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Comparing the pozzolanic activity of aerial lime mortars made with metakaolin and fluid catalytic cracking catalyst residue: A petrographic and physical-mechanical study

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HIGHLIGHTS

- FC3R shows lower pozzolanic activity than MK in aerial lime mortars.
- \bullet The big amount of particles >10 μm in FCC3R is responsible for its low reactivity.
- Metakaolin develops more aluminate phases and improves mortar strength.
- Ettringite is formed in FCC3R mortar samples.

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1. Introduction

Together with other waste materials such as blast furnace slag and fly ash, fluid catalytic cracking (FCC) catalyst residue is considered a good, alternative and sustainable source of aluminosilicates [1] intended for use in many building applications, such as mortars [2,3], cold asphalt concrete [4], roof tiles [1] and paving [5], among others. Despite the fact that FCC is a residue of the oil industry, its use in construction has been demonstrated to be environmental viable, since the concentration of leached heavy metals is under the limits established by environmental legislation [6].

The effectiveness of FCC as supplementary cementitious material in ordinary Portland cement (OPC) has been demonstrated by numerous studies, the majority of them showing the contribution of FCC (in binary or ternary systems) in the increase of OPC strength and chemical resistance [7,8]. According to those studies,

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ABSTRACT

We investigated the viability of a fluid catalytic cracking catalyst residue (FC3R) as an alternative sustainable pozzolanic additive in aerial lime mortars. The pozzolanic activity of FC3R was compared to that of metakaolin (MK) by chemical-mineralogical, petrographic and physical investigations. The FC3R showed lower pozzolanic activity than MK when added to aerial lime mortars, owed to the size of FC3R particles that generate less hydrated phases and give place to lower mechanical resistances in mortars. We also demonstrated that FC3R is not a compatible material for use in repair mortars, due to the formation of the harmful soluble salt ettringite.

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the FCC shows higher pozzolanic activity with respect to other similar additives, such as fly ashes [9], although the resistance of concrete with FCC under sulphate attack is similar to that induced by metakaolin [10].

Previous studies have demonstrated that FCC shows similar [11] or even higher [12] pozzolanic activity compared to metakaolin, when added to cement mortars. However, its effectiveness as pozzolanic material in non-hydraulic (aerial) lime mortars has not been investigated yet.

Adding pozzolanic additives to aerial lime mortars is a common practise in construction, especially in the restoration sector, as this improves the properties of aerial lime mortars both in the fresh and hardened state (e.g. mechanical strength, water permeability and durability, [13–15]). In this context, metakaolin is one of the most exploited pozzolanic materials, showing a high level of pozzolanic activity, below that of silica fume but greater than fly ashes [16,17].

With the aim to investigate the effectiveness of FCC as pozzolanic additive in aerial lime mortars, its pozzolanic activity has







been compared here to that of metakaolin, by studying the mineralogical, textural, mechanical and aesthetical properties of lime mortars after 28 days and 4 months since their preparation. Differences in the mortar properties were related to the intrinsic characteristics of the additives.

2. Materials and methods

2.1. Raw materials and mortar preparation

The raw materials used for the production of mortars were:

- a calcitic dry hydrated lime (named CL, CL90S [18]) produced by ANCASA (Seville, Spain).
- a siliceous sand (named SA) with continuous grading between 0.063 and 2 mm, supplied by the company ARGOS d.c. (Granada, Spain);
- metakaolin (named MK, CLASS N POZZOLAN [19]), produced by Burgess Pigment Company (USA);
- a fluid catalytic cracking catalyst residue (named FC3R), supplied by BP-Oil España S.A. refinery in Castellón (Spain), previously ground for 20 min [2] in the presence of DARAGRIND[®] 155, Grace Construction Products Ltd. (industrial additive added to reduce particle agglomeration).

The chemical and mineralogical composition of the two additives, MK and FC3R were studied by means of X-ray fluorescence (XRF) and X-ray diffraction (XRD). Instruments used were, respectively: a Bruker S4 Pioneer X-ray fluorescence spectrometer with wavelength dispersion, equipped with Rh X-ray tube (60 kV, 150 mA) and LIF200/PET/OVO-55 crystals; and a Panalytical X'Pert PRO MPD diffractometer, with automatic loader (45 kV voltage; 40 mA current; CuK\alpha radiation ($\lambda \approx 1.5405$ Å); 3 to 70° 20 explored area; 0.01° 20/s goniometer speed). Mineral phases were identified using the X-PowderX^{IM} software package [20]. An indicative value of the amorphous versus crystalline phases (a/c) was provided. This ratio is based on the mean value of the intensities, standard deviation and area of the crystal reflection [20].

The particle size distribution of MK and FC3R was analysed by means of a Mastersizer 2000LF from Malvern Instruments (in a range of $0.02-2000 \,\mu$ m). Samples were dispersed in ethanol and sonicated for 20 s before the measurement.

Mortars were prepared with a fixed binder-to-sand proportion, equal to 1:3 by weight, and variable dosages of additives, equal to 10, 15 and 20 wt% on the total amount of binder. Samples were named MK10, 15, 20 and FC10, 15, 20 according to the type and amount of additive. The replacing percentages were chosen as the most recommended ones for both metakaolin and FC3R [3,21]. A control mortar (BLANK), only composed of lime and sand, was also prepared with 1:3 binder-to-sand dosage by weight (Table 1). The water dosage for every mixture was established determining its flow in a range between 130 and 160 mm (Table 1), according to the European Standard EN 1015-3 [22]. After mixing [23], mortars

were casted in standardized moulds $(40 \times 40 \times 160 \text{ mm})$ and cured for 7 days in the mould and the following days out of the mould [24], under controlled temperature (T = 20 ± 5 °C) and relative humidity (RH = 60 ± 5%). The chosen curing conditions favour carbonation more than hydration, so as the aerial character of the mortar mixture is predominant on the hydraulic character of the pozzolanic components, in a similar way as in Arizzi and Cultrone [21]. Mortars were cured under the same conditions for 4 months in total before their study.

2.2. Mortar characterization

Mortar samples were analysed after 28 days and 4 months of curing. These time intervals were chosen because they are considered the most representative of the evolution of lime mortar properties over time due to the carbonation process [25]. For the study of mineralogy, porosity and texture both the external (1 cm from the surface) and the internal (core) zones of samples were analysed.

Mineral phases were determined by means of X-ray diffraction, at the same working conditions as those described above, whilst the aluminate and silicate hydrated phases (such as calcium silicate hydrates (CaO-SiO₂-H₂O, *CSH*), calcium alumina silicate hydrates (CaO-Al₂O₃-H₂O, *CASH*) and calcium alumina hydrates (CaO-Al₂O₃-H₂O, *CAH*), which are mainly amorphous) were determined by means of thermal measurements, using a SHIMADZU TGA-50H analyser (N₂ atmosphere; 10 °C/min heating rate; 25–950 °C temperature range; 70 mg sample).

The morphology and size of mineral phases and the texture of mortars were studied by means of field emission scanning electron microscopy (FESEM), using



Fig. 1. Particle size distribution of metakaolin (MK) and fluid catalytic cracking catalyst residue (FC3R).

Table 1

Mortar names, components, dosages (by weight) and flow. CL, calcitic dry hydrated lime; MK, metakaolin; FC3R, fluid catalytic cracking catalyst residue; SA, siliceous sand; L:A:S, lime:additive:sand dosage; W:L, water:lime dosage.

Mortar name	CL (g)	MK (g)	FC3R (g)	SA (g)	L:A:S	additive (% on tot. binder)	Water (%)	W:L	Flow (mm)
BLANK	500	-	-	1500	1:0:3	0	23	0.92	133
MK10	450	50	-	1500	0.9:0.1:3	10	24	1.07	134
MK15	425	75	-	1500	0.85:0.15:3	15	24	1.13	135
MK20	400	100	-	1500	0.8:0.2:3	20	25	1.25	148
FC10	450	-	50	1500	0.9:0.1:3	10	23	1.02	147
FC15	425	-	75	1500	0.85:0.15:3	15	23	1.08	151
FC20	400	-	100	1500	0.8:0.2:3	20	23	1.15	158

Table 2

Chemical and mineralogical composition of metakaolin (MK) and the fluid catalytic cracking catalyst residue (FC3R), determined by means of X-ray fluorescence (XRF) and X-ray diffraction (XRD). Legend: Qtz, quartz; Mul, mullite; Ame, amesite; Alb, albite; Fau: faujasite; a/c: amorphous versus crystalline phases ratio; - = absent; * = 0-10%; ** = 10-20%; *** = 30-35%; **** = 35-45%. Values are given in wt%.

XRF								
	SiO ₂	Al_2O_3	CaO	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	S
MK	50.80	45.26	0.22	0.44	0.66	0.30	0.24	0.03
FC3R	46.35	42.57	0.34	0.48	0.65	1.91	0.11	0.14
XRD								
	Qtz		Mul	Ame	Alb		Fau	a/c
MK	*		***	**	-		-	****
FC3R	**		-	-	***		**	***

a Carl Zeiss SMT AURIGA FESEM. Samples were oven-dried at 70 \pm 5 $^{\circ}\text{C}$ for 8 h and then carbon-coated before the observation.

Mortar porosity and pore size distribution were studied by means of mercury intrusion porosimetry (MIP), using a Micromeritics Autopore III 9410 porosimeter (pores investigated with radii in the range of 0.003–360 μm). Sample pieces of 1 cm³ were oven-dried at 70 ± 5 °C for 8 h prior to the analysis.

Flexural and compressive strength of mortars were studied by means of an INCOTECNIC-Matest hydraulic press, following the EN 1015-11 standard [26]. Flexural strength was measured on three samples per mortar (of $4 \times 4 \times 16$ cm); the six samples obtained after the flexural rupture were used for the compressive test. After the flexural rupture, samples were sprayed with a fenolftalein dissolution (2% in ethanol) to visually assess the carbonation degree achieved and to measure the carbonation border.

Table 3

Cumulative amount of metakaolin (MK) and fluid catalytic cracking catalyst residue (FC3R) particles (in %) within a range of particle size (in μ m).

	% of particles						
Particle size (in μm)	0.02-2	2-5	5-10	10-63	63-250		
MK FC3R	22 30	30 14	23 14	25 30	0 12		

Finally, to determine possible aesthetical modifications due to the addition of MK and FC3R, a Konica-Minolta CM-700d spectrophotometer (8 mm diameter; D65 illuminant; 10° view angle; SCI/SCE mode; 400–700 nm light radiation range) was used to determine the lightness (L^{*}) and chromatic (a^{*} and b^{*}) parameters, according to the CIELab system [27], as well as the whiteness (W) and the yellow indexes, calculated referring to the control white of the instrument (Z/Zn * 100). The overall colour difference (Δ E) of the mixes with additive compared to the control samples was determined as follows: $\Delta E = \sqrt{\left((L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2 \right)},$ where L^{*}₁, a^{*}₁ and b^{*}₁ are respectively the lightness and the chromatic coordinates of the control samples and L^{*}₂, a^{*}₂ and b^{*}₂ are those of the mixes with different additive percentages.

Colour was measured in 5 points of each mortar only after 28 days of curing.

3. Results and discussion

3.1. Study of MK and FC3R

The chemical composition of MK and FCC3R is very similar (XRF, Table 2), and the content of Si and Al are almost the same in both additives although they are present in the form of different aluminosilicate phases, as obtained by XRD. Metakaolin (MK) is



Fig. 2. X-ray diffraction patterns of the external (ex) and internal (in) zones of mortars after 28 days and 4 months of curing.



Fig. 3. DTG curves of the external (ex) and internal (in) zones of mortars after 28 days and 4 months of curing.

half-amorphous with little amount of amesite, mullite and quartz whilst FC3R is only partially amorphous and rich in sodium feld-spar, quartz and faujasite (XRD, Table 2).

The amorphous part of the additives (a/c, Table 2) is the main responsible for the pozzolanic properties in the mortar, as it is

mainly composed of aluminosilicate amourphous phases that react with $Ca(OH)_2$ to form hydrated calcium silicate and aluminate phases, which show cementitious properties [17].

Regarding particle size, metakaolin presents an almost unimodal particle size distribution, with the majority of particles with sizes ranging from 0.1 to 5 μ m, whilst FC3R has a polymodal particle size distribution, with the majority of particles having sizes of 0.1, 7 and 63 μ m (Fig. 1). Payá et al. [2] have shown that the FC3R additive is formed of spherical particles with sizes up to hundreds micrometers when unground whilst, after grinding, irregular particles with sizes ranging between hundreds nanometers to few micrometers are obtained.

The fact that more than 40% of FC3R particles have sizes bigger than 10 μ m (against 25% in MK, Table 3) can be due to two different reasons: 1) the FC3R is formed both by unground and ground particles, which would indicate that grinding is still incomplete after 20 min, or 2) the small ground particles have formed agglomerates during grinding, which means that the additive DARA-GRIND[®] 155 was ineffective in avoiding agglomeration. Between these two options the first one is unlikely, since a grinding period of 20 min has already been demonstrated to be the ideal for reducing the particle size of FC3R [2]. Therefore, a failure in the DARA-GRIND[®] additive (e.g. insufficient amount) in reducing particle agglomeration must be the main reason of the presence of bigger particles in FC3R. This fact can be detrimental to the reactivity of FC3R, knowing that the reactivity of a pozzolanic material does not depend only on its chemical composition, but also on the size of its particles and their specific surface area (the smallest the particles the highest the specific surface area and, consequently, the highest the dissolution rate of the amourphous phases in the pore water before their reaction with calcium hydroxide [17,28]).

The fineness of both MK and FC3R particles (respectively 22% and 30% of particles are smaller than 2 μ m, Table 3) are responsible for the increase in water demand of the mortar mixes, as previously found [3,17]. The water content, indeed, is very similar in all the mixes, although slightly higher in those made with the highest replacing amounts of additive (MK20 and FC20, Table 1). It is worth noticing that, although MK requires slightly higher water content than FC3R, mortars made with the former show values of

flow very similar to those of the control sample (BLANK, MK10 and MK15, Table 1), suggesting that the water retention ability of metakaolin is higher than that of FC3R.

3.2. Study of mortar samples

3.2.1. Mineralogical and morphological study

3.2.1.1. Hydration process. From the XRD patterns (Fig. 2), the only detectable hydrated mineral phase in the mixes is CAĈH (monocarboaluminate), which forms from the reaction between the reactive aluminates and the carbonate ions present in the mixes [17,21]. The intensity of CAĈH peak in the X-ray diffraction patterns is higher in MK mixes.

The other amorphous aluminate and silicate phases have been identified in the TG curves (Fig. 3), following the description made by Payá et al. [12]. To improve the readiness of the TG figures, only the portion of the DTG curve from 25 to 600 °C has been represented here. The following areas have been recognised (indicated by the arrows in Fig. 3 10%_4 months):

area-1) T < 100 °C, due to the loss of adsorbed water, in the form of OH;

area-2) T = 100-165, attributed to the dehydration of CSH;

area-3) T = 220–270 °C, attributed to the dehydration of aluminate phases;

area-4) T = 360–470 °C, attributed to the dehydroxylation of $Ca(OH)_2$.

On the basis of this differentiation we can observe that:

 Two different types of CSH form in MK mixes, as reflected in the two peaks centered at ~130 °C and ~140 °C in area-2, only present in MK_EX and MK_IN. More CSH phases are formed in MK mixes.



Fig. 4. FESEM images of the FC3R and MK mixes. (a) CAH hexagonal platelets in MK20_IN after 4 months; (b) CSH needles in MK15_IN after 28 days; (c) thick and elongated prismatic crystals in FC10_EX after 28 days; (d) CSH needles and elongated prismatic crystals in FC15_IN after 4 months; the inset in (c) is the EDX spectrum of the crystals indicated by the arrows.

- More aluminate phases are formed in MK mixes compared to FC mixes, as reflected in the higher intensity of the hump centered at 240 °C in area-3 in MK_EX and MK_IN. This is in agreement with what found by XRD on the bigger quantity of monocarboaluminate in MK samples.
- The presence of two peaks centered at 390 and 430 °C in area-4 might be related to the presence of calcium hydroxide particles with different sizes (the smaller the particle the earlier it thermally decomposes as its activation energy decreases, and vice versa [29]).

Table 4

Amount of calcium hydroxide (Ca(OH)₂) and calcium carbonate (CaCO₃) phases (in %) in the external (EX) and internal (IN) zones of mortar samples and their carbonation border (carb edge, in mm), measured by means of thermal analysis (TG) and phenolphthalein test after 28 days (28 d) and 4 months (4 m) of curing.

	$Ca(OH)_2$				CaCO ₃		Carb edge (mm)			
Time	28 d		4 m		28 d		4 m		28 d	4 m
zone	EX	IN	EX	IN	EX	IN	EX	IN		
BLANK	16	16	9	19	43	34	44	32	11.0	16.0
MK10	4	12	9	14	43	34	39	27	9.5	13.9
MK15	7	12	9	12	38	29	42	37	7.0	12.1
MK20	4	9	2	9	40	28	36	30	5.0	12.4
FC10	12	16	7	16	32	29	38	28	9.0	13.0
FC15	13	14	6	14	28	28	36	25	9.0	12.2
FC20	8	12	4	12	32	24	42	26	11.0	16.0

28 days	MK10	MK15	MK20	
BLANK				
	FC10	FC15	FC20	
4 months	MK10	MK15	MK20	
4 months BLANK	МК10	MK15	MK20	
4 months BLANK	ΗΚ10 Γουστορικό FC10	MK15 FC15	ΜK20 Γ Γ Γ 20	

Fig. 5. Photos of the broken faces of mortar samples, sprayed with fenolftalein right after the flexural rupture, at 28 days and 4 months of curing. The carbonation edge has been marked with a grey line.

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In general, we can also observe that more hydrated phases are formed at increasing amounts of pozzolanic additive in the mixes and that metakaolin is more reactive than FC3R, since more hydrated phases are formed in MK mixes.

FESEM observations confirm what found by XRD and TG analyses on the advance of the hydration reactions in the mixes. Generally, more hydrated phases have been observed in samples with the highest additive amounts (20 wt%). The typical plate-like morphology of the CAH phases was recognised in many of the samples with additive although it is more frequent and in bigger amounts in the MK mixes, especially those cured for 4 months (Fig. 4a). The CAH platelets were mainly observed in the pores of the matrix of the internal samples.

The needle-like morphology of the CSH phases was observed mainly in the internal samples and in bigger quantity in the MK mixes (Fig. 4b). Interestingly, FC3R samples present high amounts of thick and elongated prismatic crystals (Fig. 4c), which are not observed in MK mixes and are different from the CSH phases (thinner and amorphous, Fig. 4d). EDX analyses (inset in Fig. 4c) of these crystals revealed the presence of little amount of sulphur in their composition (proceeding from the FC3R additive, XRF Table 2), in addition to Ca, Al and Si. Both the chemical composition and the morphology of these crystals suggest that ettringite is formed in FC3R mixes, even though this phase was not detected by means of XRD almost, probably because its amount is under the resolution limit of this technique.

3.2.1.2. Carbonation process. To assess the carbonation process, the amounts of calcium hydroxide and calcium carbonate phases in the mortar samples have been quantified by means of TG analysis (Table 4). The advance of the carbonation process was also followed visually by measuring the carbonation edge in fresh



Fig. 6. FESEM image of scalenohedral calcite crystals in MK15_EX after 4 months.

broken samples (Fig. 5). From the taken images it is clear that 4 months-samples are more carbonated than the 28-days ones. According to our TG results, carbonation is slower at increasing amounts of additive in the mixes, although this was observed only in MK mixes (Fig. 5).

Only mixes with 20 wt% of metakaolin presents slightly lower amounts of $CaCO_3$ after 4 months, and this is certainly related to the formation of more monocarboaluminate phases in these samples at the same time (Figs. 2 and 3). The fact that less $Ca(OH)_2$ is present in the majority of MK samples with respect to FC3R samples is also representative of the more advanced hydration process in mixes made with metakaolin.

The matrix of the external part of the mixes is mainly composed of calcite, due to the fact that carbonation progresses from the exterior toward the interior of mortars. In MK samples, scalenohedral calcite crystals have been observed (Fig. 6).

3.2.2. Textural and mechanical study

The study of the pore system of mortars has shown that all mixes present similar open porosity values, with very small differences among them ($P_o \sim 31\%$, Table 5). The pore size distribution of mortars (Fig. 7) is also very similar since all mixes presents a main family of pores with radius comprised between 0.1 and 1 μ m (typical of non-hydraulic lime mortars [30,31]). Control samples have also a little volume of pores with radius of 0.01 μ m [31]. As already observed in a previous study [21], the presence of metakaolin generates a new family of pores between the two already described (0.01 < r < 0.1 μ m), whose volume increases at increasing amounts of this additive. These pores are not present in the FC3R mixes, whose porosity is very similar to that of control samples. This fact confirms that hydration is less intense in FC3R mixes compared to MK ones.

The lower hydraulicity of mortars made with FC3R was again confirmed by means of mechanical tests. The values of flexural and compressive resistance measured in FC3R samples are indeed very similar to those of control samples, whilst the addition of metakaolin did induce an increase of the mechanical resistance of mortars (R_f and R_c, Table 5). However, the R_f and R_c values in Table 5 also indicate that the strength enhancement is less stable in MK15 and MK20 mortars, due to a slight decrease after 4 months.

3.2.3. Study of the aesthetical features

The chromatic parameters are very similar among all the mixes, as reflected in the low values of ΔE (~18, Table 6), which represents the overall colour difference between the mixes with additive and the control samples. Moreover this value is similar in both MK and FC3R samples. The only significant chromatic variation is the increase in the values of lightness (L^{*}) and whiteness (W_i) of mortars with additives.

Table 5

Open porosity (P_o , in %) and mechanical resistances to flexural (R_f , in MPa) and compressive rupture (R_c , in MPa) of mortar samples, measured by means of mercury intrusion porosimetry analysis (MIP) and mechanical tests after 28 days (28 d) and 4 months (4 m) of curing; * value under the limit of the instrument.

	P _o (%)		$R_f(MPa)$		R_c (MPa)	
Time	28 d	4 m	28 d	4 m	28 d	4 m
BLANK	31	32	*	*	2.36 ± 0.15	2.95 ± 0.36
MK10	32	30	*	1.69 ± 0.24	5.03 ± 0.77	5.59 ± 0.24
MK15	31	31	*	2.44 ± 0.12	7.82 ± 0.25	7.59 ± 0.43
MK20	31	32	2.93 ± 0.19	2.82 ± 0.07	9.12 ± 0.20	8.40 ± 0.80
FC10	31	32	*	*	2.62 ± 0.11	3.25 ± 0.27
FC15	32	32	*	*	2.82 ± 0.28	3.07 ± 0.46
FC20	31	31	*	*	3.34 ± 0.11	3.75 ± 0.11



Fig. 7. Pore size distribution curves of the external (ex) and internal (in) parts of mortar samples measured after 28 days and 4 months of curing by means of mercury intrusion porosimetry (MIP). The pore radius (r, in µm) is plotted against the incremental pore volume (Vincr, in mL).

Table 6

Chromatic parameters (L^{*}, lightness; a^{*} and b^{*}, colour coordinates; Y_i, yellow index; W_i, whiteness index; ΔE , overall colour difference) of mortar samples measured by means of spectrophotometry and standard deviation of the values.

	L*	a	b*	Wi	Yi	ΔE
BLANK	71.38 ± 0.96	1.81 ± 0.28	5.24 ± 0.59	34.51 ± 3.73	8.52 ± 0.99	-
MK10	89.12 ± 1.30	1.57 ± 0.08	6.70 ± 0.20	42.37 ± 2.81	10.88 ± 0.45	17.80
MK15	89.81 ± 0.40	1.59 ± 0.08	7.06 ± 0.36	41.70 ± 2.01	11.36 ± 0.58	18.52
MK20	88.41 ± 0.89	1.90 ± 0.31	7.73 ± 0.36	36.49 ± 1.86	12.59 ± 0.56	17.21
FC10	90.03 ± 0.20	1.84 ± 0.17	6.46 ± 0.39	44.89 ± 2.14	10.40 ± 0.62	18.69
FC15	89.67 ± 0.38	2.05 ± 0.23	6.16 ± 0.37	45.76 ± 1.93	9.96 ± 0.60	18.31
FC20	88.36 ± 1.07	1.71 ± 0.06	7.01 ± 0.49	39.90 ± 3.82	11.42 ± 0.88	17.07

4. Conclusions

The characteristics of two pozzolanic additives and the properties they confer to non-hydraulic (aerial) lime mortars have been compared here.

In summary, the fluid catalytic cracking catalyst residue (FC3R) has shown lower pozzolanic activity with respect to metakaolin when added to non-hydraulic lime mortars, despite previous studies have demonstrated its good reactivity in cement mortars. The fact that almost half of the FC3R particles have sizes from 10 to 250 μ m is certainly a key factor in the slightly lower reactivity of this pozzolanic material compared to metakaolin. The failure of the DARAGRIND[®] additive during grinding is a possible cause of the low reactivity of FC3R. Further studies on the pozzolanic activity of FC3R both in the absence and in the presence of different amounts of the DARAGRIND[®] additive are needed to verify this hypothesis.

This study has also shown that using recycled materials in construction is not always the right choice, especially when historic buildings are concerned. In fact, despite the potential environmental benefits of the use of FC3R, this additive cannot be used in repair mortars due to the formation of ettringite, which is a harmful salt for the durability of historic buildings.

Conflict of interest

None.

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