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Sustainable Concrete With Partial Replacement Of Water And Fine Aggregate With Industrial Waste Materials

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Abtract
The increasing demand for more space in industrial landfills and proper management of final disposal of waste requires new technological alternatives for its reuse. In this sense, with the aim of reducing the consumption of potable water and natural sand in civil construction, mortars and concretes were produced by replacing natural sand with 0, 25 and 50% of treated waste foundry phenolic sand (WFPS-T) to remove the phenolic present, as well as the replacement of water with 0, 20 and 60% sugarcane vinasse wastewater (SVW). Thus, partial replacements were carried out, both with residues in the mortars and in the concretes developed. The replacement of natural sand with different proportions of WFPS-T showed that the greater amount of WFPS-T negatively affects the mechanical resistance and consistency of the mortars, due to the greater porosity of WFPS-T, in addition to the sand particles associated with resin with low adhesion to the cement matrix. On the other hand, up to 60% of SVW replacing the water contributed to increase the consistency, reducing the water requirement due to the greater absorption of WFPS-T. Finally, concrete was developed with the ideal trace obtained from the mortar results. The use of 60% vinasse as a replacement for water and 25% WFPS-T as a replacement for natural sand resulted in concrete with 94% of the mechanical strength of the control concrete, with a slump range of 10 to 16 cm and low porosity. This formulation is suitable for both structural and non-structural applications through conventional concrete pouring practices (ABNT NBR 8953:2015), as well as for specific types of pavements and foundation elements. It is concluded that these industrial by-products have satisfactory mechanical properties for use in more sustainable mortars and concretes.

Keywords: *Concrete; compressive strength; sugarcane vinasse wastewater; waste foundry phenolic sand, waste foundry sand.*

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I. Introduction

One of the problems in the construction industry is the excessive consumption of natural resources. Finding ways to reduce this demand while maintaining the high quality of the products developed is a challenge. Waste recycling offers a sustainable solution to reduce the environmental impact of both the final disposal of this waste and as a substitute for non-renewable resources (water, aggregates and cement). (KACHOUH; EL-HASSAN; EL-MAADDAWY, 2019; LIU et al., 2016). It is estimated that the construction industry is responsible for 15% of annual drinking water consumption (POMPONI; STEPHAN, 2021), in addition to the 32 to 50 billion tons of sand and gravel extracted annually, with annual extraction growth of 5% due to increasing population demand (KAZMI et al., 2021).

Therefore, residual liquids and industrial solid wastes have been studied to replace kneading water and natural sand in cementitious composites (BHARDWAJ; KUMAR, 2017; MEENA; LUHAR, 2019; SANTOS et al., 2021; YAN; SAGOE-CRENTSIL; SHAPIRO, 2012). Among the various residues, sugarcane vinasse is one of the most voluminous; it is estimated that 29.7 billion liters of ethanol will be produced in 2020/21, generating 13 to 18 liters of SVW for every liter of ethanol produced (CETESB, 2015). Tamashiro *et al.* (2022) studied the effect of sugar cane vinasse on concrete slabs and observed that vinasse retards hydration at short curing times (7 and 14 days), while at 28 days the mechanical properties of the concrete were equivalent to the control concrete, attributing these changes to the sucrose present in SVW (TAMASHIRO *et al.*, 2022).

The positive effects of using sucrose by-products, such as sugar cane molasses, are well known in the literature. Authors estimate that the addition of 0.02 to 0.06% of molasses optimizes the properties of mortars and concretes, prolonging setting time, workability and, in some cases, increasing mechanical resistance (ASSI; DEAVER; ZIEHL, 2018; LI et al., 2015; WEIFENG et al., 2014). Weifeng *et al.* (2014) studied the cement hydration process with molasses using differential scanning calorimetry analysis (WEIFENG *et al.*, 2014). An endothermic peak at 430ºC was found after 3 days of curing, associated with the absence of dehydration of $Ca(OH)_2$. It was observed that excess sucrose significantly delayed the initial hydration of tricalcium silicate (C_3S), possibly due to early exhaustion of the reactions of $CaSO_4$ $2H_2O$, C_3A and ferrite.

In terms of industrial solid waste, the foundry industry is known to generate various wastes such as returned waste foundry sand (WFS), fume dusts and blast furnace slag. WFS is the largest volume waste, with an estimated generation of 0.8 to 1.0 kg of waste per kilogram of molten metal, with an annual generation of 19 million tons (MODERN CASTING, 2019). Recent studies have shown that replacing natural sand with up to 35% WFS with a physical binder results in increased mechanical strength and reduced consistency due to the increased particle fineness and presence of impurities that contribute to greater water absorption (PAIVA et al., 2021). However, few studies have been conducted on phenolic resin-contaminated WFS and have been limited to decontamination treatments (RODRIGUES; ANDRADE; TENÓRIO, 2021) and some studies on replacing sand with WFS (MASTELLA et al., 2014; SANTOS et al., 2021). However, further research must be carried out to evaluate the interaction in the cement matrix by different amounts of resin present on the surface of the WFS, allowing a methodology for selecting WFS contaminated with resins for application in civil construction, mainly due to the composition of phenolic resin, which is highly harmful to the environment.

A previous study demonstrated that the amount of resin present in the WFS particle directly affects the mechanical strength, residue/matrix interfacial bond, and porosity of cementitious materials (DE PAIVA et al., 2023a). Therefore, this study proposes to evaluate whether sugarcane vinasse, which contributes to increase consistency, makes it possible to interact positively with other residues that have greater water absorption, reducing the need to increase the amount of water for the use of residues. as a substitute for natural sand. Thus, contributing to the conservation of water resources and allowing the reuse of two little studied industrial wastes.

II. Materials And Methods

The collection of sugarcane vinasse wastewater (SVW) was carried out in an ethanol production unit located in the municipality of Narandiba, São Paulo, Brazil. After collection, the SVW was filtered using a vacuum filtration system and filter paper with a pore size of 14 micrometers (μm) to remove suspended solids. The density of vinasse was measured to be 1.005 grams per cubic centimeter (g/cm³), while the density of water was recorded to be 0.997 g/cm³. Both densities were determined at room temperature, specifically at 23 degrees Celsius (ºC). The sucrose content of the vinasse, determined by the Lane-Eynon method, is 4.8 mg/ml.

Waste Foundry Phenolic Sand (WFPS) was obtained from the MIG foundry industry, located in the municipality of Presidente Prudente, São Paulo, Brazil. In this study, the WFPS was subjected to a treatment (named WFPS-T) in an alkaline environment to remove the phenolic resin, using sodium hydroxide (NaOH) with a purity of 97%, supplied by Anidrol Produtos para Laboratórios, located in Diadema, Brazil. As for the cementitious material, Portland cement was used, available in the Brazilian market under the CP V - ARI classification, according to the ABNT NBR standard 16697:2018, which is Type III according to the ASTM C150:2019 (ASTM C150/C150M-19A, 2019).

As part of the experimental procedure, the micrographs were acquired using a Jeol Model JSM7500F scanning electron microscope. To ensure the integrity of the scanning electron microscopy (SEM) images, the samples underwent a preparation process where they were coated with a layer of ultrathin gold. This coating process was carried out utilizing a sputter coater, specifically the Edwards Model T-STATION 75.

Characterization of fine and coarse aggregates

The characterization of the aggregates has been carried out in accordance with the standards listed in Table 1.

Table 1. Coarse and Fine Aggregate Characteristics.

Aggregate	Tests	ABNT	Similar to ASTM
Natural Sand	Determination of the fineness modulus	(NBR 7211, 2022)	(C33/C33M-18, 2018)
	Determination of water absorption and specific gravity	(NBR 16916, 2021)	(ASTM C128, 2022)
Coarse Aggregate	Determination of the fineness modulus	(NBR 7211, 2022)	(C33/C33M-18, 2018)
	Determination of water absorption and specific gravity	(NBR 16917, 2021)	(ASTM C127, 2015)

Mix Proportions

Mortar

A study of the interaction of WFPS and SVW waste was carried out to evaluate the proportions that present the best physico-mechanical responses. The objective was to evaluate whether SVW changes the consistency of these composites with WFPS and whether it contributes to improving the mechanical resistance. According to a previous study (DE PAIVA et al., 2023a), replacing sand with WFPS-T reduces the consistency of the composite, while replacing more than 60% of the mixing water with SVW contributes to the increase in consistency. (DE PAIVA et al., 2023b). Therefore, different dosages of water have been studied, identified as 280, 294 and 315 kg/m³.

Table 2. Mortar mixing proportions.

Samples	Sand (kg/m³)*	WFPS-T (kg/m³)	Cement (kg/m³)	Water (L/m³)	SVW (L/m³)
CC-280	1589.84	0	578.13	280.46	
20SVW-25WFPS-T-294	1192.38	397.46	578.13	235.20	58.80
60SVW-25WFPS-T-280	1192.38	397.46	578.13	112.18	168.28
20SVW-50WFPS-T-315	794.92	794.92	578.13	252.00	63.00
60SVW-50WFPS-T-294	794.92	794.92	578.13	117.60	176.40

*Refers to the mass of material used per 1 m^3 of mortar.

According to the sucrose content in the SVW determined by the Lane-Eynon (4,8 mg/mL) (CUNNIFF, 1995), it is estimated that the proportion of sucrose in relation to the cement mass for 20% and 60% of water replacement by SVW is 0.046 and 0.138, respectively. The proportions of the mixtures were defined on the basis of previous studies in which the physico-mechanical effects of SVW and WFPS-T on mortar composites were evaluated in isolation, defining the best proportions for application together (DE PAIVA et al., 2023a, 2023b).

An EMIC AG5 was used to prepare the mortar. The process began with the introduction of water and cement into the equipment, followed by a preliminary mixing for 30 seconds. After this step, sand was added to the mixture, which was subjected to a new mixing cycle for another 60 seconds. After this period, the equipment was deactivated for 90 seconds, at which time the mortar accumulated on the inner edges of the mixing bowl was manually scraped off, using the first 15 seconds of the pause for this purpose. After this interruption, mixing was resumed for another 60 seconds. At the end of the mixing cycle, the specimens were molded using prismatic molds measuring 4x4x16 cm. This mortar preparation method was carried out according to the guidelines of the standard ASTM C305:2020 (ASTM C305-20, 2020). A total uniform mixing time of 4 minutes for prepared mortar compositions.

Concrete

Concrete specimens were made in 10 x 20 cm cylindrical molds with a water/cement factor of 0.495 and in quintuplicate for all tests. The mix used in the concrete is described in Table 3. The sand used was characterized as having an apparent density of 2.75 g/cm³, a fineness modulus of 2.50, and a water absorption of 1.55%. The crushed stone used was No. 1 with a density of 3.00 g/cm³, a fineness modulus of 9.80, and a water absorption of 1.18%.

Table 3. Mortar mixing proportions.

Samples	Water (kg/m³)	SVW (kg/m³)	Sand (kg/m³)	WFPS-T (kg/m³)	Coarse (kg/m³)	Cement (kg/m³)	Superplasticizer
CC-0	180	-	787	-	1075	364	0.30%
60VSVW25WFPS-T	72	108	590.25	196.75	1075	364	0.30%

The calculated dosage was obtained based on the methodology proposed by the Brazilian Association of Portland Cement (ABCP). The objective was to obtain a concrete with a slump between 10 and 16 cm, in the S100 class, and a mechanical resistance between 20 and 50 MPa for structural purposes, according to the NBR 8953 (2015).

Concretes were made in a 400 liter concrete mixer. First, the gravel and 25% of the water were added and mixed for 1 minute. Then the cement and another 50% of the water were added and mixed for 1 minute. Then the sand was added and mixed for another 2 minutes. Finally, the remaining water was added and mixed for another 1 minute until homogenized. In order to guarantee the necessary workability, superplasticizers from the company ADCO Industria de Aditivos para Concreto LTDA., MidFLOW 400, based on chemical surfactants and organic raw materials with a density of 1.04 g/cm³ and a pH of 4.75, were added. The use of superplasticizers was also aimed at reducing voids (<14%) and water absorption (<6%), factors that make concrete more durable (LOPES, 2019).

The samples were molded into 10 x 20 cm cylindrical metal molds and stored in the molds for 24 hours. After this period, it was demolded and cured immersed in water at room temperature (21 ± 2 °C) for a period of 28 days to rupture and obtain mechanical strength.

Properties of mortars and concrete in the fresh state

The consistency of all mortar samples was measured using the consistency table (ASTM C1437-20, 2020). The consistency of the concrete made was evaluated by the slump of the cone, according to the ABNT NBR 16889 (2020), similarly to ASTM C143/C143M-15A (2015).

Properties of mortars and concretes in the hardened state

The mortar composites were molded into 16 x 4 x 4 cm prismatic steel molds. After 24 hours, the specimens were removed from the mold and cured while immersed in water at room temperature (21 ± 2 °C). Flexural strength of all compounds was measured in quintuplicate over the 28-day cure period. Compressive strength tests were then performed on the fracture pieces; ten pieces of prisms were used according to the ASTM C348-20 (2020) e ASTM C349-18 (2018).

The compressive strength of the concrete was evaluated after 28 days of curing, and the test was performed according to ABNT NBR 5739 (2018), similarly to ASTM C39/C39M-20 (2020), in a 1000 kN hydraulic press.

Water absorption and void ratio were determined in triplicate according to the ASTM C642-21 (2021). The mortars and concretes were prepared in 10 x 5 cm cylindrical metal molds. The mortars and concretes were cured at 21 °C for 24 hours. Later, they were removed from the moulds and cured immersed in water at room temperature (21 ± 2 °C) for 28 days. Water absorption (W%) and void index (V_I) were calculated using equations 1 and 2, respectively. These specimens were not used for mechanical resistance tests.

$$W\,(\%) = \frac{M_{SATF} - M_S}{M_S} x\ 100 \quad (1)$$

$$Vi = \frac{M_{SATF} - M_S}{M_{SATF} - M_I} x\ 100 \quad (2)$$

Onde:

W: Percentage of water absorbed (%);

M_{SATF}: Mass of saturated sample after immersion (g);

M_S: Mass of the dry sample 110 ± 5 ºC (g);

M_I: Mass of the saturated sample immersed in water (in a hydrostatic balance);

V_I: Void index

III. Results And Discussion

SEM images of natural sand and WFPS-T are shown in Fig. 1. The image of natural sand (Fig. 1A), show sand particles with smooth surface. However, it is possible to observe in WFPS-T (Fig. 1B) an irregular surface with the appearance of a film detachment (arrows in red). These films are related to the phenolic resin present on the surface of the particle, which was not completely removed by the proposed alkaline treatment.

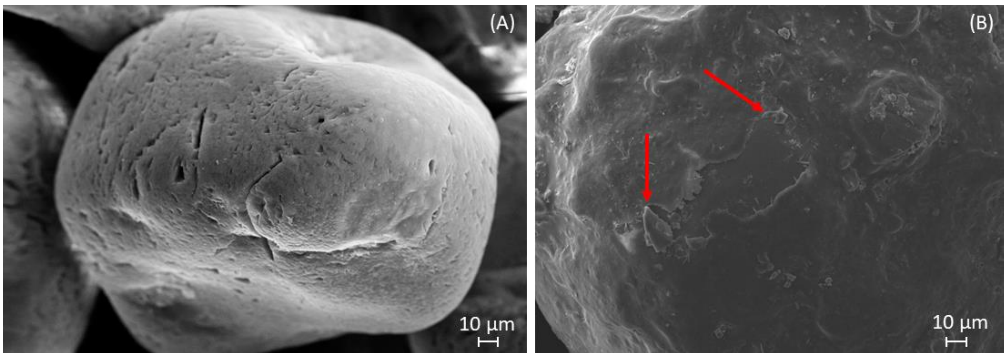

Figure 1. SEM images of Natural Sand (A) and WFPS-T (B).

The consistency results are shown in Table 4. First, it can be seen that there was no significant difference between the two WFPS-T substitutes (25 and 50%). As confirmed in the previous study (DE PAIVA et al., 2023b) that replacing kneading water with SVW (60 to 100%) results in an increase in consistency, the amount of kneading water was reduced from 294 kg/m³ to 280 kg/m³ for the 60SVW-25WFPS-T-280 composite and from 315 kg/m³ to 294 kg/m³ for the 60SVW-50WFPS-T-294 composite. The increase in kneading water from 294 kg/m³ to 315 kg/m³ for the 50% WFPS-T composite is due to WFPS being more porous and absorbing more water, requiring an increase in available water to maintain the workability of the mortar. It is concluded that 60% SVW also provides increased plasticity when processed with another residue in the same composite.

Table 4. Workability of mortars with VCA and ADF in different proportions.

Samples	Consistency (cm)
Control - CC-280	25.50 ± 0.00
20SVW-**25**WFPS-T-294	26.50 ± 0.00
60SVW-**25**WFPS-T-280	26.20 ± 0.27
20SVW-50WFPS-T-315	26.00 ± 0.30
60SVW-50WFPS-T-294	26.00 ± 0.00

Recent studies suggest that sucrose acts as a surfactant to increase the amount of free water in the cement paste, resulting in improved workability of the mortar (ALI; QURESHI, 2019; JUMADURDIYEV et al., 2005; RASHID; TARIQ; SHAUKAT, 2019).

Table 5 describes the flexural strength results. It is observed that replacing 25 and 50% of the sand with WFPS-T and both vinasse replacements did not result in significant differences in flexural strength. Sugarcane vinasse worked to increase consistency but had no effect on increasing flexural strength. Similar results were observed with DE PAIVA et al. (2023b).

Table 5. Flexural strength of mortars with VCA and ADF in different proportions and after 28 days of curing.

Samples	Flexural Strength (MPa)
Control - CC-280	6.48 ± 0.18
20SVW-**25**WFPS-T-294	5.71 ± 0.22
60SVW-**25**WFPS-T-280	5.76 ± 0.13
20SVW-50WFPS-T-315	5.53 ± 0.09
60SVW-50WFPS-T-294	5.94 ± 0.40

Table 6 shows the compressive strength results. In the composites where 25% of the natural sand was replaced by WFPS-T, it is observed that there was no effect on the mechanical resistance in the presence of 20 and 60% vinasse. However, with 50% WFPS, the 60% SVW ratio resulted in a reduction from 39.18 MPa (with 20% SVW) to 33.17 MPa. The presence of two residues in high concentration may have affected the homogeneity of the sample, thus affecting the mechanical resistance. In addition, the presence of phenolic resin in WFPS-T may have contributed to reduce the interfacial interaction between cement and WFPS-T particles, reducing the mechanical resistance between 24% and 39% compared to the control concrete.

Table 6. Compressive strength of mortars with SVW and WFPS in different proportions and after 28 days of curing.

Samples	Compressive Strength (MPa)
Control - CC-280	54.20 ± 1.44
20SVW-**25**WFPS-T-294	41.26 ± 1.32
60SVW-**25**WFPS-T-280	40.16 ± 0.91
20SVW-50WFPS-T-315	39.18 ± 0.21
60SVW-50WFPS-T-294	33.17 ± 1.42

With the results obtained in the mortars, the mixture with the best properties, both in the fresh and hardened state, was selected for the development and study of residues in the concrete. A proportion of 60% SVW was chosen to replace the mixing water and 25% WFPS-T to replace the natural sand, called 60SVW-25WFPS-T, making the comparison with the control concrete.

Table 7 shows the results of cone slump, compressive strength, water absorption, void index and bulk density. A similar result to the control was obtained in the cone slump test and within the application specification for conventional concrete pouring, which is between 10 and 16 cm. As expected, the concrete with SVW and WFS had a more porous structure with higher void content and water absorption and lower apparent density. An increase in porosity was expected due to WFPS-T's low adhesion and interlocking with the cement matrix.

However, the compressive strength of the concrete with 60SVW-25WFPS-T reached 94% of the mechanical strength of conventional concrete, a percentage higher than that obtained in the mortars produced, which was 74% in relation to the control. Therefore, the use of WFPS-T and SVW in concrete presents satisfactory properties for application in civil construction, reducing disposal in industrial landfills and valuing the waste studied.

Table 7. Compressive strength of concrete with VCA and ADF-T in different proportions and after 28 days of curing.

Samples	Cone slump (cm)	Compressive Strength (MPa)	Water Absorption (%)	Void Index (%)	Apparently density (kg/m³)
Control - CC-280	12.00	37.06 ± 2.26	2.17 ± 0.33	4.61 ± 0.12	2580 ± 24.0
60SVW-25WFPS-T-280	10.00	34.88 ± 1.78	2.84 ± 0.09	6.34 ± 0.18	2475 ± 23.0

Unlike mortar, concrete contains two additional components, crushed stone and superplasticizer. Future studies should evaluate the interface between coarse aggregate and WFPS-T to investigate the mechanisms that led to the increase in compressive strength of concrete with SVW and WFPS. The influence of the superplasticizer on the dispersion of the residuals in the cement matrix and the interaction between the residuals and the matrix must also be studied in order to better understand the resistance and fracture kinetics of structures formed with these residuals. Finally, it is also suggested that durability studies be carried out on the composite produced. However, it is noted that the results obtained so far suggest that both wastes produce a product with properties suitable for various applications in construction.

IV. Conclusions

The development of mortars and concretes with industrial waste was promising. First, in mortars, vinasse met the largest water demand of WFPS without the need to increase the water/cement factor. However, in mortars, the mechanical resistance resulted in a reduction of about 26% compared to the control mortar. However, when the concrete was developed, the physical-mechanical properties were similar to the control concrete, with a mechanical resistance of 94% with respect to the control. Therefore, SVW and WFPS can be alternatives to produce more sustainable concrete.

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