Reuse of Waste Foundry Sand Mixed with Lateritic Clayey Soils in Pavement Bases and Sub-bases Courses

Luis Miguel Gutiérrez Klinsky, Glauco Tulio Pessa Fabbri and Vivian Silveira dos Santos Bardini

Abstract This paper evaluated the reuse of WFS mixed with lateritic clayey soils in pavements sub-bases and bases. Two lateritic clayey soils and one chemically bonded WFS were used in this study. A laboratory program was conducted on mixtures of lateritic clayey soils and WFS. Atterberg Limits, Particle Size Distribution, mini-CBR, CBR, hydraulic conductivity and Cyclic Triaxial Tests were used to assess mechanical properties of soil-sand mixtures. Environmental test was performed to determine leaching potential of the WFS. The results showed that soil-sand mixtures containing WFS have mechanical properties similar to the materials commonly used in bases and sub-bases courses.

Keywords Waste foundry sand · Soil stabilization · Base and Sub-base courses · CBR · Resilient modulus

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L.M.G. Klinsky (✉)
Highways Research Center, CCR, Presidente Dutra Road km 184.3, Santa Isabel, SP, Brazil
e-mail: luis.gutierrez@grupoccr.com.br

G.T.P. Fabbri
Department of Transportation, University of São Paulo, Av. Trabalhador Sãocarlense 400, São Carlos, SP, Brazil
e-mail: glauco@sc.usp.br

V.S. dos Santos Bardini
Department of Environmental Engineering, State University of São Paulo, Presidente Dutra Road km 138.5, São José dos Campos, Brazil
e-mail: vivian.bardini@ict.unesp.br

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1 Introduction

One of the biggest challenges of the modern world is to dispose the solid waste in appropriate ways, mainly those resulting from industrial activities. The purpose is to recover material and energy, so natural resources can be preserved and environment degradation could be reduced.

The foundry industry uses sand in the mould and core-making processes, for several reasons: it is readily available almost everywhere, inexpensive and highly refractory (Javed and Lovell 1994). The largest volumes of foundry sand are used as "green sand" (clay-bonded), which consists of high-quality silica sand, approximately 10 % bentonite clay and 2 to 5 % water. Chemically bonded sand cast systems use one or more organic binders mixed with catalysts and hardeners. Chemically bonded sand is typically 97 % silica sand by weight (Winkler and Bolshakov 2000). The most common types of binders are sodium silicate, phosphate, phenolic and furan resins.

The high temperatures (1000 °C) used by foundries degrade and oxidize the binders and the sand, transforming them in a useless waste for the casting process. Therefore, the WFS must be disposed in sanitary landfills, which increase the operating costs of the foundry industry. For each ton of metal molten results approximately one ton of WFS (McIntyre et al. 1992).

In Brazil, the Waste Foundry Sand production raised considerably in the lasts years, more than three million tons of metal castings were produced in 2008 (ABIFA 2011); as a result, the requirement of new sanitary landfills increased. Therefore, the reuse of WFS becomes an important issue for the foundry industries and for the environment preservation.

Investigations have been made in recent years to reuse WFS in civil engineering constructions. The sand has appropriate characteristics for its use as aggregate in asphalt concrete (Javed and Lovell 1994), concrete products (Naik et al. 1994; Guney et al. 2010), flowable fills (Deng and Tikalsky 2008) and pavement bases and sub-bases courses (Fox and Mast 1998; Partridge and Alleman 1998; Kleven et al. 2000). The roadway construction demands high volume of natural resources, so it becomes an ideal destination for the WFS reuse. However, mechanical and environment properties must be studied to reuse the WFS in appropriate proportions.

On the other hand, lateritic soils are widely used in the State of São Paulo, Brazil, as sub-base and base courses, even though not recommended by traditional procedures (Nogami and Villibor 1991). These soils are mainly used in low volume traffic roads ($<10^7$ applications of Standard Axle Load of 80 kN). Additionally, some regions present lateritic clayey soils without the appropriate characteristics for its use in pavement layers; however the addition of sand to these soils makes them suitable for its use in road structures. Villibor et al. (2007) recommend adding natural sands to the lateritic clayey soils to improve the bearing capacity of the material.

Investigations showed that clay-bound foundry sands and WFS containing bentonite have acceptable mechanical properties for its use as an aggregate in sub-base and base courses under flexible pavements (Kleven et al. 2000; Goodhue et al. 2001; Abichou et al. 2004a). Furthermore, the clay encapsulates the WFS, reducing the risks of environmental pollution (Abichou et al. 2004b).

2 Research Significance

This investigation evaluated the reuse of Waste Foundry Sand mixed with lateritic clayey soils in bases and sub-bases courses. The region close to the city of Sertãozinho (State of São Paulo) was investigated because of its high foundry industry concentration. Also, that region has many deposits of lateritic clayey soils, but no sands or sandy soils deposits nearby. Therefore, the WFS mixed to lateritic clayey soils could be used in bases and sub-bases courses of suburban and low volume traffic roads.

A laboratory program was conducted to assess the mechanical properties of soil-sand mixtures containing WFS and lateritic clayey soils. Also, environmental tests were performed in the mixtures to determine the pollution risks of WFS reuse.

3 Materials and Methods

3.1 Waste Foundry Sand

The WFS used in this study was collected from “Pama Mecânica e Fundição Ltda.” located at the city of Sertãozinho, State of São Paulo, Brazil. According to the company, it is used a sand mix containing 98.56 % of sand; 1.2 % of phenolic resin as a binder and 0.24 % of catalyst. The particle size distribution curve of the WFS is presented in Fig. 1. Table 1 shows that WFS is classified as A-3 (AASHTO) or SP (USCS).

3.2 Soils

Two lateritic clayey soils were used in this study. Soil 1 (S1) and Soil 2 (S2), both collected nearby the city of Sertãozinho. Figure 1 presents the particle size distribution of the soils and Table 1 shows index characteristics and the soils classification according to AASHTO and USCS systems.

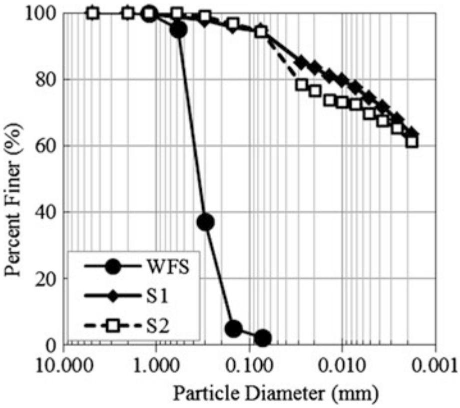


Fig. 1 Particle size distribution curves of collected materials

Table 1 Index properties of soils

Materials (1)	Specific gravity[a] (2)	Atterberg limits[b]			Classification[c]	
		Liquid limit (3)	Plastic limit (4)	Plastic index (5)	AASHTO (6)	USCS (7)
Soil S1	3.13	47	28	19	A-7-6	ML
Soil S2	3.12	47	31	16	A-7-5	ML
Waste foundry sand	2.64	NP	NP	NP	A-3	SP

[a] *ASTM D854*
[b] ASTM D4318
[c] ASTM D2487

3.3 Experimental Program and Tests

Soil S1 was used to compose soil-sand mixtures containing 20, 40, 60 and 70 % of WFS. Particle Size Analysis (ASTM D422) and Atterberg Limits Tests (ASTM D4318) were performed to obtain the required parameters to classify the soil-sand mixtures according to USCS (ASTM D2487) and AASHTO Soil Classification (M145). Even these classifications systems were not idealized for soil mixtures, they could provide some idea of the soil-sand mixtures behavior.

The Optimum Moisture Content (OMC) and maximum dry unit weight (γ_{dm}) of the soil-sand mixtures were obtained through the mini-CBR test (DNER-ME254-97). The mini-CBR test is a modification of the Iowa Bearing Value (Lafleur et al. 1960) developed in Brazil (Nogami and Villibor 1991) to determine the bearing capacity of fine grained lateritic soils using reduced size specimens. Villibor and Nogami (2009) also nominate the mini-CBR test as mini-Proctor test, because the OMC and γ_{dm} obtained from this test at Standard

Effort are similar to the OCM and γ_{dm} obtained from Proctor Test (ASTM D698). The mini-CBR or mini-Proctor test uses specimens of 50 mm in diameter and 50 mm in height. The Standard Effort (690 kN-m/m^3) and the Intermediate Effort (1660 kN-m/m^3) are commonly used in this test. The Intermediate Effort was used in this research according to the recommendations of the State Department of Highways of São Paulo (DER-SP 2005) for compaction of sub-bases and bases courses of pavements with low volume traffic.

The mini-CBR test also provides the bearing capacity, swell (after 24 h soaking) and hydraulic conductivity (DER–SP ME 194-88) of the soil-sand mixtures. As well, the California Bearing Ratio (CBR) test (ASTM D1883) was performed on the mixtures. Three specimens of 100 mm in diameter and 200 mm in height were used in the Cyclic Triaxial Test, according to AASHTO T 307-99, to obtain de resilient modulus (MR) of each soil-sand mixture.

From results observed in soil-sand mixtures containing soil S1, was determined a suitable percentage of WFS to be used in bases courses. WFS was also added to soil S2 at that suitable percentage, to compare the mechanical behavior with soil S1 mixtures, through mini-CBR and Cyclic Triaxial Test.

Finally, the Leaching Test (ABNT 10006-2004) was performed to assess the environmental risks of WFS reuse. Soil S1, WFS and a soil-sand mixture containing 50 % of soil S1 and 50 % of WFS were used to perform this test.

4 Results and Discussion

4.1 Size Distribution Curves and Atterberg Limits

The size distribution curves of the soil-sand mixtures containing soil S1 and WFS are presented in Fig. 2. As expected, high percentages of WFS reduces the content of particles smaller than 0.075 mm. The Index Properties of soil-sand mixtures obtained using soil S1 and WFS are presented in Table 2. The specific gravity of soil S1 decreased as WFS increased. Soil-sand mixtures with 60 and 70 % of WFS showed Atterberg Limits much lower than for soil S1. According to USCS and AASHTO classifications, S1 + 60 % WFS and S1 + 70 % WFS are expected to have similar behavior to SM-SC and A-4 and A-2-4, respectively; which are suitable to be used as subgrade materials.

4.2 Mini-CBR and CBR Test

Optimum Moisture Content (OMC) and maximum dry unit weight (γ_{dm}) of the soil-sand mixtures were obtained through the mini-CBR test. Figure 3 shows that adding WFS to soil S1 reduced the OMC, otherwise increased the γ_{dm}.

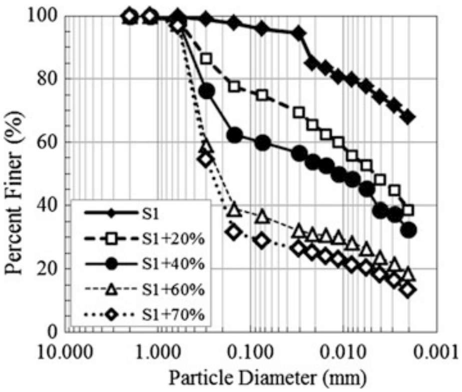


Fig. 2 Particle size distribution curves of soil-sand mixtures (S1 + WFS)

Table 2 Index properties of soil S1 containing waste foundry sand

Materials (1)	Specific gravity[a] (2)	Attenberg limits[b]			Classification[c]	
		LL (3)	LP (4)	IP (5)	AASHTO (6)	USCS (7)
S1	3.124	47	31	16	ML	A-7-5
S1 + 20 %	2.964	40	24	16	CL	A-6
S1 + 40 %	2.812	32	20	12	CL	A-6
S1 + 60 %	2.782	27	19	8	SM-SC	A-4
S1 + 70 %	2.724	23	15	8	SM-SC	A-2-4

[a,b,c] indicate the technical standards corresponding to the specific measurement or classification.

Abichou et al. (2004b) compacted WFS (containing 9.3 % of bentonita) at Proctor Standard Effort and Modified Effort, and the γ_{dm} ranged from 17 to 19 kN/m^3, with OMC values between 5 and 15 %. As presented in Fig. 3, higher values of γ_{dm} were obtained for soil-sand mixtures containing 60 and 70 % of WFS.

The specimens used to obtain OMC and γ_{dm} were also used to determine the mini-CBR value and swell, after 24 h soaking. The addition of WFS to soil S1 increased the mini-CBR value, as presented in Fig. 4. This behavior was also observed in CBR results. Further, both tests showed that the higher values were obtained for mixtures containing 60 % of WFS. Kleven et al. (2000) affirm that the average CBR of WFS is 20 %. Though, the results obtained here proved that much higher CBR values can be obtained mixing the WFS to lateritic clayey soils.

Figure 5 illustrates the swell obtained from mini-CBR and CBR tests in soil-sand mixtures. There was no swell or in S1 or in any soil-sand mixture according to the results of the mini-CBR test. The swell (obtained from CBR test) of soil S1 was 0.5 % and it was reduced to less than 0.1 % when 70 % of WFS was added. The specimens of CBR were soaked for 96 h, while the reduced-size specimens of mini-CBR were soaked for only 24 h. Probably, 24 h is not enough time to activate

Fig. 3 Optimum moisture content and maximum dry unit weight of soil-sand mixtures (S1 + WFS)

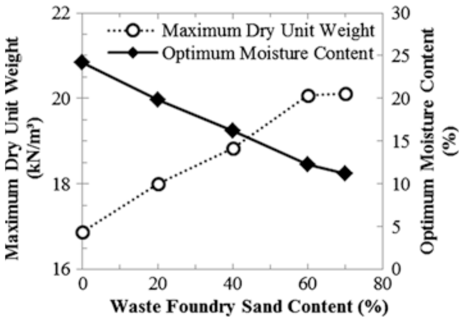


Fig. 4 CBR and mini-CBR of soil-sand mixtures (S1 + WFS)

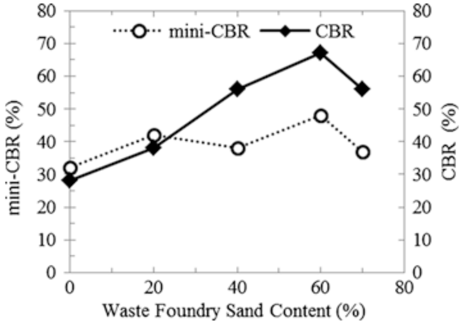
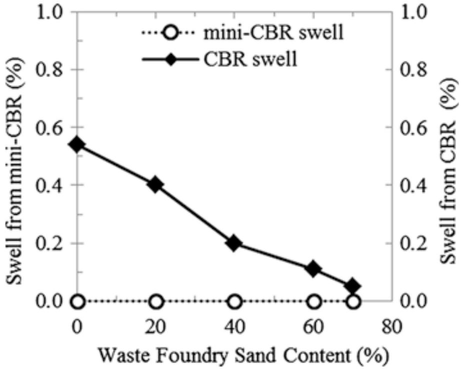


Fig. 5 CBR swell and mini-CBR swell of soil-sand mixtures (S1 + WFS)



the swell potential of the lateritic clayey soil, even for reduced-size specimens. Additionally, soil-sand mixture containing 60 % of WFS showed similar mini-CBR and CBR characteristics to typical lateritic sandy soils used as sub-base and base course materials of low volume traffic roads, according to the Pavement Manual of the Brazilian Standards (DNIT 2006).

The suitable percentage of WFS to be added to lateritic clayey soils was fixed as 60 %. Soil S2 + 60 % WFS showed similar mini-CBR values, compared to the S1 + 60 % WFS, as illustrated in Fig. 6.

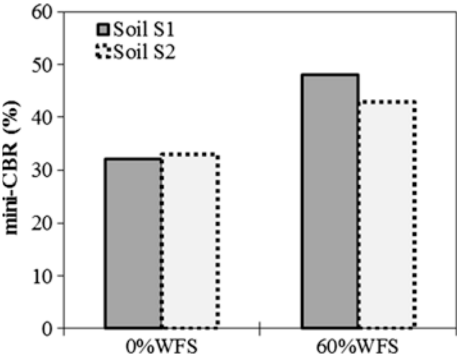


Fig. 6 Mini-CBR results for Soils S1 and S2 containing waste foundry sand (WFS) and clean sand (CS)

4.3 Hydraulic Conductivity

This test was performed using a fixed wall permeameter with falling head method. The specimens were compacted at OMC and γ_{dm} using specimens obtained from mini-CBR test at intermediate effort. The hydraulic conductivity value of soil S1 was 1.0e^{-08} cm/s. Nogami and Villibor (1991) affirm that sandy lateritic soils have permeability values smaller than cm/s. Figure 7 shows the effects of adding WFS to soil S1. The addition of the residue did not significantly increase the hydraulic conductivity. The soil-sand mixtures with 70 % of WFS had a hydraulic conductivity of cm/s.

Fox and Mast (1998) performed hydraulic conductivity tests on WFS specimens using the miniature Harvard compaction device and obtained values ranging from 1.0e^{-08} cm/s to cm/s. Also Abichou et al. (2004b) determined that WFS containing 9.3 % of bentonite has hydraulic conductivity ranging from 10–7 to 10–8 cm/s. These values can be compared to hydraulic conductivity observed in soil S1 containing 60 and 70 % of WFS.

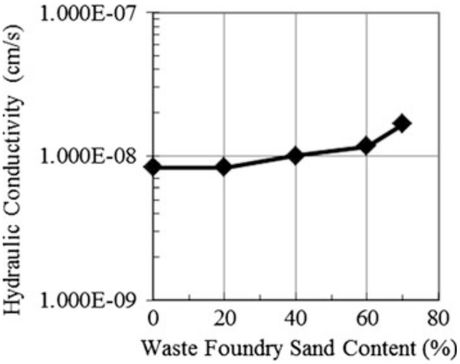


Fig. 7 Hydraulic conductivity of soil-sand mixtures (S1 + WFS)

4.4 Cyclic Triaxial Test

Three specimens for each soil-sand mixture were compacted at OMC and γ_{dm} using intermediate effort. Equation 1, recommended by NCHRP 1-28 (1997), was used to obtain the resilient modulus of the soil-sand mixtures. Table 3 shows the models of the resilient modulus of soil-sand mixtures and the coefficient of determination (R^2) of the models. It is verified that the adjustment of the NCHRP 1-28 equation was excellent ($R^2 > 0.90$) for all the materials but soil S2.

$$MR = K_1 \sigma_3^{k_2} \sigma_d^{k_3} \tag{1}$$

A common pavement structure of low volume traffic road was used to obtain the stresses of base courses composed by soil-sand mixtures. The initial characteristics of the pavement structure are described in Table 4. Single Load and Double Load were studied on the pavement structure. The Single Load was 40 kN and 0.56 MPa of tire pressure. The Double Load was constituted of two loads of 20 kN spaced 300 mm and 0.56 MPa of tire pressure.

ELSYM5 software was used to determine the stresses in the middle of the base layer. The stresses were used to calculate iteratively the Resilient Modulus (MR) of the soil-sand mixtures, as recommended by Huang (2004). The Resilient Modulus obtained applying Single Load is named MR1 and the Resilient Modulus obtained applying Double Load is named MR2. MR1 and MR2 values are also showed in Table 3.

Soil S1 had an average MR of 400 MPa for a Single Load applied in the low volume traffic road structure. Results shown in Fig. 8 reflect that MR decreased as WFS increased. However, mixtures containing 40, 60 and 70 % of WFS presented MR between 103 and 120 MPa. Figure 8 also shows that similar values of MR were obtained using Single Load and Double Load.

Kleven et al. (2000) performed cyclic triaxial tests on 13 waste foundry sands. The MR of the studied sands ranged from 90 to 200 MPa for different deviator and confining stresses. The study compares these values to traditional sub-base materials used in pavement construction. Thus, MR results of this study shows that clayey soils containing WFS could be used in sub-base pavement courses.

Soil S2 had a resilient modulus of 380 MPa, similar to soil S1. Also, when 60 % of WFS was added to S2, the MR decreased as observed in mixtures obtained from soil S1, as is shown in Fig. 9.

4.5 Environmental Tests

Leaching Test was performed on three samples: (1) Waste Foundry Sand; (2) Soil S1; (3) Mixture of Soil S1 containing 50 % of WFS. In this study the ABNT NBR 10006:2004 (Brazilian Standard) was used as reference framework to assess the

Table 3 Resilient modulus models of soil-sand mixtures

Material	Model parameters				Resilient modulus					
	K1	K2	K3	R2	Resilient modulus MR1			Resilient modulus MR2		
					Value (MPa)	Average (MPa)	Standard desviation	Value (MPa)	Average (MPa)	Standard desviation
S1	400.72	0.066	−0.020	0.92	439	400	43	445	403	47
	548.49	0.086	−0.099	0.91	407			413		
	672.35	0.051	−0.143	0.96	353			352		
S1 + 20 % of WFS	1109.16	0.037	−0.293	0.97	241	275	30	247	272	23
	948.53	0.033	−0.231	0.97	286			279		
	987.92	0.010	−0.217	0.99	299			291		
S1 + 40 % of WFS	215.16	0.444	−0.499	0.91	87	103	15	89	106	15
	193.46	0.303	−0.332	0.91	108			110		
	253.24	0.285	−0.348	0.95	115			118		
S1 + 60 % of WFS	75.30	0.555	−0.320	0.93	120	112	11	137	126	16
	67.04	0.574	−0.320	0.94	117			134		
	112.02	0.629	−0.493	0.95	100			108		
S1 + 70 % of WFS	10.05	0.851	−0.173	0.97	127	120	9	148	142	9
	7.84	0.945	−0.224	0.98	110			132		
	8.96	0.877	−0.183	0.98	122			145		
S2	651.88	0.021	−0.107	0.97	380	379	16	377	375	17
	656.26	0.019	−0.100	0.84	394			391		
	919.20	0.042	−0.188	0.88	362			358		
S2 + 60 % of WFS	36.64	0.762	−0.352	0.97	115	121	10	138	143	6
	23.72	0.735	−0.230	0.96	133			150		
	21.33	0.766	−0.256	0.97	116			141		

Table 4 Initial characteristics of the pavement structure of a low volume traffic road

Layer	Thickness (mm)	MR (MPa)	Poisson
Top asphalt Layer	25	1500	0.35
Base	150	200	0.40
Sub-base	150	100	0.40
Subgrade	Semi-infinite	50	0.45

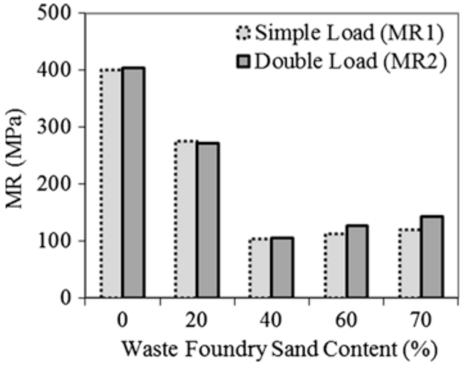


Fig. 8 Average MR values of soil-sand mixtures (S1 + WFS) in a low volume traffic road structure, for double load and simple load

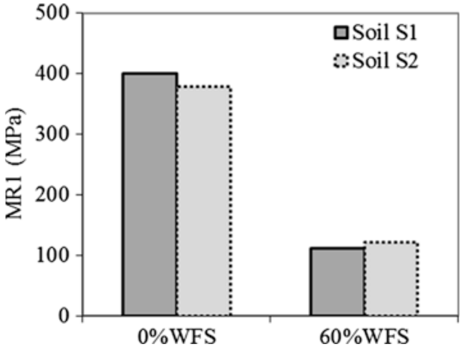


Fig. 9 Average MR values of soil-sand mixtures using control materials in a low volume traffic road structure, for simple load

studied materials. This standard is based on U.S. Environmental Protection Agency standards.

Table 5 presents the results of Leaching Test. The soil S1 containing 50 % of WFS did not attend the Brazilian Standards. Phenol and Iron content exceeded the limits. However, Table 5 shows that even the pure soil S1 did not attend these standards. The soils of the studied region are characterized by high Phenol and Iron content and are widely used in pavement activities. On the other hand, Environmental Standards in Brazil are being changed to encourage the reuse of Waste Materials. For example, for the Environmental Agency of São Paulo State

Table 5 Leaching characteristics of soil S1, WFS and S1 containing 50 % of WFS

Parameter (1)	Soil S1 (mg/l) (4)	Waste foundry sand (mg/l) (2)	Soil S1 + 50 % of WFS (mg/l) (3)	ABNT NBR (10006:2004) limit (mg/l) (5)
pH	ND	ND	ND	-
Arsenic	ND	ND	ND	0.01
Barium	ND	ND	ND	0.7
Cadmium	ND	ND	ND	0.005
Chromium	ND	ND	ND	0.05
Iron	3.2	0.07	9.28	0.5
Lead	ND	ND	ND	0.01
Manganese	ND	0.07	0.01	0.1
Mercury	<0.0001	<0.0001	<0.0001	0.001
Phenol	0.04	0.06	0.06	0.01
Selenium	ND	ND	ND	0.01
Zinc	0.11	0.1	0.12	5

(CETESB), the mixture of Soil S1 containing 50 % of WFS attends to the required specifications for its use in pavement construction.

5 Conclusions

This research assessed the feasibility of using Waste Foundry Sand mixed with clayey soils as a roadway sub-base and base course material. Lateritic clayey soils and chemically bonded WFS were used to assemble soil-sand mixtures. Mechanical properties of the soil-sand mixtures were investigated in a laboratory program. Also, Leaching Test was performed to investigate the environmental risks of their use.

The following conclusions are drawn based on results obtained in this study:

- Atterberg Limits were affected by the addition of Waste Foundry Sand. The Liquid Limit (LL) and Plastic Index (PI) decreased as WFS content increased.
- Addition of WFS decreased the Optimum Moisture Content of clayey soils. The Maximum Dry Unit Weight increased as the amount of WFS increased.
- CBR and mini-CBR results showed that soil S1 containing 60 % of WFS had similar characteristics to lateritic sandy soils used as base course materials.
- Hydraulic Conductivity of soil S1 did not significantly change as WFS content increase. Even the soil-sand mixture containing 70 % of the residue had a very small hydraulic conductivity.
- A low volume traffic road structure analysis showed that the addition of waste foundry sand to lateritic clayey soils decreased the Resilient Modulus (MR); but

the soil-sand mixtures presented appropriate MR values for its use in sub-bases courses;
- Leaching tests showed that foundry sand could not be used as pavement material according to the actual Brazilian Environmental Standards. Iron and Phenol content exceeded the recommended limits. However, even the natural soil, which is widely used in the studied region, exceeded the same parameters.

The laboratory results showed that soil-sand mixtures containing lateritic clayey soils and Waste Foundry Sand have mechanical properties similar to the commonly materials used in bases and sub-bases courses. Therefore, Waste Foundry Sand mixed with clayey soils could be reused as a partial substitute of commonly used materials. However, is recommended to perform field investigations to assess mechanical properties and environmental risks of the reuse of each kind of WFS. Finally, the beneficial reuse of Waste Foundry Sand could reduce the operating costs of foundry industries by reducing the use of sanitary landfills.

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