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Environmental and technical feasibility of a waste foundry sand applied to pavement granular layers

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Article

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Abstract

The foundry industry generates large amounts of residual byproducts, such as waste foundry sand (WFS). This high generation has motivated studies concerning the disposition of WFS, which in turn can be used for road subbases. Nevertheless, paving applications are still limited, especially regarding the behavior of WFS when added to a mixture of crushed materials. Hence, the objective of this study was to evaluate WFS reuse in mixtures with crushed materials, applied as granular layers of granulometric stabilized pavements. The crushed materials and WFS were characterized by size distribution, physical aspects, and different mixtures, and later submitted to mechanical testing. Initial tests were utilized to define mixtures (crushed material + WFS) that fulfilled the technical requirements for road subbases. California bearing ratio and resilient modulus tests indicated that WFS additions up to 12% for "A" grading improved the bearing capacity of the mixture; while in "E" grading, WFS additions up to 38% resulted in no expressive improvement in bearing characteristics. Thus, for both gradings, a structure with high density, strength, and low susceptibility to deformations can be used for road subbase construction without technical issues. Finally, the highest WFS content (38%) mixture was environmentally classified as a Class II A non-inert waste, indicating its environmental viability for road applications.

1. Introduction

Foundry industries are linked to a high solid waste generation. It is estimated that for each ton of foundry metal, 4 to 5 tons of waste foundry sand (WFS) are generated (Doğan-Sağlamtimur, 2018). WFS is a byproduct that originates from green sand, consisting of a mixture of sand, organic additives, bentonite, and water; being mostly utilized for mold manufacturing, in which liquid metal is poured to produce desired goods (Siddique & Singh, 2011; Matos et al., 2019).

Internal reuse strategies are applied to reduce WFS generation; these strategies consist in reintroducing WFS in the production process until the material is no longer able to perform the required technical functions. After that, the material is normally discarded. (Dayton et al., 2010; Bansal et al., 2019). WFS disposition is normally made on industrial waste landfills, following the indications of NBR 10004 (ABNT, 2004a); which classifies WFS as a Class II A waste (non-inert and with possible biodegradability, combustibility, or solubility in water). Therefore, the final disposition represents an additional cost to industries, in addition to the generation of environmental passives (Klinsky & Fabbri, 2009; Khan et al., 2021).

Several authors have studied alternative applications of WFS, aiming to develop technologies that may increase its value as a raw material for engineering practice. This range of applications includes civil construction; aggregates for asphalt mixtures, concrete, and ceramic goods; hydraulic barriers and reactive permeable barriers; and even subgrade fill (Abichou et al., 2002; Oliveira et al., 2011; Ganesh Prabhu et al., 2014; Dyer et al., 2018; Hossiney et al., 2018; Arulrajah et al., 2019).

Due to a high demand for aggregates, the road construction and the pavement maintenance industries have been standing out as possible WFS prospectors; especially considering that aggregates constitute about 70 – 80% of roads and pavements (Gökalp et al., 2018). In addition, more severe environmental laws have become obstacles for the exploitation of raw materials in natural deposits. Consequently, the acquisition cost of natural aggregates has highly increased. alongside the cost of transportation in general (Arulrajah et al., 2019). Thus, in addition to providing sustainability for waste recycling,

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WFS reutilization allows a reduction in the exploitation of virgin materials (Yazoghli-Marzouk et al., 2014).

Extensive research (Guney et al., 2006; Klinsky & Fabbri, 2009; Yazoghli-Marzouk et al., 2014; Matos et al., 2019) has been dedicated to studying the stabilization of clayey soils with WFS (60 – 70%) and cement (5.0 – 5.5%), for application in flexible pavement subbases with low traffic. Nevertheless, there is still a research gap in investigations focused on verifying the WFS capacity of integrating mixtures with crushed materials, frequently used as paving materials — specifically for granular layers of granulometric stabilized pavements applications. Also, full adjustment to technical and environmental conditions has still not been explored, such as swelling due to bentonite presence or leaching and solubilization of toxic compounds from WFS, considering that most research focused only on the mechanical behavior (Basar & Aksoy, 2012; Palansooriya et al., 2020).

The understanding of the mechanical and environmental behavior of WFS and crushed materials mixtures ensures that WFS recycling alternatives in road subbases satisfy the performance criteria proposed by responsible departments, securing safety for both society and the environment. Along these lines, the objective of this research consists in studying the geotechnical and environmental behavior of WFS with crushed material mixtures applied to pavement subbases that were granulometrically stabilized.

2. Materials and methods

WFS is a green sand provided by a foundry industry located in southern Brazil. Materials designated as crushed stone A (CSA), crushed stone B (CSB), and crushed stone C (CSC) were collected in a crushing unit located in the same region, that utilizes such materials for the construction of urban pavements.

The crushed materials were from volcanic floods of the Serra Geral Formation situated in the Center-South region of Brazil and were composed mostly of basalt and andesite. For all materials, sampling and reduction procedures by quartering were performed following NBR 16915 (ABNT, 2021a).

Table 1 shows the physical characterization of CSA, CSB, and CSC, as well as WFS. Considering that CSB exceeded 2% of the grains passing through the 4.75 mm sieve, the sample was divided between fine and coarse aggregates to adhere to the Brazilian standard (ABNT, 2021c).

CSC presented the largest powder content (7.98%), followed by WFS (3.57%), CSB (1.55%), and CSA (0.57%). The powder content of the natural aggregates was similar to the ones presented by Gómez-Soberón (2002) for natural aggregates of basaltic origin, although the different production processes can condition different contents of powder material, as reported by Deng & Tikalsky (2008) and Kleven et al. (2000).

Different particle size distributions were found for the four studied materials, as shown in Table 1, which are essential conditions for applying the granulometric stabilization method (DNIT, 2010a, b). In this procedure, small size grains fill the voids of the mixtures, increasing density and strength, while reducing permeability and deformability (Bernucci et al., 2008). All materials related to D10 were considered poorly graded. As for WFS, the values of Cu and Cc (2.06 and 0.92, respectively) were close to those presented by Arulrajah et al. (2017).

For WFS, the specific weight of grains presented values close to those observed by Kleven et al. (2000), which ranged from 2.52 to 2.73 g/cm^3 for 14 different WFS. The water absorption was consistent with the findings of Deng & Tikalsky (2008), Gökalp et al. (2018), and Tugrul Tunc & Esat Alyamac (2019) for basaltic originated aggregates. Variations in the specific weight of grains and water absorption could be attributed to sand mineralogy variation, gradation range, grain shape, and powder content (Deng & Tikalsky, 2008).

Although WFS addition incorporated some clay minerals to the mixtures (e.g., bentonite), the Atterberg limits indicated a non-plastic behavior for the studied waste according to

Table 1. Table synthesis of physical parameters for the studied materials.

Properties	Fine aggregate			Coarse aggregate	
	WFS	CSC	CSB	CSB	CSA
Powder content (%) - NBR NM 46 (ABNT, 2003a)	3.57	7.98	1.55		0.57
Effective diameter D_{10} (mm)*	0.12	0.11	3.65		13.30
D_{30} (mm)*	0.17	0.86	6.50		15.90
D_{60} (mm)*	0.23	1.70	9.00		20.10
Uniformity coefficient (*Cu*)*	1.97	15.18	2.47		1.51
Curvature coefficient (*Cc*)*	1.1	3.89	1.29		0.95
Specific mass (g/cm^3) - NBR 16916 (ABNT, 2021b) and NBR 16917 (ABNT, 2021c)	2.53	2.92	2.98	2.94	2.94
Water absorption (%)	1.86	3.58	3.52	1.81	1.81
Los Angeles abrasion value (%) - NBR NM 51 (ABNT, 2001)	-	-	10.64	16.06	12.26

*obtained from particle size distribution tests - NBR NM 248 (ABNT, 2003b).

NBR 7180 and NBR 6459 (ABNT, 2016; ABNT, 2017a), as also noted by Arulrajah et al. (2017) and Woodson (2011). Los Angeles abrasion values indicate that all mixtures follow the Brazilian roadway standard, DNIT 141-ES (DNIT, 2010b).

DNIT 141 - ES (DNIT, 2010b) standard criteria were utilized to select the grading conditions of the studied mixtures, using three crushed materials and WFS. The dry unit weight and optimum moisture content of the mixtures were determined in accordance with ASTM D1557 (ASTM, 2012), using the modified energy. This energy allows subbases with higher bearing capacity and resilient behavior. California bearing ratio (CBR) and swelling potential were determined following the procedures of NBR 9895 (ABNT, 2017b), for all mixtures at the optimum conditions of the compaction test. Specimens were considerable suitable for testing if the following criteria was met: ± 0.5% for optimum water content level, and ± 0.10 g/cm^3 for maximum dry density.

Specimens of 100 mm in diameter and 200 mm in height, molded in optimum compaction conditions, were utilized for the resilient modulus tests. The test procedures were as indicated by DNIT 134 – ME (DNIT, 2018) and the AASHTO T 307 (AASHTO, 2003), executed using a cyclic triaxial device. Specimens were considered suitable for testing if the 1.0% water content tolerance was met. The mathematical model proposed by Papagiannakis & Masad (2012) was utilized to calculate the test parameters, considering nonlinear elastic behavior for granular soils (i.e., less than 50% of the grains pass through the 0.075 mm sieve).

The impact of WFS addition on the mixtures was quantified following a mechanical model 1 (Equation 1), as described by Papagiannakis & Masad (2012). This model establishes that the Resilient Modulus (RM) is a nonlinear function of confining pressure (σ_3), which is typically applied for granular materials. Since a lesser amount of fine particle size (smaller than 0.75 mm) is presented into the mixtures for all the samples, a combined mechanical model 2 (Equation 2) based on the deviator stress σ_d (Equation 3) and principal stress or bulk stress θ (Equation 4) was explored.

$$RM = k_1 . \sigma_3^{k_2} \quad (1)$$

$$RM = k_1 . \theta^{k2} . \sigma_d^{k_3} \quad (2)$$

where

$$\sigma_d = \left(\sigma_1 - \sigma_3\right) \quad (3)$$

$$\theta = \left(\sigma_1 + \sigma_2 + \sigma_3\right) \quad (4)$$

k_1, k_2, and k_3 represent the model's constants obtained from a nonlinear regression, while the root mean square error (*RMSE*), as observed in Equation 5, was used to achieve the optimized model's constant. n represents the number of points used in the regression analysis, while RM_i and RM_i ^ define the observed and predicted Resilient Modulus, respectively. Also, R^2 was investigated once the optimal solution was found.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(RM_i - RM_i\,\hat{}\,\right)^2} \quad (5)$$

To compare the structural performance between the WFS and the traditional granular materials, a mechanistic analysis was performed. The mechanistic evaluation was carried out in the proposed pavement structure, in which the sublayer was replaced by WFS. The simulations were performed throughout the elastic multilayer theory and using the AEMC software, version 2.4.2 (Franco, 2020).

The structural evaluation was carried out to identify the effects of different WSF grading over the fatigue life of the asphalt layer and the potential subgrade overloading. The performance models considered for asphalt and the subgrade layers are defined by the FHWA (1976) and Dormon & Metcalf (1965), which are described in Equations 6 and 7. Both models give an estimation of the repetition number of standard wheel axles available, considering the initial elastic tensile and vertical strains.

$$N_{AASHTO} = 1{,}902.10^{-6}.\left(\varepsilon_t\right)^{-3{,}512} \quad (6)$$

$$N_{Dormon\ \&Metcalf\ (1965)} = 6{,}069.10^{-10}.\left(\varepsilon_v\right)^{-4{,}762} \quad (7)$$

Where:
ε_t - Tensile strain at the asphalt bottom layer
ε_v - Vertical strain at subgrade top layer
N - Number of permissible standard wheel axle repetition

Furthermore, the solubilization and leaching of metals from WFS were evaluated through the environmental classification of the highest WFS content mixture, according to NBR 10004 (ABNT, 2004a).

3. Analysis and results

3.1. Design mixtures

The upper and lower limits ("A" and "E") were selected to fulfill the design requirements of DNIT (2010b), regarding the mixture of three crushed materials and WFS

Grading "A" mixtures were designed to contain three crushed materials and WFS. Three mixtures were stabilized, fixing the values of coarse aggregates at 30% and 20% for CSA and CSB, respectively, reducing the content of coarse aggregates to the minimum; WFS was added as a substitution for CSC at contents of 0% (Mixture 1A), 6% (Mixture 2A), and 12% (Mixture 3A).

In the case of grading "E," only fine aggregates were added to the mixtures; WFS was added as a substitution for CSC, with 2% (Mixture 1E), 10% (Mixture 2E), 22% (Mixture 3E), and 38% (Mixture 4E).

These two ranges differ by the number "N", which is defined by the number of repetitions of a standard-axle of 82 kN during the project's lifetime, which would have the same effect as the expected traffic on the pavement structure (DNIT, 2006). Therefore, subbases made using "A" grading are intended for roads with high traffic volume (N > 5 × 106), while "E" grading ones are designed for roads with low and medium traffic volume (N < 5 × 106).

Figures 1 and 2 show the particle size distribution for grading "A" and "E". Mixture contents were established inside each range to study the influence of progressive WFS addition.

3.2. Compaction tests

Figures 3 and 4 present the Proctor curves for gradings "A" and "E" obtained through the Modified Proctor Compaction Test.

For both grading ranges, the increase in WFS content led to a reduction in dry density and an increase in moisture content. Furthermore, the maximum dry density, as well as the pattern obtained from the Proctor tests, indicated that mixtures present characteristics of sands with coarse, well-graded, and few clay particles. Mixtures of crushed material and 27% WFS, studied by Guney et al. (2006), resulted in values of dry density and water level content close to those observed in this study.

This behavior can be better seen in Figures 3 and 4, where the relationship between maximum dry density and optimum moisture content according to WFS content are identified. The reduction in the dry density parameter is associated

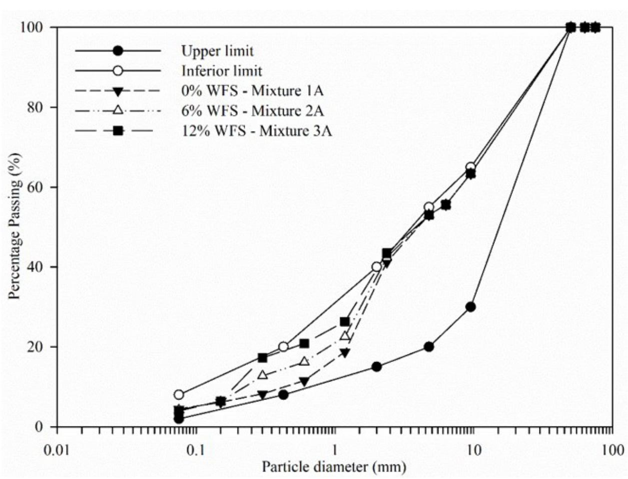

Figure 1. Particle size distribution for grade "A" mixtures.

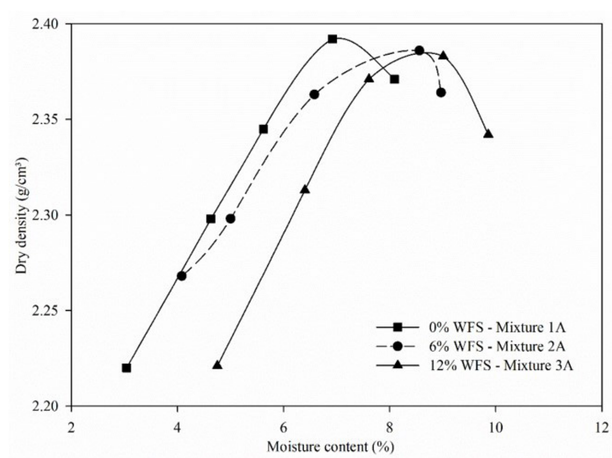

Figure 3. Compaction curves for specimens tested with different WFS contents, referring to grading "A."

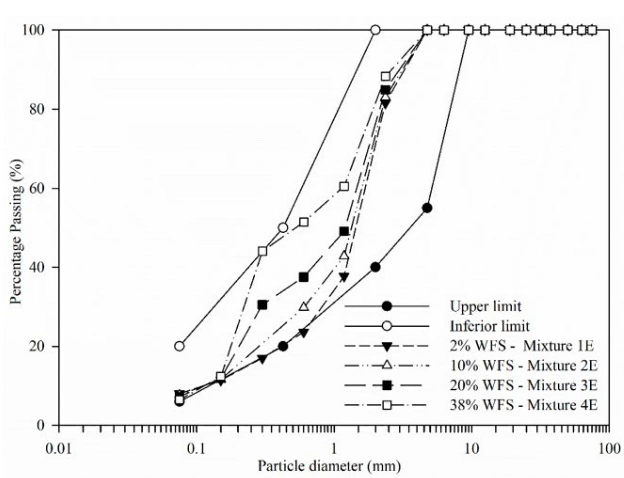

Figure 2. Particle size distribution for grade "E" mixtures.

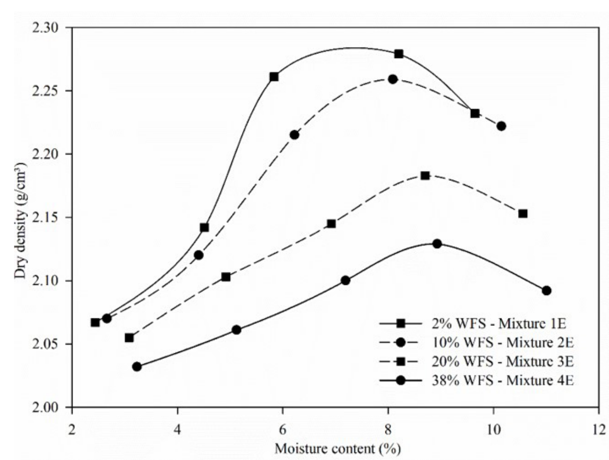

Figure 4. Compaction curves for specimens tested with different WFS contents, referring to grading "E".

with the specific unit weight of the materials, considering that WFS presents a lower density when compared to the other materials in the mixture. Pasetto & Baldo (2016), have also indicated that the specific unit weight of the materials directly affects the dry density parameter of the mixtures. Analyzing the mixtures with minimum and maximum WFS content, the dry density reduced 0.75% for grading "A" and 7.07% for grading "E". Considering that in both gradings the addition of WFS took place in substitution for CSC, the most significant reduction in the maximum dry unit weight was in grading "E"; due to the waste content being substantially higher.

Moisture content levels increased by 14.82% and 19.44% for gradings "A" and "E," respectively, considering mixtures with minimum and maximum WFS content. Mohammadinia et al. (2017) stated that the presence of materials with fine granulometry in the compaction process increases the mixture workability and consequently reduces the quantity of water needed for the process. In this context, WFS addition increased the fines content, contributing to the evidenced increase in the optimum water content level; implying that that higher volumes of water are required for compaction on site.

3.3. Swelling and California Bearing Ratio (CBR)

The results for swelling capacity and California Bearing Ratio (CBR) are presented in Table 2. The swelling was close to zero for all specimens, which was below the maximum limits set by Brazilian standards for the construction of road subbases.

The addition of WFS up to 38% presented no significant effect on the swelling of the mixtures. In fact, WFS can even reduce the swelling of soils, as observed by Klinsky & Fabbri (2009). Despite the presence of a small amount of bentonite in the mixture composition, the content of clayey material of WFS was about 1%.

CBR values for all mixtures with grading "A" and "E" were compacted under optimum conditions using modified energy, which resulted in high CBR values. Regarding grading "A", WFS addition increased CBR values by 1.5 times when compared to mixtures of lower (1A) and higher (3A) WFS content. This represented 267.50% in mixture 3A, which was the highest bearing capacity recorded for this grading. The increase in bearing capacity regarding WFS addition was due to the improvement of the granulometric mixture composition, which ensured better material stabilization. CBR values were much higher than those observed by Arulrajah et al. (2019), with a CBR of 130% for crushed material, and by Guney et al. (2006) of 80% and 155% for mixtures of crushed rock.

For grading "E" the increase in WFS content led to a decrease in CBR values. This behavior can be associated with the lower strength parameters of WFS when compared to CSC (especially regarding mineralogical characteristics). Saha & Mandal (2017), studied mixtures of crushed rock, reclaimed asphalt pavement, and cement at levels of 75%, 25%, and 1%, observing similar CBR values. The largest recorded load capacity corresponded to "1E".

Considering that all studied contents satisfied the performance criteria established for each grading, the optimum WFS content was defined based on the largest waste reutilization. Thus, for the "A" and "E" gradings, the additional contents of 3A and 4E were considered optimum.

3.4. Resilient Modulus

A total of seven cyclic triaxial tests were carried out to identify the influence of WFS on the mechanical properties of each mixture. Three samples were tested using the grading "A" (Figure 5) and the four remaining samples were prepared following grading "E" (Figure 6)

Results indicate that WFS contributed to the improvement of the mechanical performance. This behavior may be associated with the granulometric stabilization resulting from fine WFS particles. Also, WFS addition improved the original granular interlocking due to the more efficient void filling, creating a more compact structure. Once particle

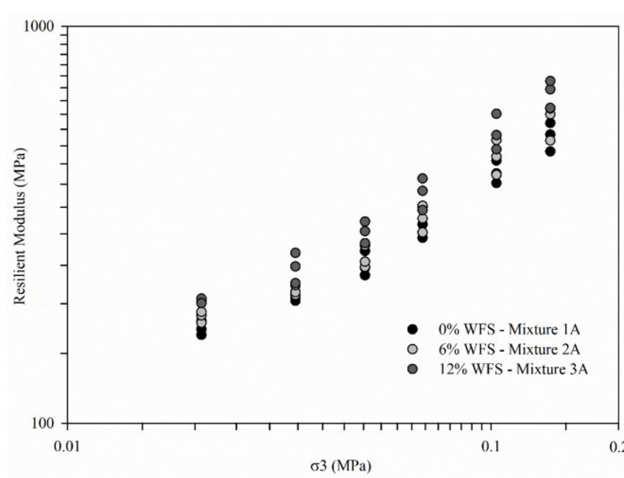

Figure 5. Resilient Modulus versus confining stress for grading "A".

Table 2. Variability of swelling and CBR for mixtures with different WFS contents, referring to gradings "A" and "E."

Mixture	Grading "E"				Grading "A"		
	1E	2E	3E	4E	1A	2A	3A
California Bearing Ratio (CBR) (%)	111.35	92.75	94.86	85.16	173.22	188.15	267.50
Swelling (%)	0.01	0.01	0.00	0.03	0.00	0.00	0.00

rearrangement occurred, higher particle contacts improved the mechanical properties, resulting in little susceptibility to deformation through the interlocking of the grains.

The regression parameters for both mechanistic models are summarized in Table 3. Considering that the first model accounts only for the effects of confining stress (Equation 1), the results indicate a satisfactory RMSE, as well as a determination coefficient (R^2) exceeding 0.94. Model 1 suggests that WFS can improve granular interlocking once it reaches higher values of k_1 and k_2. This increment is more impactful for "A" grading mixtures, in which the fine particles can fill the remaining voids, reaching higher density levels (as observed in Figures 3 and 4), and consequently, allowing the mixture to show a better response under higher confining stresses. The addition of WFS in "A" grading mixtures resulted in an increment of k_1 parameter of approximately 33%.

The regression results of the second model (Equation 2) were useful for comprehending the WFS effect on "A" grading mixtures. This model suggests that the regression constant k_2, is less impacted than k_3, which indicates that the presence of WFS should account for both the confining and deviator stress.

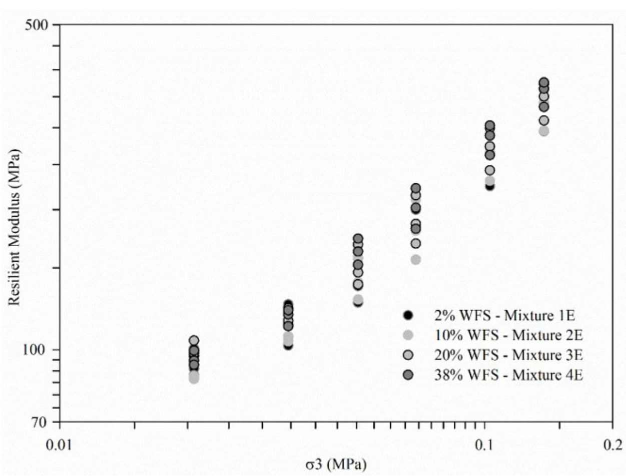

Figure 6. Resilient Modulus versus confining stress for grading "E."

Although "E" grading mixtures resulted in worse mechanical performance when compared to "A" grading, a similar pattern was detected between gradings. Even though a lesser amount of WFS was added to the raw material (mixture 1E), the analyzed data implied the increase of k_2 for both models, indicating once again that WFS improves the interlocking of particles.

Mohammadinia et al. (2017), studied mixtures of crushed materials and recycled asphalt pavement with different contents of fly ash, presenting resilient modulus results extremely similar to the ones shown in this research. In addition, k_1 values obtained for gradings "A" and "E" corresponded to a similar behavior of granite and basalt materials presented by Marmitt et al. (2010).

Geometric and mechanical properties of the materials can be found in Table 4. The conducted analysis was performed considering only the strain responses at the asphalt layer (Bottom layer tensile strain) and the top of the subgrade layer (Vertical strain). k_1 and k_2 parameters were considered as the average of grading "A" and "B"; with values of 2330 and 0.697 for "A" grading and 1496 and 0.759 for "E" grading. Both WFS gradings were considered appropriate as subbase layers. The standard double wheel axle with 82 kN (20,5 kN/wheel) was considered as the typical loading in the analysis and all structural responses were determined between two wheels.

Table 5 presents the results from the mechanistic analysis carried out with the AEMC elastic multilayer analysis. Subbase layers of WFS resulted in similar behavior to the one found on conventional asphalt bottom layers

Tensile strain results on the lower face of the pavement (fatigue criterion), indicated that the repetition number of the standard vehicle axis was 4.1 x 10^6 for the WFS mixtures and 4.9 x 10^6 for the conventional basalt gravel, following the

Table 3. Regression parameters of both models for mixtures with gradings "A" and "E."

Grading	Mix.	$RM = k_1.\sigma_3^{k_2}$				$RM = k_1.\theta^{k2}.\sigma_d^{k_3}$				
		k_1	k_2	*RMSE* (MPa)	R^2	k_1	k_2	k_3	*RMSE* (MPa)	R^2
"A"	**1A**	1930	0.661	25	0.963	1815	1.002	-0.339	16	0.984
	2A	2291	0.703	33	0.948	2111	1.022	-0.318	22	0.977
	3A	2829	0.728	36	0.957	2610	1.074	-0.345	22	0.984
"E"	**1E**	1297	0.727	17	0.946	1373	1.086	-0.305	12	0.973
	2E	1556	0.785	20	0.947	1401	1.104	-0.318	10	0.987
	3E	1517	0.756	20	0.952	1389	1.097	-0.339	11	0.984
	4E	1617	0.766	14	0.977	1517	1.199	-0.433	9	0.991
Crushed basalt - A		953	0.446			N.A.	N.A.	N.A.	N.A.	N.A.

N.A. - Not Applicable A - Frederico Wesphallen (Marmitt et al., 2010).

Table 4. Geometric and mechanical properties of pavement materials used in the simulations.

Layer	Thickness (cm)	RM (MPa)	Poisson coefficient (ν)	Reference
Asphalt	10	6300	0.27	Klinsky & Faria (2018)
Base	20	$RM = 953.\left(\sigma_3\right)^{0.446}$	0.35	This study
Subbase	20	WFS gradings A and E	0.35	Marmitt et al., (2010)
Subgrade	-	54	0.45	Santos (2019)

Table 5. Observed structural response for suggested structures.

Subbase layer	ε_t (Asphalt bottom layer)	ε_v (Subgrade top layer)	N_{AASHTO}	$N_{Dormon\ \&\ Metcalf}$ (1965)
Grading A	852	585	4.8×10^6	1.5×10^6
Grading E	903	920	4.1×10^6	1.7×10^5
Basalt crushed stone	844	541	4.9×10^6	2.2×10^6

Table 6. Results of the leaching and solubilization tests for mixture 4E.

Element	Leaching Tests NBR 10005 (ABNT, 2004b)		Solubilization Tests NBR 10006 (ABNT, 2004c)	
	Results	Limits (mg/L)	Results	Limits (mg/L)
As	*ND**	1.0	*ND**	0.01
Ba	*ND**	70.0	*ND**	0.7
Cd	*ND**	0.5	*ND**	0.005
Pb	*ND**	1.0	*ND**	0.01
Cr	*ND**	5.0	*ND**	0.05
F	*ND**	150.0	0.7	1.5
Hg	*ND**	01	*ND**	0.001
Ag	*ND**	5.0	*ND**	0.05
Se	*ND**	1.0	*ND**	0.01
Al	-	-	*ND**	0.2
Fe	-	-	2.4	0.3
Mn	-	-	0.05	0.1
Na	-	-	39.8	200.0
Zn	-	-	*ND**	5.0
Cu	-	-	*ND**	2.0

**ND:* not detected.

AASHTO model. Nevertheless, higher values of vertical strain on top of the subgrade were identified for the WFS structure when compared to the conventional one; this strain directly affects the admissible N value in the model analysis (Dormon & Metcalf, 1965). For the conducted analysis, this study admitted as a reference the lowest N value of each structure. For the same subbase thickness (20 cm), mixtures with "A" and "E" gradings resulted in a performance equivalent to 68% and 7% of the traditional materials. Although a reduction in performance was evidenced for WFS mixtures, this study suggests that such materials can meet the requirements of light to medium traffic conditions. Finally, it is important to highlight that further studies are necessary regarding permanent strain.

3.5. Leaching and solubilization of metals

On large industrial scales, the correct disposal of WFS can be very onerous, requiring large storage areas. Thus, the reutilization of this waste benefits not only industries, but also the environment, minimizing the use of natural resources and landfills areas (Penkaitis & Sígolo, 2012). Considering that all mixtures satisfied the specifications for granulometric stabilized subbases, an environmental classification by leaching and solubilization tests was carried out only on the highest WFS mixture (4E – 40% WFS). Table 6 presents the results of the leaching and solubilization tests for the mixture according to NBR 10004 (ABNT, 2004a).

The sample was classified as non-inert Class II A (ABNT, 2004a), for exceeding the solubilized iron concentration of the solubilization test; the raw waste presented similar results, considering that iron can be leached from both the molten metals of the molds and the additives of the foundry sand processing. In addition, WFS can also be classified as a nontoxic waste by NBR 10004 since none of the tested metals were detected on the leaching tests. A similar behavior was also evidenced by Alves et al. (2014). Finally, Basar & Aksoy (2012) also corroborated this behavior while studying the addition of 40% WFS in concrete mixtures.

4. Conclusion

This study evaluated the physical, geomechanical, and environmental aspects of WFS and crushed aggregate mixtures applied to road subbases using granulometric stabilization as a building method.

Low fine contents of the four materials limited the selection of grading to two options, "A" and "E," with a maximum waste content of 12% and 38%, respectively. For both gradings, WFS satisfied the minimum requirements of granulometric stabilized subbase pavement layers. Nevertheless, it is recommended to utilize WFS exclusively for subbase layers, considering that conventional materials usually result in a better mechanical performance. Also, it is recommended to investigate permanent strain properties for pavement structural evaluation.

The mixtures presented no significant swelling and showed high California Bearing Ratios, reaching maximum values of 267.50% and 111.35% for contents of 12% and 2%, corresponding to gradings "A" and "E." Regarding grading "A," the progressive WFS increase improved the support characteristics of the mixture and the Resilient Modulus. Satisfactory values of the Resilient Modulus and the California Bearing Ratio were observed for mixtures with waste contents of 12% and 38% (gradings "A" and "E," respectively), ensuring a structure with high density, strength, and little susceptibility to strain.

The highest WFS mixture (38%) was classified as a non-inert Class II A waste, indicating an environmental feasibility of using crushed material mixtures with up to 38% WFS for building road subbases.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Manuella de Morais: writing – original draft, conceptualization, methodology. William Mateus Kubiaki Levandoski: methodology, writing – reviewing and editing. Joice Batista Reis: methodology, writing – reviewing and editing. Francisco Dalla Rosa: supervision, validation. Eduardo Pavan Korf: Supervision, validation, resources.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

List of symbols

CBR	Swelling and California Bearing Ratio
C_c	Curvature coefficient
C_u	Uniformity coefficient
D_{10}	Effective diameter
D_{30}	Particle diameter equivalent to 60% of passing material extracted from particles size distribution curve
D_{60}	Particle diameter equivalent to 60% of passing material extracted from particles size distribution curve
DNIT	National Department of Transport Infrastructure of Brazil
k_1, k_2, and k_3	model's constants obtained from the nonlinear regression
N	number of permissible standard wheel axle repetition
n	the number of used points in the regression analysis
NBR	Brazilian standard from Brazilian Association of technical standards (ABNT)
ND	not detected
R^2	determination coefficient
RM	Resilient Modulus
RM_i	observed Resilient Modulus
RM_i ^	predicted Resilient Modulus
RMSE	Root Mean Square Error
WFS	waste foundry sand
ε_t	tensile strain at the asphalt bottom layer
ε_v	vertical strain at subgrade top layer
θ	principal stress or bulk stress
σ_3	confining pressure
σ_d	deviator stress

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