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The use of water treatment plant sludge ash as a mineral addition

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HIGHLIGHTS

- It is possible to obtain environmentally sound concrete by using WTP sludge ash.
- The use of WTP sludge ash helps reduce greenhouse gases emissions.
- The use of WTP sludge ash reduces the discharge of this material in watercourses.
- It is possible to reduce the consumption of cement in concrete by 37–200 kg m^{-3}.

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ABSTRACT

For decades, the sludge produced in water treatment plants (WTP) was dissolved in water and then discharged in watercourses. WTP sludge is rich in pathogens and metals and when discharged in watercourses, it increases the amount of suspended solids, eventually causing the water body to silt up. Existing legislation in Brazil prohibits the discharge of WTP sludge in watercourses, but the practice persists. This study investigated the possibility of using WTP sludge as a mineral addition. First, the pozzolanicity of WTP sludge with Portland cement and the concentration of fixed calcium hydroxide using the Chapelle test were determined after exposing the material to different calcination temperatures and residence times. The samples with the best results were used to investigate the performance of concrete mixes where WTP sludge was substituted for Portland cement in concentrations ranging from 5% to 30% in three different water/binder (w/b) ratios (0.35, 0.50 and 0.65). Results indicate that the use of WTP sludge ash improves the strength of concrete mixes when compared with concrete with rice husk ash or silica fume. By using WTP sludge ash, it is possible to obtain the same strength of a concrete mix with 100% Portland cement and reduce the consumption of cement by 37–200 kg m^{-3} of concrete, depending on the concentration of substitution and the desired strength level.

1. Introduction

The growing demand for products and services associated with population growth is responsible for the expansion of industrial activity, which in turn results in an increase in the consumption of materials. Civil construction has considerable environmental impacts because of the consumption of natural resources and the generation of waste associated with this industry.

The concrete industry is one of the major users of natural resources and its growth has resulted in significant environmental impacts associated with the use of raw materials, including water, as well as the release of greenhouse gases during the production of Portland cement.

The industry has been trying to mitigate such effects by reducing emissions during the manufacture of Portland cement. Modern plants release 0.7 metric ton of CO_2 for each metric ton of clinker produced. In addition, rice husk ash, silica fume and blast furnace slag are now used as substitutions for clinker. Recent studies have attested the viability of using other materials as mineral additions [1–4].

The use of mineral additions as partial substitutions for Portland cement has become a pressing need, not only because of the need to reduce the environmental impact associated with the manufacture of cement but also to improve the durability of concrete structures exposed to harsh environments, such as sulfates, chlorides, alkali-aggregate reactions, etc. [5–7]. This is due to the fact that mineral additions change the composition of the pore solution [8]. This way, electric conductivity is changed [9]. The substitutions refine the pore structure [10], which reduces permeability and enhances strength, even though in some cases strength increases more slowly.

The optimal concentration of a given substitution depends on the type of cementitious material used, the intended modifications

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to the concrete and the characteristics of the environment to which the concrete will be exposed.

The use of calcined clay as a partial substitution for Portland cement has been studied in detail because of its technical, economic and environmental benefits [11–15].

On the other hand, population growth also translates as an increase in water consumption, which results in more sludge being produced by water treatment plants (WTP). The amount and composition of the sludge depends on the volume of water treated in the plant, the process used and the characteristics of untreated water.

It is often the case that water suppliers criticize the quality of untreated water. However, some WTPs end up discharging their waste in water courses, which runs contrary to their own interests. WTP sludge is a type of solid waste and must be processed and disposed of accordingly to prevent environmental damage.

WTP sludge is rich in pathogens and metals. When discharged in watercourses, it increases the amount of suspended solids, eventually causing the water body to silt up [16]. Even though existing legislation in Brazil prohibits the discharge of WTP sludge in watercourses, the practice persists. Many water suppliers in Brazil have signed agreements with the government that give them up to 30 years before they fully comply with existing legislation. As a result, they will continue discharging sludge and harming the environment for years to come.

Several researchers have attested the viability of using untreated sludge as a partial substitution for fine aggregate or cement [17,18] or as a partial substitution for the siliceous material in the manufacture of cement [19]. WTP sludge has also been used as lightweight coarse aggregate (water treatment sludge and softwood sawdust composite) [20] and in the production of heavy clay [21].

However, there are few studies on the possibility of using WTP sludge ash as a pozzolanic agent in concrete and Portland cement mortars. The present study thus aims to determine the optimal temperature and residence time to yield a material with pozzolanic activity that can be used as a partial substitution for cement without compromising mechanical strength and production cycles and that can improve the sustainability of construction sites and reduce concrete costs.

2. Experimental program

2.1. Materials

High-early strength Portland cement and WTP sludge ash were used as binders in this experiment. The WTP sludge was first dried in an oven at 110 °C for 24 h. It was then homogenized and calcined in a muffle kiln at temperatures of 400, 500, 600 and 700 °C, with residence times of 1 and 2 h, except for the temperature of 700 °C, in which case a residence time of 30 min was used. After calcination, the ashes were ground in a ball mill for 1 h.

The physical and chemical characteristics of the different cementitious materials are shown in Table 1.

The fine aggregate used in the experiment consisted of natural quartz sand, with specific weight of 2.66 g/cm^3, unit mass of 1.62 g/cm^3, fineness modulus of 1.85 and maximum particle size of 1.2 mm.

The coarse aggregate consisted of crushed stone with specific weight of 2.48 g/cm^3, unit mass of 1.38 g/cm^3 and maximum particle size of 19.0 mm.

Concrete samples were prepared with a plasticizer additive, except for those with a w/b ratio of 0.35 and those with 30% sludge ash, which required a superplasticizer additive (modified carboxylic ether), even when w/b of 0.50 was used.

The casting temperature was set at 18 ± 1 °C and the mix water was heated or cooled to adjust for the temperature of the other materials [22].

The quantities of materials used per cubic meter of concrete are shown in Table 2.

2.2. Mixture proportions

A total of seven binder mixes were prepared. The reference mixes were labeled REF and the mixtures with 5%, 10%, 15%, 20%, 25% and 30% of WTP sludge ash were labeled 5SA, 10SA, 15SA, 20SA, 25SA and 30SA, respectively.

Table 1
Physical and chemical characteristics of the cementitious materials.

Characteristic	PC	Sludge ash (600 °C)
Physical properties		
Specific gravity (g/cm^3)	3.13	2.56
Specific surface area BET (m^2/g)	1.14	27.7
Particle size distribution (μm)		
$D(v,0.1)^*$	3.67	–
$D(v,0.5)^*$	14.1	20.07
$D(v,0.9)^*$	38.81	65.06
Chemical composition (weight%)		
SiO_2	20.4	66.2
Al_2O_3	4.37	17.7
Fe_2O_3	2.64	8.76
CaO	62.9	0.57
MgO	2.7	0.96
SO_3	2.2	–
Na_2O	0.13	0.32
K_2O	0.95	1.16
MnO	<0.10	0.13
TiO_2	0.29	0.86
P_2O_5	<0.10	0.33
LOI	3.16	3.37

* equivalent spherical diameter (of the same volume) 10%, 50% and 90% of the particle distribution are below.

Table 2
Composition of the concrete mixtures (kg m^{-3}).

Mixture	w/b	CM	PC	SA	Fine agg.	Coarse agg.	water	P	SP
		(kg m^{-3})							
REF	0.35	487	487	–	633	1076	170	1.46	–
	0.50	359	359	–	740	1055	180	–	–
	0.65	284	284	–	804	1045	185	–	–
5SA	0.35	487	463	24	626	1076	170	1.94	–
	0.50	359	341	18	736	1055	180	–	–
	0.65	284	270	14	798	1045	185	–	–
10SA	0.35	487	438	49	623	1076	170	4.84	1.45
	0.50	359	323	36	732	1055	180	–	–
	0.65	284	256	28	798	1045	185	–	–
15SA	0.35	487	414	73	619	1076	170	4.84	1.93
	0.50	359	305	54	731	1055	180	0.36	–
	0.65	284	241	43	797	1045	185	–	–
20SA	0.35	487	390	97	614	1076	170	4.84	2.17
	0.50	359	287	72	729	1055	180	1.07	–
	0.65	284	227	57	795	1045	185	–	–
25SA	0.35	487	365	122	609	1076	170	4.84	2.41
	0.50	359	269	90	725	1055	180	1.43	–
	0.65	284	213	71	792	1045	185	–	–
30SA	0.35	487	341	146	606	1076	170	4.84	3.13
	0.50	359	251	108	722	1055	180	3.21	–
	0.65	284	199	85	790	1045	185	0.71	–

w/b – water/binder ratio; CM – cementitious materials; PC – Portland cement; SA – sludge ash; P – plasticizer; SP – superplasticizer.

For each mixture, three w/b ratios (0.35, 0.50 and 0.65) were used with a mortar content of 51% by weight of dry materials. In the mixtures with WTP sludge ash, the amount of sand was adjusted to ensure that the mortar content was the same as that in the reference mixture. This was necessary because of the lower specific gravity of sludge ash when compared with Portland cement.

2.3. Testing procedures

2.3.1. Assessment of pozzolanic activity with Portland cement

Samples were tested according to Brazilian standard ABNT NBR 5752:2014 [23]. This procedure is similar to the one defined in ASTM C 311. The difference is the use of a plasticizer to achieve the same flow for samples with the same w/b ratio. The method consists of preparing mortar test specimens with mix proportion = 1:3 and w/b ratio = 0.48. Mortar "A" was prepared with Portland cement CP II F, while in