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Microconcrete with partial replacement of Portland cement by fly ash and hydrated lime addition.

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Abstract.

The reduction in Portland cement consumption means lower CO_2 emissions. Partial replacement of Portland cement by pozzolans such as fly ash has its limitations due to the quantity of calcium hydroxide generated in the mix. In this work we have studied the contribution of the addition of hydrated lime to Portland cement-fly ash systems. We have also studied several levels of cement replacement, ranging from 15% to 75%.

The best mechanical results were obtained replacing 50% of Portland cement by the same amount of fly ash plus the addition of hydrated lime (20% respect to the amount of fly ash). In these systems**,** an acid-base self-neutralization of the matrix has occurred through a pozzolanic reaction of fly ash with portlandite liberated in the hydration of Portland cement and the added hydrated lime. It has been identified for these mixtures a significant amount of hydrated gehlenite, typical reaction product from rich-alumina pozzolans.

Keywords: Fly ash, hydrated Lime, compressive strength, pozzolanic reaction, self-neutralization.

1. - Introduction.

CO_2 reduction, associated with the manufacture and use of Portland cement, is an important issue for Sustainable Development in the construction industry [1]. According to the World Business Council for Sustainable Development (WBCSD), emissions from Portland cement manufacturing vary in different regions of the world from 0.73 to 0.99 kg of CO_2 per kg of cement produced [2]. To reduce CO_2 emissions from a concrete structure, clinker content should be reduced by replacing part of Portland cement by supplementary cementitious materials (SCM) such as fly ash [2] [3].

When replacing a part of the Portland cement by fly ash, silica fume or fine limestone, each of these mineral additions operates differently but cooperatively depending on their particle size, chemical or physical activity [4]. The fly ash in concrete acts as an inert filler in early hydration, and as a pozzolanic material in the medium and long term. Fly ash also increases the hydration rate of Portland cement clinker due to the so-called "filler effect" [5].

Portland cement binders with high volume fly ash have been widely used in comparison to silica fume and other natural pozzolanic materials, due to the low water requirement or good workable capacity. [6] Spherical/spheroidal geometry of the fly ash particles can act as a "ball bearing" to improve the rheological properties of fresh paste [7]. By the contrast, these concretes require longer curing times to complete the development of the pozzolanic reaction [6].

The properties of concrete with high volume fly ash may be better than Portland cement concrete for certain applications. Drying shrinkage of concrete (water / binder = 0.49) containing pozzolanic materials are usually lower than Portland cement control [6]. Also, It clearly reduced the chloride penetration and corrosion of steel in concrete, in comparison to 100% Portland cement concrete [8] [9]. The carbonation rate is more difficult to predict because it is related, among other variables, to the porosity and degree of saturation: at the same conditions; the result of an accelerated carbonation largely dependent on the content of carbonatable constituents or what is the same, the alkaline reserve. [3]

For higher levels of cement replacement by fly ash, (greater than 40%) there was a decrease in the pH of the pore solution, reducing the solubility of amorphous silica and alumina present in the pozzolan. As a consequence, the pozzolanic reaction decreases and low compressive strength are obtained at early stages [6] [10]. It exists experimental solutions to activate fly ash binders in short term, such as fine grinding [11] or high curing temperatures, which can help increasing the compressive strength to an equivalent value to the control Portland cement at early age [6]. Another possibility is the use of alkaline activators [12] [13] or sulphate-based activators [13]. However, the alkaline activation can lead to alkaline-silica reaction, while sulphate-based activation may decrease the durability of concrete due to the formation of large amount of ettringite [5] [14]. Besides, many conducted studies have proved that the initial strength can be improved with small additions in the system of 5% silica fume, hydrated lime or limestone fines. [6] [14]

Fly ash replacements of around 35% are admitted without further precautions for reinforced concrete. For very high volumes of substitution, the concretes exhibit low initial resistance and $Ca(OH)_2$ may be insufficient and cause a self-neutralization at long term, that is, the removal of the matrix portlandite [15]. For cement replacement by fly ash at 40%-60% range in weight, portlandite content decreases with the progress of hydration and varies linearly with the logarithm of the age of curing [16]. For a replacement of Portland cement by fly ash in proportions greater than 60%, a complete depletion of portlandite was observed after one year of hydration [15].

The strength and durability of the fly ash concretes could be improved by the addition of hydrated lime. This compound ensures a better and complete hydration of fly ash in systems with low cement content in the mixture [2] [14]. When hydrated lime is added to a concrete containing pozzolanic materials, significant improvements in the durability can be observed. It creates a denser structure, responsible for lower level of carbonation of concrete and reinforcement corrosion to chloride attack [17]. In an investigation with large volumes of replacement, 20-60% of cement, by "lime-pozzolan" (hydrated lime and zeolitic tuff), $Ca(OH)_2$ plays an important role in the properties of the binder [18]. With a mixture of hydrated lime and a very reactive ash waste from the sugar industry, with a ratio 1/2.3, Martirena et al. [19] prepared a very eco-efficient but low performance binder. Also, in another study, using hydraulic lime with pozzolanic additions type II, according to EN 206, a compressive strength over 25.0 MPa was reached after 28 days [2]. Limes generally have a large surface area meaning a greater water demand and substantial increase cohesion in low water / binder (w / b) systems [20].

In this work we analyze microconcrete containing Portland cement and fly ash in which it is aimed to increase the extent of the pozzolanic reaction of fly ash through its combination with hydrated lime. Comparisons are made among control microconcrete with Portland cement with selected microconcretes, in which a part of the cement is replaced by fly ash. It is also discussed the effects of adding hydrated lime in the cement-fly ash systems through the evaluation of the mechanical strength, microstructure and thermogravimetric analysis.

2. Experimental program.

This work presents micro-concrete dosages, with additions of hydrated lime-fly ash varying its proportions from low to high mineral addition levels. The Portland cement used in this study was CEM I 52,5 R supplied by Cementos La Union (Valencia, Spain).

The fly ash used was supplied by the thermoelectric power plant at Compostilla (León, Spain), and corresponds to a V type fly ash according to the UNE-EN 197-1:2011 [21].

The hydrated lime used is CL 90 S type according to UNE-EN 459-1:2010 [22], produced by CALCASA Company (Arganda del Rey, Spain), with a purity of 87% in calcium hydroxide.The chemical composition and physical properties of Portland cement, fly ash and hydrated lime are listed in Table 1.

The superplasticizer was Sika ViscoCrete 3425 which is a policarboxylate modified in a water base. The amount used was between 0.45% and 1.40% of the weight of the binder (cement + fly ash).

A micro-concrete with crushed limestone aggregate was fabricated, being composed of sand 0/4 (diameter less than 4 mm) and gravel 4/6.5 (diameter between 4 and 6.5 mm), belonging to the quarry at Carasoles (Ribarroja, Spain). The proportion of sand 0/4 and 4/6.5 gravel was 4:1 for all the produced mixtures.

Table 1. Physical properties and chemical compositions of Portland cement (CEM I 52,5R), fly ash (Type V) and hydrated lime (CL 90 S)

Properties	**Portland Cement CEM I 52,5R**	**Type V fly ash**	**Hydrated lime CL 90 S**
Chemical composition (%)			
SiO_2	17.42	51.45	nd
Al_2O_3	4.30	26.00	nd
Fe_2O_3	3.30	7.65	nd
CaO	66.17	3.58	72.52
MgO	1.45	1.71	nd
SO_3	3.33	0.93	nd
K_2O	1.21	3.84	nd
Na_2O	0.46	<0.1	nd
Purity, $Ca(OH)_2$ content	-	-	87.0%
Loss on ignition	2.35	4.85	26.43
Physical properties			
Mean Particle diameter, µm	17.1	23.7	48.0
Specific gravity g/cm^3	3.2	2.5	2.3

nd: not determined

The microconcretes were prepared in a mortar mixer and prismatic molds of 40x40x160 mm^3 were used. After demoulding and curing, each prism is divided into three samples using a machine with diamond blade having nine cubic samples by batch.

From these samples, compressive strength data was obtained and phenolphthalein solution (UNE 112011:2011 [23]) was used for revealing the pH of the cementing matrix.

According to the Spanish standard EHE-08 [24] (Art no. 37.3.2) and EN 206-1:2000 [25] about limitations to the content of water and cement, we need to keep in mind that when using a mineral admixture in concrete, the effects should be evaluated in the calculation of cement content and water / cement ratio.

Therefore, we replace the cement content C (kg/m^3) by C+KF, as well as the W/C ratio by W/(C+KF) being F (kg/m^3) the mineral addition content and K its coefficient of efficiency. According to these regulations (Spanish standard EHE-08 and EN 206-1:2000), in the case of the addition of fly ash, a K value no greater than 0.40 for cement CEM I 52,5 will be taken. In phase 1 of this study, a value of K = 0.33 is adopted. (1 part of cement is replaced by 3 parts of fly ash).This work is divided into two phases due to the high pozzolanic reactivity of the fly ash which has been determined in the phase 1. That is why in Phase 2 the value of K = 1 is proposed for the fly ash. The nomenclature of the mixtures takes the following form:

CX-Y-Z

Being X number after the letter C (cement) indicates the cement percentage present in each dosage (in phase 1: X = 100, 85, 80, 75; in phase 2: X = 100, 50, 25); the second number Y indicates the K value adopted for the fly ash (Y = 0.33 for phase 1 and Y = 1 for phase 2); and the third number Z refers to the percentage of added hydrated lime based on the weight of fly ash (Z = 0, 20, 40 in phase 1, Z = 0, 20 in phase 2).

In phase 1, the value C+KF is kept constant for all cases, with K = 0.33, and the ratio of W/(C+KF) is set to 0.4. Thus, for this series, the ratio w / c varies from 0.4 for the control to

0.53. In phase 1, for the microconcrete with fly ash, cement content has been reduced by 15%, 20% and 25% compared to the control (C100). The added amounts of hydrated lime with respect to the amount of fly ash were 0%, 20% and 40%. The samples were cured under water at 20 ° C and tested in compression at the ages of 3, 7, 28 and 90 days. Table 2 summarizes the microconcrete dosage for phase 1.

Table 2. Microconcrete dosages for phase 1 (K=0.33).

Mixture	Cement (kg/m^3)	Fly ash (kg/m^3)	Hydrated lime (kg/m^3)	Water (kg/m^3)	W/C	Aggregate (kg/m^3)	W/(C+KF)
C100	425.0	0.0	0.0	170.0	0.40	1847.5	0.40
C85-0.33-0	361.3	193.0	0.0	170.0	0.47	1695.8	0.40
C85-0.33-20	361.3	193.0	38.6	170.0	0.47	1695.8	0.40
C85-0.33-40	361.3	193.0	77.2	170.0	0.47	1606.8	0.40
C80-0.33-0	340.0	257.0	0.0	170.0	0.50	1645.5	0.40
C80-0.33-20	340.0	257.0	51.4	170.0	0.50	1586.3	0.40
C80-0.33-40	340.0	257.0	102.8	170.0	0.50	1527.1	0.40
C75-0.33-0	318.8	322.0	0.0	170.0	0.53	1594.2	0.40
C75-0.33-20	318.8	322.0	64.4	170.0	0.53	1520.0	0.40
C75-0.33-40	318.8	322.0	128.8	170.0	0.53	1445.8	0.40

In phase 2, the amount of cement has been reduced by 50% and 75% compared to the control (C100), the relationship W/(C+KF) was constant. The W/C ranges from 0.4 to 1.6. In this phase, hydrated lime was added at 20% relative to the amount of fly ash.

The samples were cured under water at 20 ° C and tested in compression at the ages of 7, 28, 90 and 360 days. Table 3 summarizes the microconcrete dosage for phase 2.

Table 3. Microconcrete dosages for phase 2 (K=1).

Mixture	Cement (kg/m^3)	Fly ash (kg/m^3)	hydrated lime (kg/m^3)	Water (kg/m^3)	W/C	Aggregate (kg/m^3)	W/(C+KF)
C100*	450.0	0.0	0.0	180.0	0.40	1800.3	0.40
C50-1-0	225.0	225.0	0.0	180.0	0.80	1748.2	0.40
C50-1-20	225.0	225.0	45.0	180.0	0.80	1696.3	0.40
C25-1-0	112.5	337.5	0.0	180.0	1.60	1722.1	0.40
C25-1-20	112.5	337.5	67.5	180.0	1.60	1644.3	0.40

* Control sample in phase 2 had a higher cement content than the control C100 in phase 1.

In all microconcretes prepared, the suitable amount of additive superplasticizer was added to obtain a workability of 150mm ± 10mm according to the UNE 83-811-92 [26].

Thermogravimetric analyses were carried out in a TGA 850 Mettler-Toledo thermobalance. Sealed aluminum pinholed 100μL crucibles and nitrogen as purge gas were used. Thermal analysis curves (TG) and the corresponding derivative curves (DTG) were recorded from 35 to 600ºC. Selected microconcrete samples were observed by scanning electron microscopy (SEM) using a JEOL JSM-6300, equipped with energy dispersive X-ray microanalysis.

3. Results and discussion

3.1. Evolution of mechanical strengths.

In this section we analyze the evolution of the compressive strength of cubic specimens (40 mm size) up to 90 and 360 days, in phases 1 and 2 respectively, calculating the effects of the addition of hydrated lime on similar systems that have fly ash without hydrated lime.

3.1.1. Compressive strengths in Phase 1.

Table 4 summarized the results of the compressive strength of the microconcrete with substitutions of 15%, 20% and 25% of cement by fly ash.

Table 4. Compressive strength data (MPa) for substitution of 15%, 20% and 25% of cement by fly ash.

Mixture	**3 d**	**7 d**	**28 d**	**90 d**
C100	59.3	72.0	78.0	86.1
C85-0.33-0	62.2	72.0	89.9	103.3
C85-0.33-20	66.1	76.1	93.9	107.8
C85-0.33-40	67.5	75.9	93.2	107.3
C80-0.33-0	62.8	73.3	93.1	104.2
C80-0.33-20	63.2	72.7	94.9	103.6
C80-0.33-40	55.4	65.7	88.3	99.9
C75-0.33-0	56.9	65.2	88.9	93.2
C75-0.33-20	53.2	63.6	85.0	96.4
C75-0.33-40	53.3	65.7	82.3	97.9

In general, it appears that the replacement of cement by the ash with K = 0.33 leads to an increase of the compressive strength at all tested ages. At long term (90 days), the effect of ash is very remarkable, generating an increase in strength around 15% respect to C100 at 28 days and 20% approximately at 90 days. The addition of hydrated lime in this case represents a slight increase in the compressive strength around the 3% over the same concrete with fly ash without hydrated lime.

For 20% replacement series, it is observed, as in the previous case that strengths are higher than the one of C100 for all curing ages. However, in this case, the addition of hydrated lime provides no improvement in compressive strength. And for the mixing C80-0.33-40, the presence of hydrated lime has a negative effect on the evolution of the compressive strength. For example, the strength at 28 days of C80-0.33-0 and C80-0.33-20 is around 93-95 MPa, whereas for C80-0.33-40 the strength is less than 89 MPa.

For 25% replacement series, it is observed at early ages that the mixtures with fly ash and fly ash plus hydrated lime are below C100 concrete. This behavior is in agreement with a significant reduction of cement. However, the mixtures with fly ash developed higher strengths at the ages of 28 and 90 days.

In general, we can say that the contribution of lime has been insignificant, but in all cases the addition of 20% of hydrated lime was better than the one of 40%. Furthermore the samples with 40% of additional hydrated lime showed in fresh conditions an increasing in water demand, which required an increased dosage of the superplasticizer additive.

We can affirm that in these mixtures with those proportions of CEM/CV, the effect of added hydrated lime does not play a relevant role; probably, the amount of available portlandite generated in the hydration of the cement is sufficient for fly ash particles to react easily. Moreover, the formation of large amount of cementitious products in cement hydration makes the mechanical contribution of the pozzolanic products generated by a reaction with the added hydrated lime to be less important.

From the evolution of the mechanical strength of systems with fly ash, we deduce that the reactivity of the pozzolan is very high, especially at long term.

From the experience of the phase 1, given the strong efficiency of the fly ash, the value of K (k = 0.33) for the calculation of equivalent cement taking K = 1 for the phase 2 is reconsidered.

3.1.2. Compressive strengths in Phase 2.

In a second stage, given the strength effectiveness of this ash, dosages in which the amount of cement is reduced by 50% and 75% compared to C100 * are studied. In this phase 2, we tried to develop a mixture in which similar strength to control concrete was achieved by two ways: on one hand, increasing the curing time (longer curing times as 360 days would be interesting in order to complete pozzolanic reaction); on the other hand, by hydrated lime addition (for increasing the reacted fly ash particles, because the amount of portlandite from hydration of Portland cement is not enough for reacting with the large amoung of fly ash).

Therefore, the relationship CEM/CV is equal to 1:1 for the series C50 and 1:3 for the series C25. The cementitious material CEM+CV is equal to the one for C100 *. In this series only 20% hydrated lime is added with respect to the fly ash content.

Table 5. Compressive strength data (MPa) for microconcrete with 50% and 75% replacement of Portland cement by fly ash.

Mixture	7 d	28 d	90 d	360 d
C100*	81.6	98.6	95.3	94.9
C50-1-0	40.7	53.0	63.6	68.9
C50-1-20	47.5	68.5	81.8	92.8
C25-1-0	24.8	39.3	47.0	52.2
C25-1-20	26.6	45.7	54.4	62.3

Table 5 shows the strength values for the C50 and C25 series. At early ages (7 days), the strength of C50-1-0 is 50% compared to the C100 *, and C25-1-0 is only 30%. This behavior is typical for systems with a high proportion of fly ash with short curing times. The strength values increased with the time of curing reaching 68.9 and 52.2 MPa respectively at 360 days.

For C-50-1-0, it is reached 73% of the strength of C100 *, which means there has been an important contribution of the pozzolanic reaction to this system with high water/cement ratio (W/C=0.8). In the case of C25-1-0, it is reached 55% of the control, demonstrating that the pozzolanic contribution is important for the reaction with the W/C=1.6. It is clear that the 94.9 MPa of C100 * are not reached, which means that the initial value of K assigned in phase 1 to the fly ash was too high.

In the systems with addition of hydrated lime, C50-1-20 and C25-1-20, there is an additional contribution to the strength. This contribution is obvious at all curing ages tested, although it is more important at long term. For instance, at 7 days the C50 series show an increase of more than 6 MPa, at 360 days the increase was greater than 23 MPa. For C25 series the increase at 360 days was 10 MPa. The effect of the added hydrated lime is noticeable from very early ages, since at 7 day of curing the compressive strength of concrete with added hydrated lime is higher to the one obtained with only fly ash concrete. Barbhuiya et al. [14] also found that the mechanical effect of hydrated lime was better for high cement replacement (50% vs 30%) by fly ash.

It is remarkable that the strength at 360 days of the C50-1-20 series is similar to the strength of C100 *. This means that the addition of hydrated lime has allowed the fly ash to undergo a reaction with a K value of approximately 1 (in fact, for C50-1-20 mixture, if hydrated lime addition is taking into account as mineral addition, the replacement of 225 kg/m^3 of cement by a mixture of fly ash (225kg/m^3) and hydrated lime (45kg/m^3) would yield a K=225/(225+270)=0.83). In this case, the fly ash react with the present portlandite released in the hydration of the cement, but since there is a contribution of 20% hydrated lime, it is clear that it has reacted in a significant way with this alkaline addition. This represents a relevant increase in mechanical strength. Therefore, it is demonstrated that the role played by the hydrated lime added will depend largely on the amount of cement and fly ash.

3.2. Microstrutural studies.

In order to perform thermogravimetric analysis, internal parts of the specimens were selected. In all cases the complete material is milled, including the aggregate. For the selected curing time, part of the specimen sample was taken and ground, and the hydration process was stopped by addition of acetone. Subsequently, the mixture was filtered and dried in a furnace at 60ºC during 30 min.

The figure 1 shows the DTG curves for the microconcretes cured during 360 days. The derivative curve (DTG) of the TG curve allows us to identify different decomposition processes as observed in Figure 1. Additionally, weight loss associated to the combined water of calcium silicates hydrates (peak 1), ettringite (peak 2), calcium aluminate hydrates and calcium aluminosilicate hydrates (hydrated gehlenite) (peak 3) are identified. The weight loss that occurs in the temperature range 520-600 ºC (peak 4) is related to the dehydroxilation of porlandite.

The sample C100 * has a total loss in the temperature range 35-600 ° C of 5.30%, which is attributed to the removal of water from the hydrates. Specifically around 550 ° C a peak can be observed in the DTG curve which corresponds to the decomposition of the portlandite. Such loss is about 0.52%, which corresponds to 2.14% of portlandite.

In the sample C50-1-0, portlandite has not been detected (absence of peak at the DTG curve at 550 ° C), which is an indicative that all the calcium hydroxide released by the hydration of cement is combined pozzolanically with the fly ash. We can affirm that a self neutralization of matrix has occurred by a pozzolanic reaction, that is, a complete consumption of portlandite by combination with fly ash. Hanehara et al. [15] found a self neutralization process occurred in the hardened pastes cured at 20ºC and 40ºC with the substitution rate of fly ash by 60% and the maximum substitution of fly ash for maintaining the presence of portlandite was approximately 40%. Zhang et al. [16] also established the higher the replacement of cement by fly ash was, the more the reduction in potlandite content was, finding that for sample cured at 20ºC with 60% replacement level, the amount of portlandite was negligible. Furthermore, in this case the total amount of hydrates is much lower than in the previous case: the total loss is about 2.47%. This suggests that a significant portion of the ash has not reacted. The last fact is confirmed by the results for the sample C50-1-20 for which the total loss is 5.11%. Furthermore, despite having added 20% of hydrated lime to the mixture of cement and ash, the amount of remaining portlandite is very low (0.21%).

This is the reason why we can say that all the available calcium hydroxide has reacted with the fly ash, not only the calcium hydroxide released by the hydration of cement but also the one added as hydrated lime.

The self-neutralization of the matrix due to the pozzolanic reaction in the sample C50-1-20 has not been totally achieved.

The high amount of reacted fly ash is confirmed also through the peak on the DTG curve at 200-225 °C (peak 3). This peak is due to the dehydration of the hydrated gehlenite (hydrated calcium aluminosilicate, CASH) and it is characteristic of alumina-rich pozzolans.

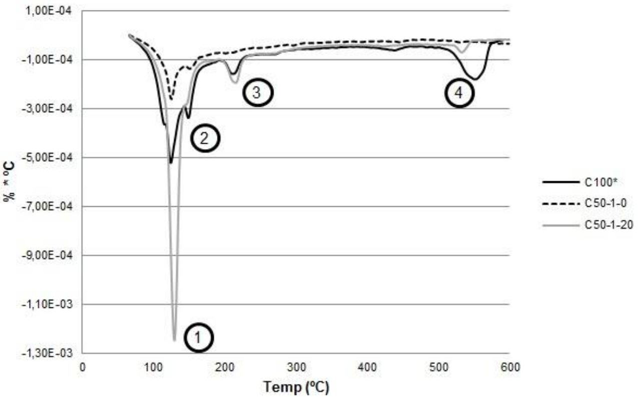

Figure 1. Thermogravimetric analysis (DTG curves) of microconcretes (curing time 360 days).

To determine the degree of neutralisation/carbonation of the specimens, after breaking prismatic specimens by bending test, the concrete was sprayed with phenolphthalein alcohol solution at 1%. For this test, a result with a pH above 10 in the sample is violet colored and below 8.6 it is colorless.

After one year exposing the samples to the laboratory environment, prismatic specimens were tested in flexural mode, and fresh fracture surfaces were sprayed with phenolphthalein solution The following mortars were tested: cement (C100 *), 50% fly ash replacement (C50-1-0) and 50% fly ash replacement plus 20% hydrated lime (C50-1-20). Obtained results are shown in figure 2.

Firstly, the sample C100 shows a coloration that corresponds to concrete with pH higher than 10. This behavior is related to thermogravimetric results: the presence of portlandite in the matrix produced a pH value higher than 10. Secondly, in the sample C50-1-20, a violet coloration is observable: in this case, the pH was higher than 10, and this fact is also related to the presence of small amount of portlandite in the matrix. For C50-1-20 a small front of carbonation was observed because samples were stored in laboratory atmosphere and this part was neutralized by the action of CO_2. . However, thirdly, for the sample C50-1-0, some randomly distributed coloured spots can be observed and no presence of carbonation front was identified. This behavior suggests that a self-neutralization process of the matrix was produced: all available portlandite from cement hydration was consumed by means of pozzolanic reaction and the pH yielded after 360 days of curing was lower than 8.6. This fact is in agreement to the results obtained if figure 3 (peak for portlandite decomposition was not observed in the DTG curve). These coloured spots were attributed to the presence of some zones of the matrix in which alkalinity of calcium silicate hydrates was high.

Figure 3 shows micrographs of Sample C100 * in which we can notice a dense matrix, the formation of hydration products (mainly CSH) (Fig. 3a) and the presence of portlandite located in one of the pores (Fig. 3b -3c).

Figure 2. Application of the phenolphthalein indicator solution to a fresh fracture surface of concrete. From left to right C100*, C50-1-0 and C50-1-20.

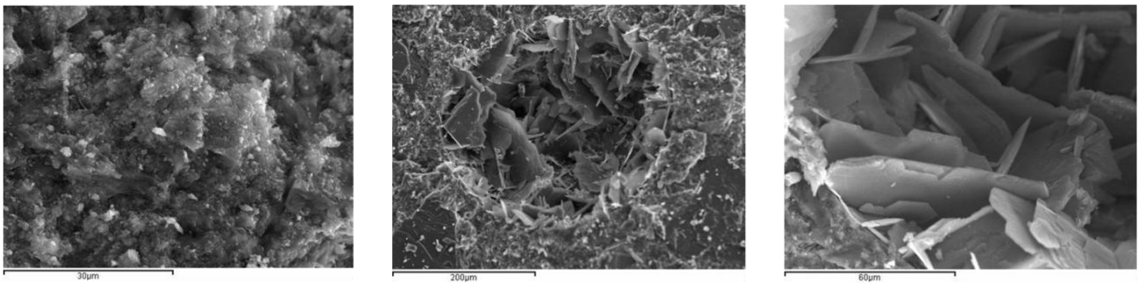

Figure 3. Scanning electron microscopy micrographs for C100* mortar.

Figure 4 presents sample C50-1-0 in which we can observe spherical fly ash particles which have still smooth parts of its surface without reacting (Fig. 4a). This could be due to the fact that the production of portlandite by the cement is not sufficient to make the ash particles to react completely (Fig. 4b). Similarly, we observe a macropore (Fig. 4c) in which the formation of hydration products does not appear (in comparison with the sample C100 *).

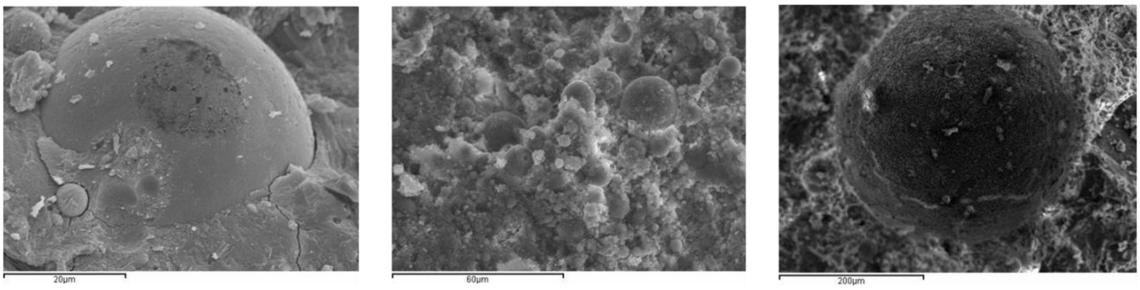

Figure 4. Scanning electron microscopy micrographs for C50-1-0 mortar.

In Figure 5, we observe the sample C50-1-20, in which we notice a dense matrix where fly ash particles have completely or almost reacted (Fig. 5a), and due to the higher initial presence of calcium hydroxide (5b), we can see in this sample the formation of ettringite and hydrated gehlenite which fill the interior of the pores (Fig. 5c). In this case, there is no crystallized portlandite, however hydrated gehlenite can be identified since it is a typical product in a pozzolanic reaction for rich-alumina pozzolans.

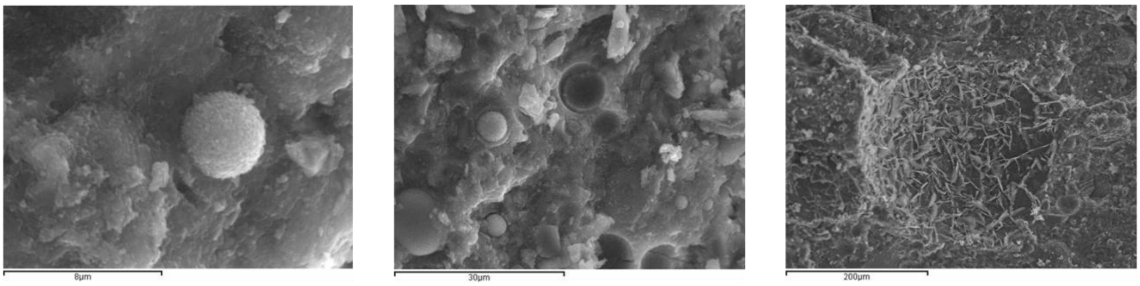

Figure 5. Scanning electron microscopy micrographs for C50-1-20 mortar.

4. Conclusions.

In microconcretes with low reduction of Portland cement (15%-25%), there are no important enhancements in the mechanical strength through the addition of fly ash and hydrated lime. Despite existing a large amount of ash in the corresponding dosages to the phase 1 (K=0.33), the addition of hydrated lime up to 40% with respect to the ash do not lead to significant increases of the mechanical strength.

In microconcretes with high reduction of Portland cement (50%-75%) and the addition of fly ash (phase 2, K=1), it is observed a pozzolanic reaction not only through mechanical measurements but also thermogravimetric analysis. In this case, when it is added 20% of hydrated lime respect to the fly ash content, the increase of strength is very noticeable, which shows the mechanical contribution of the generated products through the reaction of the mixed hydrated lime with the ash.

For a system with 50% of cement substitution by fly ash plus the addition of 20% of hydrated lime, high reactivity was achieved, enough to confirm that the factor of efficiency for fly ash is equal to 1, since the same mechanical stregnth for a control microconcrete is reached only with Portland cement.

It has been demonstrated through scanning electron microscopy and thermogravimetric analysis that the nature and quantity of the hydration products and the pozzolanic reaction change significantly depending on the components of the material (cement, fly ash and hydrated lime). The presence of hydrated gehlenite in the ternary systems (cement+fly ash+hydrated lime) and the considerable reduction in the calcium hydroxide content proves the high degree of the pozzolanic reaction in these systems.

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