Substitution of aggregates by waste foundry sand: effects on physical properties of mortars

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ABSTRACT: The substitution of the normalized aggregate by residual foundry sand (WFS) was studied on the physical properties of mortars by means of resistance to compression and capillary absorption tests. The aggregate was replaced by WFS in its natural state (WFS), washed residual foundry sand (WFSW) and heat treated residual foundry sand (WFST). The WFS had a percentage of bentonite, which was sought to be thermally activated. It was found that the physical behavior of the mortars containing WFS and WFSW was similar to that of the control sample. The clay recovered from the sand washing was evaluated for its pozzolanic potential, it was found that, with the thermal treatment, the montmorillonite acquires pozzolanic behavior. Mortars with WFST presented a drop in compressive strength. The pozzolanic effect achieved in the clay was not reflected in the compressive strength of the mortars with WFST.

KEYWORDS: Waste treatment; Pozzolan; Aggregate; Mortar; Compressive strength.

RESUMEN: *Sustitución de áridos por arena de fundición residual: efectos sobre las propiedades físicas de morteros.* Se estudió la sustitución del árido normalizado por arena de fundición residual (WFS) sobre las propiedades físicas de morteros mediante ensayos de resistencia a la compresión y absorción capilar. El agregado fue reemplazado por WFS en su estado natural (WFS), arena de fundición residual lavada (WFSW) y arena de fundición residual tratada térmicamente (WFST). La WFS tenía porcentaje de bentonita, que se buscó activar térmicamente. Se encontró que el comportamiento físico de los morteros que contienen WFS y WFSW, fue similar al de la muestra control. A la arcilla recuperada del lavado de arena se le evaluó su potencial puzolánico, se encontró que, con el tratamiento térmico, la montmorillonita adquiere comportamiento puzolánico. Los morteros con WFST, presentaron una caída en la resistencia a la compresión. El efecto puzolánico logrado en la arcilla no se reflejó en la resistencia a la compresión de los morteros con WFST.

PALABRAS CLAVE: Tratamiento de residuos; Puzolana; Árido, Mortero; Resistencia a la Compresión.

1. INTRODUCTION

Today, concrete is the most widely used construction material in the world (1), becoming the structural material par excellence. The annual global consumption amounts to approximately 25 billion tons (2), which is because it is the key element in the development of infrastructure (roads, bridges, buildings, warehouses, airports, ports, terminals, etc.) of countries and this, in turn, contributes to economic growth. The main ingredients in a concrete mix are cement, mineral admixtures, aggregates (fine and coarse) and water. Of these components, aggregates occupy approximately 70% to 80% of the volume of concrete (3).

Aggregates are elements of great importance in the formulation and development of the properties of concrete and mortars. The type and amount of sand (fine aggregate) used is of relevance because it provides a mixture with specific properties. The production of natural sands is generally carried out by mechanical extraction activity that generates an impact on the environment due to the erosion of the soil resource and the alteration of air and water quality (4).

The large consumption of aggregates poses a series of challenges in the construction sector since it can lead to depletion or shortage of resources, environmental restrictions and in the increase of the cost of production. (3). To address these problems, several authors have investigated the possibility of replacing fine aggregates with industrial waste such as fly ash, bottom ash and blast furnace slag in order to promote the circular economy (5). The total or partial replacement of this component is a key challenge to face the negative environmental effects and costs associated with the aggregate extraction process, obviously, without significantly affecting the properties of the concretes and mortars made with them. Among the materials that have been studied as an alternative to replace fine aggregate is residual foundry sand (WFS).

WFS is a by-product of the foundry industry with a high content of silica. The sand grains are covered with a thin film of burnt charcoal, bentonite clay (6) or chemicals (7). WFS has been used as a raw material in the manufacture of Portland cement and as a substitute for fine aggregate in construction. In the works of Fiore and collaborators (8) they studied the reuse and recycling of foundry sands. After investigating foundry sands of different sizes, they classified the waste into 3 categories based on particle size and suggested that particles below 0.1 mm to 0.025 mm be recycled as raw material for the concrete industry.

The shape of the particles is typically sub-angular to round and does not meet the classification requirements for fine aggregates. In general, WFS is too fine to be used as a complete replacement for normal sand (9). The modulus of fineness of WFS has been found in the range of 0.9 to 1.6, which is very low compared to 2.3-3.1 for normal sand. The mean diameter of the residual foundry sand particles is 28.8 μm (10). Therefore, only partial replacement of natural sand by WFS is recommended to meet the standard specifications for fine aggregate. Table 1 shows the ranges of some physical properties of the WFS used by different authors for their research studies (1, 7, 9, 11-14). The modulus of fineness of WFS has been found, on average, to be 1.82 compared to 2.7 which is a common value for natural sand, therefore only partial replacement with coarser sand is recommended to meet the standard specifications of fine aggregate.

TABLE 1. Ranges of some WFS physical properties used.

Property	Rank	
	Minimum	Maximum
Specific Gravity	1.97	2.79
Density (kg/m³)	1538	1784
Fineness module	1.32	2.32
Water absorption (%)	0.42	5

The variation in the chemical composition of WFS as reported by various investigators (1, 6, 15-18) is presented in Table 2.

TABLE 2. WFS Chemical Composition Range.

Compound	Rank	
	Minimum (%)	Maximum (%)
SiO_2	76	87.48
Al_2O_3	0.81	5.21
Fe_2O_3	1.31	5.39
CaO	0.22	3.56
MgO	0.18	1.98
SO_3	0.07	0.84
MnO	0.047	0.46

The residual foundry sand is rich in silica content and is coated with a thin film of burnt carbon, dust, and residual binder such as bentonite clay (6).

Some investigations (7, 10, 18, 19) reported a constant increase in the strength of concrete with WFS, when it was used up to 30% as a replacement for sand this increase being attributable to densification of the concrete matrix due to the finer particles of WFS. At 20% replacement, the compressive strength was comparable to a control concrete. After a 30% replacement by WFS, the compressive strength of the mortars drastically decreased.

Therefore, the authors recommend using between 20% and 30% replacement of natural sand by WFS in concrete and mortar.

Regarding bentonite clays, they are mainly (more than 65%) made up of a mineral from the smectite family: montmorillonite (20). They have a high percentage of calcium or sodium aluminosilicate and may have non-clay minerals such as anorthite and quartz (21). Authors have reported that it is possible to activate montmorillonite (bentonite) clays for use as supplemental cementitious materials with promising results (22-25).

The hypothesis of this research is that, since the residual foundry sand residue contains around 10% bentonite clay, this clay could be exploited by thermally activating it in search of a cooperation between a physical effect of the fineness of WFS and a pozzolanic effect given by the thermal treatment of the clay present in WFS and thus achieve better mechanical behavior of the mortars. That is why this research evaluates and explains the effect of unwashed (WFS), washed (WFSW) and unwashed but heat treated (WFST) residual foundry sand substitution on the physical properties of mortars such as resistance to compression and porosity.

2. MATERIALS AND METHODS

2.1. Materials and mixing proportions

For the preparation of mortars, local cement, Ottawa standard sand according to ASTM C-778 and residual foundry sand were used as a partial substitute for standardized sand. While for the pastes, the cement was replaced by 15%, 20% and 25% raw clay or heat-treated clay. The clay was obtained from washing residual foundry sand. The water / material-cementing ratio was 0.5 for all samples. The proportions of materials used for the preparation of mortars and pastes are presented in Tables 3 and 4 respectively.

TABLE 3. Mix proportions used for mortars.

MORTARS	
Cement	Local (Grade: 42.5 MPa)
Aggregate	Ottawa Sand (Mortar Control)
	Waste Foundry Sand (WFS)
	Washed Waste Foundry Sand (WFSW)
	Heat treated Waste Foundry Sand (WFST)
water/cementitious-materials ratio (w/c)	0.5
Aggregate replacement percentage	15%
	20%
	25%

TABLE 4. Mix proportions for pastes.

PASTES	
Cement	Local (Grade: 36.6 MPa)
Clay	Raw Clay (R.C.)
	Heat Treated Clay (T.C.)
water/cementitious-materials ratio (w/c)	0.5
Cement replacement percentage	15%
	20%
	25%

TABLE 5. Variations in the amount of aggregate that is replaced by WFS, WFSW, or WFST.

Mix name	w/c	Cement (g/cm³)	Aggregate (g/cm³)	WFS (g/cm³)	WFSW (g/cm³)	WFST (g/cm³)	Water (g/cm³)
Control	0.5	0.667	1.84	0	0	0	0.335
WFS15%	0.5	0.667	1.564	0.276	0	0	0.335
WFS20%	0.5	0.667	1.472	0.368	0	0	0.335
WFS25%	0.5	0.667	1.38	0.46	0	0	0.335
WFSW15%	0.5	0.667	1.564	0	0.276	0	0.335
WFSW20%	0.5	0.667	1.472	0	0.368	0	0.335
WFSW25%	0.5	0.667	1.38	0	0.46	0	0.335
WFST15%	0.5	0.667	1.564	0	0	0.276	0.335
WFST20%	0.5	0.667	1.472	0	0	0.368	0.335
WFST25%	0.5	0.667	1.38	0	0	0.46	0.335

Three types of mortar were made with WFS, washed WFS (WFSW) and heat-treated or calcined WFS (WFST) with substitutions of 15%, 20% and 25%. Table 5 shows the design of the mixture.

2.2. WFS and clay treatment

The WFS was washed to separate it from the accompanying bentonite clay. Once the washing material (sand and clay) had been recovered, an X-ray diffraction analysis (XRD) was performed on both. The WFS was ground to a size that passed 200 mesh (<75 μm). The XRD tests were performed on PANalytical X 'Pert PRO MPD equipment, in a 2θ interval between 4° and 70°, with a step of 0.02° and an accumulation time of 56 seconds. A copper anode with Kα = 1.5406 Å was used and analyzed with X'Pert HighScore Plus software.

The clay recovered from the washing was also analyzed by thermogravimetric analysis to evaluate the changes it undergoes when exposed to a temperature range between 25 to 900°C with a gradual increase of 10°C / min, and thus find the temperature at which the material is completely dehydroxylated.

For heat treatment, the residual foundry sand samples were calcined in a furnace from room temperature to the temperature determined in thermogravimetric analysis, with a speed of 10°C / min and maintaining this temperature for 60 minutes. The calcined material was allowed to cool to room temperature in a dry room. In the same way, this heat treatment was applied to the clay recovered from washing (R.C.) to obtain a heat-treated clay (T.C.).

2.3. Compressive strength and capillary suction

Control mortars and mortars with WFS, WFSW and WFST were evaluated for their physical properties (resistance to compression and capillary suction). For the compressive strength tests, specimens of size 50 x 50 x 50 mm were prepared and the parameters established in ASTM C305 and ASTM C109 were followed. Once the specimens were made, they were subjected to a curing process in water saturated with lime at a room temperature of 23°C ± 2°, up to the ages of 1, 3, 7 and 28 days. The test was carried out in a Controls brand press, Model CT-0151/E, with a measurement range between 0-150 KN. Loading rate 1300 N/s.

The compressive strength of the control mortars and with replacement of 15%, 20% and 25% of conventional aggregate by WFS, WFSW and WFST was measured and a comparative resistance index (CRI) was calculated, as to the relationship between the

resistance to the compression of the mortar containing substitution and the compressive strength of the control mortar.

For the capillary absorption test, cylindrical specimens 30 mm high and 30 mm in diameter were manufactured. Once the specimens were made, they were subjected to a curing process in water saturated with lime at room temperature of 23°C ± 2° to avoid the leaching of calcium hydroxide, until the ages of 1, 7 and 28 days, to start the capillary absorption test. The conditioning of the samples was based on the Spanish standard UNE 83966. The calculation of the effective porosity and the absorption coefficient were based on the weight gain in the samples.

2.4. Specific surface area and porosimetry

Specific surface area and porosity were determined for raw and heat-treated clay. The test was carried out on a Micromeritics chemisorption analyzer AutoChem 2950 HP kit, using nitrogen adsorption isotherms. The value of the specific surface area was calculated by the Brunauer, Emmett and Teller (BET) method. The information obtained from the volume of nitrogen adsorbed allows to determine the specific surface, the size and the volume of the pores of the sample.

2.5. Lime fixation by Frattini and thermogravimetry

The lime-binding capacity of the raw and heat-treated clay was determined by Frattini and thermogravimetry tests. The Frattini test was performed at 7 and 28 days; using a replacement of 15%, 20% and 25% of the cement by raw clay (R.C.) and treated (T.C.). The greater distance between the point obtained and the solubility curve of $Ca(OH)_2$, measured on the vertical axis corresponding to the OH concentration which was determined indicates the decrease in the concentration of Ca^{2+} in solution and this is attributed to the increase in pozzolanic activity.

To determine the pozzolanic reactivity, the content of calcium hydroxide (portlandite) in the pastes was also evaluated by thermogravimetric analysis. This test was run from room temperature to 900°C in a nitrogen atmosphere and with a speed of 10°C/min. A pozzolanic material has the ability to assimilate calcium hydroxide, so as this material is added, the content of portlandite in the mixture will be reduced beyond the dilution effect and this will be reflected in a decrease in the loss of water in the thermal range corresponding to the decomposition process of calcium hydroxide (26, 27).

The fixed lime was determined from the content of calcium hydroxide in the cement paste following the information reported in (28) since the authors

calculate the present and fixed lime from thermo-gravimetric analyses.

3. RESULTS AND DISCUSSION

3.1. X-Ray Diffraction (XRD)

Figures 1 and 2 show the mineralogy of sand and clay respectively. It can be seen that in the two materials the main mineralogical species correspond to quartz, in position 2θ at 26.5° with great fineness, the characteristic peaks of montmorillonite clay are also found, which are around 6.96°, 19.71° and 34.74°. Other phases present correspond to aluminosilicates in the form of albite in small quantities. There are no major differences between the two diffractograms because the main phase (quartz) is highly crystalline and masks the clay phases, however, in the diffractogram of the clay recovered from the WFS wash, the peaks correspond to the mineralogical species such as montmorillonite.

3.2. Thermogravimetric (TG) and Differential Thermogravimetric (DTG) Analysis

The results of the thermogravimetric and differential thermogravimetric analyses are presented in Figure 3. In general, a mass loss between 50 to 100°C is observed, associated with the loss of free water; then a second event between 450°C and 700°C associated with the dehydroxylation of montmorillonite, which confirms the presence of this mineralogical phase and its small amount in the sample (a mass loss close to 5.6%). Therefore, 730°C was defined to calcine the WFS and clay samples obtained from the WFS wash and thus guarantee the complete dehydroxylation of the clay.

3.3. Porosimetry and surface area

Table 6 presents the results of specific surface area and pore size for raw and calcined clays. The results in Table 6 indicate that the treated clay has a higher surface area, therefore it is expected to be more re-
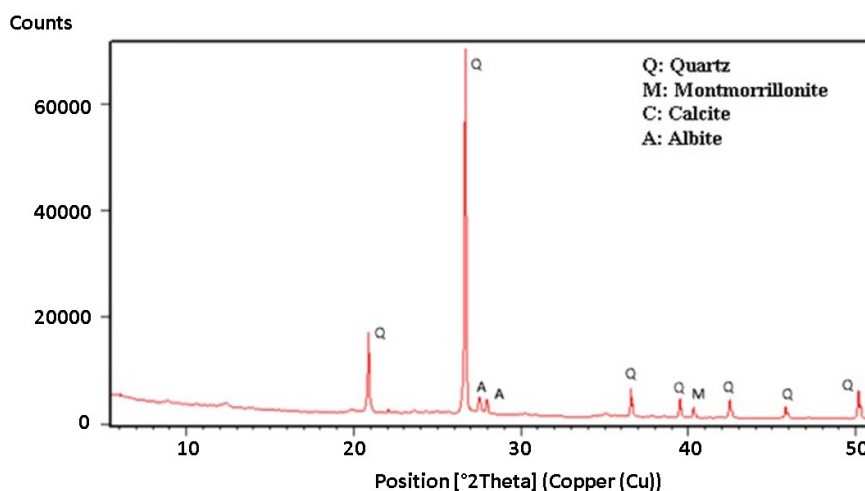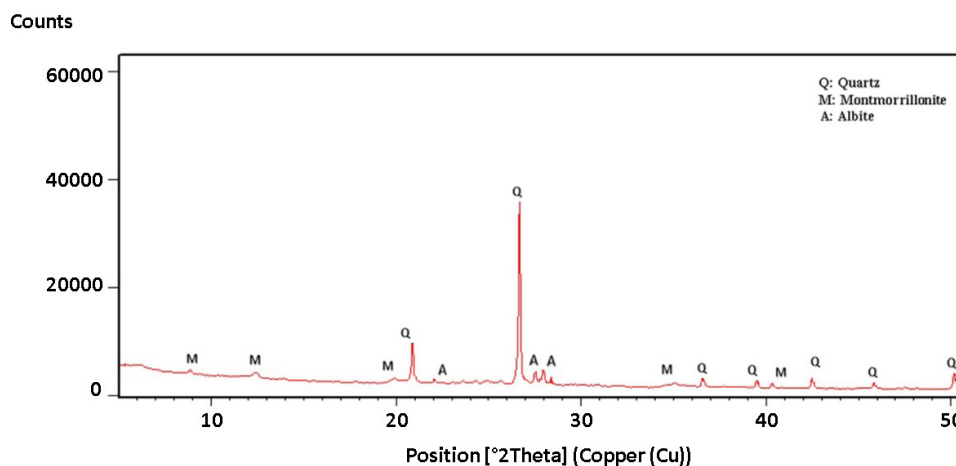

FIGURE 1. WFS diffractogram.

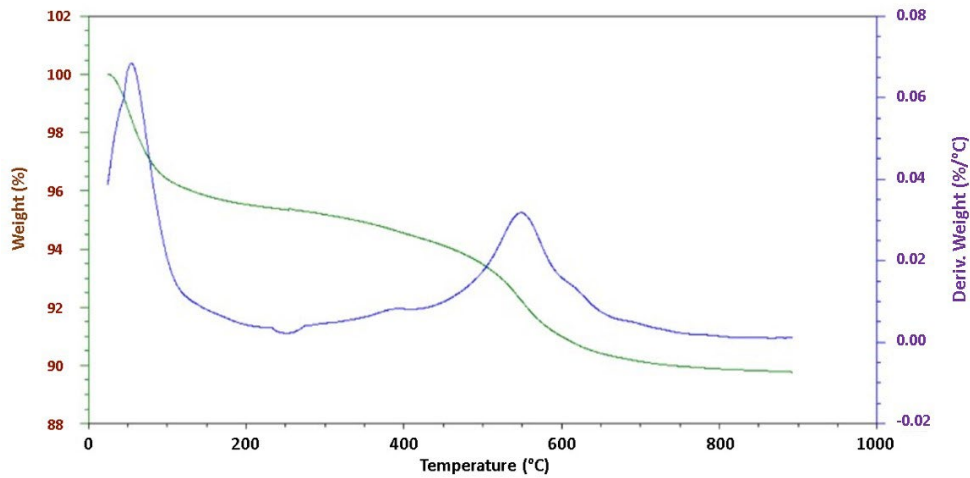FIGURE 2. Clay diffractogram recovered from WFS wash.

Figure 3. TG analysis of the WFS wash clay (raw clay).

active and, in addition, to have a higher average pore size. As some authors have shown, the reactivity of calcined samples is related to their specific surface: the larger the surface, the greater the reactivity (22).

Table 6. Surface Area and Average Pore Size of Raw and Heat-Treated Clays.

Clay	Surface Area (m^2/g)	Pore size (nm)
Raw Clay	17.91	5.34
Treated Clay	29.22	14.63

Figure 4 shows the radius of the pores against their accumulated volume for clays. It can be seen that T.C. presents a lower accumulated pore volume with the smallest radii (less than 2 nm). The T.C. sample has a greater volume of pores with a radius greater than 20 nm, that is, the heat-treated clay has a greater volume of capillary pores.

The increase in porosity (average size and volume) and in the specific surface area occurs due to the fact that the thermal treatment produces a deterioration of the montmorillonite sheets and that when the interlaminar water is released in the form of vapor, the structure widens and this in turn causes disorder in the structure (22).

3.4. Particle Size Distribution (PSD)

Figure 5 shows the curve of the particle size distribution for WFS. The modulus of fineness of WFS has been found in the range of 0.9-1.6, this specific material has a modulus of fineness of 1.2 compared to 2.3-3.1 for normal sand. According to the particle size distribution of the residual foundry sand, the size corresponding to 50% (d50) was around 0.23 mm and it was observed that the mean diameter of the dry sand particle was 0.18 mm. The WFS particle size distribution is very uniform, with approximately 85% of the material between 0.6 and 0.15 mm. It can be seen that 5 to 12% of the residual foundry sand is less than 0.075mm, as mentioned in the literature, and about 8% less than the 200-sieve opening. WFS does not meet the classification requirements for fine aggregates according to ASTM C33 and mortar aggregates according to ASTM C144 (9). Therefore, only partial replacements were made to meet standard aggregate specifications.

Figure 6 presents the results of the particle size distribution of the conventional aggregate with
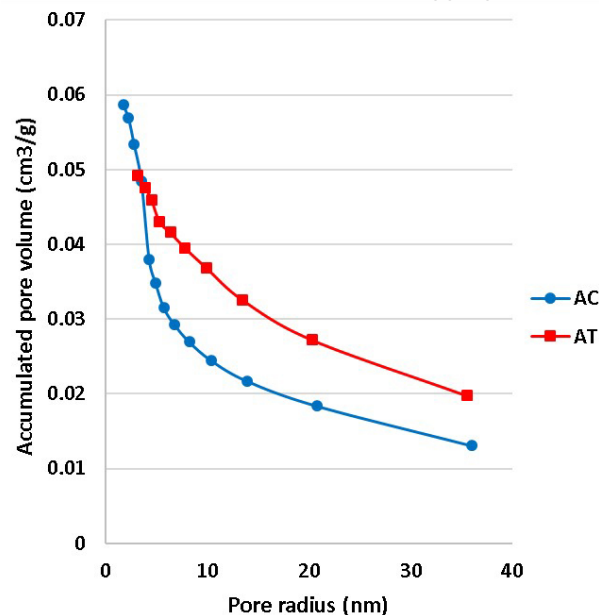

Figure 4. Comparison of cumulative size and pore volume distributions in raw and heat-treated clay.

20% substitution of WFS, together with them also the upper and lower limits of ASTM C-144 for mortar aggregates. The aggregate does not meet the specifications of ASTM C-144, the granulometric curve of CA + WFS 20% is within the limits for particle size less than 300 microns, but being such a fine material in the upper sieves is where non-compliance occurs since there is a large percentage of passing material.

ASTM C33 and ASTM C144 mention that for aggregate that does not meet the gradation requirements and so, it must meet the requirements of the mortar of the specified class made with the aggregate under consideration. That is, it shall have relevant properties which shall at least be equal to those of a mortar made with conventional materials. In this investigation, relevant physical properties such as: compressive strength and porosity will be evaluated to clarify if residual foundry sand can act as a potential substitute for conventional

aggregate despite not meeting the specifications of ASTM C 144.

3.5. Frattini

Figure 7 and Figure 8 show the results of the Frattini test carried out on the clay obtained from washing, calcination and without calcination. The two samples consume $Ca(OH)_2$ from cement hydration, indicating that they could be used as pozzolans. It should be noted that, at 7 days, the calcined clay was more active, while at 28 days both samples produced similar concentrations of Ca^{2+} and OH^- with a slight advantage over the calcined clay.

In his work, (29) he mentions that montmorillonite is a clay that has a great cation exchange capacity which would cause the results of the Frattini test to be more fictitious than real in terms of its capacity to
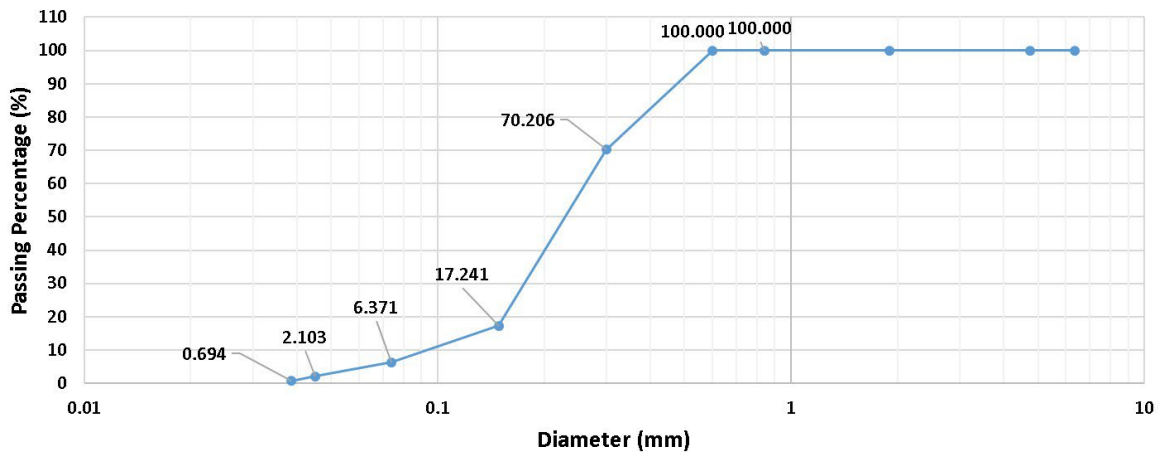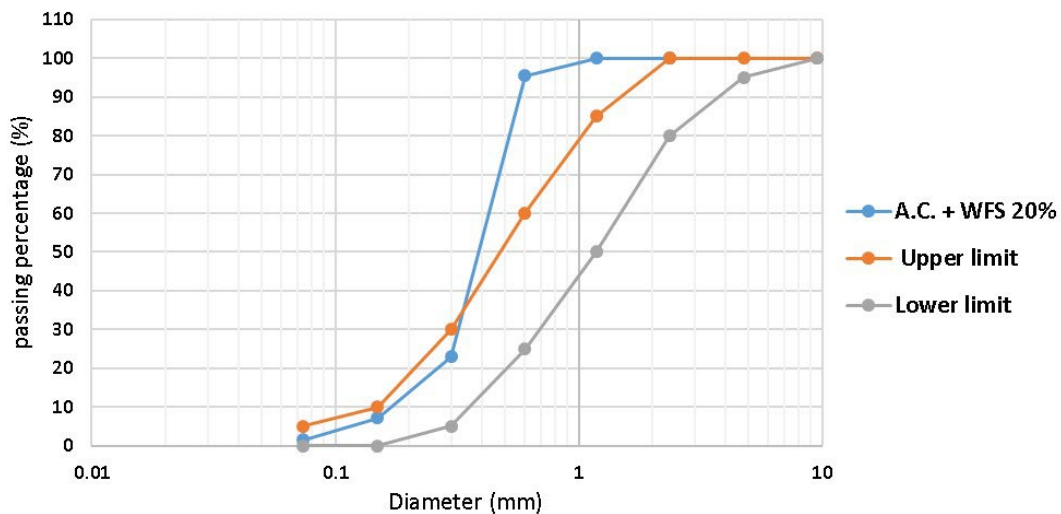

FIGURE 5. PSD of WFS.

FIGURE 6. PSD of Ottawa Sand + 20% WFS with limits established by ASTMC-33 and ASTM C-144.

fix Ca^{2+} ions. In the work of (30), it is proposed that having a large cationic exchange capacity is what causes the liquid phase of the Frattini test to become saturated with exchangeable ions of the clay thereby causing the decrease of the Ca^{2+} ion but not due to a pozzolanic reaction.

3.6. Thermal analysis of paste

Figure 9 shows the TG curves of the reference paste and the pastes added with raw and calcined clay with a 20% substitution and at 28 days of curing.

Since the dehydroxylation of calcium hydroxide begins at around 400ºC (31-33), which is the product of hydration of cement that reacts with a pozzolan,

the pozzolanic activity of clay can be evaluated by consuming this product. It can observed that the percentage of loss of mass of calcium hydroxide is lower for the samples added with clay, either raw (R.C.) or treated (T.C.), the latter being the mixture that had the least loss, coincided with the results of Frattini which also determined this clay to be the most reactive.

Based on these data, the lime present and the lime fixation of each sample were determined following that proposed by (28) and obtaining the results that are presented in Table 7.

The samples of the pastes with 20% raw clay and 20% treated clay show lower percentages of lime present when compared to the control sample, these result are given, among other things, by the lower amount of cement in the added samples
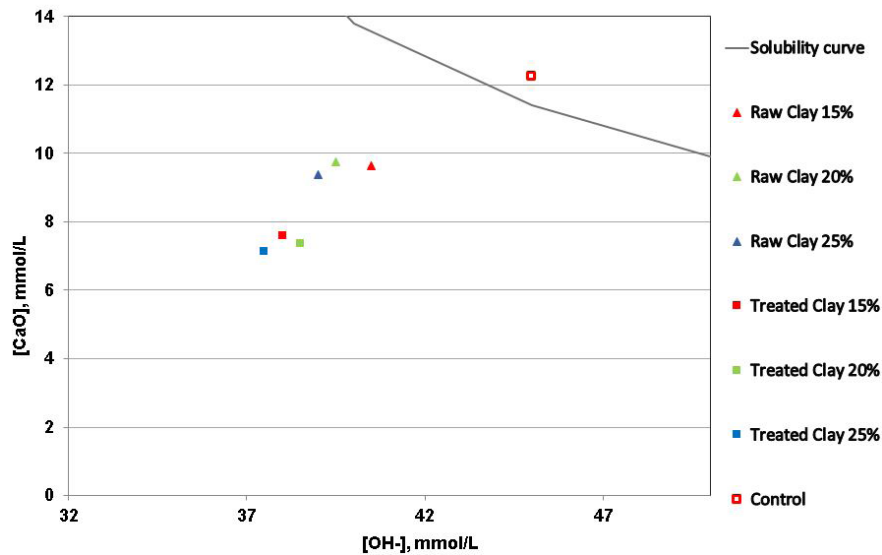

FIGURE 7. Frattini test of pastes containing 20% of raw clay and heat treated clay at 7 days of curing.
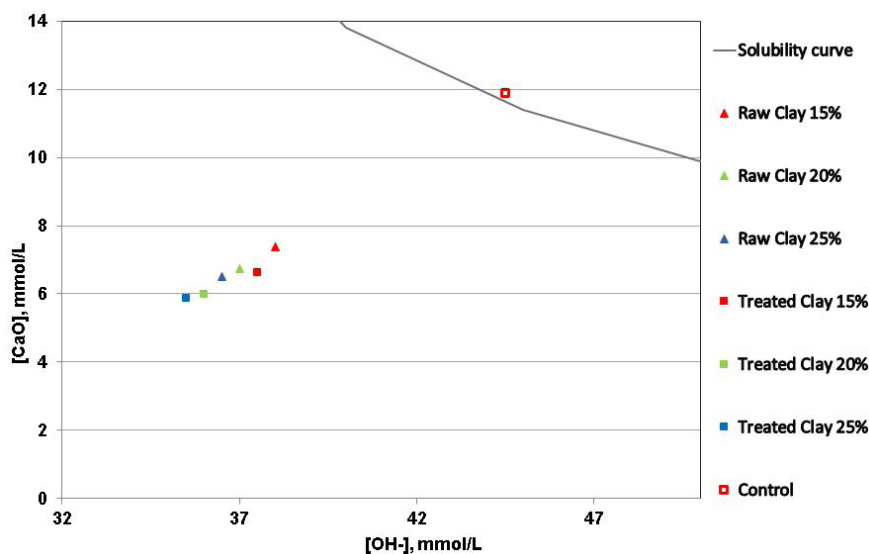

FIGURE 8. Frattini test of pastes containing 20% of raw clay and heat-treated clay at 28 days of curing.
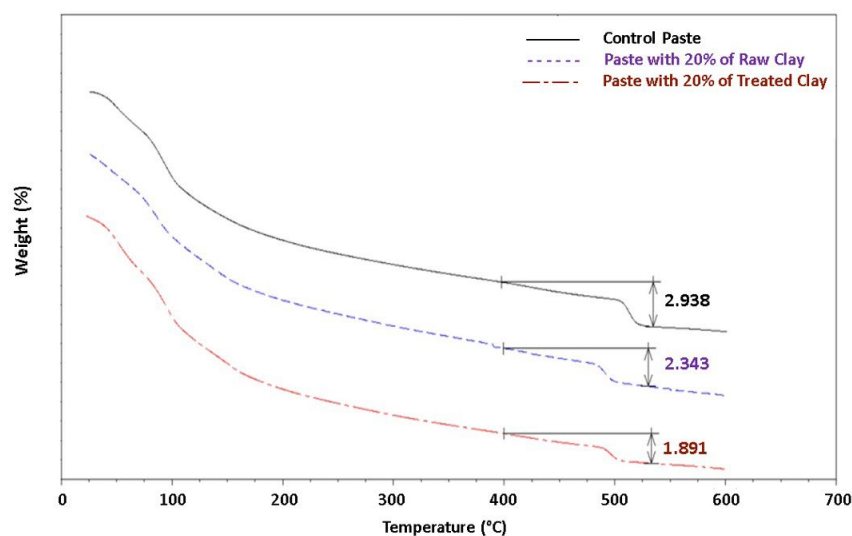
FIGURE 9. TG analysis of the pastes; with 20% raw clay, 20% treated clay and control paste at 28 days.

TABLE 7. Percentages of lime present and lime foxatopm fpr samples containing raw and treated clay.

Sample	Lime Present (%)	Lime Fixation (%)
Control Paste	12.1	-
Paste with 20% of Raw clay	9.54	1.46
Paste with 20% of Treated clay	7.75	19.9

at 28 days of curing the raw and treated clay samples present with 9.54% and 7.75% of lime present respectively, which for the sample with raw clay is 80.5% of the total portlandite and for the sample with treated clay, 64% of the total of portlandite present in the control sample. These values are given by dilution, but they also demonstrate the binding capacity of this addition, especially for the clay-treated sample since the value of 64% is significantly lower than the value that would be expected solely due to the dilution effect.

The percentage of lime fixed for the paste with 20% raw clay is low (1.46%) while for the paste with 20% treated clay it is higher, reaching 19.9% at 28 days of curing (Table 7), which confirms that the applied heat treatment had a positive effect, activating the clay and providing it with pozzolanic activity. These lime fixation results also demonstrate that, although montmorillonite clays have a great cation exchange capacity that can mask the results of the Frattini test, those with an appropriate heat treatment can be activated to convert them into pozzolans.

The decarbonation percentage was similar for all samples thus indicating that the lime fixation corresponds to the pozzolanic reaction.

3.7. Flow of mortars

Figure 10 shows the fluidity of mortars made with WFS, WFSW and WFST with their different substitution percentages following the ASTM standard.

The control sample is the most fluid, for the other samples it is observed that, as the percentage of substitution increases, the fluidity falls, that is, for the substitutions of 25% with the three sands (WFS, WFSW and WFST) we have the lowest flows. This shows that these foundry sands cause a significant increase in the water demand of the mortars. This water demand is especially reflected in the mortars with WFST since they are the least fluid which can be explained because the clay present in WFST has a greater volume of pores, larger pores and greater specific surface area and therefore more water absorption and adsorption.

3.8. Compressive strength

Figure 11 shows the average compressive strength results and standard deviation for each of the samples at 28 days of cure. A trend is seen towards a decrease in the compressive strength of mortars with the increase in the percentage of substitution. However, the WFS and WFSW mortars do not present great differences between them and, as to the control mortar, it can be stated that, from the statistical point of view, the results with 15 and 20% substitution are the same as those found for the control sample.

The performance of mortars with WFS and WFSW, compared to conventional mortar, shows that despite being mortars with aggregates that do
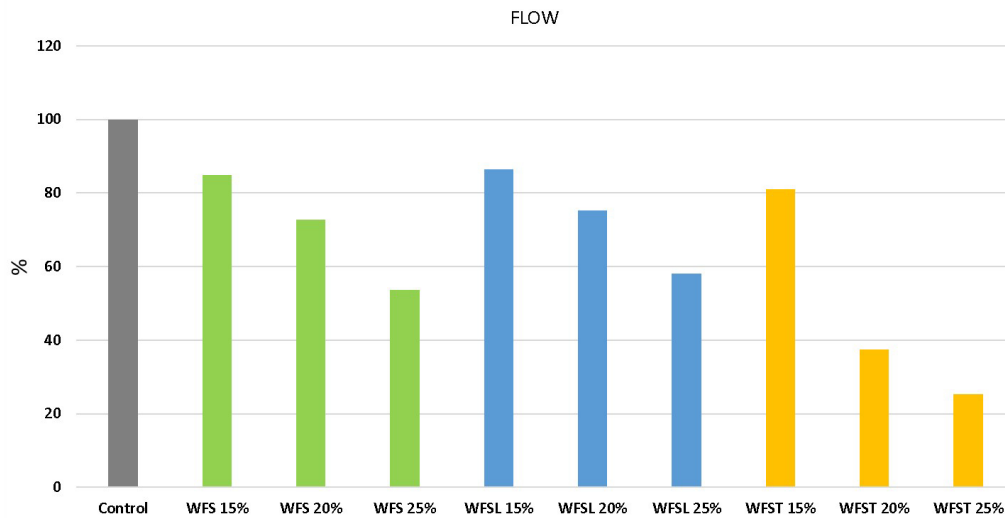
FIGURE 10. Flow of mortars made with WFS, WFSW and WFST.

not comply with the granulometric gradation, the resistances can be optimized and reach values similar or higher than conventional mortar. For the 25% replacements of WFS and WFSW, small drops in the values of compressive strength were found for all ages, results similar to the works of (34, 35): these authors mention that these fine particles in greater quantity confer a negative effect due to the packing of the particles and that they agglomerate causing an increase in the volume of pores, a less optimal compaction and probably a lower coverage by the cement paste. The results for mortars with WFST show that with substitutions of 20% and 25% the values of compressive strength drop notably up to a little more than 50% with respect to what was found for the control sample. These behaviors are similar in all ages studied.

Table 8 shows the compressive strength values and the comparative resistance index (CSI) for the mortars made with WFS, WFSW and WFST with their respective replacements. For all the ages an-

alyzed, the compressive strength developed by the mortar made with WFS is higher than those made with WFST, a result contrary to that found for the pozzolanic activity of raw and calcined clays.

When analyzing the compressive strength developed (Figure 11) or the CSI (Figure 12) for mortars manufactured with WFST, although the values are acceptable for the 15% substitution, they are not as good as expected considering the results obtained from the heat-treated clay in the Frattini analysis and in the pozzolanic activity measured by thermogravimetry. A synergistic effect between the fineness of the sand and the pozzolanic activity of the clay present in it was expected to improve the compressive strength. This synergistic effect was clearly not found.

The behavior of compressive strengths for the WFST aggregate was probably affected by the porosity of the aggregates because after heat treatment, the distribution and pore sizes for the clay were increased (Figure 4). Authors such as (22) mention that after their thermal treatment their clays increased in volume and
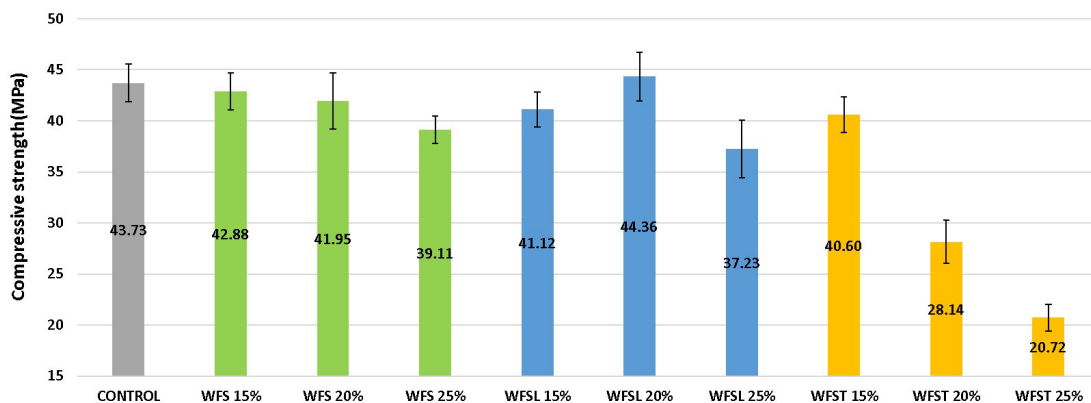

FIGURE 11. Comparison of compressive strengths of the different mixtures (control, WFS, WFSW, WFST) at the age of 28 days.

TABLE 8. Compressive strength values and comparative strength indices of the mixtures (control, WFS, WFSW, WFST) at different ages.

Age days		Control	WFS			WFSW			WSFT		
			15%	20%	25%	15%	20%	25%	15%	20%	25%
1	S. Compressive	12.52	13.72	14.7	13.25	14.41	14.69	12.03	13.2	7.17	6.47
	CSI		1.10	1.17	1.06	1.15	1.17	0.96	1.05	0.57	0.52
3	S. Compressive	25.09	27.25	27.45	25.79	27.66	28.75	24.82	22.21	14.07	11.06
	CSI		1.09	1.09	1.03	1.10	1.15	0.99	0.89	0.56	0.44
7	S. Compressive	33.67	35.34	34.45	31.03	35.46	37.27	30.24	29.39	19.84	15.75
	CSI		1.05	1.02	0.92	1.05	1.11	0.90	0.87	0.59	0.47
28	S. Compressive	43.73	42.88	41.95	39.11	41.12	44.36	37.23	40.6	28.14	20.72
	CSI		0.98	0.96	0.89	0.94	1.01	0.85	0.93	0.64	0.47

when they were used in pastes, they caused capillary pores greater than 20 nm in radius, causing detriment to compressive strength and impermeability. The adhesion between the aggregate and the paste could also have been negatively affected contributing to the drop in resistance since, as seen in Figure 11, the water demand of the mortars with WFST is higher, which could allow a larger water film to be generated around the aggregate, increasing the thickness of the interfacial transition zone (ITZ) and therefore decreasing its resistance to compression, as other authors have pointed out (36).

3.9. Capillary suction

Figure 13 shows the average values obtained for the effective porosity for each of the mortars according to the mixture designs at 28 days after curing. It was verified that, for the control sample and the mortars with WFS and WFSW, the effective porosity was close to the 10% that characterizes (according to the Red Durar document) (37)

the concretes and mortars that can perform with adequate durability in a aggressive environment.

The mortars with WFST with 15% substitution are classified in the environment of effective porosity between 11 and 15%, that is, of moderate quality. However, for substitutions greater than 15% of WFST, the porosity of the mortars increased significantly compared to the control sample (between 4 and 5 percentage points) thus classifying these mortars as permeable and not suitable for aggressive environments and consequentially of lower mechanical strength.

Figure 14 shows the capillary suction curve with 20% substitution. This curve is associated with weight gain according to the methodology presented in Tobón et al. (38). The control sample has a curve with a low slope like WFS and WFSW with a slight improvement in the pore structure when using WFSW, unlike WFST where in the first hours its weight gain is very fast to the point of being practically saturated in 3 hours while for WFS and WFSW the saturation point is between 2 and 3 days.
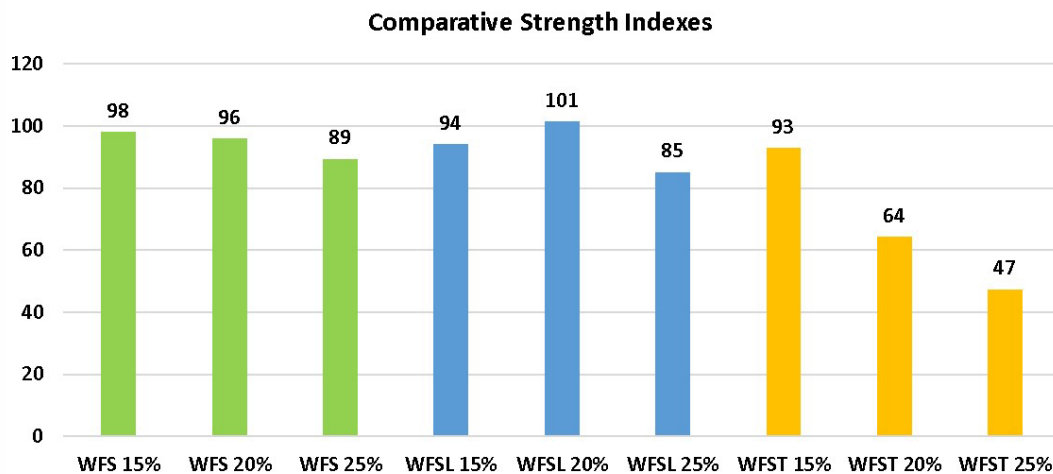

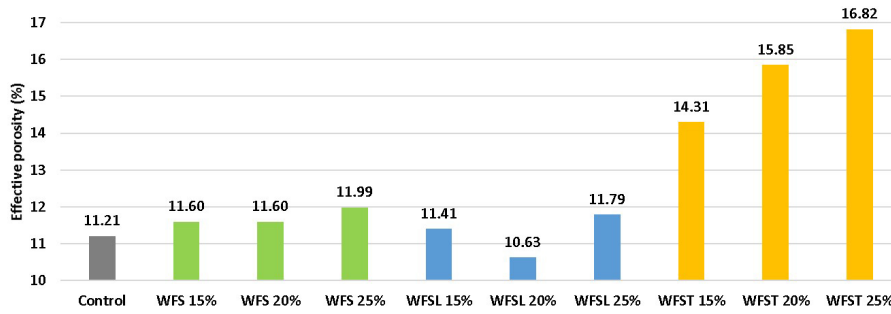FIGURE 12. Comparative Strength Indexes at 28 days of curing.

FIGURE 13. Effective porosity of the mixtures (control, WFS, WFSW, WFST) at 28 days.
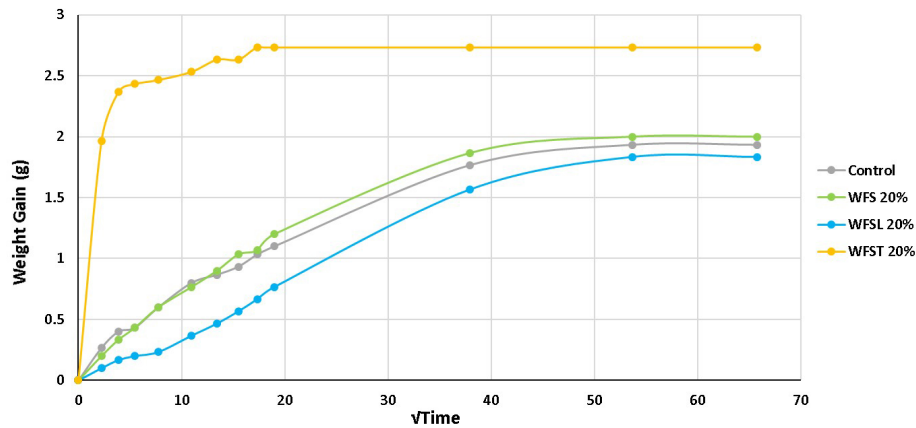

FIGURE 14. Mixture weight gain curves (control, WFS, WFSW, WFST) at 28 days.

4. CONCLUSIONS

The results obtained during all the experimentation on pastes and mortars carried out in this research allow to establish the following conclusions:

• The behavior of WFS and WFSW as aggregate in mortars is to fill voids causing less porosity due to physical effect, which allows them to achieve similar and even higher values of compressive strength with respect to the control sample, up to a maximum of 20% replacement. Thus, concluding that with substitutions of 15% and 20% it is possible to manufacture mortars with resistance similar to that of a conventional mortar thanks to its filler effect.

• The compressive strength values found for all the samples are attributed to the coefficients obtained in the capillary suction test (effective porosity, absorption coefficient and absorption speed) since, with the lower porosity and lower absorption speed, the mortar presented a greater mechanical resistance and that specifically happens with WSF (15% and 20%) and WFSW (15 and 20%), while for WFST the coefficients yielded higher values thus explaining the drop in the compressive strength of these mixtures.

• The compressive strength in mortars with WFST decreased dramatically for substitutions of 20% and 25%. This was due to the significant increase in the capillary porosity of the mortars as a consequence of the clays present in this sand which, when thermally activated, increased their size and volume of pores and their specific surface, therefore, the demand for mixing water increased and the penetration of curing water into these mortars.

• The Frattini test suggested that the raw clay from the residual foundry sand had pozzolanic activity, but this was disproved by the lime fixation test by thermogravimetry, showing that the Frattini results are not reliable for the evaluation of pozzolanicity in this type of montmorillonite clays with great cation exchange capacity.

• Thermally treated clays showed pozzolanic activity in the Frattini test and this pozzolanicity was verified with the calculation of lime present and lime fixation using thermogravimetry. In addition, it was found that this activity increases with the curing time, which means that these types of thermally treated clays are pozzolans with slow reactivity.

• For this treated clay, unlike raw clay, the results of Frattini agree with the results of fixed lime, showing that Frattini is not able to differentiate between the exchange capacity of the calcium ion and the fixation of lime through the pozzolanic reaction of these type of clays.

• The heat treatment, despite giving pozzolanic properties to the clay, also provides a negative effect to the clay recovered from washing, giving it a greater specific surface area and porosity, which significantly increased its water demand and the porosity in mortars. As a consequence, the results of resistance to compression and capillary suction were negatively affected in mortars containing WFST.

• It was shown that montmorillonitic clays with an adequate thermal treatment reach an important pozzolanic activity, which was verified with the calculation of lime fixation measured by thermogravimetric analysis.

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