J. Transp. Eng.* **2011**, *137*, 393–403. [CrossRef]
85. *DIRENG: AC 150/5380-6A*; Guia e Procedimentos para Manutenção dos Pavimentos nos Aeroportos, Documentos e Informação. Universidade Federal do Ceará: Fortaleza, Brazil, 2003.
86. Thom, N. *Principles of Pavement Engineering*; Thomas Telford: London, UK, 2008; p. 470.
87. Ahmad, S.; Abdul Mujeebu, M.; Farooqi, M.A. Energy harvesting from pavements and roadways: A comprehensive review of technologies, materials, and challenges. *Int. J. Energy Res.* **2019**, *43*, 1974–2015. [CrossRef]
88. Shill, S.K.; Al-Deen, S.; Ashraf, M. Concrete durability issues due to temperature effects and aviation oil spillage at military airbase–A comprehensive review. *Constr. Build. Mater.* **2018**, *160*, 240–251. [CrossRef]
89. Shill, S.K.; Al-Deen, S.; Ashraf, M. Thermal and Chemical Degradation of Portland Cement Concrete in the Military Airbase (No. 712). Easy Chair. 2019. Available online: https://easychair.org/publications/preprint/b24Q (accessed on 20 June 2022).
90. Guyot, X. High Performance Asphalt for Airfield Pavement. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2021; Volume 1075, No. 1; p. 012001.
91. Husain, N.M.; Karim, M.R.; Mahmud, H. Characterization of superplasticized blended cement grout for the application on semi-rigid pavement. In Proceedings of the Eastern Asia Society for Transportation Studies (8th International Conference of Eastern Asia Society for Transportation Studies), Surabaya, Indonesia, 16–19 November 2009; Eastern Asia Society for Transportation Studies: Tokyo, Japan, 2009; Volume 7, p. 295.
92. Mohod, M.V.; Kadam, K.N. A comparative study on rigid and flexible pavement: A review. *IOSR J. Mech. Civ. Eng. IOSR-JMCE* **2016**, *13*, 84–88.
93. Tennis, P.D.; Leming, M.L.; Akers, D.J. *Pervious Concrete Pavements (No. PCA Serial No. 2828)*; Portland Cement Association: Skokie, IL, USA, 2004.
94. *DNER-ME 043/1995*; Misturas Betuminosas a Quente—Ensaio Marshall. Departamento Nacional de Infraestrutura de Transportes: Brasilia, Brazil, 1995.
95. Sultana, M.; Chai, G.; Martin, T.; Chowdhury, S. Modeling the postflood short-term behavior of flexible pavements. *J. Transp. Eng.* **2016**, *142*, 04016042. [CrossRef]
96. Qiao, Y.; Dawson, A.R.; Parry, T.; Flintsch, G.; Wang, W. Flexible pavements and climate change: A comprehensive review and implications. *Sustainability* **2020**, *12*, 1057. [CrossRef]
97. Debbarma, S.; Selvam, M.; Singh, S. Can flexible pavements' waste (RAP) be utilized in cement concrete pavements?–A critical review. *Constr. Build. Mater.* **2020**, *259*, 120417. [CrossRef]
98. Branco, F.; Pereira, P.; E Santos, L.P. *Pavimentos Rodoviários*; Coimbra: Almedina, Portugal, 2006.
99. Gopalakrishnan, K.; Thompson, M.R. Characterization of NAPTF subgrade soils for mechanistic-based analysis and design of airport flexible pavements. *Int. J. Pavement Eng.* **2007**, *8*, 307–321. [CrossRef]
100. Vinicius, M. 2015. Available online: http://pt.slideshare.net/MarcosVinicius414/pavimentos-flexiveiserigidos-lucasadada (accessed on 26 June 2022).
101. Ansarilari, Z.; Golroo, A. Integrated airport pavement management using a hybrid approach of Markov Chain and supervised multi-objective genetic algorithms. *Int. J. Pavement Eng.* **2020**, *21*, 1864–1873. [CrossRef]

102. Park, H.W.; Kim, D.H.; Lim, J.S.; Shim, C.S.; Jeong, J.H. Prediction of differential drying shrinkage of airport concrete pavement slabs. *Int. J. Pavement Eng.* **2021**, *22*, 752–762. [CrossRef]
103. García-Rojo, R.; Herrmann, H.J. Shakedown of unbound granular material. *Granul. Matter* **2005**, *7*, 109–118. [CrossRef]
104. Ghadimi, B.; Nikraz, H.; Rosano, M. Dynamic simulation of a flexible pavement layers considering shakedown effects and soil-asphalt interaction. *Transp. Geotech.* **2016**, *7*, 40–58. [CrossRef]
105. Do, M.T.; Tang, Z.; Kane, M.; de Larrard, F. Pavement polishing—Development of a dedicated laboratory test and its correlation with road results. *Wear* **2007**, *263*, 36–42. [CrossRef]
106. Mallela, J.; Quintus, H.V.; Smith, K. Consideration of lime-stabilized layers in mechanistic-empirical pavement design. *Natl. Lime Assoc.* **2004**, *200*, 1–40.
107. Amu, O.O.; Bamisaye, O.F.; Komolafe, I.A. The suitability and lime stabilization requirement of some lateritic soil samples as pavement. *Int. J. Pure Appl. Sci. Technol.* **2011**, *2*, 29–46.
108. Al-Qadi, I.L.; Wang, H.; Tutumluer, E. Dynamic analysis of thin asphalt pavements by using cross-anisotropic stress-dependent properties for granular layer. *Transp. Res. Rec.* **2010**, *2154*, 156–163. [CrossRef]
109. Xiao, Y.; Tutumluer, E.; Siekmeier, J. Mechanistic–Empirical Evaluation of Aggregate Base and Granular Subbase Quality Affecting Flexible Pavement Performance in Minnesota. *Transp. Res. Rec.* **2011**, *2227*, 97–106. [CrossRef]
110. Frost, M.W.; Fleming, P.R.; Rogers, C.D. Cyclic triaxial tests on clay subgrades for analytical pavement design. *J. Transp. Eng.* **2004**, *130*, 378–386. [CrossRef]
111. Lv, S.; Liu, C.; Zheng, J.; You, Z.; You, L. Viscoelastic fatigue damage properties of asphalt mixture with different aging degrees. *KSCE J. Civ. Eng.* **2018**, *22*, 2073–2081. [CrossRef]
112. Cheng, H.; Liu, J.; Sun, L.; Liu, L. Critical position of fatigue damage within asphalt pavement considering temperature and strain distribution. *Int. J. Pavement Eng.* **2021**, *22*, 1773–1784. [CrossRef]
113. Darabi, M.K.; Al-Rub, R.K.A.; Masad, E.A.; Little, D.N. Constitutive modeling of fatigue damage response of asphalt concrete materials with consideration of micro-damage healing. *Int. J. Solids Struct.* **2013**, *50*, 2901–2913. [CrossRef]
114. Li, Q.; Xiao, D.X.; Wang, K.C.; Hall, K.D.; Qiu, Y. Mechanistic-empirical pavement design guide (MEPDG): A bird's-eye view. *J. Mod. Transp.* **2011**, *19*, 114–133. [CrossRef]
115. Monteiro, F.F.; de Oliveira, F.H.L.; Zitllau, O.; de Aguiar, M.F.P.; de Carvalho, L.M.C. CBR Value Estimation Using Dynamic Cone Penetrometer—A Case Study of Brazil's Midwest Federal Highway. *Electron. J. Geotech. Eng.* **2016**, *21*, 4649–4656.
116. Trong, D.K.; Pham, B.T.; Jalal, F.E.; Iqbal, M.; Roussis, P.C.; Mamou, A.; Ferentinou, M.; Vu, D.Q.; Duc Dam, N.; Tran, Q.A.; et al. On Random Subspace Optimization-Based Hybrid Computing Models Predicting the California Bearing Ratio of Soils. *Materials* **2021**, *14*, 6516. [CrossRef] [PubMed]
117. Farias, I.G.; Araujo, W.; Ruiz, G. Prediction of California bearing ratio from index properties of soils using parametric and non-parametric models. *Geotech. Geol. Eng.* **2018**, *36*, 3485–3498. [CrossRef]
118. Bernucci, L.B.; Motta, L.M.G.; DA Ceratti, J.A.P.; Soares, J.B. *Pavimentação Asfáltica: Formação básica Para Engenheiros*; Petrobras Abeda: Rio de Janeiro, Brazil, 2010.
119. Nacimento, L.A.H. Nova Abordagem da Dosagem de Misturas Asfálticas Densas com Uso do Compactador Giratório e Foco na Deformação Permanente. Master's Thesis, Universidade Federal do Rio de Janeiro, Programa de Pós-graduação em Engenharia Civil, Rio de Janeiro, Brazil, 2008.
120. Norouzi, A.; Kim, D.; Kim, Y.R. Numerical evaluation of pavement design parameters for the fatigue cracking and rutting performance of asphalt pavements. *Mater. Struct.* **2016**, *49*, 3619–3634. [CrossRef]
121. Saghafi, M.; Tirado, C.; Abdallah, I.N.; Nazarian, S. Considering Pavement Structure in Laboratory Fatigue Cracking Assessment. In *International Conference on Transportation and Development, Seattle, WA, USA, 26–29 May 2020*; American Society of Civil Engineers: Reston, VA, USA, 2020; pp. 187–199.
122. Airey, G.D. Fundamental binder and practical mixture evaluation of polymer modified bituminous materials. *Int. J. Pavement Eng.* **2004**, *5*, 137–151. [CrossRef]
123. Fontes, L.P.T.L.; Trichês, G.; Pais, J.C.; Pereira, P.A.A. Evaluating permanent deformation in asphalt rubber mixtures. *Constr. Build. Mater.* **2010**, *24*, 1193–1200. [CrossRef]
124. Neto, M.L.Q.; Amorim, E.F.; de França, F.A.N.; Medeiros, M.K.S. Evaluation of an experimental hot asphalt concrete urban paving section using construction and works demolition waste (CDW) as a coating layer. *Rev. Gestão Ambient. Sustentabilidade* **2020**, *9*, 16108.
125. Pacheco-Torres, R.; Cerro-Prada, E.; Escolano, F.; Varela, F. Fatigue performance of waste rubber concrete for rigid road pavements. *Constr. Build. Mater.* **2018**, *176*, 539–548. [CrossRef]
126. Solla, M.; Pérez-Gracia, V.; Fontul, S. A Review of GPR Application on Transport Infrastructures: Troubleshooting and Best Practices. *Remote Sens.* **2021**, *13*, 672. [CrossRef]
127. Bhargava, N.; Siddagangaiah, A.K.; Ryntathiang, T.L. Sustainable Development with Microsurfacing: A Review. *J. Test. Eval.* **2019**, *49*, 1284–1306. [CrossRef]
128. Hu, J.; Gao, Q.; Yu, X. Characterization of the optical and mechanical properties of innovative multifunctional thermochromic asphalt binders. *J. Mater. Civ. Eng.* **2015**, *27*, 04014171. [CrossRef]
129. Badin, G.; Ahmad, N.; Ali, H.M.; Ahmad, T.; Jameel, M.S. Effect of addition of pigments on thermal characteristics and the resulting performance enhancement of asphalt. *Constr. Build. Mater.* **2021**, *302*, 124212. [CrossRef]

130. Cambridge Systematics. *Traffic Congestion and Reliability Trends and Advanced Strategies for Congestion Mitigation. With Texas Transportation Institute date September 1*; Cambridge Systematics, Inc.: Cambridge, MA, USA, 2005.
131. Fernando, E.G.; Middleton, D.; Carlson, T.; Longmire, R.; Sepulveda, E.; Ruback, L.; Freeman, T.; Oh, J. *Deploying Weigh-In-Motion Installations on Asphalt Concrete Pavements*; (No. FHWA/TX-09/0-5551-1); Texas Transportation Institute: College Station, TX, USA, 2010.
132. Wilson, F. *Building Materials Evaluation Handbook*; Springer: Boston, MA, USA, 1984; pp. 205–266.
133. Huang, Y.H. *Pavement Analysis and Design*; Pearson Education: Upper Saddle River, NJ, USA, 2004.
134. Hintz, C. Understanding Mechanisms Leading to Asphalt Binder Fatigue. Ph.D. Thesis, University of Wisconsin, Madison, WI, USA, 2012.
135. Monismith, C.L. Asphalt Concrete: An Extraordinary Material for Engineering Applications. In *Thirtieth Henry M. Shaw Lecture in Civil Engineering*; Departamento de Engenharia Civil; North Carolina State University: Raleigh, NC, USA, 1998.
136. Daniel, J.S.; Kim, Y.R. Development of a simplified fatigue test and analysis procedure using a viscoelastic, continuum damage model. *J. Assoc. Asph. Paving Technol.* **2002**, *71*, 619–650.
137. Schapery, R.A. A Theory of Mechanical Behavior of Elastic Media with Growing Damage and Other Changes in Structure. *J. Mech. Phys. Solids* **1990**, *38*, 215–253. [CrossRef]
138. Schapery, R.A. Correspondence principles and a generalized j-integral for large deformation and fracture analysis of viscoelastic media. *Int. J. Fract.* **1984**, *25*, 195–223. [CrossRef]
139. Lee, H.J.; Kim, Y.R. Viscoelastic Constitutive Model for Asphalt Concrete Under Cyclic Loading. *J. Eng. Mech.* **1998**, *124*, 32–40. [CrossRef]
140. Lee, H.J.; Kim, Y.R. Viscoelastic Continuum Damage Model of Asphalt Concrete with Healing. *J. Eng. Mech.* **1998**, *124*, 1224–1232. [CrossRef]
141. Schapery, R.A. Simplifications in the Behavior of Viscoelastic Composites with Growing Damage. In Proceedings of the Symposium on Inelastic Deformation of Composite Materials, New York, NY, USA, 29 May–1 June 1990; pp. 193–214.
142. Park, S.W.; Kim, Y.R.; Schapery, R.A. A viscoelastic continuum damage model and its application to uniaxial behavior of asphalt concrete. *Mech. Mater.* **1996**, *24*, 241–255. [CrossRef]
143. Abo-Qudais, S.; Al-Shweily, H. Effect of aggregate properties on asphalt mixtures stripping and creep behavior. *Constr. Build. Mater.* **2007**, *21*, 1886–1898. [CrossRef]
144. Xu, G.; Wang, H. Molecular dynamics study of interfacial mechanical behavior between asphalt binder and mineral aggregate. *Constr. Build. Mater.* **2016**, *121*, 246–254. [CrossRef]
145. Netto, R.M. *Materiais Pozolânicos*; Monografia (Engenharia Civil); Escola de Engenharia da Universidade Federal de Minas Gerais–UFMG: Belo Horizonte, Brazil, 2006.
146. Leandro, R.P.; Fabbri, G.T.P. *Aproveitamento da Cinza Pesada de Carvão, Mineral na Construção de Bases e Sub-Bases de Pavimentos Flexíveis*; Faculdade de Engenharia Civil (FECIV), Universidade Federal de Uberlândia: São Carlos, São Paulo, Brazil, 2001; pp. 1–8.
147. Cordeiro, G.C.; Toledo Filho, R.D.; Tavares, L.M.; Fairbairn, E.M.R. Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars. *Cem. Concr. Compos.* **2008**, *30*, 410–418. [CrossRef]
148. Tucker, E.L.; Ferraro, C.C.; Laux, S.J.; Townsend, T.G. Economic and life cycle assessment of recycling municipal glass as a pozzolan in portland cement concrete production. *Resour. Conserv. Recycl.* **2018**, *129*, 240–247. [CrossRef]
149. Farias, E.R. A utilização de Misturas Solos/Cinza Pesada na Pavimentação—Análise de Aspectos de Comportamento Mecânico e Ambiental. Master's Thesis, Universidade Federal de Santa Catarina, Florianópolis, Brazil, 2005.
150. Lopes, L.S.E. Análise do Comportamento Mecânico e Ambiental de Misturas Solo-Cinzas de Carvão Mineral Para Camadas de Base de Pavimentos. Master's Thesis, Pontifícia Universidade Católica, PUC-Rio, Rio de Janeiro, Brazil, 2011.
151. Balbo, J.T. *Pavimentação Asfáltica—Materiais, Projeto e Restauração*; Oficina de Textos: São Paulo, Brazil, 2007; 558p.
152. Vizcarra, G.O.C.; Szelica, L.; Casagrande, M.D.T.; Motta, L.M.G. *Aplicabilidade de Cinzas de Incineração de Resíduos Sólidos Urbano em Camadas de Bases de Pavimentos*; 40ª RAPv: Rio de Janeiro, Brazil, 2010.
153. UBbaldo, M.O. Uso de cinzas de carvão da composição de uma cobertura de rejeitos de mineração. Master's Thesis, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil, 2005.
154. Purchase, B.S.; Wynne, A.T.; Meyer, E.; Van Antwerpen, R. Is there profit in cane trash? Another dimension to the assessment of trashing versus burning. *Proc. S. Afr. Sug. Technol. Ass.* **2008**, *81*, 86–99.
155. Environment, U.N.; Scrivener, K.L.; John, V.M.; Gartner, E.M. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. *Cem. Concr. Res.* **2018**, *114*, 2–26.
156. Alloway, B.; Ayres, D.C. *Chemical Principles of Environmental Pollution*; CRC Press: Boca Raton, FL, USA, 1997.
157. Wu, S.; Ye, Q.; Li, N. Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. *Constr. Build. Mater.* **2008**, *22*, 2111–2115. [CrossRef]
158. Sushil, S.; Batra, V.S. Analysis of fly ash heavy metal content and disposal in three thermal power plants in India. *Fuel* **2006**, *85*, 2676–2679. [CrossRef]
159. Dermatas, D.; Meng, X. Utilization of fly ash for stabilization/solidification of heavy metal contaminated soils. *Eng. Geol.* **2003**, *70*, 377–394. [CrossRef]

160. Verma, C.; Madan, S.; Hussain, A. Heavy metal contamination of groundwater due to fly ash disposal of coal-fired thermal power plant, Parichha, Jhansi, India. *Cogent Eng.* **2016**, *3*, 1179243. [CrossRef]
161. Rhode, G.M.; Zwonok, O.; Chies, F.; Silva, N.I.W. *Cinzas de Carvão Fóssil no Brasil—Aspectos Técnicos e Ambientais*; CIENTEC: Porto Alegre, Brazil, 2006; Volume 1.
162. Orsati, S.A. Análise de Impactos Ambientais e Econômicos na Escolha de Locais para Disposição Final de Resíduos Sólidos. Dissertação. Master's Thesis, Faculdade de Engenharia de Ilha Solteira, Universidade Estadual Paulista, USP, Ilha Solteira, Brazil, 2006.
163. Blissett, R.S.; Rowson, N.A. A review of the multi-component utilisation of coal fly ash. *Fuel* **2012**, *97*, 1–23. [CrossRef]
164. Redlingshöfer, B.; Barles, S.; Weisz, H. Are waste hierarchies effective in reducing environmental impacts from food waste? A systematic review for OECD countries. *Resour. Conserv. Recycl.* **2020**, *156*, 104723. [CrossRef]
165. *Associação Brasileira de Normas Técnicas (ABNT-NBR 10004)*; Resíduos Sólidos—Classificação: Rio de Janeiro, Brazil, 2004.
166. Predeanu, G.; Popescu, L.G.; Abagiu, T.A.; Panaitescu, C.; Valentim, B.; Guedes, A. Characterization of bottom ash of Pliocene lignite as ceramic composites raw material by petrographic, SEM/EDS and Raman microspectroscopical methods. *Int. J. Coal Geol.* **2016**, *168*, 131–145. [CrossRef]
167. Zhang, W.; Honaker, R. Calcination pretreatment effects on acid leaching characteristics of rare earth elements from middlings and coarse refuse material associated with a bituminous coal source. *Fuel* **2019**, *249*, 130–145. [CrossRef]
168. Valentim, B. Petrography of coal combustion char: A review. *Fuel* **2020**, *277*, 118271. [CrossRef]
169. Blissett, R.S.; Smalley, N.; Rowson, N.A. An investigation into six coal fly ashes from the United Kingdom and Poland to evaluate rare earth element content. *Fuel* **2014**, *119*, 236–239. [CrossRef]
170. Ahmaruzzaman, M. A review on the utilization of fly ash. *Prog. Energy Combust. Sci.* **2010**, *36*, 327–363. [CrossRef]
171. Hower, J.C.; Henke, K.R.; Dai, S.; Ward, C.R.; French, D.; Liu, S.; Graham, U.M. Generation and nature of coal fly ash and bottom ash. In *Coal Combustion Products (CCP's)*; Woodhead Publishing: Sawston, UK, 2017; pp. 21–65.
172. Anastasiou, E.; Filikas, K.G.; Stefanidou, M. Utilization of fine recycled aggregates in concrete with fly ash and steel slag. *Constr. Build. Mater.* **2014**, *50*, 154–161. [CrossRef]
173. Kürklü, G. The effect of high temperature on the design of blast furnace slag and coarse fly ash-based geopolymer mortar. *Compos. Part B Eng.* **2016**, *92*, 9–18. [CrossRef]
174. Vereshchagin, S.N.; Kurteeva, L.I.; Anshits, A.G. Content of Various Size and Density Particles in Cenosphere Concentrates of Volatile Coal Combustion Ashes from the Kuznetsk Coalfield. *Chem. Sustain. Dev.* **2008**, *16*, 521–528.
175. Silva, L.F.; DaBoit, K.; Sampaio, C.H.; Jasper, A.; Andrade, M.L.; Kostova, I.J.; Waanders, F.B.; Henke, K.R.; Hower, J.C. The occurrence of hazardous volatile elements and nanoparticles in Bulgarian coal fly ashes and the effect on human health exposure. *Sci. Total Environ.* **2012**, *416*, 513–526. [CrossRef] [PubMed]
176. Mackiewicz, S.M.; Ferguson, E.G. Stabilization of soil with self-cementing coal ashes. In Proceedings of the 2005 World of Coal Ash (WOCA), Lexington, KT, USA, 11–15 April 2005; pp. 1–7.
177. Misra, A.; Biswas, D.; Upadhyaya, S. Physico-mechanical behavior of self-cementing class C fly ash–clay mixtures. *Fuel* **2005**, *84*, 1410–1422. [CrossRef]
178. Nardi, J.V.; Hotza, D. Termelétricas da Região Sul do Brasil Enfocadas como Agentes de Poluição Ambiental: Solução do Problema da Cinza em Função da Engenharia Rodoviária. In *3º Encontro Ibero*; Americano de Unidades Ambientais do Setor Transportes: Florianópolis, Brazil, 1998.
179. da Silva, N.I.W.; Calarge, L.M.; Chies, F.; Mallmann, J.E.; Zwonok, O. Caracterização de cinzas volantes para aproveitamento cerâmico. *Cerâmica* **1999**, *45*. [CrossRef]
180. Malmann, J.E.C. Estabilização Pozolânica de Cinzas Volantes e Pesada com cal Dolomítica Hidratada e Areia, Curadas Pelos Processos de Autoclavagem e Câmara à Temperatura Constante. Master's Thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, 1996.
181. Dias, C.R.C. Estudos de Misturas Areia-Asfalto e Cinza-Cal para Emprego em Pavimentos Urbanos. Master's Thesis, Universidade Federal do Rio Grande do Sul—UFRGS, Porto Alegre, Brazil, 2004.
182. Rosa, A.D. Estudo dos Parâmetros-Chave no Controle da Resistência de Misturas Solocinza-Cal. Master's Thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, 2009.
183. Lucca, A.C.K. *Reação Álcali-Agregado: Efeito do Uso de Cinza Volante*; Monografia (Engenharia Civil); Universidade Federal do Rio Grande do Sul—UFRGS: Porto Alegre, Brazil, 2010.
184. Cezar, D.S. Características de Durabilidade de Concretos com Cinza Volante e Cinza de Casca de Arroz com e Sem Beneficiamento. Master's Thesis, Engenharia Civil. Universidade Federal de Santa Maria—UFSM, Santa Maria, Brazil, 2011.
185. Pereira, K.L. Estabilização de um Solo com Cimento e Cinza de Lodo para Uso em Pavimentos. Master's Thesis, UFRN, Natal, Brazil, 2012.
186. Salvani, C. Influência da Temperatura de cura no Comportamento Mecânico de Misturas Areia- cinza volante- cal. Master's Thesis, Universidade Federal do Rio grande do Sul—UFRGS, Porto Alegre, Brazil, 2013.
187. Instituto de Asfalto. *Tradução do Manual de Asfalto*; Série do Manual N° 4 (MS4); Conselho Editorial da UFGD: Dourados, Brazil, 1998.
188. *DNIT 031/2006-ES*; Pavimentos flexíveis—Concreto Asfáltico—Especificação de Serviço. Diretoria de Planejamento e Pesquisa: Rio de Janiero, Brazil, 2006.

189. *DNER-ME133/94*; Determinacao do Modulo de Resilencia de Misturas Bituminosas. Instituto de Pesquisas Rodoviárias: Rio de Janiero, Brazil, 1994.
190. Amekudzi, A.A.; Khisty, C.J.; Khayesi, M. Using the sustainability footprint model to assess development impacts of transportation systems. *Transp. Res. Part A Policy Pract.* **2009**, *43*, 339–348. [CrossRef]
191. Haynes, K.; Button, K.J. Transportation systems and economic development. In *Handbook of Transport Systems and Traffic Control*; Emerald Group Publishing Limited: Bingley, UK, 2001.
192. Medina, J. *Mecânica dos Pavimentos*; Editora da UFRJ: Rio de Janeiro, Brazil, 1997.