Influence of fly ash blending on hydration and physical behavior of belite–alite–ye’elimite cements

D. Londono-Zuluaga · J. I. Tobón · M. A. G. Aranda · I. Santacruz · A. G. De la Torre

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Abstract A cement powder, composed of belite, alite and ye’elimite, was blended with 0, 15 and 30 wt% of fly ash and the resulting blended cements were further characterized. During hydration, the presence of fly ash caused the partial inhibition of both AFt degradation and belite reactivity, even after 180 days. The compressive strength of the corresponding mortars increased by increasing the fly ash content (68, 73 and 82 MPa for mortars with 0, 15 and 30 wt% of fly ash, respectively, at 180 curing days), mainly due to the diminishing porosity and pore size values. Although pozzolanic reaction has not been directly proved there are indirect evidences.

Keywords Belite–alite–ye’elimite cement · Fly ash · Hydration · Rietveld method · Phase evolution · NMR · Compressive strength

1 Introduction

An environmental strategy to reduce the negative effect of the CO₂ footprint of the Portland Cement (PC) industry consists on its partial substitution by reactive industrial by-products, such as fly ash [1, 2]. Fly ash (FA) is the major solid waste generated from coal-fired power stations. From the power station’s perspective, there are methods to exploit fly ash disposal in an economically advantageous way. From the building industry’s perspective, FA is looked upon as a supplementary cementitious material (SCM) which is used in mass as a cement replacement material [3]. Furthermore, the addition of FA to cement can modify its properties, such as reduced hydration heat and thermal cracking in concrete at early ages, durability, enhanced ultimate strength, and improved workability of fresh mortar/concrete when cement is replaced by FA [3, 4]. Despite the benefits offered by PC cement/concrete blended with FA, there are some limitations related to the variability of the mineralogy and chemical composition of the FA [5], and the maximum amount of FA that can be added.
Another alternative to reduce CO\textsubscript{2} emissions consists of the development of eco-cements composed by less calcite demanding phases, such as belite and ye’elimite. That is the case of calcium sulfoaluminate (CSA) clinkers that, in general, contain 50–70 wt% of ye’elimite (C\textsubscript{4}A\textsubscript{3}/C\textsubscript{2}S),\textsuperscript{1} and other phases such as belite and calcium aluminates [6–10]. Their main hydration products are ettringite, monosulfoaluminate and aluminum hydroxide [11–16]. Nowadays, belite–ye’elimite–ferrite (BYF) cements have been studied as potential substitutes of PC [15, 17–22]. The mineralogical composition of BYF clinkers/cements includes belite and ye’elimite as main and secondary phases, respectively. Since the reactivity of β-C\textsubscript{2}S is slow, these materials may develop low mechanical strengths at early ages. A possible solution to this problem goes through the production of cements composed by belite jointly with alite and ye’elimite, known as belite–alite–ye’elimite (BAY) cements [23–29]. In these types of systems, the main hydration products are ettringite, monosulfoaluminate, C-S-H gel, C\textsubscript{4}ASH\textsubscript{4} (silicon hydrogarnet or katoite) and C\textsubscript{2}ASH\textsubscript{8} (stratlingite). CH and/or AH\textsubscript{3} can also be formed, depending on the C\textsubscript{3}S and C\textsubscript{4}A\textsubscript{3}S ratio [23–25]. According to the hydration products, the reaction of alite and ye’elimite with water yield to the development of high mechanical strengths at early ages, while belite contributes to later values [23, 25]. The inclusion of FA in BAY cements reduces the environmental impact and improves the performance of fresh and hardened states, but this has not been studied yet. From previous studies, it is known that the addition of fly ash to PC plays an important role as a pozzolanic addition and as a filler [1–3, 5, 30, 31]. Recent studies, focused on the effects of FA on CSA cements [32–36], have demonstrated that FA works as both a filler and a dilutor.

The aim of this work is to study the hydration and mechanical properties of a blended BAY cement with 0, 15 and 30 wt% of FA. The present study helps to understand the effect of FA on the mechanisms of BAY hydration and its impact on the mechanical strengths. The characterization of these cement pastes has been performed by Rietveld quantitative phase analysis (RQPA) to determine the phase assemblage during hydration, rheological measurements, isothermal calorimetry, thermogravimetric analysis and magic-angle-spinning nuclear-magnetic resonance spectroscopy. Finally, the mechanical properties of the corresponding BAY blended mortars were measured.

2 Experimental

2.1 Materials

2.1.1 Blended BAY cements with fly ash

BAY cement was produced as published elsewhere [23]. Blended cements were produced by mixing the BAY cement for 60 min in a micro-Deval machine at 100 rpm, without balls, with 15 and 30 wt% of Class F fly ash. FA was supplied by the power station of Lada (Spain) [35]. Blended cements will be henceforth labeled as FA0BAY (without any addition), FA15BAY and FA30BAY (with 15 and 30 wt% FA, respectively), and their general name will be FA#BAY. Table 1 shows the mineralogical composition (including amorphous and non-quantified crystalline phases, ACn) of BAY cement and FA powders, determined through RQPA combined with the internal standard methodology, as detailed below. The three studied cements showed similar Blaine values, ~ 5250 (± 100) cm\textsuperscript{2}/g, where the differences are within the measurement error. The particle size distribution of the three cements and fly ash was measured by laser diffraction (Mastersizer S, Malvern, UK);

| Table 1 RQPA results, in wt%, of the anhydrous BAY cement (FA0BAY) and fly ash powders |
|-----------------------------------------------|
| FA0BAY cement | Fly ash |
| --- | --- | --- |
| β-C\textsubscript{2}S | 41.3(2) | Mullite | 10.9(2) |
| γ-C\textsubscript{2}S | 1.1(1) | Hematite | 0.5(1) |
| C\textsubscript{4}AF | 3.6(2) | Quartz | 4.6(3) |
| CS | 9.3(2) | Lime | 0.2(2) |
| o-C\textsubscript{4}A\textsubscript{3}S | 7.0(2) | Periclase | 0.2(1) |
| C\textsubscript{3}S | 9.6(1) | MagnesioFerrite | 1.2(2) |
| C\textsubscript{12}A\textsubscript{7} | 5.4(1) | | |
| F-ellestadite | 3.1(1) | | |
| ACn | 19.6(2) | ACn | 82.3(3) |

\textsuperscript{1} Cement nomenclature will be used in the whole manuscript: C = CaO, S = SiO\textsubscript{2}, A = Al\textsubscript{2}O\textsubscript{3}, F = Fe\textsubscript{2}O\textsubscript{3}, S = SO\textsubscript{3}, M = MgO and H = H\textsubscript{2}O.
UK) and is shown in Figure S1, deposited as electronic supplementary material. The three cements show a trimodal behavior, where the median particle size by volume \((D_{v50})\) slightly increase with the presence of fly ash, as expected, being \(\sim 4\), \(\sim 5\) and \(\sim 6\) \(\mu\)m for FA0BAY, FA15BAY and FA30BAY, respectively.

### 2.1.2 Cement paste preparation

Cement pastes were prepared with deionized water using a water-to-cement \((w/c)\) mass ratio of 0.40, following UNE-EN 196-3 standard. Thus, FA0BAY, FA15BAY and FA30BAY pastes show water/solid \((w/s)\) of 0.40, 0.34 and 0.28, respectively. To improve the workability, a polycarboxylate-based superplasticizer \((SP)\) (Floadis 1623, Adex Polymer S.L., Madrid, Spain), with 25 wt\% of active matter, was added to the pastes (from 0.2 to 0.6 wt\% of active matter referred to the solid content). The moisture of the superplasticizer was considered for the preparation of cement pastes and mortars. Moreover, FA0BAY and FA30BAY cements were selected to be hydrated at a \(w/c\) ratio of 0.57, with the aim of understanding the \(w/c\) effect (the latter has a \(w/s\) of 0.40). All pastes were cast into hermetically closed cylinders of polytetrafluoroethylene (PTFE), volume of 2.8 cm\(^3\), and rotated during the first 24 h, at 16 rpm, at 20±1°C. Afterward, all samples were removed and kept within water at 20±1°C. The hydration of cement pastes at a \(w/c\) of 0.40 was arrested as detailed in [35] at 1, 7, 28, 90 and 180 days of curing ages, and the hydration of pastes at a \(w/c\) of 0.57 was arrested at 28 and 90 curing days.

### 2.1.3 Cement mortar preparation

All cement mortars were prepared according to UNE-EN196-1 at cement/sand and \(w/c\) of 1/3 and 0.40, respectively, with the optimum amount of superplasticizer. CEN EN196-1 standard sand was used. Cubes \((3 \times 3 \times 3\) cm\(^3\)) were cast and cured at 20±1°C and 99% relative humidity \((RH)\) for 24 h; then the cubes were demolded and cured in a water bath at 20±1°C until testing (compressive strength) at the same curing ages than pastes were characterized (1, 7, 28, 90 and 180 days).

### 2.2 Characterization

#### 2.2.1 Rheological behavior

Pastes for rheological characterization were prepared by mechanical stirring with helices according to EN196-3:2005 standard procedure. The rheological behavior of the pastes was studied using a viscometer (VT550 Model, Thermo Haake, Karlsruhe, Germany) with a serrated coaxial cylinder sensor, SV2P, provided with a cap to reduce evaporation. Flow curves were obtained under controlled rate \((CR)\) measurements. Firstly, the shear rate was increased from 0 to 100 s\(^{-1}\) with ramp times of 6 s, for a total of 11 ramps. Secondly, the shear rate was decreased from 100 to 0 s\(^{-1}\) following the same ramp times. Before starting the rheological measurement, the pastes were pre-sheared for 30 s at 100 s\(^{-1}\).

#### 2.2.2 Isothermal calorimetric study

An eight channel TAM Air Isothermal Calorimeter (TA Instruments, USA) was used to measure the heat flow at 25°C during 72 h. An automatic admix device was used to mix the powder samples with water inside the calorimeter for 2 min in order to avoid any data loss at the beginning of the reaction. To understand the superplasticizer effect on the early hydration and heat flow, the anhydrous powder cement \((2\) g) was hydrated at a \(w/c\) of 0.40 with and without SP. The heat flow of three separate runs for each cement was recorded during 72 h according to ASTM C1679 – 13. No significant differences were observed between the three runs, so the arithmetic average was used.

#### 2.2.3 Laboratory X-ray powder diffraction (LXRPD) data collection and analysis

Powder patterns for the anhydrous cements and stopped pastes were recorded on a D8 ADVANCE (Bruker AXS, Germany) diffractometer (BRUKER), located in SCAI at University of Malaga (Spain), using monochromatic MoK\(_\alpha1\) radiation (\(\lambda = 0.7093\) Å) [Ge (111) primary monochromator] with LYNXEYE XE 500 µm linear dispersive energy detector, optimized for high-energy radiation, with the maximum opening angle. This diffractometer works on transmission geometry and samples are placed between kapton.
foils and are rotated at 10 rpm during data collection. Data were collected from 185 to 105 °C (20). To determine the amorphous and crystalline non-quantified (ACn) content, an internal standard approach was employed [38, 39]. As internal standard, Quartz (99.56%, ABCR GmbH & Co. KG), was added to the samples to a total content of ~20 wt%. The mixtures (sample-standard) were homogenized for 15 min in an agate mortar. In addition, an in situ LXRPD study of FA#BAY with and without superplasticizer was performed to understand its effect on early hydration. To do so, LXRPD were collected on the same D8 ADVANCE diffractometer by using an Anton Paar MHC-trans chamber. Data were collected at 25 °C and relative humidity (RH) value of 95%. These X-ray diffraction patterns were collected every 15 min. All patterns were measured between 2° and 27° (2θ) with a step size of 0.017° and counting time of 0.5 s per step (total time per pattern 8 min).

All the patterns were analyzed by the Rietveld method using GSAS software package [40] by using a pseudo-Voigt peak shape function [41] with the asymmetry correction included [42] to obtain RQPA. The refined overall parameters were: phase scale factors, background coefficients, unit cell parameters, zero-shift error, peak shape parameters and preferred orientation coefficient, if needed (March–Dollase ellipsoidal preferred orientation correction algorithm [43]). The crystal structure descriptions used for all phases were given in references [44] and [45], and updated crystallographic descriptions were used for stratlingite [46], orthorhombic [47] and pseudo-cubic [48] ye’elimite.

2.2.4 Thermal analysis

Thermogravimetric (TGA) and differential thermogravimetric (DTG) analyses were performed in a SDT-Q600 analyzer (TA instrument, New Castle, DE) for a ground fraction (~30 mg) of every paste after the hydration was arrested. The samples were heated up to 1000 °C at a heating rate of 10 °C/min. Measurements were carried out in an open platinum crucible under air flow (100 mL/min). The weight loss from RT to 600 °C was computed to be chemically bounded water (used to calculate the free water (FW) content of the pastes), and that from 600 to 1000 °C was considered as CO₂.

2.2.5 Mercury intrusion porosimetry (MIP) analysis

MIP has been employed to characterize the pore structure (open porosity and pore size distribution) of FA#BAY cement pastes at 180 curing days, for the sake of comparison. The cylindrical specimens (15 mm length and 10 mm diameter) were first immersed in isopropanol for 72 h, and then dried at 40 °C until the weight loss of the samples was stable. The surface of this cylinder was removed prior to the analysis. A Micromeritics Autopore IV 9500 instrument (Micromeritics Instrument Corporation, Norcross- GA, US) was used, and the pressure applied by the intrusion porosimetry ranged from 0 to 300 MPa. A constant contact angle θ of 130° was assumed for data evaluation.

2.2.6 Solid state magic angle spinning nuclear magnetic resonance (MAS-NMR)

Solid state 27Al and 29Si MAS-NMR spectra were recorded on a Bruker AVIII HD 600 NMR spectrometer, located at SCAI at University of Malaga (Spain), (field strength of 14.1 T) at 156.4 MHz with a 2.5 mm triple-resonance DVT probe using zirconia rotors at 20 and 15 kHz spinning rates (respectively for 27Al and 29Si). 27Al experiment was performed with (Hpedec) and without (One pulse) 1H decoupling by applying a single pulse (π/12), an excitation pulse of 1 μs, 5.0 s relaxation delay and 200 scans. The chemical shift was referenced to an external solutions of 1 M of Al(NO₃)₃. 29Si MAS-NMR experiments were performed with 1H decoupling (cw sequence) by applying a single pulse (π/2), an excitation pulse of 5 μs, 30 s relaxation delay and 10800 scans. The chemical shift was referenced to an external solution of tetramethylsilane (TMS).

2.2.7 Compressive strengths

The compressive strength of cubic mortars (3 × 3 × 3 cm³) was measured in a Model Autotest 200/10 W (Ibertest, Spain) press. Three cubic mortars were tested, at every studied hydration age, to obtain the standard deviation values according to UNE-EN196-1. A corrector factor was applied to the obtained values to be compared with standard prisms (4 × 4 × 16 cm³).
3 Results and discussion

3.1 Rheological study

A good dispersion of fresh cement pastes and mortars is necessary to prepare homogeneous specimens. To achieve that, the preparation of pastes/mortars with the right amount of SP is essential, mainly when low water contents are used. Here, the addition of SP was optimized through the rheological behavior of the cement pastes. Figure S2, deposited as electronic supplementary material, shows the flow curves of the cement pastes prepared with 0, 15 and 30 wt% of fly ash, respectively (w/c = 0.40) with different SP contents. Pastes without SP could not be measured due to their high viscosity values. In general, by adding SP, the viscosity of all pastes decreased to a minimum value, which corresponds to the optimum amount. From there, the viscosity of all pastes was kept constant or even slightly increased. This can be seen on detail in Fig. 1, where the deflocculation curves of all pastes, taken from the up-curves at the shear rate of 100 s$^{-1}$, are shown. In the case of the FA0BAY family, pastes with 0.5 and 0.6 wt% SP show the lowest viscosity values and show similar rheological behaviors (Figs. 1 and S2), where the paste with 0.5 wt% SP shows the smallest thixotropic cycle (58 and 157 Pa/s for pastes with 0.5 and 0.6 wt%, respectively). In the case of the FA15BAY family, pastes with 0.5 and 0.6 wt% SP also show the lowest viscosity values, and identical rheological behaviors (similar thixotropic cycle), Figure S2. Finally, in the FA30BAY family, the paste with 0.5 wt% SP shows the lowest viscosity value (Figs. 1 and S2) and, when the SP content was increased up to 0.6 wt%, the viscosity slightly increased. Thus, in all cases, 0.5 wt% of SP was selected as the optimum SP content for further studies. In addition, the viscosity of the pastes increased by increasing the FA content, Fig. 1, due to the higher solid content (same w/c, but different w/s ratios) as described in the Experimental section.

3.2 Effect of the superplasticizer on FA0BAY early-age hydration

In-situ LXRPD of the FA0BAY paste was performed to determine the phase assemblage within the first hours of hydration; the obtained results were correlated with the heat flow. Figure 2 shows the in situ RQPA results and heat release measured by isothermal calorimetric for FA0BAY prepared without SP (Fig. 2a) and with 0.5 wt% SP (Fig. 2b). The heat released during the initial period, 0-0.2 h, is mainly assigned to the partial dissolution of anhydrite, mayenite, alite and ye’elimite, and the initial precipitation of AFt [13, 49, 50]. The difference in the intensity of the heat flow between both pastes at the initial period is likely due to the effect of superplasticizer on the rate of both phase dissolution and formation of hydrates; it is known that polycarboxylates have a retarder effect on the hydration of cement pastes [51]. After 5 min of hydration, the sample without SP reaches a maximum heat flow of 0.052 ± 0.008 W/g, while the sample with SP reaches about half of it (~ 0.024 ± 0.001 W/g). Once the

![Deflocculation curves of FA#BAY pastes at the shear rate of 100 s$^{-1}$](image)
initial period is finished, the rate of the heat evolution and phase dissolution can be described by a pronounced exothermic peak in Fig. 2a and a shoulder in Fig. 2b centered at 8 h of hydration in both figures. In both cases, alite dissolves at a slower rate than ye’elimite, as expected [23, 49, 52, 53]. The most interesting result of this study is that the addition of SP has mainly retarded the dissolution of anhydrite and, to a lower extent, of C12A7, meanwhile ye’elimite dissolves at the same rate in both pastes.

The heat released during the hydration of all samples, prepared without and with SP, was also measured. The results taken at 5 and 24 h are given in Table S1, deposited as electronic supplementary material. It is clear that the addition of 0.5 wt% of SP (referred to the solid content) provokes a delay in the hydration and consequently less heat is released in all the systems at any time.

3.3 Hydration study of FA#BAY cements

The hydration behavior of all cement pastes, after arresting hydration, was also studied at different curing ages. Table 2 gives the RQPA results of pastes hydrated at 1, 3, 7, 28, 90 and 180 days, including ACn and free water (FW) contents. Figures 3 and 3S (the latter deposited as electronic supplementary material) show the TGA-DTG plots for FA0BAY, FA15BAY and FA30BAY cement pastes at all curing ages. All pastes were prepared with 0.5 wt% SP, as optimized before. Figure 4 shows Rietveld plots of FA15BAY at 180 days (w/c = 0.40), with peaks labeled, as a representative example. From Table 2, it can be observed that C4A3S and C3S phases have been totally dissolved after 1 and 7 days of hydration, respectively, in all cements. On the one hand, ye’elimite reacts with anhydrite and water to form ettringite and amorphous aluminum hydroxide [54]; however, in the presence of portlandite, ye’elimite will react to give only ettringite [53]. This portlandite comes from the early hydration of C3S that will also yield C–S–H gel. Consequently, crystalline aluminum hydroxide (called gibbsite) or crystalline portlandite were not detected by LXRPD, see inset in Fig. 4. Furthermore, crystalline portlandite was only found in FA0BAY, by TGA-DTG, after 28 hydration days, where a small peak was detected at 450 °C, Figs. 3 and S3 (the latter deposited as supplementary electronic material). These results are in agreement with Winnefeld and Lothenbach [55] where portlandite was not detected in related systems. Portlandite, in these types of pastes, seems to initially favor the formation of ettringite [53]. Later, in the absence of calcium sulfate and ye’elimite (after 24 h), portlandite reacts with AH3 and ettringite to produce AFm-type phases [52, 56]. This will justify the reduction of the AFt amount and the increase of AFm-type phase contents, from 28 to 180 days of hydration in FA0BAY. Table 2. Moreover, the hydration of C3S and β-C2S have yielded a silicate-rich hydration environment in which AFt is unstable [24, 49] and stratlingite and katoite are formed [46, 57]. Consequently, the presence of stratlingite in FA0BAY paste at 1 day, and in FA15BAY and FA30BAY pastes at 7 days, is noticeable. This is in agreement with the thermal analysis of FA#BAY (w/c = 0.40). In all cases, two typical decomposition events were found: (1) the first one, at ~ 110 °C, corresponds to the dehydration of C–S–H and AFt [53, 58, 59]; these two processes are strongly overlapped and consequently, these results cannot be directly compared to those obtained by LXRPD. (2) The second group of signals corresponds to the dehydration of AFm-types phases: between 120 and 180 °C, which is associated with the dehydration of monosulfoaluminate [50, 59], and between 180 and 220 °C is associated with the dehydration of stratlingite [16, 32, 60]. As mentioned before, the hydration of alite yields portlandite and favors the formation of AFt during the first hydration hours [53, 59, 61], so CH was not detected by TGA, as expected, in agreement with Winnefeld and Barlag [59], Trauchessec et al. [52] and Hargis et al. [56].

Belite showed a slow hydration behavior, and only after 28 days, this phase starts its reaction with water in FA0BAY, but the reaction of this phase in FA15BAY and FA30BAY is even slower (i.e. β-C2S reacts 41, 25 and 8% from 28 to 90 days, for pastes with 0, 15 and 30 wt% FA, respectively). These results might be justified by the low amount of water used, i.e. w/c = 0.40 (w/s of 0.40, 0.34 and 0.28, for 0, 15 and 30 wt% of FA, respectively). In order to test this last statement, FA0BAY and FA30BAY pastes were also prepared at a w/c of 0.57. Table 3 shows the RQPA
| Phases          | FA0BAY \( t_0 \) | 1 days | 7 days | 28 days | 90 days | 180 days | FA15BAY \( t_0 \) | 1 days | 7 days | 28 days | 90 days | 180 days | FA30BAY \( t_0 \) | 1 days | 7 days | 28 days | 90 days | 180 days |
|----------------|------------------|--------|--------|---------|---------|----------|------------------|--------|--------|---------|---------|---------|------------------|--------|--------|---------|---------|---------|
| Ca\(_2\)AS  | 5.1(1)           | 1.3(1) | –      | –       | –       | –        | 5.3(1)           | 2.4(1) | –      | –       | –       | –       | 4.3(1)           | 1.0(1) | –      | –       | –       | –       |
| γ-C\(_2\)S  | 1.2(1)           | 1.3(1) | 1.3(1) | 1.1(1)  | 1.0(1)  | –        | 1.5(2)           | 1.4(1) | 1.3(1) | 1.4(1)  | 0.8(1)  | 0.8(1)  | 1.4(1)           | 1.1(1) | 1.2(1) | 1.3(1)  | 1.3(1)  | 0.8(1)  |
| β-C\(_2\)S  | 32.3(1)          | 32.9(1)| 32.4(1)| 27.9(1) | 16.5(2) | 14.4(3)  | 25.0(2)          | 28.6(2)| 28.1(2)| 27.2(2) | 20.3(2) | 18.6(2) | 19.8(2)          | 23.2(2)| 23.2(2)| 21.5(2) | 19.8(2) | 19.8(2) |
| C\(_2\)S    | 7.9(2)           | 3.0(2) | 1.0(1) | –       | –       | –        | 7.4(3)           | 2.4(2) | –      | –       | –       | –       | 6.0(2)           | 1.5(1) | –      | –       | –       | –       |
| C\(_2\)A\(_6\)| 4.3(1)           | 2.0(1) | –      | –       | –       | –        | 3.6(1)           | 1.9(1) | –      | –       | –       | –       | 2.7(1)           | 1.6(1) | –      | –       | –       | –       |
| Fe-ellestadite| 2.2(1)           | 3.0(2) | 2.7(1) | 2.3(1)  | 3.2(3)  | 3.0(3)   | 3.4(3)           | 3.4(2) | 2.3(2) | 2.5(1)  | 2.6(1)  | 2.1(1)  | 3.1(3)           | 2.3(1) | 2.0(1) | 2.1(1)  | 2.3(2)  | 2.2(2)  |
| C\(_2\)AF   | 3.3(1)           | 2.6(1) | –      | –       | –       | –        | 2.6(1)           | 2.7(1) | 0.2(1) | –       | –       | –       | 2.1(1)           | 1.6(1) | –      | –       | –       | –       |
| CS\(_3\)    | 7.1(1)           | –      | –      | –       | –       | –        | 5.6(1)           | –      | –      | –       | –       | –       | 4.7(2)           | –      | –      | –       | –       | –       |
| Mullite      | –                | –      | –      | –       | –       | –        | 0.5(1)           | 0.5(1) | 1.0(1) | 1.0(1)  | 2.1(1)  | 2.1(1)  | 1.9(2)           | 2.1(2) | 2.4(2) | 2.1(1)  | 2.3(1)  | 1.6(1)  |
| Quartz       | –                | –      | 1.0(1) | 1.0(1)  | 1.4(1)  | 1.1(1)   | 0.4(1)           | 0.4(1) | 0.4(1) | 0.4(1)  | 0.4(1)  | 0.4(1)  | 0.6(1)           | 0.7(1) | 0.8(1) | 0.7(1)  | 0.7(1)  | 0.7(1)  |
| C–S–H\(^b\)| –                | –      | 2.4(1) | 3.0(1)  | 5.0(1)  | 5.3(1)   | –               | –      | 0.4(1) | 1.4(1)  | 7.0(3)  | 6.7(3)  | –               | –      | 1.0(1) | 2.1(1)  | 3.4(1)  |
| AFm          | –                | –      | 19.5(1)| 16.4(1) | 16.6(1) | 12.5(2)  | 12.7(3)          | –      | 17.5(1)| 15.3(1) | 15.0(1) | 15.4(2) | 15.2(2)          | 14.9(2)| 13.9(1)| 13.4(1) | 13.3(2) | 13.4(2) |
| AFt          | –                | –      | 4.0(2) | 7.1(2)  | 4.1(2)  | 3.2(2)   | –               | 2.8(2) | 4.0(2) | 4.8(2)  | 5.5(2)  | –       | –               | 2.6(2) | 2.2(3) | 3.1(3)  | 2.7(2)  |
| Katoite      | –                | –      | –      | –       | 3.3(2)  | 9.2(7)   | –               | 4.8(4) | 6.5(4) | 6.6(4)  | 7.3(2)  | –       | –               | 1.7(1) | 1.9(2) | 2.8(2)  | 2.8(2)  |
| Stratlingite | –                | –      | 5.4(3) | 6.3(3)  | 6.4(3)  | 9.2(7)   | –               | 4.8(4) | 6.5(4) | 6.6(4)  | 7.3(2)  | –       | –               | 1.7(1) | 1.9(2) | 2.8(2)  | 2.8(2)  |
| ACn          | 8.1              | 19.7   | 23.6   | 26.2    | 45.4    | 48.2     | 19.3             | 27.5   | 33.8   | 32.4    | 32.5    | 38.8    | 31.3             | 40.9   | 43.9   | 47.0    | 47.7    | 49.4    |
| FW           | 28.6             | 12.6   | 9.7    | 8.3     | 5.9     | 2.9      | 25.4             | 11.3   | 8.5    | 7.0     | 5.2     | 2.2     | 21.9             | 9.1    | 6.7    | 5.4     | 4.3     | 2.7     |

\(^a\)Also contains 0.1 and 0.3 wt% of CH at 90 and 180 days respectively

\(^b\)C–S–H as clinotobermorite
results of both pastes at 28 and 90 days. The main result obtained by this test is that the degree of reaction of belite in FA0BAY is almost the same, in spite of the w/c, and reached \*45% at 90 days. In addition, the belite hydration has been inhibited in FA30BAY at any w/c. Consequently, the hydration behavior of belite is not influenced by the w/c under these experimental conditions but it seems to be influenced by the addition of FA. Moreover, the w/c affects the phase assemblage, concretely, the katoite/stratlingite. Pastes prepared at w/c = 0.40 presented both phases, while samples at the w/c of 0.57 only contained stratlingite (see Tables 2, 3). This is in agreement with Jeong et al. [62], who found that stratlingite content increased in CSA cements by increasing the w/c.

27Al and 29Si MAS NMR spectra for FA#BAY pastes at 7, 90 and 180 hydration days are shown in Figure S4, deposited as electronic supplementary material. 27Al MAS NMR spectra (Figure S4, left site) shows AlVI octahedrally-coordinated of ettringite centered at \*13.5 ppm [63, 64]. The wide band may be considered as two resonances, the first one centered
at \( \approx 10.5 \) ppm assigned to the overlapping AFm-type phases including stratlingite and monosulfoaluminate [63, 65, 66] and the second one, of less intensity, centered at \( \approx 9.6 \) ppm which is likely due to the aluminium present in the aluminium hydroxide gel. These signals are common in all pastes at any age [54]. In Figure S4, right site, \(^{29}\)Si MAS NMR spectra of all samples showed, at around \(-72\) ppm, a signal corresponding to isolated SiO\(_4\) tetrahedra (Q\(_0\) sites) of non-hydrated belite [64, 67]. In addition, signals located around \(-79\) and \(-84\) ppm, assigned to Q\(_1\) and Q\(_2\) species, are typical of the end and middle chain of SiO\(_4\) tetrahedra in C–S–H gel, respectively [67, 68]; they appear after 90 days in FA0BAY and FA15BAY, although they are very weak in FA30BAY, corroborating the results obtained by LXRPD given in Table 2. To obtain deeper information from these data, the deconvolution of FA#BAY, at 180 hydration days, was carried out (Fig. 5). Here, FA0BAY and FA15BAY at 180 days showed the characteristic Q\(_1\) and Q\(_2\) signals of C–S–H, although they are slightly weaker in FA15BAY. The hydration of belite and the formation of C–S–H gel at later ages has been proven with these results. In addition, these signals were not detected in the FA30BAY sample, confirming that the belite hydration was inhibited. In all cements, the characteristic Q\(_2\) and Q\(_2(2\text{Al})\) signals of stratlingite were detected, corroborating the results obtained by LXRPD and TGA-DTG.

### Table 3: RQPA comparative results (wt%), obtained from LXRPD, of FA0BAY and FA30BAY cement pastes prepared (w/c = 0.57), as a function of the hydration time

| Phases         | FA0BAY* | FA30BAY |
|----------------|---------|---------|
|                | w/c 0.57 | w/c 0.57 |
|                | \( t_o \) | 28 days | 90 days | \( t_o \) | 28 days | 90 days |
| C\(_4\)A\(_3\)S | 4.5(1)   | –       | –       | 4.0(1)   | –       | –       |
| \( \gamma \)-C\(_2\)S | 1.1(1)   | 1.9(2)  | 1.4(2)  | 1.2(1)   | 1.1(1)  | 1.1(1)  |
| \( \beta \)-C\(_2\)S | 28.8(1)  | 28.4(2) | 16.5(2) | 18.1(2)  | 18.3(2) | 18.1(2) |
| C\(_3\)S        | 7.1(2)   | –       | –       | 5.5(2)   | –       | –       |
| C\(_{12}\)A\(_7\) | 3.8(1)   | –       | –       | 2.5(1)   | –       | –       |
| F-ellestadite   | 2.0(1)   | 2.5(2)  | 2.4(2)  | 2.9(1)   | 1.4(2)  | 1.5(2)  |
| C\(_4\)AF       | 2.9(1)   | –       | –       | 2.0(1)   | –       | –       |
| CS             | 6.3(1)   | –       | –       | 4.3(2)   | –       | –       |
| Mullite         | –        | –       | –       | 1.8(1)   | 2.5(1)  | 2.2(1)  |
| Quartz         | –        | –       | –       | 0.6(1)   | 0.7(1)  | 0.7(1)  |
| C–S–H\(^b\)    | –        | 1.4(1)  | 3.6(1)  | –        | 5.1(1)  | 3.0(1)  |
| AFm            | –        | 5.7(1)  | 5.6(1)  | –        | 3.4(1)  | 4.6(1)  |
| AFt            | –        | 24.0(2) | 12.7(3) | –        | 15.4(2) | 15.0(2) |
| Katoite        | –        | –       | –       | –        | –       | –       |
| Stratlingite   | –        | 7.5(3)  | 9.5(4)  | –        | 2.2(2)  | 2.0(2)  |
| ACn            | 7.2      | 12.0    | 22.4    | 28.7     | 36.5    | 40.6    |
| FW             | 36.3     | 16.6    | 15.1    | 28.5     | 13.6    | 11.2    |

\(^*\)Also contains 0.1 and 0.3 wt% of CH at 90 and 180 days respectively

\(^b\)C–S–H as clinotobermorite

by LXRPD. Moreover, other signals centered at \(-81\) and \(-86\) ppm, asterisk in Figure S4, which correspond to Q\(_2(1\text{Al})\) and Q\(_2\) of stratlingite [63, 66], are noticeable at 90 and 180 days in all the cements, although they are very weak in FA30BAY, corroborating the results obtained by LXRPD in Table 2. To obtain deeper information from these data, the deconvolution of FA#BAY, at 180 hydration days, was carried out (Fig. 5). Here, FA0BAY and FA15BAY at 180 days showed the characteristic Q\(_1\) and Q\(_2\) signals of C–S–H, although they are slightly weaker in FA15BAY. The hydration of belite and the formation of C–S–H gel at later ages has been proven with these results. In addition, these signals were not detected in the FA30BAY sample, confirming that the belite hydration was inhibited. In all cements, the characteristic Q\(_2\) and Q\(_2(2\text{Al})\) signals of stratlingite were detected, corroborating the results obtained by LXRPD and TGA-DTG.
3.4 Compressive strength of FA#BAY mortars

Figure 6 represents the compressive strength values of FA#BAY mortars, which increase by increasing both the curing age and the FA content. Table 4 displays the percentages of increase of strength of blended mortars referred to FA0BAY at the same ages. The compressive strength, at 1 day, increased by 15% and 43% for FA15BAY and FA30BAY, respectively, referred to FA0BAY mortar at the same age. This increase in mechanical strengths might have several explanations: (1) decrease in porosity; (2) pozzolanic reaction; (3) filler effect. However, the observation of the increase in compressive strengths after 28 days, where there is not a significant belite reaction, could be an indirect evidence of some degree of pozzolanic reaction. Changes in crystalline phase assemblage with time and amount of FA are not high enough to justify this increase in compressive strengths. Consequently, the pore structure of the pastes was studied. The inset of Fig. 6 shows the pore size distribution of FA#BAY pastes at 180 hydration days, where the pore size diameter decreases by increasing the FA content. In addition, the open porosity of pastes also decreased by increasing the FA content (16, 13 and 9 vol% for FA0BAY, FA15BAY and FA30BAY, respectively). Thus, the higher compressive strength values can be justified by the lower porosity measured in pastes where higher FA contents are added, mainly due to the filler effect, in agreement with García-Mate et al. [35].

4 Conclusions

The addition of a small amount of superplasticizer, 0.5 wt% (of active matter referred to solids), made possible the preparation of homogeneous pastes with low viscosity values (viz. 0.31, 0.42 and 0.71 Pa.s at 100 s\(^{-1}\) for pastes with 0, 15 and 30 wt% of fly ash). The isothermal calorimetric study reveals that the superplasticizer affects the hydration behavior of calcium aluminate phases in BAY, at early ages, where less heat flow was released. The evolution of all pastes with time was studied through Rietveld quantitative phase analysis, thermal analysis and \(^{27}\)Al and \(^{29}\)Si MAS NMR. The presence of fly ash slightly affected the hydration mechanism or kinetics of BAY cement pastes. FA0BAY had slightly different chemical hydration behavior than that of FA15BAY and FA30BAY. In all systems, the main hydration products were AFt, AFm-phases (monosulfoaluminate and stratlingite), katoite and C–S–H. In silicon and aluminum rich-systems, stratlingite and katoite can coexist with C–S–H. In FA0BAY, AFt was unstable from 28 days of hydration. Concerning belite hydration, high additions of fly ash inhibited the
reactivity of belite. In these experimental conditions, we only have found indirect evidence of pozzolanic chemical reaction with FA. The increase of water content of these types of systems (w/c from 0.40 to 0.57) affected the katoite/stratlingite, i.e. higher w/c yielded to higher contents of stratlingite and lower amounts of katoite.

Finally, the compressive strengths of these blended mortars increased with the fly ash addition, mainly due to the decrease in porosity (and pore size) of the corresponding mortars.

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Fig. 6 Compressive strength values of FA#BAY mortars. Inset: Pore size distribution of FA#BAY pastes at 180 hydration days

Table 4 Increase of the strength (in percentage) referred to FA0BAY at the same ages

| Mortar  | Curing age, days |
|---------|-----------------|
|         | 1 | 7 | 28 | 90 | 180 |
| FA15BAY | 15 | 21 | 5 | 19 | 6 |
| FA30BAY | 43 | 42 | 24 | 24 | 19 |

Raw data sharing All powder diffraction raw data files underlying this work can be accessed on Zenodo at https://doi.org/10.5281/zenodo.1297485, and used under the Creative Commons Attribution license.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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