Chapter

Challenges in the Construction of Highways in the Brazilian Amazonia Environment: Part I - Identification of Engineering Problems

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Abstract

The construction of highways in the Brazilian Amazonia Region is always problematic, mainly because it involves environmental obstacles but also technical, economic, and natural challenges. The environmental issues concern the deforestation of the virgin forest and the resulting environmental impacts. The technical ones are related to the natural subgrade, formed by the geologically young alluvial soils that are plastic, being highly compressible or expansive, present in the vast Amazon Basin, whereas the economic issues refer to the final costs of inputs for the construction of the layers of the highway since granular soils and stony materials are located in limited areas that are distant from the work sites, given the geographic immensity of the Brazilian Amazonia. There is also the cost of purging low-bearing capacity soil from the natural subgrade of the highway. Added to all this are the issues of nature, which involve high annual rainfall and the hydrological regime of river flooding and ebbing, which induce the saturation of the pavement layers and the loss of the global geotechnical stability of the compacted earth embankment, respectively. This work points out the Engineering difficulties to be faced in road infrastructure works in the Brazilian Amazon.

Keywords: highway, pavement, soft soil, expansive soil, synthetic coarse aggregate of calcined clay (SCACC), reinforced piled embankment, recycled material, Brazilian Amazonia

1. Introduction

Brazil is a large country of 8.5 million km^2 [1]. The International Amazonia is vast, covering parts of nine countries (Brazil, Bolivia, Colombia, Ecuador, Guyana, French Guiana, Suriname, Peru, and Venezuela), equivalent to 8 million square kilometers of South America (**Figure 1**), of which approximately 65% is located in Brazil [2, 3]. The Brazilian population in this region is approximately 20 million [1].

Brazil has a wide climatic and geomorphological variety. This variety is responsible for the presence of several important biomes and ecosystems, which are home to approximately 20% of the living species known worldwide. It is estimated that there are approximately 2 million species of plants, animals, and microorganisms in Brazil [4]. The most important biomes of Brazil are the Amazon Forest and deciduous forests in the North, the rainforest of the Eastern Coast (known as the Atlantic Forest), the savanna areas (*Cerrado*) in the Centre, the thorn forest (*Caatinga*) in the Northeast, the *Pantanal* in the Midwest, and the pine forests and *Pampa* fields in the South. Also noteworthy are the humid riparian forest in the Northwest (*Campinarana*), coastal mangroves, sand dunes, and salt marshes, all transition zones, and many small areas where special combinations of climate, altitude, and soil produce unique ecosystems [4, 3]. **Figure 1** displays these main biomes.

Brazil is at the top of 18 megadiverse countries, home to 15–20% of the world's biological diversity, with more than 120,000 invertebrate species, approximately 9000 vertebrates, and more than 4000 plant species [5]. The Brazilian flora comprises approximately 55,000 described species [6, 7], a number that represents

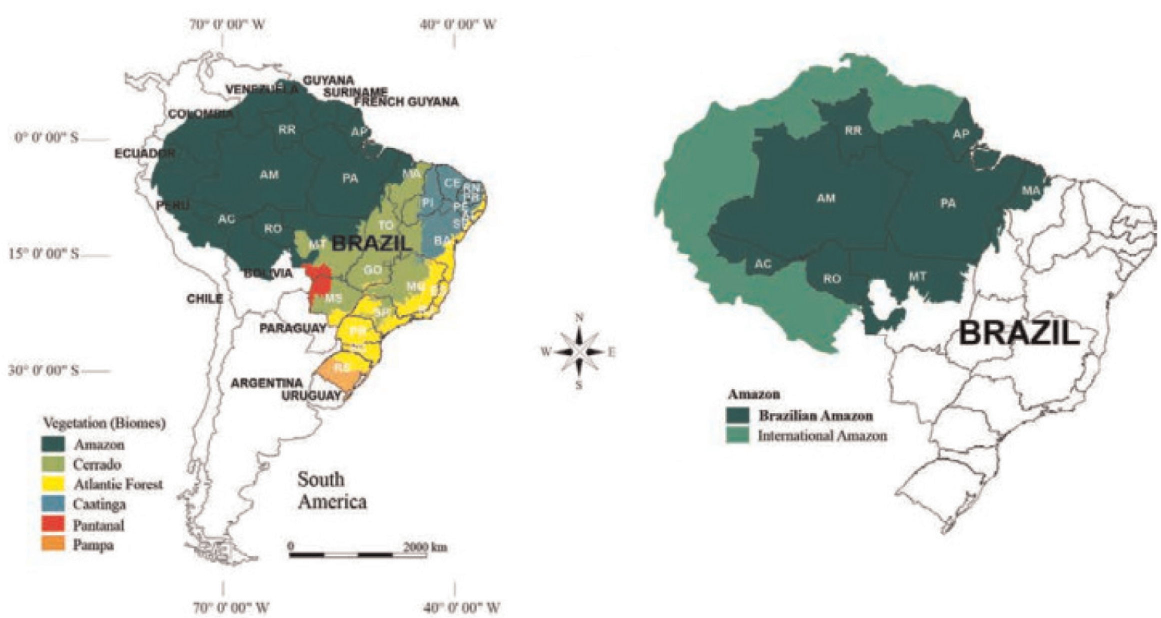
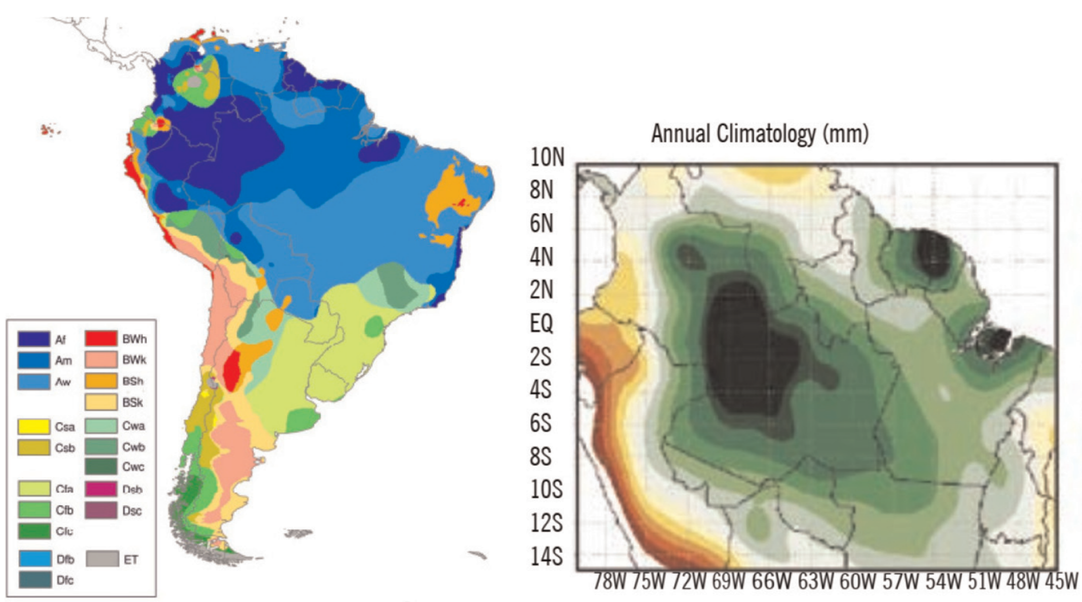


Figure 1.
Distribution of the main biomes of the International Amazonia in South America [3].

approximately 22% of the world's total species [8]. The Brazilian fauna is also very diverse, with approximately 524 species of mammals, 517 of amphibians, 1622 of birds, 468 of reptiles, more than 3000 species of freshwater fish, and 10–15 million species of insects [8].

The climate of the International Amazonia is classified as humid equatorial—Af, Am, and Aw [9], as shown in **Figure 2a**. The average temperature is between 24 and 26°C, and the annual range is between 1 and 2°C. The rainy season of most of the Amazon Basin is between November and May, and the dry season runs from June to September. In the rainiest months, the relative humidity varies between 80 and 90%, and during the dry season, it reaches at least 75% [10]. **Figure 2b** shows the average annual rainfall accumulation throughout the region. Maximum precipitation values above 2500 mm per year are observed in the Northwest sector of the Amazon Basin and on the North coast [11].

The Amazon River Basin (ARB) hosts the largest tropical forest and natural drainage basin on the planet (formed by large rivers and those of smaller volume, locally known as *igarapés*). Its drainage area covers more than a third of the South American continent, and the discharge of the Amazon River is responsible for almost a fifth of the total discharge of all rivers in the world. This basin contains several subbasins, the most important being the Negro and Madeira Rivers (**Figure 3**) in the North and Southwest, respectively [12]. As seen in this figure, the Amazon River Basin is a large plain, with a predominant altitude below 250 m. The extents of the areas periodically flooded in these regions depend on the size of the basins, the river flow, the slope, and the geomorphology of the adjacent lowlands, and they vary in width from a few hundred meters to 100 km [13]. The vertical amplitudes of the flood pulses [14] are larger in the central part of the Amazon Basin, reaching approximately 10 m, near the confluence of the Solimões and Negro Rivers ("Meeting of the Waters"), but may reach up to 15 m in some regions [15]. These floods affect many roads in the region, lowering the stability of the road embankments, especially in the ebb cycle (lowering of the water level of the watercourse, lasting 4–6 months), which may induce the



(a) (b)

Figure 2.
(a) South American climate classification [9]; (b) average annual rainfall in the International Amazonia [11].

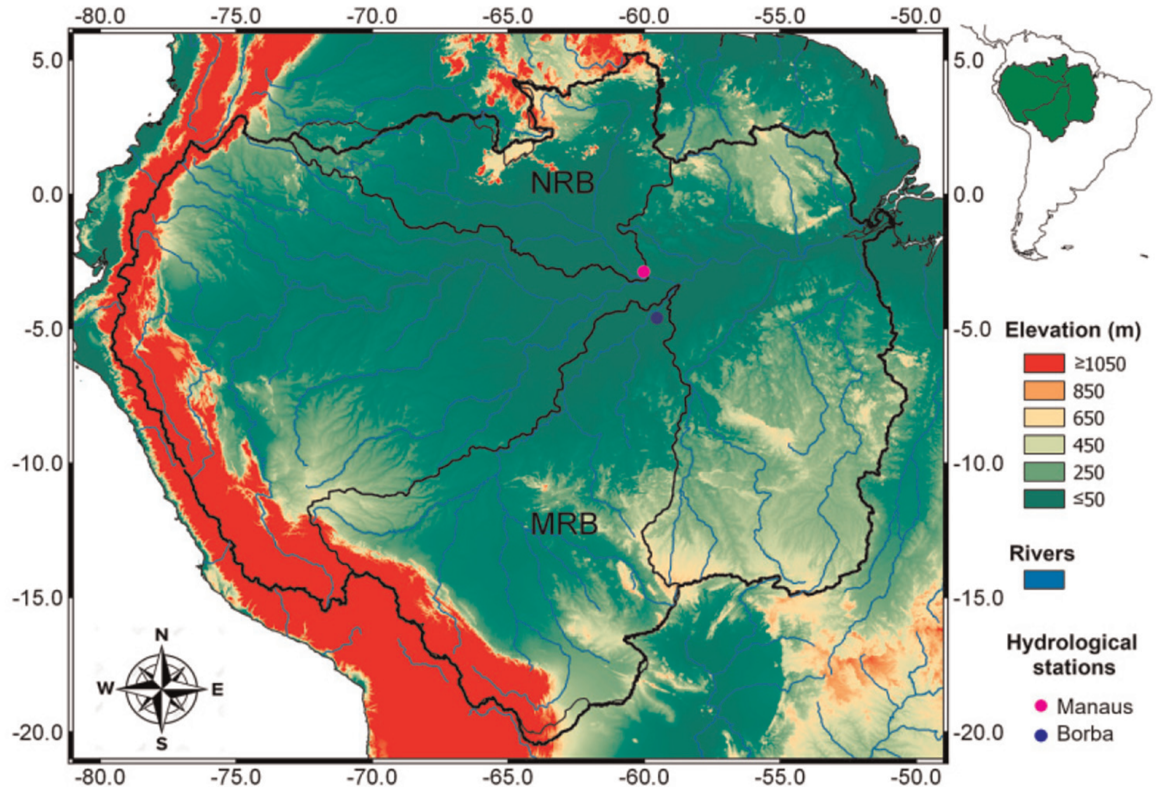


Figure 3.
Amazon River basin (ARB) and its respective elevations [12]. Negro River Basin (NRB) and Madeira River Basin (MRB).

rupture of the natural slopes and embankments [16]. Approximately 72% of the area of the Amazon Basin has a slope between 0 and 8% [17].

Upland forests represent approximately 83% of the Amazon Basin and are located above the maximum levels of the seasonal flooding of rivers, lakes, and large streams. The floodplain forests are seasonally flooded by nutrient-rich white-water rivers for 6–8 months, and water level fluctuations can reach up to 15 m, covering approximately 7% of the Amazon Basin [18]. The floodplain areas have different altitudes in the interior of the basin, all lower than 30 m altitude, close to the “Meeting of the Waters.” **Figure 4** shows a typical cross section of a river in the Amazon Basin [19].

In the Amazonia, approximately 75% of the topsoil (0–50 cm) of the region is formed predominantly by a fine fraction of silts and clays [17], in both the upland (*terras firmes*, **Figure 4**) and lowland areas (*várzeas*). The latter are recent alluvial deposits, with a high amount of organic matter incorporated in the voids; sometimes, these deposits of low bearing capacity extend for tens of meters below the ground surface. Often, mineralogy shows the presence of expansive clay minerals, which show great shrinkage after drying (**Figure 5a**); sometimes they have a dispersed structure [20] that liquefies under the vibration of earthmoving equipment (**Figure 5b**). Generally, *terra firme* soils show pedogenetic evolution of lateralization (colors in red tones) (**Figure 6a**), but this process is not observed for *várzea* soils (**Figure 6b**).

Much of the soil diversity in the Amazon originated from the considerable differences in geology and the history of geomorphology that have arisen throughout the ARB [21]. These authors classified soils according to the main factors that condition their morphological, chemical, and physical properties. Thus, to demonstrate the diversity of Amazonian soils, each of the 14 different reference soil groups surveyed

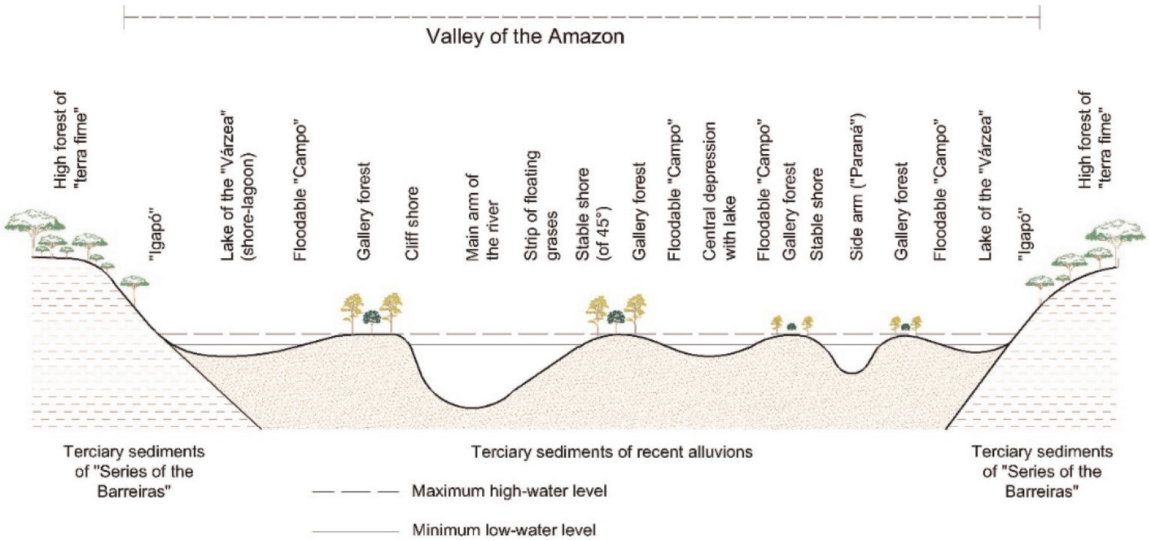


Figure 4.
Schematic representation of some local denominations of flooded and non-flooded areas in the Amazon Basin (adapted from Ref. [19]).

Figure 5.
(a) Topsoil after natural drying. (b) Loss of resistance of soil with a dispersed structure (right) (photos: NS Campelo).

was summarized by limited weathering age, humid tropical climate, topography, and drainage and source material.

The natural drainage network formed by the ARB makes the rivers the true "roads" that connect the various interior cities to the capitals. In the Legal Amazon (formed by nine Brazilian States), the few existing federal roads (**Figure 7**) were opened slightly more than 60 years ago as part of the physical integration project of the national territory [22], in a time of strong deforestation for agrarian colonization, opening of fronts for agriculture, and predatory logging, a time that was characterized by the lack of concern about the deforestation of the native forest.

Deposits of commercial rocky materials are limited to regions outside the Amazon Sedimentary Basin. Therefore, the coarse aggregate (crushed stone or pebble) is an input that makes paving services more expensive, given the large distances it needs to cover [23, 24]. **Figure 8** shows the locations of the pebble extraction and crushed stone exploration areas in the state of Amazonas.

(a) (b)

Figure 6.
Vicinal roads were built on (a) terra firme *(upland area) (lateritic soil), and (b) on* várzea *(floodplain area) (photos: NS Campelo).*

Figure 7.
The most important federal and state highways are located in the Brazilian Legal Amazon [22].

In the Brazilian Amazonia, roads increase access to the forest, which is followed by deforestation with its ecological impacts [25–27]. The main roads have opened forest areas for settlement and resource extraction [28] and agricultural and timber activities [4], and most of the deforestation occurs in the areas less than 100 km from the main highways under the federal development program, which concentrates almost 90% of

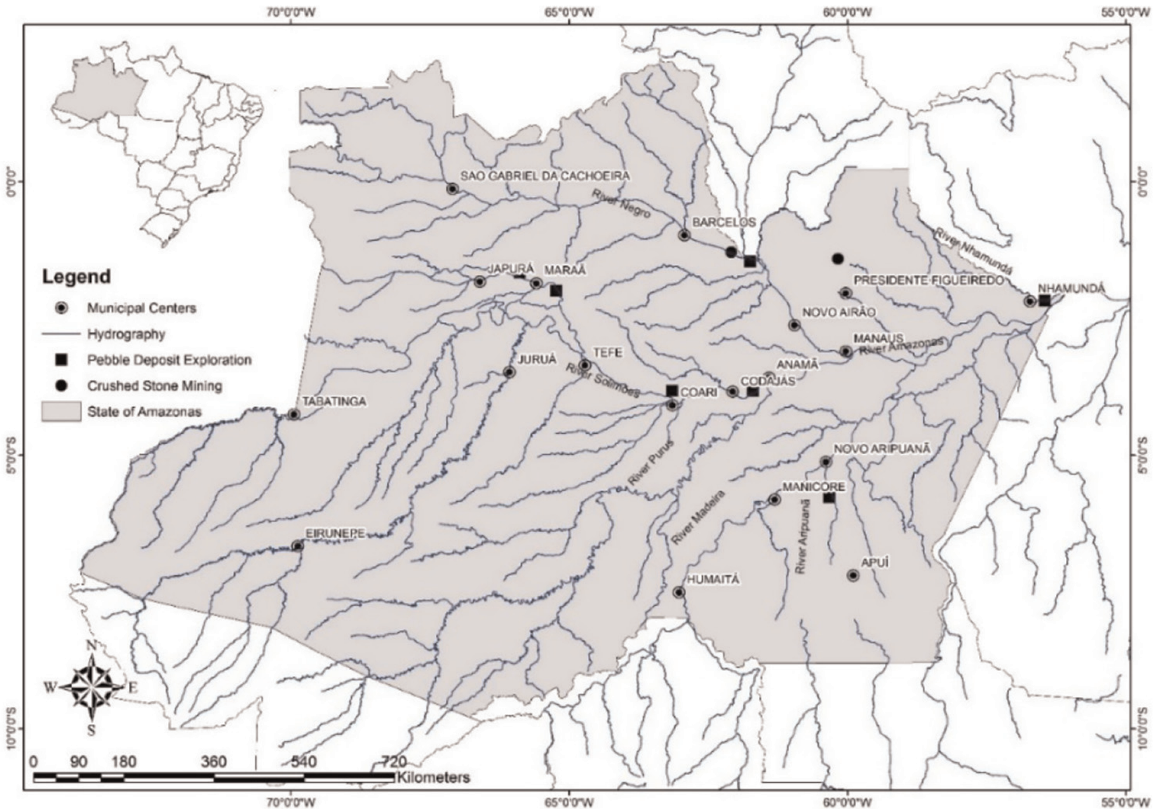


Figure 8.
Locations of natural coarse aggregate (crushed rock and pebble) extraction in the State of Amazonas, Brazil [23].

the deforestation measured [29]. However, there are more serious cases, in which 94.9% of all deforestation analyzed occurred in a well-defined accessible zone within 5.5 km of some type of road or 1.0 km of a navigable river [28].

Brazil has approximately 1.7 million km of federal, state, and municipal highways, of which only 12.4% are paved [30]. In the Legal Amazon, there are approximately 274,000 km of highways (**Figure 7**), and if the same proportion applies as does at the national level, then only 34,000 km of them are paved.

The National Department of Transportation Infrastructure (DNIT) is the official regulator of Brazilian federal highways. According to the requirements of this organ, the granular layers of the pavement should have a minimum thickness of 15 cm, with minimum California Bearing Ratio (CBR) values and maximum expansions provided in **Table 1**, as a function of the pavement layer.

Thus, as seen in the previous paragraphs, the construction of highways in Brazilian Amazonia is problematic. The obstacles can be grouped into:

- Natural: high annual rainfall; large natural drainage basin (rivers, lakes, channels, and *igarapés*), with large floodplains (*várzeas*) with annual flood cycles of 6 months or more; high vertical amplitude of flooding, approximately 10–15 m; low slope of the region (<8%); lack of natural stone material; silty and clayey topsoils, with low permeability, sometimes associated with expansive clay minerals with a dispersed structure;

- Technical: natural foundation ground (subgrade) composed of soils with low bearing capacity and poor drainage;

Layer	CBR	Compaction energy	Expansion	Standard
Base	≥80%, for N > 5·106	Modified	≤0.5%	DNIT 141/2010—ES
	≥60%, for N ≤ 5·106			
Subbase	ISC ≥ 20%	Intermediate	≤1%	DNIT 139/2010—ES
Reinforcement of the Subgrade	CBR > than that of the Subgrade	Normal	≤1%	DNIT 138/2010—ES
Subgrade	CBR ≥ 2%	Normal	≤2%	DNIT 108/2009—ES

Table 1.
CBR and pavement layer expansion values.

- Economic: inputs (aggregates and construction materials) are expensive due to the lack of occurrence of suitable materials and the long transport distance between the source and the construction site;

- Environmental: deforestation and ecological impacts on fauna, flora, soil, and water quality.

2. Literature review

2.1 Regional and local geology, pedology, and natural drainage of the Brazilian Amazonia

The Amazon Sedimentary Basin (ASB) is an intracratonic sedimentary unit that borders two main areas of the Archean-Proterozoic basement—to the North, the Guianas Craton, and to the South, the Brazil-Central Craton [31]. The ASB is geologically characterized by an extensive Phanerozoic sedimentary cover distributed in the Acre, Solimões, Amazonas, and Alto Tapajós Basins, which were deposited on a Precambrian rocky substrate, where rocks of igneous, metamorphic, and sedimentary nature predominate [32]. **Figure 9** shows the tectonic map of South America [33].

With a drainage area of 6.10^6 km^2, the Amazon River Basin (ARB) is the largest hydrographic basin in the world, covering approximately 5% of the planet's land. The Amazon River has an average annual flow of approximately 210.10^3 m^3/s, contributing approximately 20% of the annual global freshwater discharge to the ocean. Considering its enormous scale, it is not surprising that among the 10 largest rivers in terms of water discharge in the world, four mega-rivers (defined as those with a mean annual discharge $>17\cdot10^3$ m^3/s) flow into the ARB (i.e., the Amazon, Madeira, Negro, and Japurá rivers), and 24 of the 34 largest tropical rivers also flow through it [34].

The Amazon River rises in the Eastern Cordillera of the Peruvian Andes, at an altitude of approximately 5300 m, and throughout its course, it has many tributaries, the most important of which are the Ucayali and Napo in Peru, and the Javari, Juruá, Purus, Madeira, Tapajós, Xingu, Içá, Japurá, Negro, Trombetas, and Jari in Brazil. In part of the interior of Brazil, the Amazon River is called the Solimões and has, as tributaries of the left bank, the Putumayo-Içá and Caqueta-Japurá Rivers that were born in the Andes of Colombia. On the right bank is the Javari River, which marks the border between Brazil and Peru; the Jutaí, located in Brazil; and the Juruá and Purus, with their sources in Peru. Near the city of Manaus, State of Amazon, the Solimões

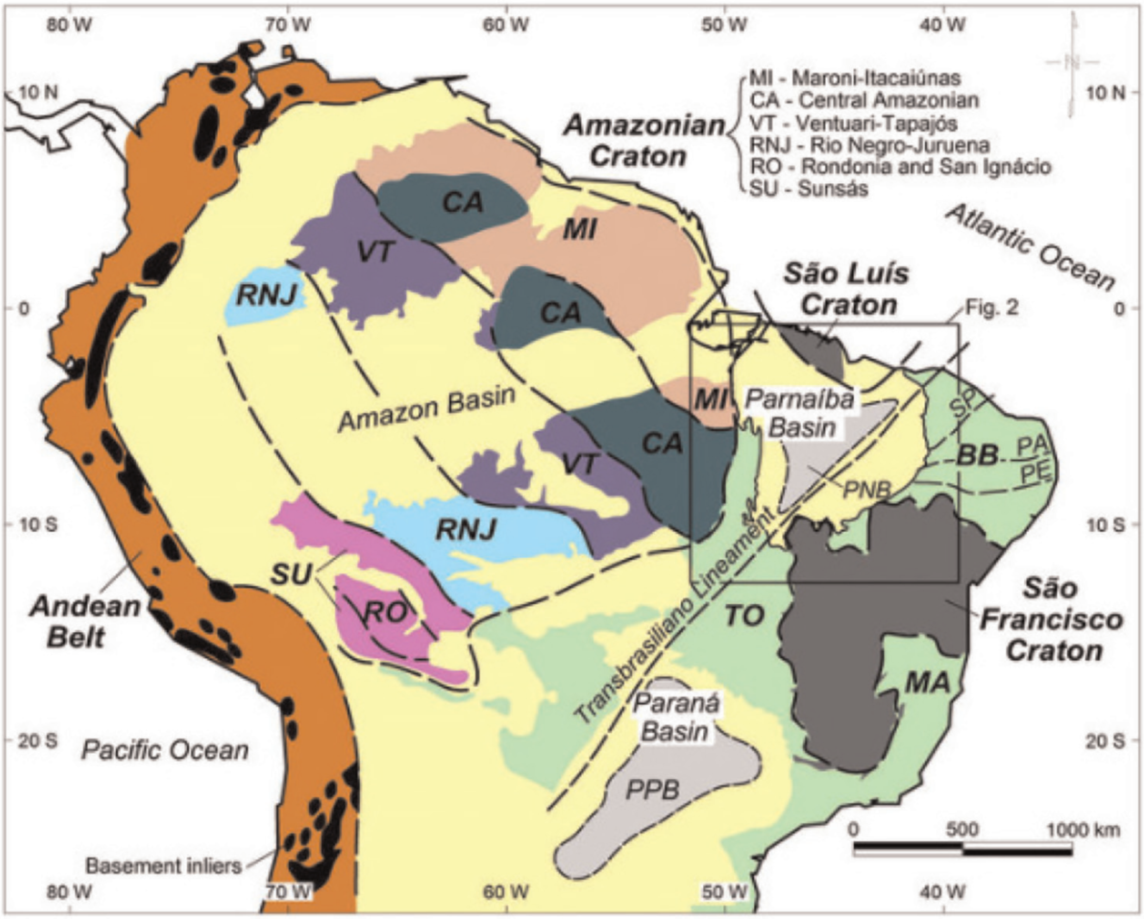


Figure 9.
Simplified tectonic map of northern and southern South America [33].

River, together with the Negro River, forms the Amazon River, in what was conventionally called the "Meeting of the Waters." The Negro River rises in Colombia at an altitude of approximately 1660 m. The Madeira River, which drains the Eastern Andes of Bolivia and Peru downstream of Manaus, joins the Amazon River on its right bank [35–37]. **Figures 7** and **8** show part of the tributaries of the ARB.

This region is characterized by a great diversity of aquatic environments gathered in the same watershed. The variety of environments is related to the size of the natural drainage area and their strong relationship with environmental factors, relief, pedology, soil, climate, and the different types of vegetation present around the rivers and streams, which are responsible for the notable difference in the composition physics and chemistry of waters [38–41].

In the Shield region, the Amazonian soils are well drained, but in the ASB, in relation to their drainage capacity, they may appear poorly drained, imperfectly drained, or well drained [42, 43]. **Figure 10** shows the main groups of soils found in the International Amazonia [21]. The main classes of soils found in the Brazilian Amazonia are latosols (oxisols) and argisols (ultisols), representing approximately 75% of the superficial soils of the region [44]. Schaefer et al. [45] stated that the distribution of Amazonian soils is marked by geomorphological control—upland and flattened residual geoforms of low plateaus are commonly associated with red–yellow latosols in areas of crystalline rocks or with yellow latosols in areas of Tertiary sediments. In the middle and lower thirds of the hills or flattened residuals, there are argisols, with or without plinthite or petroplinthite, as well as quartzarenic neosols

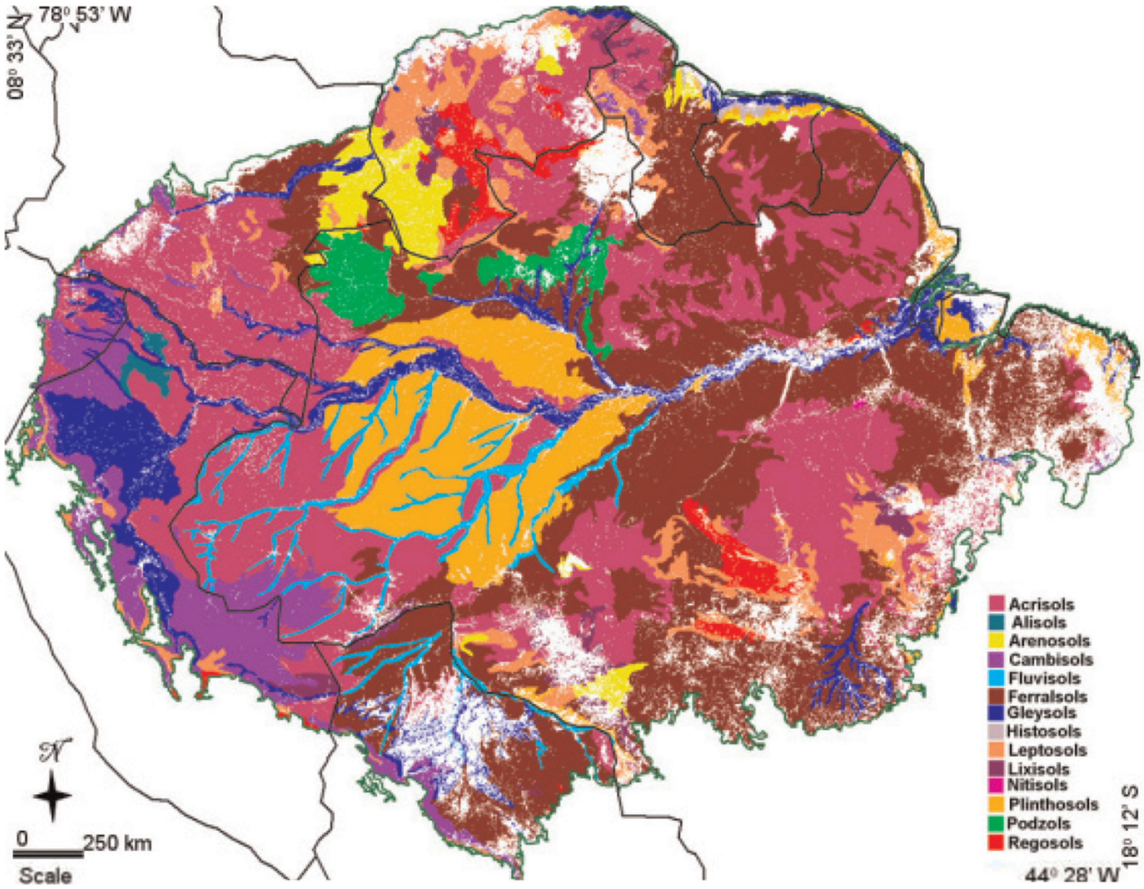


Figure 10.
Soil distribution map of the Amazon Basin, based on the SOTERLAC-ISRIC database [21].

and spodosols. In the floodplain of white-water rivers, gleysols and Fluvic neosols predominate. Plinthosol soils predominate in the lowlands of the Upper Amazon River and in the Madeira/Purus/Juruá and Solimões/Japurá interfluves.

The chemical and mineralogical characteristics of Amazonian soils are largely dictated by the nature of the source material. Extensive areas of rich and eutrophic soils only exist where there is a current (alluvial plain) or past influence (terraces and low plateaus of the Acre and Upper Amazon River Basins) of Andean sediments or where rocks of higher chemical richness emerge (limestones and marls in Monte Alegre-Ererê; basalts and diabases in Roraima, Pará, and Amapá States). In general, in the other areas, the current bioclimatic conditions, the characteristics of the source material, and the geoforms lead to the formation of deep and weathered soils [46].

2.2 MCT classification of tropical soils

The technical deficiencies in the highways of the Amazonia are the result—for the most part—of the use of local materials analyzed under the same experimental techniques based on research carried out in regions of low temperatures (temperate climate) and well-distributed rainfall throughout the year; this condition is totally different from the climate of the equatorial zone, which is characterized by intense climatic variations, high temperatures, and high rainfall incidence [47]. In addition, the traditional soil classification systems—TRB and USCS—disregard the essential evaluation of the mechanical and hydraulic attributes of geomaterials [48]. The use of those conventional methodologies for the classification of natural materials for application in road pavement results in the neglect of materials with potential properties for use in pavement layers when the object of study is tropical soils [49]. As an alternative, in the last three decades, several scientific studies have confirmed the importance of adopting the MCT system (nomenclature for Miniature, Compacted, Tropical)—created by Nogami and Villibor [50]—for the study of fine-grained tropical soils. The main purpose of the MCT methodology is to provide an understanding of the importance of rationalizing the use of tropical soils on highways, to reduce the costs of road work and its impacts on the environment, and establish the difference between lateritic soils (oxisols) and saprolitic (argisols) [51].

The MCT methodology has undergone several modifications over time to improve this classification system for practical road purposes, taking advantage of the lateritic tropical soils, which are abundant in many areas of Brazil [52–54]. It has a structured laboratory test program that is composed of the Mini-MCV and Mass Loss by Immersion with both tests carried out on compacted miniaturized samples. These tests yield the values of classification indexes c′ (determined from the deformability curve slope), d′ (angular coefficient of the dry side of the compaction curve, corresponding to 10 blows), e′ (laterization index), and Pi (mass loss by immersion, in %). These values are graphed and placed in a classification abacus (**Figure 11**), which performs a pedological separation of the materials.

On the other hand, it is worth noting that tropical soils also have horizons of occurrences consisting of, in addition to the fine-material content, a portion of coarse granulation formed by a gravel fraction of lateritic concretions (known as *piçarra*, in Brazilian Amazonia region). For this reason, Villibor and Alves [55, 56] suggested a new classification (termed G-MCT), considering the fine and coarse granulation contents (the distribution of the particle size is determined by the integral soil particle size tests and the G-MCT abacus), whereas the original MCT classification addresses only the percentage of fine-grained material. **Figure 12** shows the structure of the test program for the new G-MCT classification proposed by the authors (**Figure 12a**) and the classification of the coarse materials by particle size (**Figure 12b**). The connection of associated parameters in the G-MCT system aims to qualify the analysis of the results that determine the classification of the material, letting verify the feasibility of applying the material to the base and subbase layers.

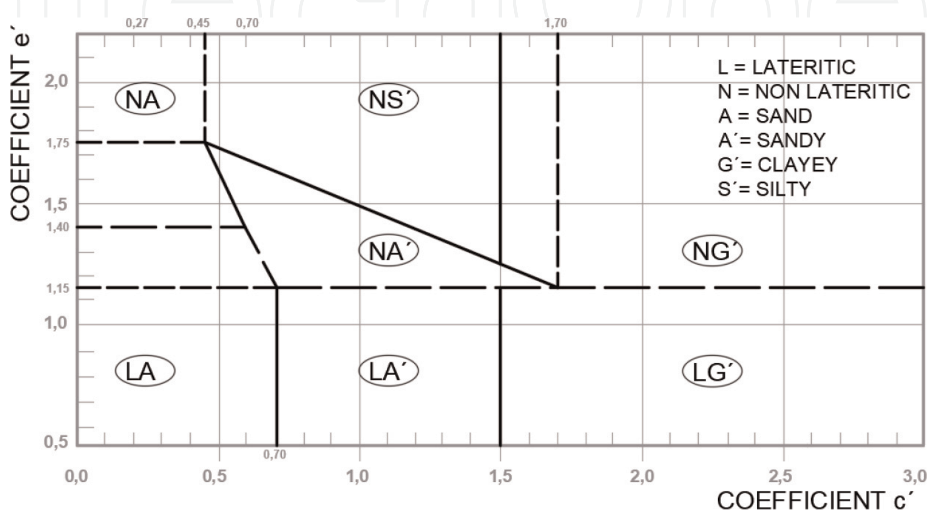


Figure 11.
Graph for soil classification by the MCT method (adapted from [52]).

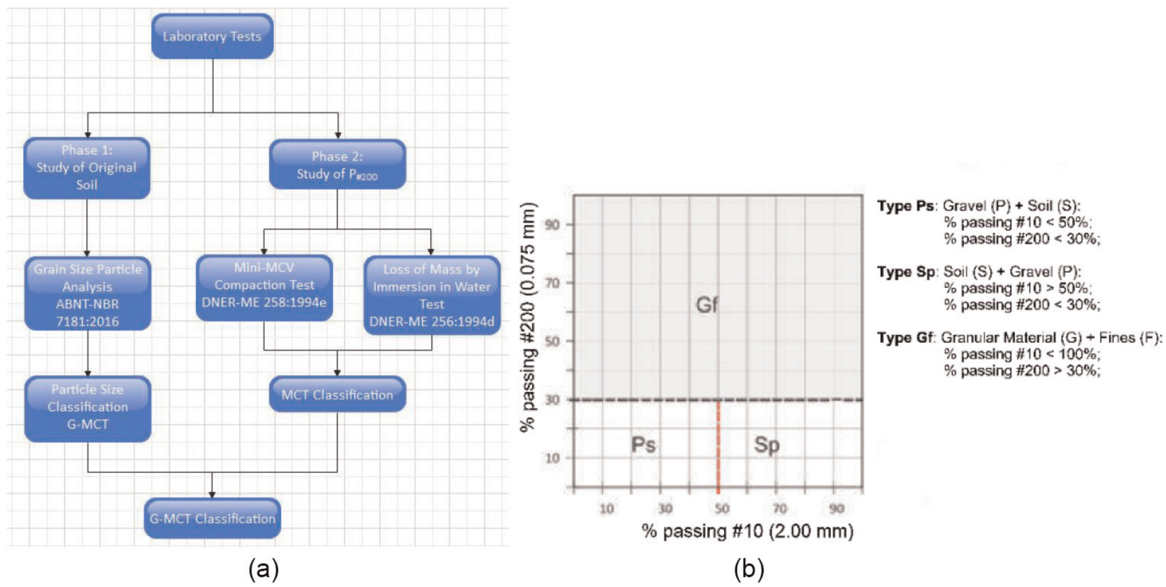


Figure 12.
Test program for the G-MCT classification. (a) Flowchart; (b) classification (adapted from ref. [56]).

Vertamatti [57] conducted the first study of the MCT methodology for Amazonian soils, evaluating the use of fine and coarse (lateritic concretions compatible with the gravel fraction size) texture of lateritic soils in airport projects in the Brazilian Amazonia. He found that the soils generally showed good stability against the water (rains) influence due to the fine plastics present, resulting in a cohesive structure responsible for the great durability of the base layer of airports runways without asphalt course, even under successive periods of heavy rains in the region.

Sant'Ana [58] studied 20 samples of lateritic soil in the State of Maranhão to compare the mini-MCV test and the "rapid disk" method, a test proposed by Nogami and Villibor [59] in which a fraction of soil passed through a #40 (0.42 mm) sieve is molded in a stainless steel ring, measured its contraction (after drying in an oven), and penetrated by a standard needle (after saturation in water), within the MCT methodology. The author found a better classification relationship of the lateritic soils with the results of the mini-MCV test.

Santos and Guimarães [60] evaluated the mechanical behavior of coarse lateritic concretion soils used in road paving in the city of Porto Velho, State of Rondônia, Brazil. These authors found high values of resilient modulus (between 350 and 600 MPa) and low values of permanent deformation of these soil types. In the study made by Barbosa [61], the MCT methodology was applied to soil samples collected in a deposit located in the city of Rio Branco, State of Acre, Brazil, for the production of a synthetic coarse aggregate of calcined clay (SCACC), and mixtures for base courses. Baia [47] and Baia et al. [51] performed a comparative analysis between the tests of the USCS and TRB and the MCT soil classification systems, with geomaterial samples collected from the rural zone (lateritic soil) and the margin of *várzeas*, in the city of Manaus, State of Amazonas, and found good results for the use of lateritic soil in road works.

Almeida [72] evaluated a tropical clayey soil collected from a deposit in the metropolitan region of the city of Manaus using the MCT methodology for the application of the material with a chemical additive (synthetic zeolite cement) as a solution for low traffic volume rural road.

Delgado [62] studied the application of an essentially clayey soil with a high plasticity index for use as a subballast layer in an expansive stretch of the Carajás Railway in the

Western region of the State of Maranhão. This soil would be discarded for the proposed purpose, considering the conventional standards of subballast selection, imported mostly from temperate climate countries. However, due to its tropical soil nature, the results obtained indicated high resilience modulus and low total permanent deformation values, showing that it is a material that, despite not meeting the criteria of traditional soil classification systems, would be adequate for use in the real field situations.

Although normalized by highway agencies in Brazil, there is still a lack of details about the MCT methodology of Brazilian tropical soils. It is important to continue efforts that yield new field and research data to define the geotechnical classification of these types of soils [56].

2.3 Stabilization of Amazonian soils with chemical additives

Before, during, and after floods caused by river floods or intense rains, the quality of the road infrastructure is essential [63]. During these events, pavement layers consisting of nonconsolidated (flexible) materials are more susceptible to erosion, while consolidated (rigid) materials are prone to failure when the lower layers are subject to erosion. Thus, evaluating pavements consisting of the *in situ* transformation of natural subgrade in a rigid base layer with cement and specific additives may be an option for regions with a lack of stone materials and flood risk. Some studies have shown the benefits, even in subgrades of low bearing capacity [64] of a reduction in the final thickness of the asphalt course.

The properties of cement-stabilized materials are strongly determined by the nature of the raw material used, which may be clay, silt, sand, or gravel. The type of soil influences the choice of stabilizer and controls the structural properties of the stabilized product. To a large extent, the variability of soil properties comes from the particle size distribution, arrangement of the particles, shape of the grains, and mineralogical composition [65].

Soil-cement structures are prone to hydraulic retraction, especially during the moisture loss caused by cement hydration or temperature changes. The accumulation of cracks caused by shrinkage can accelerate the damage to the pavement, the erosion processes, and the reduction of the strength and durability of the base layer. Conversely, the addition of synthetic zeolite (ZS) additive, together with cement, for *in situ* soil transformation modifies the cement hydration process on a nanometric scale, improving the formation processes of the crystalline microstructure, exchange ionization, adsorption, and immobilization of potentially harmful compounds in soils that, in a traditional approach, would need to be removed or discarded, at significant cost, making them relevant and suitable materials to be used in road construction [66] (**Figure 13**). ZS additives can increase the strength and stiffness of the soil–cement composites and improve the overall performance of the stabilized layers of pavement [67–69]. In the State of Amazonas, laboratory tests performed in clayey soils have revealed a gain in simple compressive strength (SCS) tests when adding ZS (RoadCem®) to its composition [70–72]. For field application, this additive is used at a low dosage (1.2–2.4 kg/m^3) [73]. The dosage of the additive can be increased based on the local conditions, such as the soil characteristics, the time of the opening of traffic, and the climatic conditions present during construction.

Figure 14a shows scanning electron microscopy (SEM) images of soil stabilized with 8.2% cement, without additive, and with 0.174% ZS additive (RoadCem®) (**Figure 14b**) for the submerged curing condition. The samples were cured for 28 days, and the products of cement hydration and pozzolanic reactions (cation

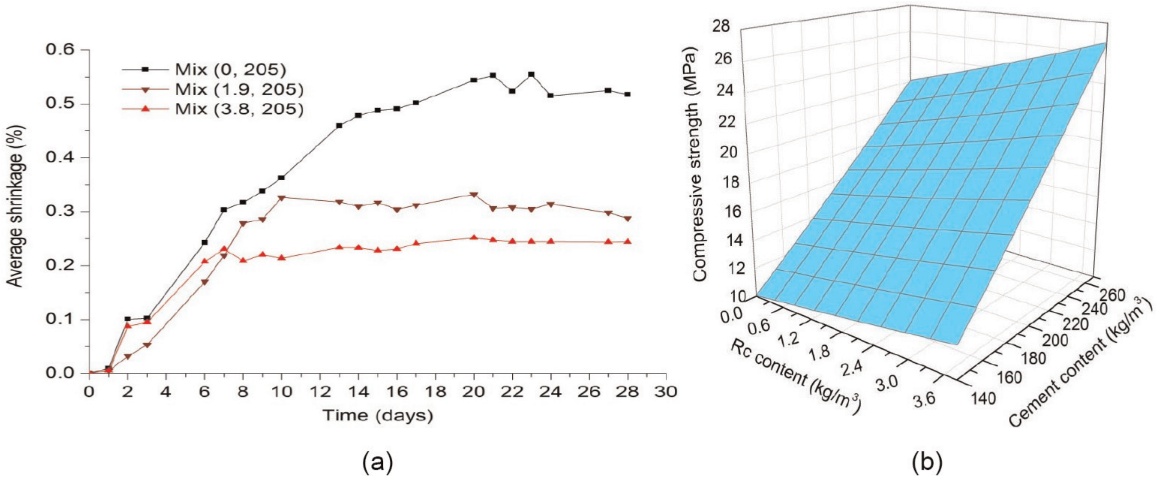


Figure 13.
(a) Effect of synthetic zeolite on shrinkage reduction and (b) on SCS gain as a function of dosage (adapted from [73]).

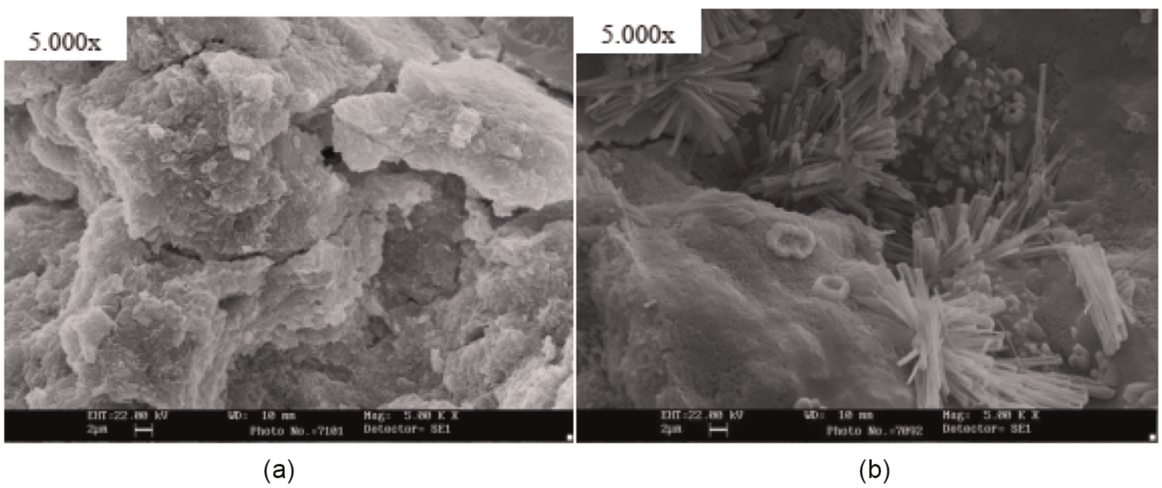


Figure 14.
Scanning electron microscopy (SEM) images of stabilized soil with 8.2% cement: (a) without; and (b) with RoadCem® additive, for submerged curing at 28 days [72].

exchange and flocculation) already took place, joining the flocculated clay particles. A denser and more complex structure was observed in the samples with additives, indicating a greater amount of cement hydration products. Ettringite crystals (calcium sulfate and hydrated aluminate, with a size of 1 μm) were formed in needle shape in samples with the ZS additive under both curing conditions.

2.4 Synthetic coarse aggregate of calcined clay (SCACC) in road paving

The execution of the base, subbase, and asphalt courses consumes a large volume of coarse aggregate. As explained in Item 1, there is a shortage of natural stone material (crushed stone or pebble) in the ASB, so there is a high cost of road paving construction services in this area.

The process of producing light expanded clay aggregates in a rotary kiln began in 1908 [74]. Depending on the clay mineral constituent of the raw material there are some types of clay that, when burned at temperatures below 800°C, do not generate light aggregates but only a calcined, coarse synthetic aggregate that is not expanded

[75]. This latter material is designated here as SCACC [76] or "burnt clay" and can be used both in pavement subbases and bases, and in asphalt coatings and surface treatments [77].

The Texas Highway Department established a classification system for synthetic clay aggregates [78]. Moore et al. [79] stated that the firing temperature to produce the calcined aggregate should in general lower than that of the expanded clay aggregate, only hot enough to completely dehydrate the clay, approximately 550–750°C, for approximately 15 min.

There are reports of the use of SCACC in Nigeria [80], English Guiana, Sudan, Australia [81], and Thailand [82]. Their results showed greater durability of the road pavings using SCACC, in addition to better skid resistance, than with the conventional aggregate.

In Brazil, research on light aggregates has been done since 1966 [83]. Fabrício [84] developed a mobile prototype plant for the manufacture of expanded clay aggregates or SCACC in road paving works in Amazonia. Campelo et al. [85] demonstrated—from laboratory tests—the technical, economic, and environmental feasibility of using SCACC in asphalt mixtures burning *in natura* clay from the potter pole of the cities of Iranduba and Manacapuru, State of Amazonas. Cabral et al. [86] reported the use of SCACC in structural concrete of Portland cement in the State of Amazonas, concluding that the mechanical strengths were similar to those with natural aggregates (pebble) with the same cement consumption.

Campelo et al. [23] studied SCACC because it is an alternative material that offers a competitive price in relation to the conventional aggregate (crushed stone or pebble), in addition to the fact that the raw material is a *várzea* clay, which is an abundant

Material	Brazilian standard	Title	Acceptance Parameters
SCAAC	DNER—ME 225/94	Synthetic aggregate of calcined clay—Pressure slaking test	Less than 6%
SCAAC	DNER@—ME 222/94	Synthetic aggregate of calcined clay—Los Angeles abrasion test	Less than 35%
SCAAC, Pebble	NBR NM 53/2009	Coarse aggregate—Determination of the bulk specific gravity, apparent specific gravity, and water absorption	Greater than 0.88 and 2.00 g/cm^3; less than 18%, respectively
Pebble	NBR NM 51/2001	Coarse aggregate—Test method for resistance to degradation by Los Angeles machine	Less than 50%
SCAAC, Pebble, Sand, Filler	NBR NM 248/2003	Aggregates—Sieve analysis of fine and coarse aggregates	Within granulometric range
SCAAC, Pebble	NBR 12583/1992	Coarse aggregate—Coating to bituminous binder	Qualitative test (visual analysis)
Sand	NBR NM 52/2009	Fine aggregate—Determination of the bulk specific gravity and apparent specific gravity	Greater than 1.60 and 2.60 g/cm^3, respectively
Filler	NBR NM 23/2001	Portland cement and other powdered material—Determination of density	Greater than 3.00 g/cm^3

Table 2.
Natural and synthetic aggregate characterization tests [23].

mineral resource in the Amazon Basin. This aggregate can be used in the subbase, base, and asphalt courses of the pavement, in addition to the surface and deep drainage layers of the pavement. **Table 2** shows the technological properties that the SCACC must have to be used in pavement layers. Campos et al. stated that the SCACC can be calcined at the temperatures at which bricks and ceramic tiles are normally produced, that is, between 850 and 950°C. For the base or subbase courses, these temperatures may be lower. The asphalt mixtures made with SCACC offer a better fit between their components than those produced with rolled pebbles, favoring greater mechanical strength. The SCACC aggregate, when applied in asphalt mixtures, represents a more resistant structural skeleton than the pebble, although the latter is the most used in the State of Amazonas.

2.5 Stabilization of Amazonian soils with soil-emulsion mixtures

The execution of stabilization with asphalt emulsion consists of two stages, spreading and compaction [87]. According to a study by Klinsky [88], soil-emulsion stabilization can occur in the following combinations:

- Sand-Asphalt: Generates cohesion effect in materials with a fraction passing through the #200 sieve (0.074 mm) of between 5 and 12% and a plasticity index (PI) < 10%;

- Soil-Asphalt: Reduces capillarity and infiltrability in clay-silty and clay-sandy soils;

- Gravel-Bitumen: Provides cohesive effect in materials with a fraction passing through the #200 sieve of <12% and PI <10%.

In the study by Rebelo [89] with a soil sample from the city of Coari, State of Amazonas, it was demonstrated that after 7 days of curing, the addition of asphalt emulsion in the geomaterial provided increased resistance to the mixture. Sant'Ana [58], when evaluating soil samples from the Northwest region of the State of Maranhão, suggested specific guidelines and conditions for the acceptance of materials and dosages for asphalt stabilization. This author recommended determining the "optimum" content through its correlation with the SCS tests or tensile strength by diametral compression (TSDC) tests under the conditions of dry curing (air) and immersion for 7 days. The author considered immersed curing because he observed that specimens with 7 days of air curing showed more resistance, even without emulsion, though the same did not occur when applying immersion in steps that preceded the SCS test, as shown in **Figure 15**.

Soils to be stabilized with high levels of emulsifier should be discarded because they make the stabilization services unfeasible economically [58]. In addition, according to Ingles and Metclaf [90], excess binder impairs the interaction between the grains caused by the lubrication of the particles, thus decreasing the resistance of the mixture.

Baia [47], when evaluating the microstructure of soil samples extracted in the rural area of the city of Manaus, with and without the addition of asphalt emulsion (optimum content of 4%), found a certain volume increase (**Figure 16b**) of the solid-phase soil caused by the inclusion of the emulsion in the intergranular spaces. Similar behavior had been observed in soils of the city of Rio de Janeiro by Miceli Jr. [91], who concluded that the higher the binder content in the soil, the greater the volumetric expansion.

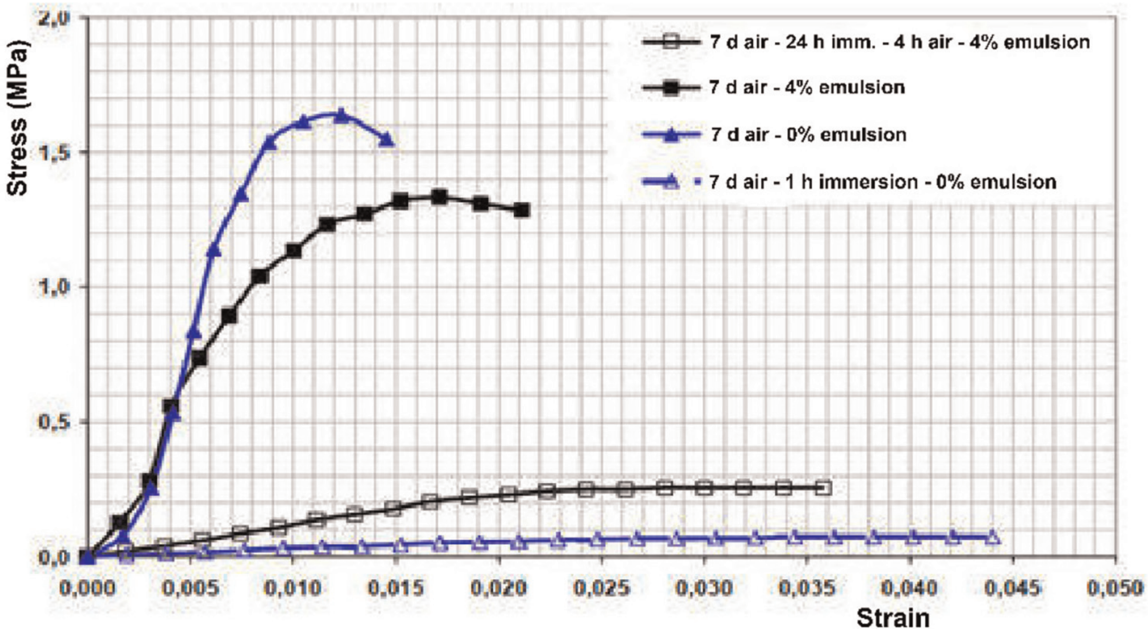


Figure 15.
SCS test results of lateritic soil without emulsion, and with 4% emulsion, with 7 days of curing, immersed and non-immersed [58].

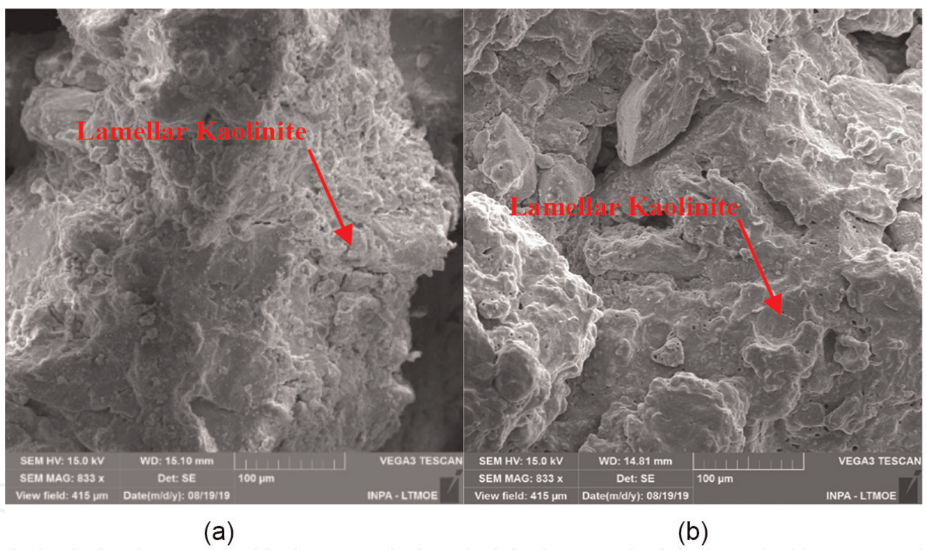


Figure 16.
Scanning electron microscopy (SEM) images—magnified 500× (100 μm). (a) Natural soil; (b) soil with 4% RL-1C asphalt emulsion [47].

2.6 Stabilization of Amazonian soils with ceramic waste

It is common to have a loss in the production process of red ceramics due to several factors, including the failure in the process of mixing and homogenization of the raw material *in natura*, the conformation, drying, and inadequate burning and transport of the product [92].

Waste ceramics are stacked in inappropriate places (**Figure 17**) within the pottery industry yard limits and may be a refuge for venomous and disease-transmitting animals [85]. This material is reused in the pottery industry itself [93], as a reducer of the plasticity of the *in natura* clay [94], or in base and subbase courses of road pavings [95]. According to Campelo et al. [94], the loss of burnt red ceramic products

Figure 17.
Ceramic waste stacked in the pottery yards (photos: NS Campelo).

(ceramic bricks and tiles) in the main production center of the State of Amazonas varied, on average, between 3 and 5% of production, though there were some ceramic industries in which this loss could reach 10%, which at that time would reach a total of 10,000 t/year.

Dias [95] evaluated the mechanical behavior of the typical soil (a yellow lateritic sandy silty-clay) of the city of Manaus, stabilizing it with ceramic waste to apply it in base and subbase courses. This author stated that the loss of red ceramic products (nonstructural and structural bricks, and tiles) was approximately 135 t/day of ceramic waste in the potter pole of the cities of Iranduba and Manacapuru. The author analyzed several soil-ceramic waste mixtures with different proportions, concluding that the mixture with the best performance to be used in the base or subbase course was 30% natural clayey soil, 30% sand, and 40% ceramic waste.

According to the study of Dias [95], based on the proportion of use of ceramic waste determined in the laboratory, it is then possible to construct a base or subbase course 65 km long, with 7 m of platform width, and 10 cm of thickness compacted, considering the bulk density of the ceramic waste as 1.81 t/m^3. Considering the small total length of the urban and rural roads of the interior cities typical of the Brazilian Amazonia (cities with fewer than 30,000 inhabitants in the urban area), this length of 65 km represents a considerable portion of the total of the existing roads in these cities; therefore, the reuse of this waste would bring environmental, economic, and human health gains.

2.7 Reinforced piled embankment in highways of the Brazilian Amazonia

Historically, wooden piles have been used in the Brazilian Amazon, especially since the peak of natural rubber exploitation (1870–1920), in which European companies—mostly of British origin—were responsible for the construction of the infrastructure (concessionaires of water, sewage, electricity, ports, urban transport by electric trams, in addition to the paving of urban and rural roads, buildings, bridges, etc.) in the cities of Manaus and Belém, the two largest capitals of the Brazilian Amazonia.

Until the end of the 1980s, it was possible to use wooden piles for not very high loads in the Brazilian Amazonia, but then, due to a series of restrictions imposed by environmental laws, it is now virtually impossible to use this type of material unless it comes from certified areas. However, it is possible to use other types of piles, such as precast concrete and on-site piles.

A reinforced piled embankment consists of a geogrid-reinforced landfill on a pile foundation; generally, one or more horizontal geosynthetic reinforcement layers are installed at the base of the landfill. This geotechnical solution can be used for the construction of a road or railroad, when a traditional construction method would require a long construction time or when the excavation of soil with low bearing capacity could affect buildings in the neighborhood or even result in a substantial residual settlement, making frequent maintenance of these works necessary [96]. This is an excellent option for sites with natural subgrade formed by thick layers of soils with low bearing capacity, in which it is uneconomical to purge this material, either due to the volume of excavation or the time to be spent in the service.

Unfortunately, although this type of solution had already been used in some road works in the Brazilian Amazonia, this was not documented, except in those found by Silva [97] (**Figure 18**) and Maccaferri [98]. Silva [97] showed the use of wooden piles in a road embankment on a natural subgrade consisting of a very soft clay layer, 35 m thickness, driving the piles with dimensions of 25 cm in diameter and 10 m in length in equal spacings of 1.60 m in the plan. This road embankment is adjacent to a trapezoidal earthen open channel, using a geotextile reinforcement layer above the pile cap of the piles.

2.8 Use of lateritic concretions in road Pavings in the Brazilian Amazonia

According to Swanson [99], the term *laterite* comes from the Latin word *later*, which means brick or tile, and was first suggested by Buchanan because the predominant color of laterite is red and it is often hard. Laterites arose from the decomposition of aluminous minerals by changes that seem peculiar to the tropics due to the action of the tropical forest on the soil. The laterite deposits are geographically restricted because they require tropical heat, intense rainfall, and luxuriant vegetation for their formation. They also require rainy and dry seasons and elevated plains on gently sloping terrain surfaces, which are not subject to appreciable erosion.

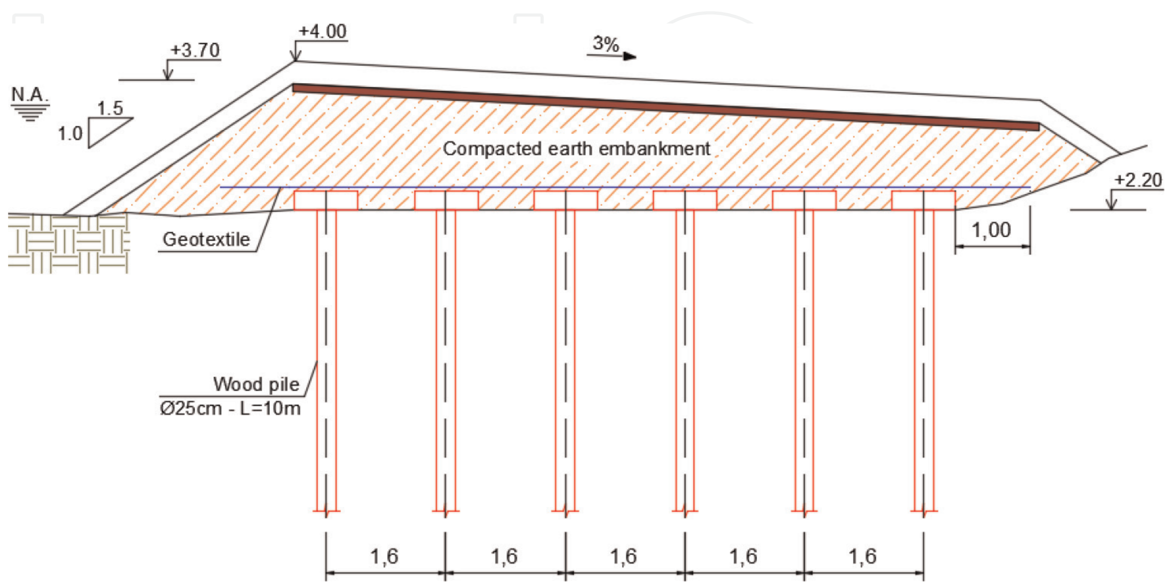


Figure 18.
Use of wooden piles for the construction of a road embankment near the trapezoidal open channel (adapted from Ref. [97]).

Much of the Amazonia landscape developed in lateritic terrain [100, 101]. The mature laterites are strongly leached from SiO_2 and alkalis but enriched in Al_2O_3 and Fe_2O_3 [102–104]. The laterites of the Amazon are masked by thick sandy-clayey to sandy-clayey latosols and/or by sedimentary cover [102, 105, 106]. Laterite profiles typical of the Amazon are illustrated in **Figure 19**, showing their main horizons [107, 105]. Tropical residual soils, especially lateritic deposits, which have been the subject of research in the Amazonia for use in road paving, can also be identified [47, 60, 108, 109] due to their peculiarities in comparison to sedimentary soils, as previously described. Keller et al. [110] stated that the materials commonly used in the Amazonia region for road paving include local laterite deposits but that despite being a hard and cemented material, they may still contain a high clay content. As a paving material, it is widely used for the structural layers of highways, but the first challenge is to locate the deposits with an adequate quantity and quality of the material. **Figure 20** shows some unusual uses of wood for the drainage of small watercourses (*igarapés*) in rural roads with low traffic volume in the Amazonia, such as rustic wooden bridges (locally called *pinguelas*) and "tubes" of drainage formed by hollow tree trunks. Washed coarse laterite (to remove fine grains) has also been used in

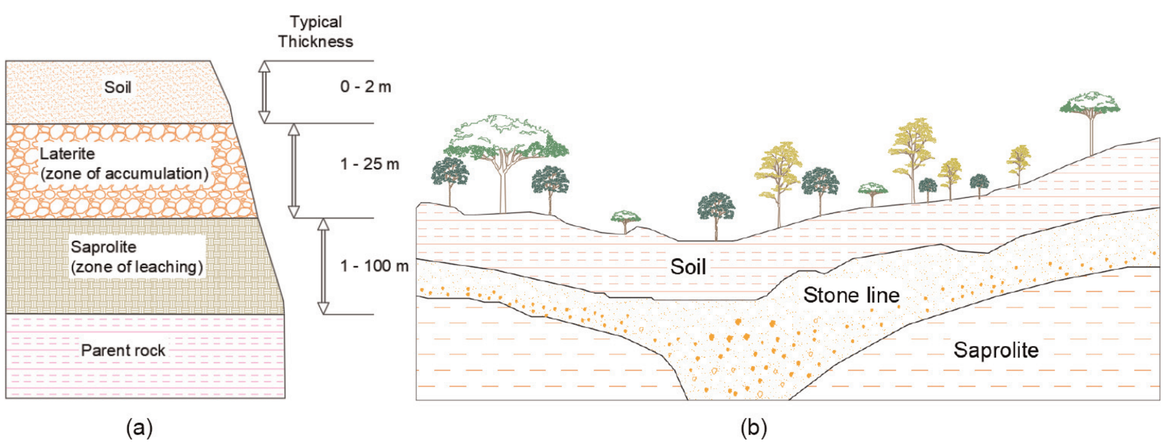


Figure 19.
Typical profile of laterite from the Brazilian Amazonia and its main horizons: (a) adapted from Ref. [107]; (b) adapted from Ref. [105].

Figure 20.
Use of wood in the drainage of igarapés *crossing roads with low traffic volume in the Brazilian Amazonia. (a) Wooden bridge (*pinguela*); (b) hollow wood "tube" [110].*

Brazilian standard	Title	Acceptance parameters
DNER-ME 030/94	Soils-determination of the silica-alumina and silica-sesquioxide relations of soils	≤2
DNER-ME 172/2016	Soils—determination of the California Bearing Ratio (CBR) using deformed and unhandled soil samples	Expansion ≤2% CBR ≥ 80% (N > $5{\cdot}10^6$) CBR ≥ 60% (N ≤ $5{\cdot}10^6$)
NBR-NM 248/2003	Aggregates—Sieve analysis of fine and coarse aggregates	$P_{\#200}$ ≤ 30% $P_{\#200} \leq (2/3){\cdot}P_{\#40}$
DNER-ME 082/94	Soils—determination of the plastic limit	$P_{\#}40$: LL ≤ 40%; IP ≤ 15%
NBR-NM 51/2001	Coarse aggregate—test method for resistance to degradation by Los Angeles machine	≤65%

Notes: $P_{\#200}$, $P_{\#40}$: percentage of particles passing through the #200 and #40 sieves, respectively; LL: liquid limit; PI: plasticity index.

Table 3.
Technical specifications for granulometrically stabilized base services using lateritic soil [111].

asphalt mixtures. **Table 3** shows the requirements for the use of laterite as a natural coarse aggregate in base or subbase layers, according to specifications [111].

2.9 Concepts of unsaturated soil mechanics applied to tropical soils

Much of the tropical topsoil is subject to unsaturated conditions, that is, not all its voids are filled by the aqueous phase. This is true both in the *terra firme* (non-flooded regions) and in the *várzea* (lowlands) areas of the Amazonia when these are not subject to the flood pulse. This unsaturated condition means a different behavior of the soil massif in terms of shear strength, in comparison to that under the saturated soil condition [112].

Many engineering problems involve unsaturated soils. The construction of earth dams, highways, and airport runways uses compacted soils that are not saturated. An element of unsaturated soil can, therefore, be viewed as a mixture with two phases that reach equilibrium under applied stress gradients (i.e., soil particles and contractile skin) and two phases that flow under applied stress gradients (i.e., air and water) [113].

In unsaturated soils, the pore-water pressures are negative in relation to atmospheric conditions; this negative pore pressure is called matric suction when referring to the air pressure [114, 115]. As the soil approaches saturation, the pore-water pressure approaches the pore-air pressure. Therefore, the matric suction tends to zero, and there is a smooth transition to the stress state of saturated soil [114].

Fredlund and Rahardjo [116] reported that in recent years there is a better understanding of the role of negative pore pressure (or matric suctions) in increasing the shear strength of the soil, and that it is appropriate to perform an analysis of slope stability including the matric suction contribution.

Regarding slope stability, Ching et al. [117] reported that soil suction profiles play a significant role in the long-term stability of many natural slopes and steep cutting slopes. However, during or after periods of intense and prolonged rainfall, slope failures often occur because rains cause infiltration in the ground and reduce soil resistance because of matric suction loss. This augments the safety factors by considering the actual matric suctions of the soil, and therefore, they contribute substantially to the increases in shear strength [118, 119] and slope stability in unsaturated conditions [117, 114, 120, 121].

In tropical and subtropical areas, slope failures induced by rain are closely related to soil properties, slope geometry, groundwater position, and certain environmental factors, vegetation, and weathering effects [122]. Thus, the slopes are stable, with a high safety factor during dry periods, and tend to fail only during rainy periods [119].

3. Conclusions

The construction of highways in the Brazilian Amazonia is problematic because it faces nature-related, technical, economic, and environmental issues, which are interrelated.

The natural questions come from a range of origins, the main ones being geological-geotechnical, pedological, relief-related, and climate-related, and obviously cannot be gotten around given their territorial scope. The technical issues concern the natural subgrade, especially in floodplains (*várzeas*), formed by fine alluvial soils (silts and clays), which are plastic, impermeable, highly compressible, or expansive, present in the vast Amazon Basin. The economic issues are related to the costs of transporting stone material and lateritic soils—some with the presence of lateritic concretions (*picarras*)—to the construction sites since they occur in limited portions of the Amazonia (*terras firmes*). Environmental issues fall into a vicious circle since the construction of more highways tends to reach areas of virgin forest, which may be subject to new deforestation processes and other environmental impacts, affecting the rich fauna and flora of the region, in addition to native communities. Luckily, Brazilian environmental laws have become increasingly rigid, requiring in-depth studies of environmental impacts and public hearings before the construction of roadworks is licensed.

Acknowledgements

The authors would like to thank CAPES for the grant of a scholarship for an academic master's degree to the Civil Engineer Daniel Jardim Almeida.

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