NONFERROUS WASTE FOUNDRY SAND AND MILLING FLY ASH AS ALTERNATIVE LOW MECHANICAL STRENGTH MATERIALS FOR CONSTRUCTION INDUSTRY:
EFFECT ON MORTARS AT EARLY AGES

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An alternative solution to reduce environmental pollution using aluminum waste foundry sand (AWFS) and fly ash (FA) to produce sustainable construction materials was studied. New mortars were prepared by partially replacing ordinary Portland cement with fly ash at 5, 10 and 15 % mass. and a total replace of Ottawa sand (OS) with AWFS. The specimens were cured at 25°C with a 100% relative humidity. The mechanical behavior was evaluated by compression test at the ages of 7, 14 and 28 days. The microstructural characteristics were analyzed by scanning electron microscopy (SEM). The results indicate that the addition of milling fly ash in AWFS mortars increases the mechanical resistance, mostly at 5% mass reaching the maximum value of 10 MPa at 28 days of age. Microstructurally, it was found a porous cement matrix with some cracking caused by the reaction of portland cement with the metallic aluminum remaining in the waste sand, which is correlated to the low mechanical resistance obtained. The final mechanical characteristic makes this new product a serious candidate to be used as a sustainable building material working at low load.

Keywords: *construction, mortars, Portland cement, fly ash, composite, pollution*

1. Introduction

The metal foundry produces a large amount of waste sand. With the increasing of environmental awareness, the cycle life and the environment impact of foundry sand have been investigated. Waste sand is disposed without any regulation resulting in serious problems related to the storage of the waste causing environmental pollution. Air is contaminated due to the organic remnants of phenolic resins used in molding process as well as soils and aquifers could be contaminated due to the metals leaching[1]. Barbara S. Q. Alves et al. 2014 studied and quantified the toxic leached metals presents in ferrous foundry waste sand, they found that the concentration exceeds the maximum levels of contaminants in groundwater [2]. Robert S. Dungan and Nikki H. Dees 2009 analyzed the total of leached metals coming from the waste sand used in the molding process resulting in a dangerous concentration[3]. Some researchers have been studied the addition of organic compounds in sand to improve the molding process in terms of grain consolidation, which increase the risk of pollution once the sand reaches its life time and must be disposal [4].

On the other hand, S. Ji, L. Wan and Z. Fan. 2001 evaluated the leaching of organic and metallic compounds [5]. J. Chiarenzelli et. al. 1998 in their research concluded that the organic compounds coming from resins after their use and in a dried state could be volatized in contact with the outdoor [6]. As an alternative, it has been tried to use by-products coming from the metallurgy industry in several applications [7,8]. One of this alternative includes the conventional application as a simple replacement of portland cement for special purposes and environmental considerations [9-17].

Some by-products have been applied in soil stabilization systems. On the other hand, industrial by-products have been extensively studied for building materials applications finding that some residues generally improve the properties of these materials [18-24].

This practice considers also the waste foundry sand that has been analyzed to use it in materials for construction.The addition of waste foundry sand in concrete affects negatively the paste workability; in fact, it is reported a diminish in

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mechanical resistance of the concretes when increasing the replacement percentage of waste sand by conventional sand; however, they meet the requirements of the ACI (American Concrete Institute). Meanwhile, replaced waste sand in 10 %, 20 % and 30 mass. % resulted in the obtaining of good mechanical resistance [25-29]. Researchers have proposed the use of foundry sand in concrete product. Foundry sand also is used for pavement construction [30-33].

The pretreatment of supplementary cementitious materials (milling fly ash) may also help to improve the use of by-products in building materials [34-35]. A. Zaldívar-Cadena et al. 2013 studied the effect of mechanical milling on fly ash used in portland cement mortars, finding an increase in resistance at 28 days [36].

By other hand, the (American Concrete Institute (ACI) Committee 229, 2013)[37] defines a low resistance material controlled as a self-compacting cementitious material, mainly used as filler material, also known as fluid filler, non-fouling filler, fluid mortar, soil-cement, etc. These materials can develop a maximum compressive strength as low as 8.3 MPa making them an attractive alternative to be applied as building materials.

Considering the above mentioned, the aim of this work was to study the feasibility of manufacture new mortars for the building industry with sustainable characteristics by the replacements of Ottawa sand with waste foundry sand from casting of aluminum automotive parts and the partially replacing of ordinary portland cement with fly ash generated by the electric power generation industry. Reusing the waste products generated by industrial processes is an environmentally responsible and sustainable approach that aims to manage waste-generated pollution and preserve our world.

2. Experimental Procedure

2.1 Raw Materials

Ordinary portland cement (OPC), fly ash (FA), milled fly ash (MFA), Ottawa standard sand (OS) and aluminum waste foundry sand (AWFS) were used as staring raw materials in the preparations of mortars. The OPC is a local cement from a local cement company (Nuevo Leon, Mexico). Fly ash is obtained from a local company for electric power generation industry (Coahuila, Mexico), while waste sand is collected from a local company for casting of aluminum automotive parts (Nuevo Leon, Mexico).

The Ottawa standard sand and the waste foundry sand were sieving using a 40 Tyler mesh (0.425 mm) according to the ASTM C778 standard [38]. Figure 1 shows the microstructure of the waste foundry sand bonded with phenol urethane, where can be seen the grain morphology (spherical shape) and size (< 425 μm).

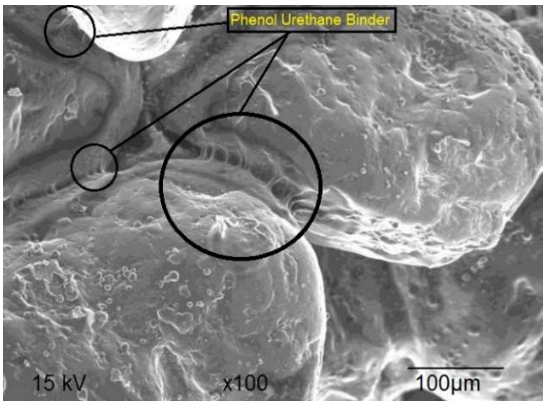

Fig. 1 - Silica sand bonded with phenol urethane from non-ferrous foundry [39].

A mechanical milling process for 1 hour at 2000 rotations per minute using a Retsch planetary ball mill, model PM400 modified the particle size of the fly ash. The characterization of the particle size distribution was conducted using a Microtrac laser diffraction particle size analyzer, model S-3500.

Figure 2a shows the particle size distribution curve (histogram) of fly ash before the milling process, where the d_{50} is establish at 102 μm. Meanwhile, Figure 2b shows the particle size distribution curve of fly ash after the milling process, where the d_{50} is establish at 33 μm.

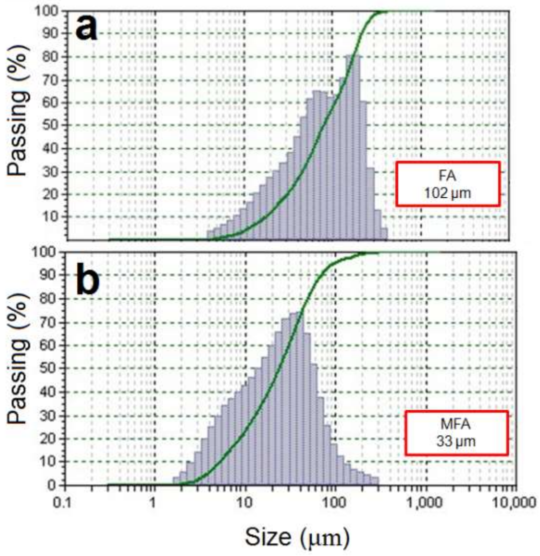

Fig. 2 - Particle size distribution curve of fly ash used in this research work. a) unmodified fly ash, d_{50}= 102 μm. b) milled fly ash, d_{50}= 33 μm.

Figure 3a shows the morphology of unmodified fly ash by scanning electronic microscopy, where can be seen common spherical particles corresponding to unmodified fly ash with some irregular quartz particles (bright angular particles).The morphology of milling fly ash is shown in Figure 3b. As can be seen the spherical particles were modified by an irregular particle shape, which is related to a higher reactivity.

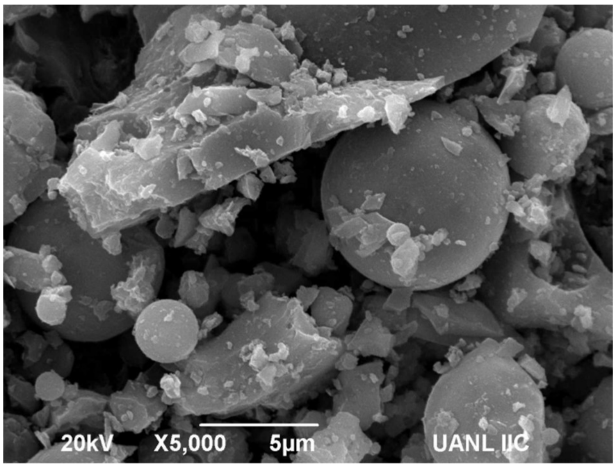

Fig. 3a - Unmodified fly ash, where can be seen spherical and angular particles.

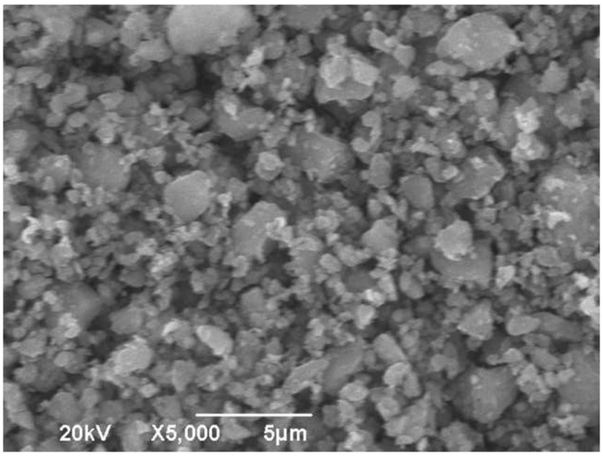

Fig. 3b - Fly ash mechanically mill for 1 hour.

The chemical composition of the raw materials determined by a Philips X-ray fluorescence (XRF) equipment, model X Pert is presented in Table 1. As it is shown, the waste foundry sand has a high content of silica and a high percentage of Al_2O_3 and others metallic oxides coming from the casting process.

The crystalline phases of fly ash and waste sand were identified by X-ray diffraction analysis using a Bruker D8 Advance model diffractometer with Cuk$_\alpha$ radiation (λ= 1.5406Å) operated at 35 kV and 25 mA. The scans were performing in the 2θ range from 5 to 80° with a step scan of 0.025° and 1.5s per step in a continuous mode. Figure 4a shows the crystalline phases of waste sand, where are identified at 41° and 46° peaks corresponding to the metallic aluminum, while at 21°, 29° and 50° is observed the common peaks corresponding to SiO_2 phase, which is the mainly phase in silica sand. Figure 4b shows as mainly crystalline phases of milled fly ash: mullite and quartz, as well as an amorphous halo at 20° and 30°.

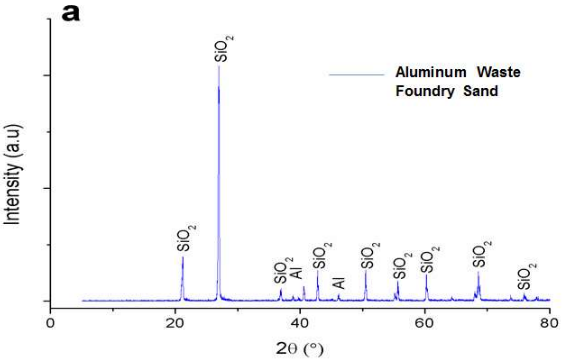

Fig. 4a - XRD pattern of aluminum waste foundry sand (AWFS). SiO_2= quartz; Al= aluminum.

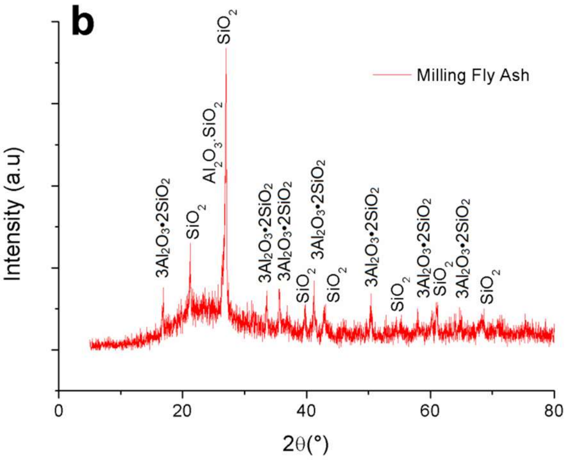

Fig. 4b - XRD pattern of milling fly ash.$3Al_2O_3•2SiO_2$= mullite; SiO_2= quartz.

2.2. Proportioning of mixtures and preparation of mortars

Mortars with replacements of 100 %OS with AWFS and partial replacement of OPC by FA and MFA were elaborated according to the ASTM C109 standard [40]. The mixing process was carried out according to the ASTM C305 standard [41] using a Hobart N50 mixer with 5 Kg of capacity at 281 rpm. After mixing and casting processes, the mortars were cured at 25 °C and a RH above 80 %. The mixture designs of the mortars are shown in Table 2.

Table 1

Chemical composition of the raw materials (wt. %) determined by XRF

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Others
OPC	18.9	4.1	1.8	66.8	1.9	5.3	0.4	1.23	-
AWFS	89.5	6.1	2.1	0.9	0.2	-	0.2	0.1	-
MFA	63.8	25.1	4.9	2.3	0.8	-	0.6	0.2	2.3

Table 2

Proportioning of mixtures

Mixture	Proportions (wt. %)
OS	100%CP + 100%OS
OS+5FA	95%CP+5%FA+100%OS
OS+10FA	90%CP + 10%FA + 100%OS
OS+15FA	85%CP + 15%FA + 100%OS
AWFS	100%CP + 100%AWFS
AWFS+5MFA	95% CP + 5%MFA + 100%AWFS
AWFS+10MFA	90% CP + 10% MFA + 100%AWFS
AWFS+15MFA	85% CP + 15% MFA + 100%AWFS

Table 3

Particle size of AWFS used for mortars elaboration

Size (mm)	Mesh	Partial retained (g)	Partial retained (%)	Accumulated Retained (%)	Passing the mesh
297	50	54.68	28.68	28.68	71.3
149	100	116.00	60.84	89.52	10.5
74	200	17.45	9.15	98.68	1.3
44	325	1.87	0.98	99.66	0.3
<44	Recipient	0.65	0.34	100	-
	Σ	190.65	99.99	-	-

Table 3 shows the particle size of AWFS used for the mortars elaboration according to the ASTM C136 standard [42].

2.3. Mechanical and microstructural evaluation

The mechanical behavior was evaluated by a compressive test on cylindrical specimens with dimensions of 254 mm diameter and 508 mm in height at 7, 14 and 28 days after its elaboration in accordance with the ASTM C39 standard [43]. The mortars were evaluated at the previously mentioned ages due to at these specific ages are generated most of the hydration reaction of portland cement; therefore, it is obtained most of its mechanical resistance i.e. more than 80% of its final resistance [44].

An ELE International model ABR-AUTO mechanical test machine was used to perform the compressive tests. The loading rate during the compression test was 0.5 MPa/s. For each ageing time, five specimens were tested, and the mean value was taken. The microstructure was analyzed by scanning electron microscopy using a JEOLJSM-6490LV electronic microscope on mortars polished to a mirror finish using 1 and 0.5 μm diamond suspension and gold powder coating.

3. Results

Figure 5 shows the results of the mechanical behavior of analyzed mortars at 7, 14 and 28 days. After 7 days, the mortars corresponding to the OS and OS+FA series reached a compressive strength around 15 ± 2 MPa. These values result very attractive since the replacement of OPC by FA negligibly affect the mechanical resistance. Meanwhile, the mortars corresponding to the AWFS and AWFS+MFA series indicate a lower resistance than OS and OS+FA series. In fact, the mortars with 100 % of replacement of OS by AWFS registered a 70% lower mechanical strength than OS mortars.AWFS+5MFA mortars developed around 30% of the compressive resistance reported for OS+5FA mortars. ForAWFS+10MFA andAWFS+15MFA mortars, the negative tendency continued since the reported values reaches around 20 % of the resistance reported for OS+10FA and OS+15FA mortars.

In general, at 14 days the mortars corresponding to the OS and OS+FA series reached a resistance value around 21 ± 1 MPa, while mortars corresponding to the AWFS+MFA series obtained resistance values around 4 ± 2 MPa, that's means 25 % of the compressive resistance reached by the OS+FA mortars.

At 28 days, the OS+FA mortars reached a highlighted compressive resistance (around 25 MPa), except for OS+5FA mortars, which reached 22 MPa. Mortars corresponding to the AWFS+MFA series reduced its compressive resistance registering values around 4 MPa; however, the AWFS+5MFA reached a compressive resistance of 10 MPa, this result leads to the feasibility to use replacement of MFA for OPC in mortars made up

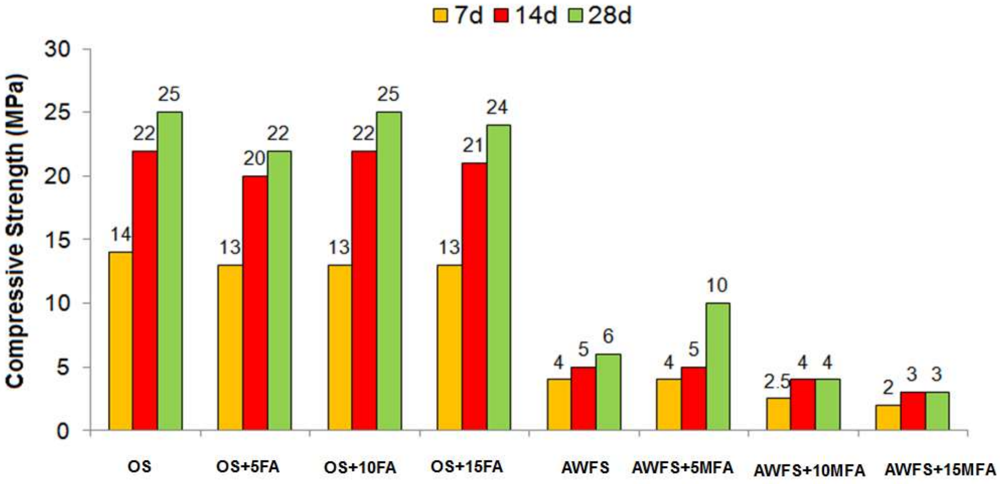

Fig. 5 - Compressive resistance of mortars evaluated at different ages.

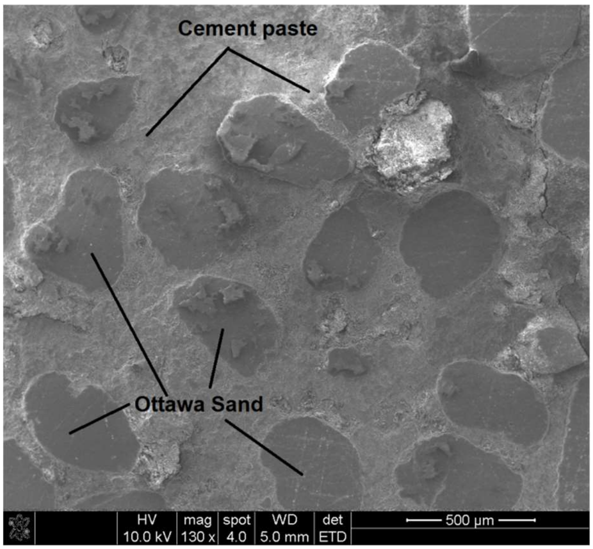

Fig. 6 - Microstructure of the reference mortars elaborated with OPC and OS.

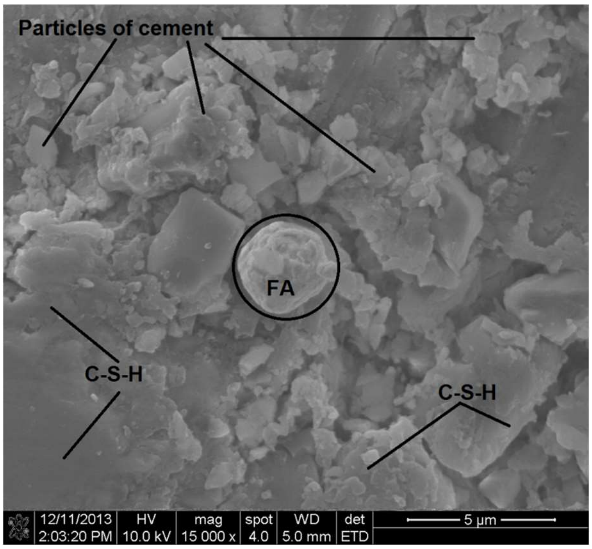

Fig. 7 - Microstructure of the OS+5FA mortars where can be seen fly ash particles reacting with calcium hydroxide and the presence of C-S-H gel.

aluminum waste foundry sand for nonstructural applications

In some research works are found that with lower replacement (10-50 wt.%) of waste foundry sand, mechanical properties can be improved. Also, some researchers have evaluated the mechanical resistance at longer ages (180-365 d) finding an increment of 10-15 % after 28 d in concretes with a 50 wt.% partial replacement of waste foundry sand [45-47].

Figure 6 shows the microstructure of the OS mortars where can be observed a homogeneous grains distribution corresponding to the silica sand embebbed in a cementitious matrix. In addition, it is observed a good densification (1.96 g/cm^3) due to the absence of porosity and cracking related to the presence of a detrimental reaction. The porosity percentage of OS mortars was around 16%.

The microstructure of the OS+5FA mortars is shown in Figure 7.The C-S-H gels were observed due to the reaction between calcium hydroxides and fly ash. In addition, it can be observed some unreacted cement particles.

Figure 8 shows the microstructure of the AWFS mortars. The microstructural analysis showed a high porosity (36-38 %) associated to the reaction of the cement with the metallic aluminum. This reaction produces hydrogen gas that generates microcracking in the cementitious matrix as was reported by Radhi Alzubaidi (2017) [48]; thus, the low mechanical resistances reached by AWFS mortars are directly related to this detrimental phenomenon. This behavior contrasts the results found by Maria Gheorghe et al. [49, 50], where the use of secondary aluminum slags did not disturb a positive evolution of the mortars compression strength up to 360 days.

In Figure 9a corresponding to the microstructure of OS mortars, it is observed a dense matrix with a homogeneous particles size. The appearance of a dense matrix is totally in accordance with the density values (around 2 g/cm^3) and the apparent porosity (around 16%) evaluated by the Archimedes method. In addition, it is observed C-S-H gel (bright masses with nodules and big chalky gel parts) gets spread over the

Fig. 8 - Cracking caused by the reaction of hydrogen gas in the AWFS mortars.

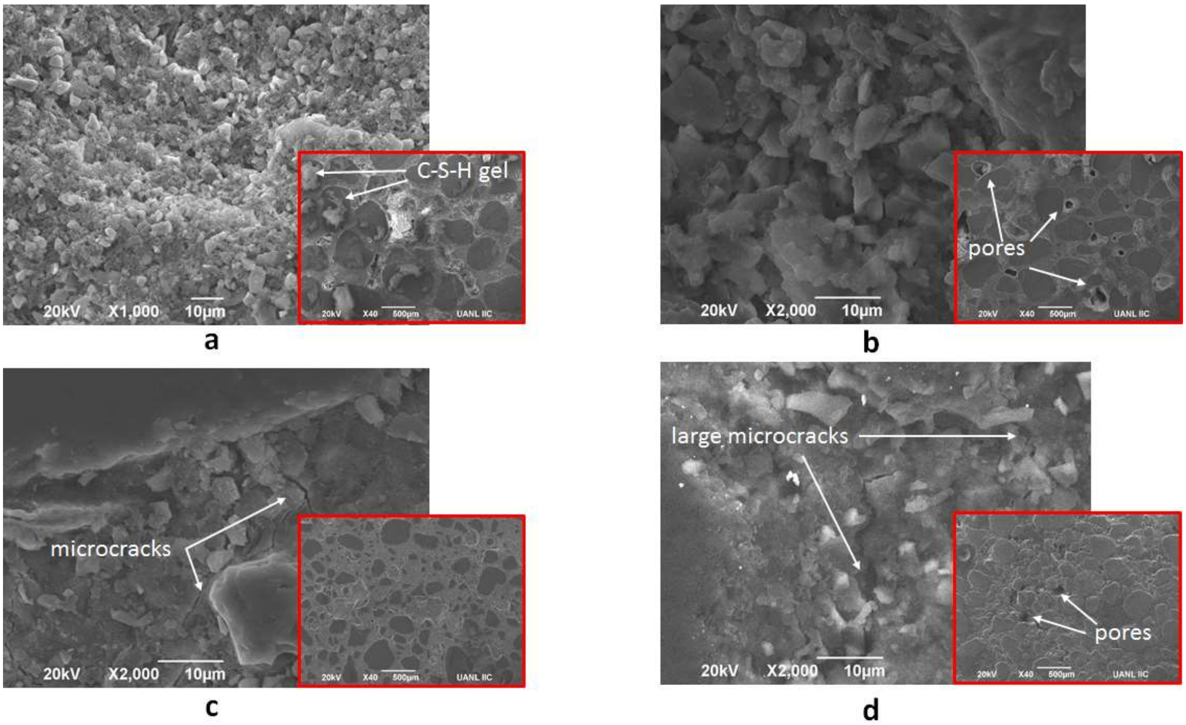

Fig. 9 - Microstructure of a) OS mortars where can be seen C-S-H gels on OS particles. b) AWFS mortars where can be seen the presence of high porosity. c) AWFS+5MFA mortars where can be seen microcracks and presence of C-S-H gel spreads over the fly ash. d)AWFS+10MFA mortars where can be seen large microcracks through the entire matrix.

aggregates (OS particles) acting as binder for the paste. These microstructural appearances impact the compression resistance values reaching a maximum value of 25 MPa.

The microstructure of AWFS mortars is shown in Figure 9b. The microstructural analysis shown the presence of large pores in the range of 254 to 63 µm. For these mortars, the bulk density and the apparent porosity were 1.63 g/cm^3 and 38%, respectively. The high porosity is a phenomenon that can be associated to the reactions between the cement and the metallic aluminum resulting in the production of hydrogen gas, thus it was generated microcracks in the cementitious matrix. This detrimental phenomenon led to a radical diminish in compression resistance (4 MPa).

Figure 9c showed the microstructure corresponding to AWFS+5MFA mortars. Results indicated a less concentration of pores compared to the AWFS mortars. For these mortars, the bulk density was 1.65 g/cm^3 and the apparent porosity reported was of 36%. By the microstructural analysis, it was detected some microcracks originated by the hydrogen gas formation. In addition, it was observed C-S-H gel spreads over the fly ash; thus, a chemical reaction between de calcium hydroxide and the fly ash took place. This reaction leads to the dissolution of fly ash and its activation generating nucleation sites, where C-S-H gels grew up. This new gel formation improved the compressive resistance reaching 10 MPa. The microstructure of the AWFS+10MFA mortars is observed in Figure 9d.

The analysis indicated the presence of microcracks and a reduction of C-S-H gel concentration compared to AWFS+5MFA mortars. This phenomenon could be associated to the cement amount since the cement is substituted by fly ash leading to a limited formation of C-S-H gels, therefore a clear diminish in compressive resistance was observed (4 MPa).

4. Conclusions

Our research work demonstrated the feasibility of reusing industrial by-products such as fly ash and waste sand from nonferrous smelters (aluminum) in the obtaining of mortars as a sustainable alternative for low controlled strength construction materials.

Large pores in the range of 254 to 63 µm were detected in AWFS mortars due to the reactions between the cement and the metallic aluminum, resulting in the production of hydrogen gas, thus it was generated large microcracks and pores in the cementitious matrix. Therefore, it was not possible to obtain a densified cementitious matrix, which could be affect, the mechanical resistance; however, these mortars can be used in low strength applications.

The results of compressive strength showed a clear tendency to diminish in resistance due to the incorporation of AWFS. It is considered that the reduction of resistance is significant when light aggregates are replaced by AWFS, since metallic aluminum remnant of this sand reacts with the compounds of the portland cement generating expansive gases causing cracks and high porosity.

By the microstructural analysis, it was observed that the C-S-H gel spreads over the fly ash in AWFS+5MFA mortars; thus, a chemical reaction between the calcium hydroxide and the fly ash could be carried out. This reaction leads to the dissolution of fly ash and its activation generating nucleation sites, where new C-S-H gels grew up. This new gel formation improved the compressive resistance. Since AWFS+5MFA mortars reached a compressive resistance of 10 MPa, this result leads to the feasibility to use replacements of MFA for OPC in mortars made up aluminum foundry waste sand for nonstructural uses. The results present a viable alternative for the reuse of industrial by-products such as fly ash and waste sand from nonferrous smelters (aluminum) in common applications of non-structural elements. This new product could be represented a sustainable construction material. However, it is recommended to study the physico-mechanical properties of new cement mortars up to 360 days.

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