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Assessing the Potential for Valorisation of a Pulp and Paper Industry Byproduct for the Construction of Unpaved Forest Roads: A Geotechnical Perspective

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Abstract: Integration of sustainability into industry has encouraged practices of circular economy, reusing and recycling resources. This paper studies alternative solutions to materials traditionally used for unpaved roads, with a byproduct of the pulp and paper industry (not pre-treated), and analyses its valorisation potential from a geotechnical perspective. Two approaches were adopted: (1) assessment of geotechnical properties of base materials (aggregate, local soil and byproduct) and mixtures (aggregate/local soil and byproduct, 3% or 6%); (2) design of the base layer (case study), considering different solutions for the material forming that layer, assessing its height and life cycle. The small incorporation percentages studied changed the geotechnical properties of aggregate and local soil, reducing sensitivity to water and increasing the water content for optimum compaction. The CBR of mixtures reduced with the incorporation of the byproduct. For the case study, incorporation of byproduct (6% maximum) in the local soil did not significantly affect the base layer height. Total replacement with the byproduct is mechanically possible. For the fixed height of the base layer, incorporating the byproduct in traditional materials reduced the unpaved road life cycle, reflecting CBR reductions. From a geotechnical perspective, the valorisation of this byproduct is promising, and from an industry point of view, its use (geotechnical valorisation) represents a way to promote circular economy and sustainability.

Keywords: unpaved forest road; byproduct; California Bearing Ratio (CBR); design; base layer

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1. Introduction

The concept of sustainability has been actively incorporated into various industries, promoting new practices and solutions that consider economic, environmental and social impacts [1]. Thus, reducing waste and dependency on fossil fuels and derived products are key to addressing current societal challenges, such as climate change, rising population and consumption patterns. The concept of circular economy highlights the necessity of reusing and recycling resources, focusing on the decrease of carbon emissions [2].

Among other industries, the pulp and paper industry produces a significant number of residues, wastes and byproducts. The kraft process is well-known for the conversion of wood into wood pulp, producing residues such as dregs, grits, lime mud, biological and mill sludge, fly ash and exhausted sands [3]. Creating innovative approaches that incorporate these materials and encourage sustainable practices is crucial, focusing on efficiently repurposing these wastes and adding new value to their use [2]. Waste valorisation means any process of converting waste materials into valuable resources or products through recycling, reusing or conversion [4]. The aim is to avoid disposal, minimise environmental impacts and simultaneously create economic and social benefits. Some examples of valorisation of wastes and byproducts from the pulp and paper industry have been reported. Skels et al. [5]

considered the incorporation of fly ash from the energy production boilers into an unbound pavement structure, studying the soil stabilisation potential. Modolo et al. [6] considered the binding potential of fly ash in a commercial mortar. Modolo et al. [7] assessed the replacement of traditional aggregates used in a rendering mortar formulation with exhausted sands produced in the same energy production process. Other wastes from pulp and paper fabrication processes, such as paper sludge, have potential uses in biochemical and thermal processes, potentialising the reduction of environmental impacts and generating economic benefits (e.g., [8]). Nienov et al. [9] analysed the benefits of adding waste from the paper industry, combined with the incorporation of an agglomerant (lime or cement), on the geotechnical properties of clay soil.

Roads can be divided into paved and unpaved. Usually, forest roads are unpaved due to low traffic volume, and the investment in the pavement structure tends to be reduced. The main objective of the pavement structure is to ensure the trafficability of a road with adequate levels of safety and comfort, matching the type of road and traffic volume considered in the design. Thus, the pavement structure design needs to consider the characteristics of the materials used to form it, as well as the stresses caused by traffic and climatic conditions [10]. Unpaved roads are formed by two or three layers: subgrade, base, and surface layer (seldom used). The base layer can be formed by a good-quality aggregate, locally available soil, or a mixture of these materials. To increase the sustainability of the solutions adopted, replacing materials traditionally used with wastes, byproducts, or their mixtures with other materials is pivotal. However, most design methods for unpaved roads are not prepared to include these alternative solutions.

In unpaved forest roads, two types of failure may occur: structural and surface defects [11]. The presence of structural defects can be associated with irregular surfaces, large depressions or pavement loss; mostly, they are a consequence of the construction materials and their properties, the road geometry (cross and longitudinal sections), and/or drainage. Surface defects affect the ride quality and include roughness, potholes, corrugations, scouring/erosion, ravelling, rutting, loss of surface material, dustiness, stoniness and slippery surfaces [11].

Most existing design methods focus on structural stability and avoiding structural defects by ensuring a stable foundation for aggregate surfacing due to the application of surface loads (top of the aggregate). The key failure mode is bearing capacity, namely punching or rutting failure. Such failures occur along the soils surrounding the loaded area (Figure 1) and are typical of loose or soft subgrade layers and/or base layers with insufficient height [12]. Thus, the output of most design methods is the height of the base layer that avoids bearing capacity failure for the design loading (associated with traffic conditions and service life of the road) as a function of the shear strength of the subgrade layer and for a given base layer material.

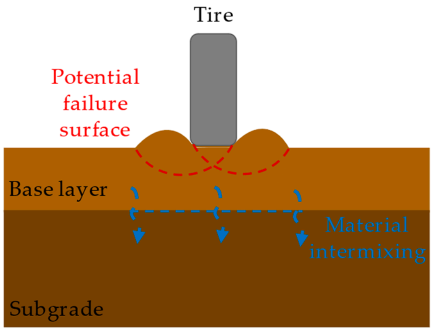


Figure 1. Potential failure surface of an unpaved road.

Over the years, several researchers developed different approaches to pavement design, mostly for paved roads: a traditional, empirical approach and a more recent approach that introduced a mechanistical component in the empirical-base design. Most empirical design methods consider the properties of the materials that form the pavement structure and the stresses imposed by traffic (as a wheel load or equivalent standard axle load) to calculate the height of the base layer. The mechanistic-empirical approach can adapt to more innovative design conditions, such as heavier loads and new pavement materials, allowing for the mechanical behaviour of the materials that form the pavement structure at certain points in the pavement [13]. Usually, the initial investment in unpaved roads (often designated as low-volume roads) is very low compared to higher-capacity infrastructure (paved roads). Typically, unpaved forest roads are formed by the subgrade and a base layer (with no bonded surface layer). Thus, empirical-based design methods are generally used due to their simplicity; nevertheless, designers need to be aware of their limitations [14].

Most empirical-based design methods represent the materials forming the pavement structure and their response to loading by their California Bearing Ratio (CBR) value. The CBR is measured using a standardised laboratory test (e.g., [15]) or directly in the field (e.g., [16]). These two methods lead to different estimates of the CBR. The field test results are influenced by factors such as the existing subgrade soil, and the boundary conditions. The laboratory test includes very well-defined boundary conditions but has other limitations, including the representativeness of the specimens tested and the upper limits to the maximum particle size of the material to be characterised.

Essentially, the CBR test is a bearing capacity test that mobilises both elastic and plastic strains within the soil. The test conditions correspond mostly to a rigid punch. Thus, a uniform penetration of the plunger is expected; the stress distribution at the soil in contact with the plunger will vary with the type of soil tested. Nevertheless, the stresses and strains within the material are heterogeneous, with the coexistence of plastic responses (close to the plunger) and elastic responses; therefore, a proper mechanical interpretation of CBR test results is limited [17]. Some finite element models of CBR tests have shown that, for coarse-grained materials, there is a linear relation between the friction angle of the soil and its CBR value [18]. Traditionally, the CBR value of soil is correlated with its Young's modulus. However, other parameters, such as particle size and shape and compressibility due to particle crushing, are particularly important in the elastic domain [19].

Many unpaved road design methods available in the literature assume that the base layer is formed by a good-quality aggregate. As far as the material properties are concerned, the heigh of the base layer is based on the CBR of the subgrade only (or other similar property). Examples of methods with such an approach include Hammit [20], Giroud and Noiray [21], TM 5-822-12 [22] and Skorseth and Selim [23]. Nevertheless, design methods that consider the characteristics of the different layers forming unpaved roads (base and subgrade) are available in the literature. Examples include the Waterways Experiment Station (WES) method [24] and the method proposed by Giroud and Han [25]. Table 1 summarises the design parameters incorporated in these methods, which include equivalent single axle load (P), the number of axle passes (N), equivalent tyre contact area (A), rut depth (r), CBR of the subgrade (CBR_{SG}) and CBR of the base layer (CBR_{BL}). In the method by Giroud and Han [25], the CBR of the materials forming the base layer has little effect on the design, as the ratio of stiffnesses of the base and subgrade materials is limited to a maximum of five, defined as a function of the corresponding CBR values.

This paper focuses on the geotechnical characterization of a byproduct to assess its potential valorisation for the construction of unpaved forest roads, namely its inclusion in the base layer. Previously, this byproduct has been declassified as waste, to be used as an aggregate to fabricate concrete and asphalt pavements after pre-treatment (washing). Herein, the solutions analysed included a small proportion of byproduct mixed with materials traditionally used to form a base layer, with no previous treatment.

Table 1. Parameters relevant for unpaved road design methods from the literature.

Parameters	Method/Reference					
	Hammit (1970) [20]	Giroud and Noiray (1981) [21]	WES (1992) [24]	TM 5-822-12 (1990) [22]	Skorseth and Selim (2000) [23]	Giroud and Han (2004) [25]
P	Yes	Yes	Yes	No	No	Yes
N	Yes	Yes	Yes	No	No	Yes
A	Yes	No	No	No	No	Yes
r	No	No	Yes	No	No	Yes
CBR_{SG}	Yes	Yes	Yes	No	No	Yes
CBR_{BL}	No	No	Yes	Yes	Yes	Yes

Equivalent single axle load (P); number of axle passes (N); equivalent tyre contact area (A); rut depth (r); CBR of the subgrade (CBR_{SG}); CBR of the base layer (CBR_{BL}).

This study is divided into two parts. First, the key geotechnical properties of the different materials and base layer solutions are analysed via an experimental programme. Two materials traditionally used (aggregate and local soil) and the byproduct selected are studied, as well as mixtures in which the byproduct is incorporated in the aggregate or the local soil. Two values for the incorporation percentage are analysed. Then, the road cross section (namely the height of the base layer) is designed, aiming to assess its variation with the different incorporation percentages of the byproduct studied. For the design of the base layer, a method from the literature [24] was selected, which considers the properties of both the subgrade and the base layer material.

Different solutions for the material forming the base layer are studied: aggregate, local soil, aggregate + byproduct (two values for the incorporation percentage), local soil + byproduct (two values for the incorporation percentage), and byproduct. Using the same design method and for a fixed height of the base layer, changes in the life cycle of the unpaved road analysed are discussed. The case study is included in a wider research project which involves a stakeholder from the pulp and paper industry as a partner. The partner company works in all stages of the process, including forestry activities, forest management, and pulp and paper production. Based on the results presented, the potential for geotechnical valorisation of the byproduct studied is discussed.

2. Materials and Methods

The experimental programme implemented aimed to perform a geotechnical characterisation of the materials studied and of mixtures of those materials. Two materials traditionally used in the construction of unpaved roads are studied: an aggregate and a local soil. The byproduct to be valorised originates from the pulp and paper industry. These materials are presented in Section 2.1, and the methods used for the geotechnical characterisation are described in Section 2.2. The pavement structure of an unpaved forest road is designed adopting the different materials and mixtures studied. The design method selected is presented in Section 2.3, and the case study analysed is described in Section 2.4.

2.1. Materials

The byproduct (BP) to be valorised results from the pulp and paper industry (kraft process), namely from a co-generation biomass boiler with a fluidised bed. Residual particles collected at the boiler's base originate from exhausted sands from fluidised bed boilers. Herein, an exhausted sand from a boiler located in Cacia, Aveiro (Portugal), is studied.

The exhausted sand is formed by the calibrated sand of the fluidised bed and ashes resulting from biomass combustion (in this case, eucalyptus barks). The base sand consists primarily of silica (silicon dioxide, SiO_2, 99%), has a particle density of 2.64 g·cm^{-3} and particle sizes ranging between 0.2 and 1.4 mm. The chemical composition of an exhausted sand from the same boiler has been presented by Gonçalves et al. [26] (percentages by weight): SiO_2 (64.57%), CaO (20.00%), Al_2O_3 (2.86%), MgO (2.16%), K_2O (2.01%), Na_2O (1.69%), Fe_2O_3 (1.24%), P_2O_5 (1.03%), SO_3 (0.55%), MnO (0.39%), Cl (0.22%), TiO_2 (0.22%), Sr (0.05%) and Ba (0.03%). The particle morphology corresponds to an irregular grain form.

This byproduct has been declassified as waste to be used as an aggregate to fabricate concrete and asphalt pavements after pre-treatment (washing). Herein, the focus is on assessing the potential for valorisation of the byproduct from a geotechnical perspective for new applications, such as unpaved forest roads. Its chemical characterisation and potential for leaching are under analysis separately and are not discussed in this paper. If the potential for geotechnical valorisation is confirmed and if necessary (from the chemical perspective), possible pre-treatments (including washing) will be studied. Therefore, in this paper, the byproduct was not submitted to previous treatment, i.e., it was analysed as received.

The traditional solutions used on unpaved roads make use of a base layer formed by a good-quality aggregate and/or locally available soil. The aggregate (AG) selected for this study is supplied by a quarry in Pombal, Leiria (Portugal). In addition, a sample of local soil (LS) from an unpaved road located in the region of Sever do Vouga, Aveiro (Portugal) is used. Figure 2 shows the materials selected for this study.

(**a**) (**b**) (**c**)

Figure 2. Materials selected for the study: (**a**) BP; (**b**) AG; (**c**) LS.

Herein, different scenarios are studied: the base layer formed by each single material (AG, LS, BP) and alternative solutions, namely mixtures of AG and LS with BP.

The aggregates used in the construction of base layers are materials with extended particle size distribution (PSD), i.e., it is a well-graded material. Adding a material with a more uniform PSD (as is the case for BP) will influence the mechanical properties of the mixture. Therefore, in this study, small percentages of BP were considered. Mixtures with two different percentages of BP were analysed: 3% and 6%, in weight, respectively, AG + 3%BP, AG + 6%BP, LS + 3%BP and LS + 6%BP. Each mixture was prepared by adding a mass of BP corresponding to 3% or 6% of the mass of the base material (AG or LS). The materials were mixed by hand until a homogeneous mixture was formed; for the compaction and the CBR tests, the water required for the optimum water content was then added, and the sample was mixed again by hand. The percentages of BP selected are low and were chosen to address possible environmental limitations to the use of this type of byproduct. These limitations are not considered herein and will be analysed in detail in the future. A complementary study is being carried out to analyse the environmental impact of using this byproduct.

2.2. Geotechnical Characterization

The geotechnical characterisation of the different materials and mixtures includes the quantification of physical and identification properties, and of mechanical properties. The latter include compaction properties, load-penetration response and the California Bearing Ratio (CBR) value. The characterisation is performed according to standardised laboratory procedures. The results are used to classify the materials according to two international soil classification systems: the Unified Soil Classification System (USCS, ASTM D2487-11 [27]) and LCPC/SETRA [28], assuming all materials are natural soils. In addition, BP is also classified according to LCPC/SETRA [28], namely using the industrial byproducts classification.

2.2.1. Physical and Identification Properties

The PSD of each material is assessed according to EN ISO 933-1:2012 [29]. From the resulting data, multiple parameters can be determined, including 10%, 30%, 50% and 60% effective particle size diameters (D_{10}, D_{30}, D_{50} and D_{60}, respectively); percentage of fine particles (PFP, i.e., particles smaller than 0.075 mm); curvature coefficient (C_C), Equation (1); uniformity coefficient (C_U), Equation (2).

$$C_C = \frac{{D_{30}}^2}{D_{10} \times D_{60}} \tag{1}$$

$$C_U = \frac{D_{60}}{D_{10}} \tag{2}$$

The particle density (ρ_s) is determined following the pycnometer method described in EN ISO 17892-3:2015 [30] and is obtained from the average of 3 specimens.

To characterise the fine particles of the materials and mixtures considered, Atterberg or consistency limits are used. The tests to measure the liquid and plastic limits (w_L and w_p, respectively) are carried out as described in ISO/TS 17892-12 [31].

Methylene blue tests are carried out to assess the sensitivity of materials and mixtures to water (EN ISO 933-9:2022 [32]). In the same way, the assessment of fines of materials and mixtures was evaluated with a sand equivalent test (EN ISO 933-8 [33]).

2.2.2. Mechanical Properties

The compaction properties of the materials and mixtures, optimum water content (w_{opt}) and maximum dry density ($\rho_{d,max}$) are evaluated through modified Proctor tests following ASTM D1557-07 [34].

Herein, the modified Proctor tests performed followed Method C from this standard, which uses cylindrical specimens (152 mm diameter and 125 mm height). The specimens are formed by five layers of material, each compacted with 56 blows from a rammer of 4.54 kg dropped from a height of 457 mm. To comply with the standardised test procedure, particles larger than 19 mm are removed from the materials and mixtures before preparing the test specimens.

CBR tests are used to assess the load-penetration response and to quantify the CBR value, performed using the procedures described in ASTM D1883-10 [15]; Method C of the modified Proctor test (ASTM D1557-07 [34]) was used to prepare the specimens, as described before.

The specimens were tested unsoaked, and, as in the modified Proctor tests, particles larger than 19 mm were removed before preparing the test specimens. The CBR values reported herein refer to the average of 3 specimens per condition. This parameter is obtained as the ratio of the load measured during the test for a value of penetration of 2.54 mm and the corresponding load for a standard material (13.29 kN).

2.3. Unpaved Road Design Method—WES Method

The WES is part of the United States Army Corps of Engineers [24]. In 1992, WES started to develop a formula to calculate the height of the base layer of unpaved roads based on the work of Barber et al. [35], who had developed work to estimate the rut depth. WES proposed Equation (3), validated using two tests [24]. In the first test, 10 log trucks with a central tyre inflation system were used on a section made up of pit-run aggregate submitted to around 4000 axle passes. The second test was performed during winter/spring; the material tested was an aggregate, the vehicles were log trucks with a central tyre inflation system, and the number of axle passes was low. The WES design method is adequate for the design of the base layer of unpaved roads; however, it has been reported as conservative [24].

$$\log(h) = 0.3241 \times \frac{P^{0.2135} \times {t_p}^{0.2357} \times N^{0.0719}}{r^{0.2334} \times {CBR_{BL}}^{0.2508} \times {CBR_{SG}}^{0.0739}} \quad (3)$$

In Equation (3), h is the heigh of the base layer (in inches), P is the equivalent single axle loads (in kips), t_p is tyre pressure (in psi), N is the number of axle passes, r is the rut depth (in inches). CBR_{BL} refers to the CBR of the base layer, and CBR_{SG} is the CBR of the subgrade. The original WES method, Equation (3), relies on imperial units. Herein, that equation was manipulated to include units from the International System of Units (SI), resulting in Equation (4).

$$\log(h) = -1.5952 + 0.0634 \times \frac{P^{0.2135} \times {t_p}^{0.2357} \times N^{0.0719}}{r^{0.2334} \times {CBR_{BL}}^{0.2508} \times {CBR_{SG}}^{0.0739}} \quad (4)$$

where h is the heigh of the base layer (in m), P is the equivalent single axle loads (in kN), t_p is tyre pressure (kPa), N is the number of axle passes, r is the rut depth (m).

2.4. Case Study

The case study analysed is that of an unpaved forest road on a clay subgrade (CBR_{SG} = 4.99%). Different solutions for the base layer are analysed, as described before: AG, LS, mixtures of AG + 3%BP and AG + 6%BP, LS + 3%BP and LS + 6%BP, and BP. The case study was defined within the context of the partner company that generates wastes and byproducts, builds and maintains forest roads, and, therefore, is interested in promoting a circular economy within its industrial activity. This analysis aims to understand the influence of partially replacing materials traditionally used for these roads with the byproduct studied on both the height of the base layer and traffic volume (represented by the number of axle passes). The remaining design parameters (tyre pressure, equivalent single axle load, and rut depth) were selected to represent typical unpaved forest roads, considering values representative of the Portuguese reality and information collected from the literature.

The case study was analysed in two parts: (1) a fixed number of standard axle passes and (2) a fixed height of the base layer.

Based on design manuals (Austroads [36], New Zealand Forest Road Engineering [37]) and the work by Giummarra [38], this case study assumes a traffic volume of 20 vehicles per day on the forest road network, as these roads are used for forest harvesting operations. The number of vehicle axles was chosen considering the type of vehicle that generally circulates on this type of road, as is the case of a tractor with a semi-trailer (5 axles). The number of axle passes [39] depends on the life cycle of the base layer: the longer the life cycle, the greater the number of axle passes. Herein, for the first part of the case study, the conditions assumed are N = 365,000 and a life cycle of the layers of 10 years.

Table 2 summarises the various design parameters, the values assumed for the case study and the corresponding original reference. The equivalent single axle load (P) refers to the standard axle load used in Portugal and is the most common value for designing pavement structures. Giroud and Han [25] consider an acceptable rut depth of 0.075 m, also adopted by the US Army Corps of Engineers (e.g., Hammit [20], cited by Giroud and Han [25]). The tyre pressure of 600 kPa for a standard 80 kN single axle was obtained from an empirical-mechanical design method, the Shell pavement design method, described by Branco et al. [10].

In the second part of the case study, the height of the base layer was fixed as that for the base formed by one of the traditional materials. Considering the results of the first part, a constant height for the base layer was defined, and the corresponding maximum number of axle passes was calculated using the other design parameters set as constants and assuming the values presented in Table 2. These analyses are described in more detail in Section 3.2.

Table 2. Constant design parameters defined for the first part of the case study.

Reference	Parameter	Value	Unit
Branco et al. [10]	P	80	kN
Branco et al. [10]	t_p	600	kPa
Austroads [36]; New Zealand [37]; Giummarra [38]	N	365,000	-
Giroud and Han [25]	r	0.075	m
Giroud and Han [25]	CBR_{SG}	4.99	%

3. Results and Discussion

This section presents the results from the geotechnical characterisation of the selected materials and mixtures, as well as the outcomes from the case study. The results are discussed, and significant changes associated with the incorporation of the byproduct in traditionally used materials for unpaved road structures are discussed. Finally, the potential for geotechnical valorisation of the byproduct in forest roads is discussed.

3.1. Geotechnical Characterisation

As mentioned above, the laboratory tests performed allowed quantifying several geotechnical properties of the materials and mixtures selected, including physical and identification properties, and mechanical properties (compaction, load-penetration response and CBR values). Table 3 summarises the main results obtained from the laboratory tests. The results for each property studied are presented and discussed hereafter. The discussion of results focuses on any changes in AG and LS properties by the incorporation of BP; special attention is given to changes in the CBR value and load-penetration response caused by the different incorporation percentages studied.

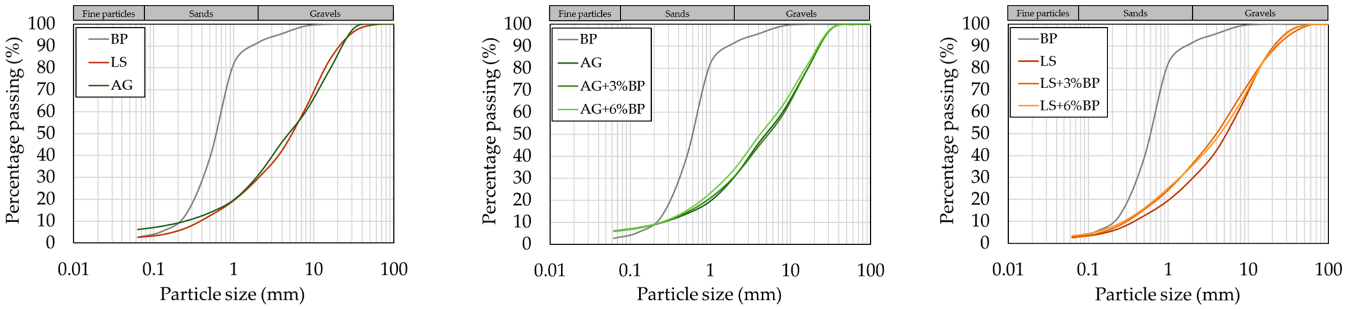
Table 3. Geotechnical characteristics of the selected materials and mixtures.

Properties	Materials and Mixtures						
	BP	AG	AG + 3%BP	AG + 6%BP	LS	LS + 3%BP	LS + 6%BP
Particle size distribution [29]							
D_{50} (mm)	0.6	5.0	5.2	4.1	5.4	4.0	4.1
C_U (-)	3	33	25	26	20	20	24
C_C (-)	1	2	1	1	1	1	1
PFP (%)	3.2	6.4	6.2	6.1	2.9	2.8	3.8
Methylene blue [32], MB ($g{\cdot}kg^{-1}$)							
$MB_{0–2}$, fraction 0–2 mm	0.25	3.50	3.25	2.00	1.50	1.00	0.75
$MB_{0–50}$, fraction 0–50 mm	0.23	1.08	1.01	0.69	0.45	0.37	0.27
Sand equivalent [33], SE (%)	87	60	62	68	72	75	74
Particle density [30]							
ρ_s ($g{\cdot}cm^{-3}$)	2.638 (0.033)	2.695 (0.002)	2.609 (0.019)	2.657 (0.026)	2.696 (0.017)	2.665 (0.014)	2.696 (0.021)
Atterberg Limits [31]							
w_L (%)	35.1	15.6	18.1	20.0	29.3	29.6	30.9
w_P (%)	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Classification							
USCS, ASTM D2487-11 [27]	SP	SW-SM	SW-SM	SW-SM	SW	SW	SW
LCPC/SETRA [28]	D_1	B_3	B_3	D_2	D_2	D_2	D_2
Modified Proctor [34]							
w_{opt} (%)	10.8	6.4	7.4	7.5	3.0	5.0	5.7
$\rho_{d,max}$ ($g{\cdot}cm^{-3}$)	1.671	2.196	2.229	2.210	1.962	1.959	1.935
CBR [15] (%)	34.3 (1.3)	90.9 (10.1)	86.2 (4.0)	62.8 (11.5)	65.0 (2.6)	57.4 (4.1)	59.4 (2.0)

N.D.—not defined, inconclusive test result; SP—poorly-graded sand; SW—Well-graded sand with gravel; SW-SM –Well-graded sand with silt and gravel; D_1—clean alluvial sands, dune sands; D_2—clean alluvial gravel and sand; B_3—gravel with silt; standard deviation values in brackets.

3.1.1. Physical and Identification Properties

The PSD of the different materials and mixtures is included in Figure 3. Table 3 contains some relevant parameters (D_{50}, C_U, C_C, and PFP) obtained from the PSD. BP is essentially formed by sand-sized particles (88.4%), gravel (8.4%) and fine particles (3.2%, silt and clay size). BP is poorly graded (C_U = 3 and C_C = 1). AG and LS have very similar PSD (Figure 3a): ~70% of gravel, ~24–27% of sand, and 6.4 and 2.9% of fine particles, respectively: the main difference is their PFP, higher for AG than for LS. AG and LS are well-graded materials. Figure 3b,c present the PSD of the mixtures of AG and LS with BP, respectively. The percentages of BP considered (3% and 6%) are low and do not affect the PSD significantly (curves of the base material and mixtures are very close to each other). If the incorporation percentage were to be increased, given that BP is essentially formed by sand particles, the mixtures would have a larger proportion of sand-size particles.



(**a**) (**b**) (**c**)

Figure 3. Particle size distribution of the materials and mixtures studied: (**a**) base materials, AG, LS and BP; (**b**) mixtures of AG and BP, AG + 3%BP and AG + 6%BP; (**c**) mixtures of LS and BP, LS + 3%BP and LS + 6%BP.

Methylene blue tests were carried out to assess the sensitivity of materials and mixtures to water, as they give information on the presence and properties of clay minerals. The tests (EN ISO 933-9:2022 [32]) are performed considering the fraction 0–2 mm of the materials, leading to the corresponding methylene blue value ($MB_{0–2}$). LCPC/SETRA [28] categorises soils according to their methylene blue value for the fraction 0–50 mm ($MB_{0–50}$); $MB_{0–50}$ is obtained from $MB_{0–2}$ using a proportionality rule for their PSD (Equation (5)).

$$MB_{0-50} = MB_{0-2} \times \frac{\text{Percentage passing 2 mm sieve}}{\text{Percentage passing 50 mm sieve}} \quad (5)$$

According to LCPC/SETRA [28], soils with $MB_{0–50}$ up to 1.00 g·kg^{-1} are insensitive to water; $MB_{0–50}$ = 2.00 g·kg^{-1} is the limit at which sensitivity to water is likely to occur. BP and LS are water-insensitive materials ($MB_{0–50}$, respectively, 0.23 g·kg^{-1} and 0.45 g·kg^{-1}), while AG is likely to be sensitive to water ($MB_{0–50}$ = 1.08 g·kg^{-1}). Mixtures AG + 3%BP, AG + 6%BP, LS + 3%BP, and LS + 6%BP exhibit reduced sensitivity to water relative to AG and LS. For example, AG is above the limit at which soils are insensitive to the water, while AG + 6%BP ($MB_{0–50}$ = 0.69 g·kg^{-1}) is insensitive to water. These results suggest that BP may be useful for overcoming water-sensitivity issues of some materials. The results of sand equivalent tests (SE value) point in the same direction. The increase of SE values (Table 3) observed in the mixtures relative to the base materials suggests that the inclusion of the byproduct improves the behaviour of the material fine particle fraction.

The particle density, quantified using the pycnometer method, is ρ_s = 2.638 g·cm^{-3} for BP (similar to ρ_s of the boiler fluidised bed calibrated sand), and very similar between AG and LS, 2.695 g·cm^{-3} and 2.696 g·cm^{-3}, respectively. The particle density obtained agrees with those reported for natural geotechnical materials. The particle density of the mixtures decreased relative to the corresponding base materials. This occurs as the particles of BP are less dense. However, the results did not show a clear downward trend in particle density with larger incorporation percentages of BP studied. The variability of results (Table 3) and the PSD of each sample of AG and LS may explain this. Thus, it may be necessary to increase the number of specimens tested.

As aforementioned, the liquid and plastic limits of the fine fraction of the materials and selected mixtures were estimated. The fraction of particles smaller than 0.4 mm (range of applicability of the test) is small and consists mostly of fine sand particles. Thus, because of a very small clay fraction, the materials and mixtures tested exhibit non-plastic behaviour. This makes it impossible to carry out the plasticity limit test (represented by "N.D.—not defined, inconclusive test result" in Table 3). Fall-cone tests were carried out to quantify the liquid limit. The materials with lower PFP (BP and LS) exhibited higher w_L, i.e., their fine particle fraction requires more water to behave like a liquid. Despite a similar PFP, the w_L of BP (35.1%) was higher than that of LS (29.3%). This suggests that the fine particles of LS are finer and may have some plasticity, in comparison with BP, and therefore are more sensitive to water. The results also show that the incorporation of BP in AG or LS increased the liquid limit: w_L = 15.6% for AG; w_L = 18.1% for AG + 3%BP; w_L = 20.0% for AG + 6%BP; w_L = 29.3% for LS; w_L = 29.6% for LS + 3%BP; w_L = 30.9% for LS + 6%BP. This means that the behaviour of the finer fraction of AG and LS will be improved with the incorporation of BP, even with small percentages, since more water will have to be added for this fraction to behave like a liquid. The results also suggest that BP could be useful for overcoming water-sensitivity issues of some materials, confirming the conclusions drawn from the methylene blue test results.

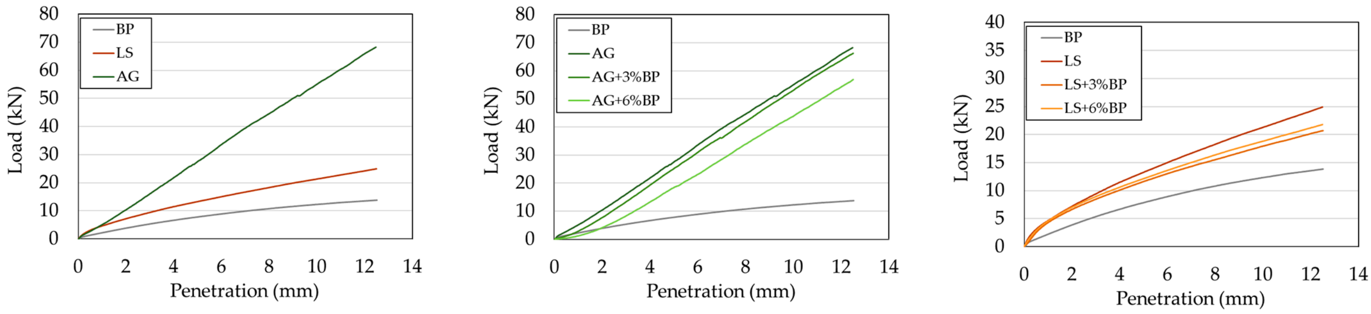
The materials and the mixtures were classified according to the USCS (ASTM D2487-11 [27]) and LCPC/SETRA [28], assuming they can be classified as natural soils. The USCS considers that the sand fraction of soil ranges between 0.075 mm and 4.75 mm (different from Figure 3). According to USCS, BP is SP—poorly-graded sand, AG is SW—well-graded sand with gravel, and LS is SW-SM –well-graded sand with silt and gravel. The classification of the base materials (AG and LS) remained unchanged with the inclusion of the byproduct. According to LCPC/SETRA [28], BP is D_1—clean alluvial sand, dune sand, AG is B_3—gravel with silt, and LS is D_2—clean alluvial gravel and sand. In addition, BP can be classified in Class F_9 for industrial byproducts of LCPC/SETRA [28]. Also important is that the incorporation of BP in LS does not change the classification of mixtures comparatively to the base material. However, the classification of the AG + 6%BP was changed for D_2—clean alluvial gravel and sand.

3.1.2. Mechanical Properties

The compaction properties of coarse geotechnical materials are greatly influenced by their PSD. In general, it is easier to reduce the void ratio and achieve higher maximum dry densities in well-graded materials (high C_U) than in uniform or poorly graded materials (C_U~1). This is true for the materials studied: BP, a poorly graded material (C_U = 3 and C_C = 1), exhibits the lowest $\rho_{d,max}$, while AG (C_U = 33 and C_C = 2) presents the highest $\rho_{d,max}$; LS has $\rho_{d,max}$ higher than BP. The other key compaction parameter is the optimum water content. The water has a lubricating action on the soil's solid skeleton, reducing friction between particles and enabling air to be expelled from voids. The maximum dry density is reached for the optimum water content. In most cases, it is necessary to add more water to achieve the $\rho_{d,max}$ of finer soils with poorer PSD. For this reason, w_{opt} obtained for BP is higher (w_{opt} = 10.8%) than for AG (w_{opt} = 6.4%) and LS (w_{opt} = 3.0%). Likewise, w_{opt} of LS is smaller because its PFP (2.9%) is lower than for AG (6.4%).

The results show that replacing AG and LS with BP slightly modified the corresponding $\rho_{d,max}$, marginally increasing $\rho_{d,max}$ of AG; the contrary was observed for LS. However, these changes are so small that they may be due to the inherent variability of the samples (as no clear trend is observed). More visible and significant is the change in the w_{opt} required to reach $\rho_{d,max}$ of the mixtures of AG and LS with BP. As expected, the addition of a material with a finer grain size (BP) increases the amount of water required for the compaction process.

The load-penetration response obtained from CBR tests is represented in Figure 4 by a single curve per test condition (the most representative specimen). The average CBR values (and some measures of dispersion) of the materials and mixtures analysed can be found in Figure 5 and Table 3.



(**a**) (**b**) (**c**)

Figure 4. Load-penetration response of the materials and mixtures studied (one curve per condition; most representative specimen): (**a**) base materials, AG, LS and BP; (**b**) mixtures of aggregate AG with BP, AG + 3%BP, AG + 6%BP; (**c**) mixtures of local soil LS with BP, LS + 3%BP, LS + 6%BP (Note: the scale on the vertical axis is different).

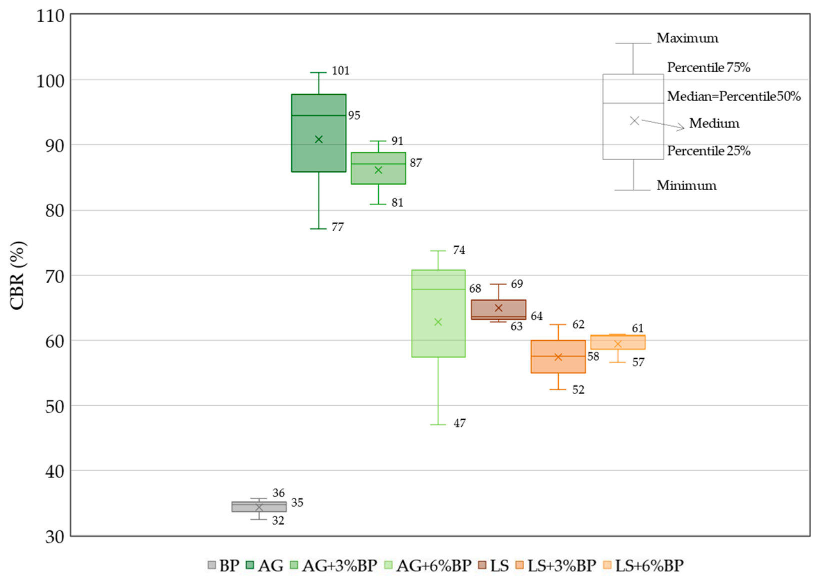


Figure 5. Box-plot of the CBR tests results of the selected materials and mixtures, illustrating the scatter of results.

The load-penetration responses of AG, LS and BP match the typical response for natural materials with equivalent PSD. Consequently, the corresponding CBR values fit reference values reported in the literature (e.g., WSDOT Pavement Guide [39]): the CBR of BP (34.3%) is within the range of values for sandy soils (5–40%); the CBR of AG (90.9%) is inside the reference interval reported for high-quality base materials (80–100%); for LS (CBR = 65.0%) the CBR values are within the reference values for coarse-grained soils (20–80%). The scatter of results is illustrated by the standard deviation (Table 3) and the corresponding coefficient of variation (approximately 11%, 4% and 4% for AG, LS, and BP, respectively). The scatter may be partially caused by the larger particles of AG and LS, with dimensions close to the diameter of the CBR test plunger (50 mm) and to some variability of the soil specimens tested.

The incorporation of BP in AG and LS modified the load-penetration response observed. For similar levels of penetration, mixtures of AG and LS with BP supported lower loads, i.e., their bearing capacity decreased. In the same way, as the CBR value of BP is lower than that of AG and LS, it is expected that the incorporation of BP in these materials will lead to decreased CBR, i.e., a decline in bearing capacity. This was observed for AG + 3%BP, AG + 6%BP, LS + 3%BP and LS + 6%BP. Considering average values, the CBR decreased 5.2% (AG + 3%BP) and 30.9% (AG + 6%BP) relative to AG; for LS, the average CBR decreased 11.7% (LS + 3%BP) and 8.6% (LS + 6%BP). The addition of 3% of BP to AG and LS is acceptable, as it is not too large; the same for 6% of BP to LS. Conversely, the CBR reduction for AG + 6%BP relative to AG is substantial (30.9%), indicating that this percentage may be excessive for this material. However, the corresponding scatter of results is important, with a coefficient of variation for the CBR of 18% (AG + 6%BP), larger than for the other mixtures studied: 5% (AG + 3%BP), 7% (LS + 3%BP) and 3% (LS + 6%BP). Figure 5 better illustrates the scatter of results, which are particularly important for AG and AG + 6%BP. Possible causes for this result include the sampling and compaction processes required for the tests, which may have caused particle segregation and some heterogeneity of the water content along the mould (for each specimen); in addition, this may have influenced the specimens tested differently. Thus, the trends discussed should be read with caution. To confirm the trends observed and to increase the statistical significance of the results, further work should include a larger number of specimens.

Although a proper mechanical interpretation of CBR test results is limited [17], herein, the test results are analysed using two theoretical approaches to estimate the Young's modulus, E, of the materials studied. The first approach is based on the theory of elasticity (Equation (6)), assuming that there is a conical stress distribution below the plunger, which reaches the perimeter of the CBR mould, underlain by a mass of soil under homogeneous stress distribution.

$$E = \frac{p_m d}{\Delta h_e D}\left[H + \frac{d(L - H)}{D}\right] \tag{6}$$

In Equation (7), p_m is the mean stress under the plunger; Δh_e is the elastic displacement of the plunger; d is the diameter of the plunger; D and L are the diameter of the CBR mould and the height of the specimen, respectively; and H is the height of the cone. As recommended by Magnan and Ndiaye [40], H is obtained considering an angle of load spread equal to the angle of friction of the soil.

The second approach assumes high-stress concentration at the edges of the plunger by considering non-Hertzian contacts [41] within an elastic framework (Equation (7)). Nevertheless, similar trends emerge from an elastoplastic analysis of the CBR test [19], namely at the vicinity of the plunger, with localised plastic stresses at its edges and high compressive stress under its centre, while most of the soil exhibits elastic stresses. Equation (7) also depends on the Poisson's ratio (ν) of the soil.

$$E = \frac{p_m}{\Delta h_e}\frac{\pi d}{4}\left(1 - \nu^2\right) \tag{7}$$

The materials and mixtures tested herein are coarse materials with a relatively small PFP. Thus, their response during the CBR test can be considered drained. An analysis of the CBR tests assuming an elastic regime using Equations (6) and (7) is summarised in Table 4. Conservative estimates of the angle of friction of the materials and mixtures (listed in Table 4) were adopted [42] (Table 4) were adopted [42], based on their maximum dry density from the Proctor tests, as in the CBR tests, similar conditions were used.

Assuming that the angle of friction of the mixtures and its base material is the same, Young's modulus of the mixtures reduces compared to the base material, reflecting the change in response observed during the CBR test. Overall, the values for E from Equation (7) are lower than the estimates obtained using Equation (6). These estimates were compared to typical values for the elastic modulus of soils presented by the WSDOT Pavement Guide [39], which, for sandy soils (SW, SP, SM, SC, according to the USCS), range between 48 MPa and 207 MPa. The estimates obtained using Equation (6) and Equation (7) are conservative and, for most cases, are below the minimum value for that range (exception for AG, AG + 3%BP and LS). This trend may indicate that the stresses within the soil mass are different from what was assumed in Equation (6) (conical stress distribution below the plunger, which reaches the perimeter of the CBR mould, underlain by a mass of soil under homogeneous stress distribution) and in Equation (7) (high-stress concentration at the edges of the plunger, by considering non-Hertzian contacts within an elastic framework).

Table 4. Young's modulus estimates.

Materials and Mixtures	Effective Friction Angle (°)	E (MPa)	
		Equation (6)	Equation (7)
BP	32	29	18
AG	40	66	47
AG + 3%BP	40	63	45
AG + 6%BP	40	46	33
LS	38	49	34
LS + 3%BP	38	43	30
LS + 6%BP	38	45	31

3.2. Case Study

The case study was analysed in two parts, described in detail in the following subsections: (1) fixed number of axle passes; (2) fixed height of the base layer.

3.2.1. Fixed Number of Axle Passes (10-Year Life Cycle)

First, the height of the base layer (h) was defined using Equation (4) and the parameters summarised in Table 2, i.e., 365,000 passes of an axle load of 80 kN and tyre pressure of 600 kPa, a maximum rut depth of 0.075 m and a 10-year life cycle. Seven scenarios were studied, depending on the material or mixture forming the base layer: AG, AG + 3%BP, AG + 6%BP, LS, LS + 3%BP, LS + 6%BP, and BP, each represented by the corresponding CBR value.

Figure 6 summarises the results from this first analysis. When comparing AG, LS and BP, the lowest h was obtained for AG (h = 0.23 m), followed by LS (h = 0.28 m) and BP h = 0.43 m). This is consistent with the CBR values for these materials and Equation (4): the weaker the material forming the base layer, the larger the height required to ensure the same number of axle passes.

The incorporation of BP in AG or LS influenced the height of the base layer: AG + 3%BP, h = 0.24 m (~3% increase), AG + 6%BP, h = 0.29 m (~24% increase), and LS + 3%BP, h = 0.31 m (~8% increase), LS + 6%BP, h = 0.30 m (~6% increase). For AG, the large reduction of CBR value (~31%) for AG + 6%BP meant that h increased by ~0.06 m. The results seem to indicate that for LS, the consideration of BP percentages up to 6% does not significantly affect the height of the base layer and may provide an application for BP.

Alternatively, a base layer formed by BP led to a design height of 0.43 m, 85% and 52% larger than for AG and LS, respectively. Thus, fully replacing AG or LS with BP influences the base layer design significantly. If there are no significant environmental impacts from the use of BP on its own, this solution may be a valid alternative for the valorisation of BP. These aspects need to be further explored to ensure BP can be used as a single base layer material without significant environmental impacts (not covered herein). Other aspects of the base layer performance need to be further explored to ensure that a base layer with BP meets not only structural requirements but also adequate regarding the prevention of surface defects.

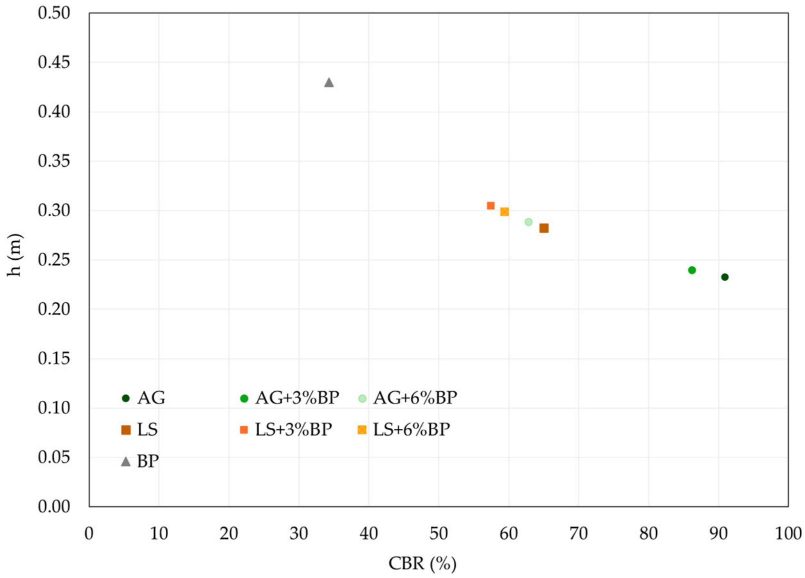


Figure 6. Height of the base layer (h) obtained for the different solutions analysed (365,000 passes of an axle load of 80 kN and tyre pressure of 600 kPa, maximum rut depth of 0.075 m and 10-year life cycle): AG, AG + 3%BP, AG + 6%BP, LS, LS + 3%BP, LS + 6%BP and BP, as a function of the corresponding CBR, CBR_{BL}.

Although the cross-section of the unpaved forest road analysed seems simple, its performance tends to be complex [43]. On the one hand, it is the result of the combined response of two very different materials, which, for the case study analysed, are fine soil as a subgrade layer and a base layer formed with coarser soil. On the other hand, traffic and the associated load repetitions (represented by the number of axle passes) tend to modify the road cross-section.

The base layer of an unpaved road is flexible, i.e., it will undergo plastic deformations due to loading; such plastic deformations tend to accumulate and will lead to rutting, which, if excessive, can prevent trafficking of the road. The rutting can be attributed to four different mechanisms (Figure 7), acting isolated or combined [44]: mechanism A is due to the compaction of unsaturated materials and can be observed through thinning of the base layer; mechanism B corresponds to shear deformation within the base layer, close to the road surface; mechanism C refers to shear deformation within the subgrade layer, which is accompanied by the base layer; mechanism D is more localised and refers to particle damage leading to rutting (manifested as for mechanism A). These mechanisms may be enhanced by freeze-thaw cycles; however, in Portugal, that is not a common situation. Due to their geometry, in unpaved forest roads, traffic tends to occur always along the same area of the road (i.e., canalised trafficking), which will lead to the prevalence of mechanism A [45]. As with an increased number of load repetitions (vehicle passes) the compaction of the base layer tends to reach an asymptotic response, and mechanism A tends to stabilise for a constant value of the rut depth [45].

The solutions analysed for the base layer materials show that it is possible to ensure structural stability by adjusting the base layer height. The base layer material needs to be compacted adequately during construction to minimise the influence of mechanism A. Low shear strength of the material in the base layer may lead to mechanism B, characterised by local shear failure below the wheel load and lateral heave within the base layer. To prevent mechanism B, the base layer can be improved (by compaction, chemical stabilisation and reinforcement with a geosynthetic); in some cases, drainage corrections can also increase the available shear strength.

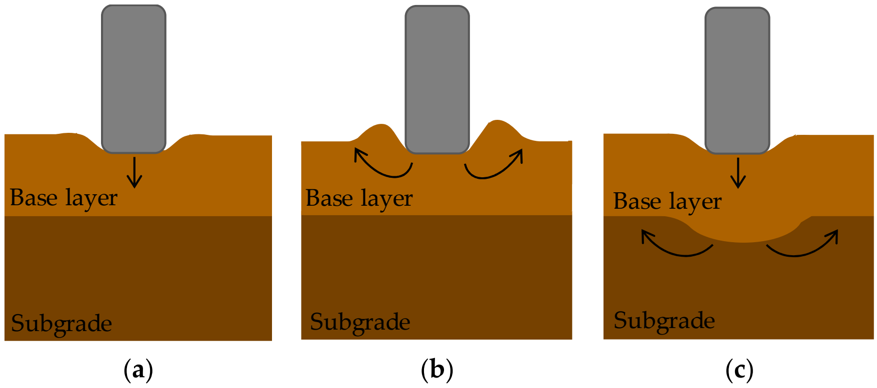


Figure 7. Schematic illustration of some rutting mechanisms (**a**) mechanisms A and D; (**b**) mechanisms B; (**c**) mechanism C.

For the case study analysed, geosynthetic reinforcement of BP seems a viable solution that may lead to increased shear strength of the composite material and reduction of the corresponding base layer height. If the base layer has adequate shear strength and the subgrade layer is weak, mechanism C will tend to prevail. In this case, if the improvement of the subgrade layer is not a viable option (which is mostly the case for unpaved forest roads), a larger load spread within the base layer is required. In order to achieve it, the base layer may have increased thickness or be formed by a material with higher shear strength (and thus, higher load-spread angle); alternatively, traffic restrictions may be forced (limiting the axle load of the vehicles trafficking the road). Lastly, particle damage may lead to mechanism D; thus, particles less prone to fragmentation and abrasion damage may be used to minimise its influence on the road performance. Such response of the base materials analysed was not studied, but its particle damage is more likely for AG and LS (with larger particles) than for BP.

On unpaved roads, one of the objectives of the maintenance operations is to correct the structural and surface defects due to traffic. The low initial investment typical of these infrastructures tends to lead to frequent maintenance operations that increase the life cycle costs. Thus, a full life cycle analysis should be carried out.

3.2.2. Fixed Height of the Base Layer

Then, solutions using mixtures of AG and LS with BP (BP percentages of 3% and 6%) were further analysed. For this, the height of the base layer was fixed; the result from the first analysis (Section 3.2.1) and corresponding base material, AG or LS, was rounded to the upper multiple of 5 cm (used in practice), leading to h = 0.25 m for AG and h = 0.30 m for LS. Then, the corresponding maximum number of axle passes (N) was estimated using Equation (4) for the cases in which the base layer was formed by AG + 3%BP, AG + 6%BP, LS + 3%BP and LS + 6%BP. This calculation was done for an axle load of 80 kN, tyre pressure of 600 kPa, and a maximum rut depth of 0.075 m. This enabled assessing changes in the number of axle passes of the unpaved road designed when BP was incorporated in AG and LS, as well as the associated life cycle (Table 5). The life cycle time (t) was calculated assuming a constant traffic volume of 20 trucks per day (tractor with semi-trailer, five axles, and a maximum load of 40 tonnes) and represents the time period necessary to reach the number of axle passes (N).

For a base layer 0.25 m high, using AG + 3%BP or AG + 6%BP as alternatives to AG led to important reductions in the number of axle passes. The life cycle obtained for AG (15.7 years) was reduced to 2.7 years and 11.4 years for AG + 3%BP and AG + 6%BP, respectively. Thus, partially replacing AG with BP had a significant impact on the life cycle of the unpaved road case analysed. When LS is considered, namely alternative solutions LS + 3%BP or LS + 6%BP and a base layer 0.30 m, the variations in the life cycle are also present, observing the following reductions: 5.0 years and 3.8 years, respectively, for a life cycle of 14.2 years (LS). However, the increase in the percentage of BP mixed with LS did not have the same impact as for AG. Therefore, it was noted that increasing the percentage of BP led to a smaller reduction in the life cycle, with a relatively small difference between the two values. The main differences observed are associated with the corresponding changes in CBR value, as discussed before. The influence of BP percentage in the mixtures is more important when the material (AG or LS) is of better quality. Depending on the availability of BP and the distance between the production plant and the unpaved road to be constructed, using incorporation of BP may be worthwhile. Additional analyses are needed to fully assess the impact of these solutions, for example considering overall costs and carbon dioxide emissions.

Table 5. Influence of the incorporation percentage of BP on the life cycle of the unpaved road, also represented by the variation in number of axle passes (obtained for fixed height of the base layer).

Case Study	h (m)	N (-)	ΔN (-)	t (years)	Δt (years)
AG	0.25	573,710	-	15.7	-
AG + 3%BP		475,770	−97,940	13.0	−2.7
AG + 6%BP		157,961	−415,749	4.3	−11.4
LS	0.30	517,386	-	14.2	-
LS + 3%BP		335,515	−181,871	9.2	−5.0
LS + 6%BP		377,640	−139,746	10.3	−3.8

For 5-axis vehicles, axle load of 80 kN, tyre pressure of 600 kPa, maximum rut depth of 0.075 m. Number of axle passes (N); life cycle time (t); variation of the number of axle passes (ΔN); variation of the life cycle time (Δt).

3.3. Potential for Geotechnical Valorisation

In order to assess the potential application of the materials and mixtures analysed to form the base layer of unpaved roads, their properties were compared with the requirements for unbound layer materials, as defined by the Portuguese Transportation Infrastructure entity (Infraestruturas de Portugal, IP) [46].

Although some of the test methods included in [46] are not the same as those used herein for the geotechnical characterisation, most resulting quantities are essentially the same and, thus, can be compared.

The specifications distinguish between natural soils (referred to as selected soils) and natural aggregates, which can be compared, respectively, to LS and AG; for their mixtures with BP, a similar comparison was carried out. The requirements limit parameters for the selected soils, such as maximum particle size of 50 mm or 2/3 of the layer thickness [47]; maximum percentage fines (PFP), i.e., material passing ASTM nº 200 sieve (0.063 mm) [47], of 10% to 20%; maximum liquid limit [48], w_L, of 35%; maximum plastic limit [48], w_P, of 6% to 10%. Regarding natural aggregates, the requirements refer only to the quality of fines: if PFP < 3% (i.e., particles with dimension smaller than 0.063 mm), the fines can be considered non-detrimental; if PFP > 3%, then the sand equivalent value [33], SE $\geq$ 40%; otherwise, if SE < 40% then the Methylene blue test value [32] $MB_{0\text{–}2} \leq 2.5\ g{\cdot}kg^{-1}$.

Considering the results from the tests (Table 3), the AG and LS meet all the requirements for both natural soils and natural aggregates. In addition, although BP is not a natural soil but a residue, this material meets all the properties requirements for selected soils and natural aggregates (its liquid limit, 35.1%, can be considered within the limit of 35%). Also, the mixtures of AG and LS with the BP fulfil all the requirements for unbound layer materials, as defined by [46]. It is also important to note that these requirements are defined for unbound layers that are part of pavement structures for paved national roads, which need to be designed with more stringent requirements than forest roads.

Considering its physical and chemical properties, BP is a uniform sand (in relation to its PSD) composed mainly of silica (silicon dioxide) and lime (calcium oxide). BP is compatible with the application studied, fulfilling the requirements typically used in Portugal for its use as a material for unbound layers, both alone and mixed with AG and

LS. Nevertheless, further research is necessary to assess the leaching potential of BP and the need for its pre-treatment.

Its chemical characterisation (with no treatment) was performed by RAIZ, a non-profit research centre in Portugal. According to Table 6, the results indicate that this material is not admissible for inert waste (IW) landfills but is eligible for disposal in non-hazardous waste (N-HW) landfills, as defined in the Portuguese legislation, Decree-Law nº. 102-D/2020 [49]. The parameters that prevent the disposal in inert waste landfills are Antimonium and Selenium (the test method used does not allow quantifying of the corresponding values with enough accuracy) and Chlorides (the upper limit is exceeded). Within the European Union (EU) waste list [50], sands from fluidized bed boilers (code 10 01 24) used in energy production are always considered non-hazardous waste (N-HW).

Table 6. Criteria for disposal in inert waste (IW) landfills and in non-hazardous waste (N-HW) landfills according to Decree-Law nº. 102-D/2020 [49].

Parameter	Unit	Criteria for Admission as N-HW (DL 102/2020)	Criteria for Admission as IW (DL 101/2020)	Criteria Fulfilled by BP
Waste analysis				
pH (20 °C)	Sor. Scale	-	-	NA
Loss at 105 °C (Humidity)	%	-	-	
Conductivity	$mS \cdot cm^{-1}$	-	-	
Specific gravity	$g \cdot cm^{-3}$	-	-	
COT		50,000	30,000	IW
BTEX	$mg \cdot kg^{-1}$ bs	999	6	IW
PCB	$mg \cdot kg^{-1}$ bs	50	1	IW
Mineral oils (C10 to C40)	$mg \cdot kg^{-1}$ bs	999	500	IW
HAP	$mg \cdot kg^{-1}$ bs	100	100	IW
Eluate analysis				
Arsenic (As)	$mg \cdot kg^{-1}$ bs	5	0.5	IW
Barium (Ba)	$mg \cdot kg^{-1}$ bs	100	20	IW
Cadmium (Cd)	$mg \cdot kg^{-1}$ bs	2	0.04	IW
Chromium (Cr)	$mg \cdot kg^{-1}$ bs	20	0.5	IW
Cupper (Cu)	$mg \cdot kg^{-1}$ bs	50	2	IW
Mercury (Hg)	$mg \cdot kg^{-1}$ bs	0.5	0.01	IW
Molybdenum (Mo)	$mg \cdot kg^{-1}$ bs	10	0.5	IW
Nickel (Ni)	$mg \cdot kg^{-1}$ bs	10	0.4	IW
Lead (Pb)	$mg \cdot kg^{-1}$ bs	10	0.5	IW
Antimonium (Sb)	$mg \cdot kg^{-1}$ bs	0.7	0.06	N-HW *
Selenium (Se)	$mg \cdot kg^{-1}$ bs	0.5	0.1	N-HW *
Zinc (Zn)	$mg \cdot kg^{-1}$ bs	50	4	IW
Chlorides	$mg \cdot kg^{-1}$ bs	50,000	800	N-HW
Fluorides	$mg \cdot kg^{-1}$ bs	250	10	IW
Sulphates	$mg \cdot kg^{-1}$ bs	20,000	1000	IW

* The test method used does not allow to quantify values with enough accuracy to check the criteria for IW.

Regarding the mechanical performance, the load-penetration response of BP and its mixture with AG and LS is acceptable (particularly for the mixtures). For the case study analysed, a base layer formed by BP mixed with AG and LS led to increased base layer height, which is not excessive for practical applications. If the base layer is formed by BP only, a significantly higher base layer is needed. Nevertheless, the case for using BP as a base layer material has its merits, namely from the perspective of a company that generates BP and must dispose of it or find alternative applications, promoting a circular economy. Using a significant quantity of this material for unpaved forest roads within their forest areas is an excellent alternative to landfill deposition. Such application will lead to saves in natural resources (as the quantities of natural materials required to form base layers will decrease), costs, and carbon emissions. Such benefits will need to be quantified to fully support the application of BP; they will depend on the location of each project / unpaved road, their distance to production plants (where BP is generated) and to quarries (where natural aggregates are obtained).

Alternatively, different solutions for valorising BP can be explored. For example, in the case of unpaved roads, instead of using a single-layer system (base layer), a two-layered system can be adopted. In that case, BP could form a sub-base layer with a base layer on top of it. Another possible application is to use BP to form a sub-base layer for paved roads (with either rigid or flexible pavements). This is possible as BP fulfils all of the requirements defined by the Portuguese Transportation Infrastructure entity [46] for this type of application.

Thus, BP has valorisation potential from a geotechnical perspective, promoting sustainability and a circular economy.

4. Conclusions

This paper studies alternative solutions to materials traditionally used to build unpaved roads, using a byproduct of the pulp and paper industry and analysing its valorisation potential from a geotechnical perspective. Two complementary approaches were adopted: (1) quantification and comparison of geotechnical properties of the base materials (aggregate, local soil, and byproduct) and mixtures (aggregate and local soil with 3% and 6% of byproduct); (2) design of the base layer for a case study, considering different solutions (each base material and mixture, forming the base layer), and assessing the height of the base layer and its life cycle.

The main results of this study can be summarized as follows:

- The small incorporation percentages studied induced changes to some geotechnical properties of both the aggregate and the local soil, reducing the sensitivity of fine particles to water. The incorporation of byproduct led to increased water content necessary to reach optimum compaction.
- Generally, the CBR values of the mixtures were reduced with the incorporation of the byproduct in the aggregate and the local soil studied. Considering 6% of byproduct and aggregate may be excessive, with a large reduction of CBR. Nevertheless, the results need to be confirmed by a larger number of test specimens to allow a detailed statistical analysis.
- The soil stress state within the CBR mould is not mostly elastic, as often assumed in the literature. The estimates of the materials' Young's modulus showed that such assumptions might be too conservative.
- The case study analysed confirmed that the weaker the material forming the base layer, the larger the base layer height required to ensure the same number of axles passes. Particularly for the local soil, the incorporation of byproduct up to 6% did not significantly affect the height of the base layer. Mechanically, the extreme case of total replacement of the traditional materials with the byproduct is possible. Nevertheless, the analysis needs to include the assessment of associated environmental impacts (not carried out herein).

- The solutions analysed for the base layer materials show that it is possible to ensure structural stability by adjusting the base layer height. Different mechanisms that lead to rutting were analysed and possible mitigation measures have been discussed. Such measures include compaction, chemical stabilisation, reinforcement with a geosynthetic, drainage corrections, increased thickness of the base layer or using a material with high shear strength. If other alternatives are not viable, traffic restrictions may be forced.
- If the height of the base layer is fixed, partially replacing the traditional materials with the byproduct studied led to reductions in the unpaved road life cycle. Those were particularly important for solutions using the aggregate and larger byproduct percentage (6%), reflecting the significant reductions of CBR observed.
- On unpaved roads, one of the objectives of the maintenance operations is to correct the structural and surface defects due to traffic. The low initial investment typical of these infrastructures tends to lead to frequent maintenance operations that increase the life cycle costs. Thus, a full life cycle analysis should be carried out.

From a geotechnical perspective, the valorisation of the byproduct studied is possible, particularly for the small incorporation percentages considered herein. Based on the requirements for unbound layer materials, as defined by the Portuguese Transportation Infrastructure entity, the byproduct fulfils all applicable requirements. Other potential applications for valorising can be explored and include its use as a sub-base layer in a two layered system, both in unpaved and paved roads.

Nevertheless, there are some open questions that need to be further investigated, as it is necessary to increase the statistical significance of experimental data to confirm some of the trends observed. The environmental impacts related to replacing traditional materials with the byproduct need to be assessed (e.g., leachability tests), complemented by full life cycle analyses. From the perspective of the company generating the byproduct, its use (namely its geotechnical valorisation) represents a step forward in increasing the sustainability of the industrial processes associated with pulp and paper production, promoting a circular economy.

The work presented herein shows that it is possible to use the type of byproduct studied (exhausted sand from a fluidised bed boiler used for biomass combustion) as a geotechnical material. From a geotechnical perspective, the byproduct can be used as a partial (or even total) replacement of natural aggregate or selected soils to form the base layer of unpaved forest roads unbounded. This application is new, as most of the work reported in the literature refers to the use of similar byproducts with binders, resulting in a bounded material and, thus, with very different characteristics. Partial (or even total) replacement of natural materials with such byproducts will contribute to the promotion of circular economy and sustainability while addressing sustainable development goals (SDG), as defined by the United Nations. In particular, the adoption of this material in unpaved forest roads will contribute to SDG9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), SDG11 (Make cities and human settlements inclusive, safe, resilient and sustainable), and SGD12 (Ensure sustainable consumption and production patterns).

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