Alite hydration mechanism in presence of ye'elimite related to BAY cements

Diana Londono-Zuluaga[1,2,3,a], Jorge Ivan Tobon[2,b], Miguel Angel G. Aranda[1,4,c], Isabel Santacruz[1,d], Angeles G. De la Torre [1,e]

[1]*Department of Inorganic Chemistry, University of Malaga, Malaga, Spain*
[2]*Cement and Building Materials Group, National University of Colombia, Medellin, Colombia*
[3]*Laboratory of Construction Material, Ecole Polytechnique Federal de Lausanne, Lausanne, Switzerland*
[4]*ALBA Synchroton, Barcelona, Spain*

[a]dlondonoz@uma.es
[b]jitobon@uma.es
[c]g_aranda@uma.es
[d]isantacruz@uma.es
[e]mgd@uma.es

ABSTRACT

One alternative to decrease CO_2 emissions from ordinary Portland Cement (OPC) production consists on the development of a new kind of eco-cements composed by less calcite demanding phases. That is the case of Belite-Ye'elimite-Ferrite (BYF) cements, which have β-belite as a main phase and ye'elimite as a secondary phase. But the low reactivity of β-belite is well known, consequently these materials develop low mechanical strengths at early/intermediate hydration ages. A possible solution proposed to solve this problem consists on the production of cements which contain belite, alite and ye'elimite together, known as Belite-Alite-Ye'elimite (BAY) cements. Consequently, the reaction of alite and ye'elimite with water would develop cements with higher mechanical strengths at early ages, while β-belite will contribute to later ages.

The main objective of this work is to better understand the hydration behavior of monoclinic alite in presence of ye'elimite (both stoichiometric and pseudo-cubic polymorphs), in order to be compared with a BAY eco-cement systems. The hydration of systems with selected alite/ye'elimite ratios were studied for the first 24 hours. The main techniques used for this study were in-situ synchrotron X-ray powder diffraction combined with Rietveld methodology and isothermal calorimetry.

1. INTRODUCTION

Calcium sulfoaluminate (CSA) cements are more environmentally friendly materials than Portland cement (PC) and are characterized by low CO_2 emissions, low alkalinity, good early strength, good dimensional stability, and good durability. In the past few decades, many types of CSA cements have been developed for a wide range of applications (Bullerjahn, Boehm-Courjault, Zajac, Ben Haha, & Scrivener, 2019; Chen & Juenger, 2011; Gartner, 2004; Gartner & Sui, 2017; Péra & Ambroise, 2004; Winnefeld & Barlag, 2010). Moreover some fundamental studies for calcium sulfoaluminate phase ($C_4A_3\$$ or ye'elimite), which is the dominant mineral in CSA cement clinker, have been reported (Cuesta, Álvarez-Pinazo, et al., 2014; Hargis, Telesca, & Monteiro, 2014; Jansen, Spies, Neubauer, Ectors, & Goetz-Neunhoeffer, 2017; Khessaimi et al., 2018; Puertas, Blanco-Varela, & Giménez-Molina, 1995; Zhao & Chang, 2017). However, its production is considered expensive due to the need of high purity bauxite as a rich-source of Al_2O_3 (Angeles G. De la Torre et al., 2018; June et al., 2010; Ludwig & Zhang, 2015; Scrivener, John, & Gartner, 2018).

In recent studies, Belite-Ye'elimite-Ferrite (BYF) cements, have been thought as the potential substitute of PC at large scales (Cuberos et al., 2010; Koga, Albert, Roche, & Pereira Nogueira, 2018; X. Lu et al., 2018; Senff, Castela, Hajjaji, Hotza, & Labrincha, 2011). Nevertheless, the mechanical strength of mortar shows a slow increase owing to the low reactivity of C_2S at medium hydration ages (between 7 d and 28 d). On the other hand, C_3S is responsible for early and medium mechanical strengths in Portland cements. Hence, a possible approach is to bring in C_3S minerals in the production of the CSA clinker. Recently, extensive researches on the formation and coexistence of $C_4A_3\$$ and C_3S minerals with doping minor elements has been carried out, which could lower the viscosity and the formation temperature of liquid phase, and promote the formation of C_3S (Chitvoranund, Lothenbach, Winnefeld, & Hargis, 2017; Duvallet, Zhou, Robl, & Andrews, 2014; Hu et al., 2018; Li, Xu, Wang, Tang, & Shen, 2014; Liu, Li, Qi, Liu, & Li, 2009; Londono-Zuluaga, Tobon, Aranda, Santacruz, & De la Torre, 2017; L. Lu, Chang, Cheng, Liu, & Yuan, 2005; Pérez-Bravo et al., 2014). However, its hydration mechanism and mineralogy are strictly dependent on C_3S and $C_4A_3\$$ ratio. Thus, the main objective of this study is focused on the interactions that occur between C_3S and different polymorph of $C_4A_3\$$ during early hydration.

2. MATERIALS AND METHODS

2.1 Materials

Alite was supplied by Sarl Mineral Research Processing (France). $C_4A_3\$$ samples were synthesized following the methodology reported by Cuesta et al (Cuesta et al., 2013; Cuesta, De la Torre, Losilla, Santacruz, & Aranda, 2014). The orthorhombic phase, $oC_4A_3\$$ was obtained by heating a stoichiometric blend of finely-ground reagent grade of Al_2O_3 (99.997%, AlfaAesar), $CaCO_3$ (99.95%, AlfaAesar) and Gypsum (98%, Sigma-Aldrich) in an electric furnace at 1300 °C for 4 h. While the pseudo-cubic phase, $cC_4A_3\$$, was synthesized by heating the same reagent grade blend with additional Fe_2O_3 (99.945%, AlfaAesar), SiO_2 (99.5%, AlfaAesar) and Na_2CO_3 (99.999%, Sigma-Aldrich) at 1250 °C for 4h. After cooling, both samples were ground in a microdeval ball mill to pass a 75 µm (#200) mesh sieve. Finally, anhydrite (C$) was previously prepared following the methodology reported by Londono-Zuluaga et al (Londono-Zuluaga et al., 2017) by heating a commercial micronized gypsum ($C\$H_2$), marketed by BELITH S.P.R.L. (Belgium), at 700 °C for 60 min. Their particle size distribution were measured in an isopropyl alcohol suspension using a MALVERN MASTERSIZER S Laser Diffraction Particle Size Distribution Analyzer. The $D_{v,50}$ were 13.8, 9.0, 5.6, and 8.9 µm for C_3S, $oC_4A_3\$$, $cC_4A_3\$$ and C$ respectively, as can be seen in Figure 1.
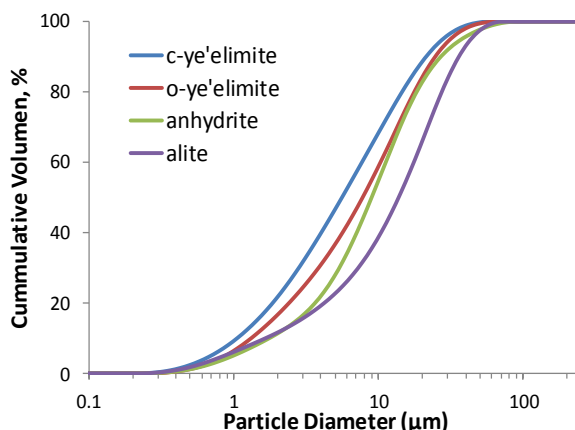
Figure 1. Particle size distribution of $cC_4A_3\$$, $oC_4A_3\$$, $C\$$ and C_3S.

The mix designs of the investigated systems are given in Table 1, including water/binder (w/b) ratio. Freshly twice-boiled deionized water was mixed with all blended samples at room temperature for 2 min to make the pastes used for Synchrotron X-ray Powder Diffraction (SXRPD) and Isothermal Calorimetry (IC) *in-situ* studies.

Table 1. Paste compositions, in weight percentages (wt%).

Mixture nomenclature	$oC_4A_3\$$	$cC_4A_3\$$	C_3S	$C\$$	w/s
o2.74_0.59*	23.9	-	65.4	10.7	0.59
o2.74_1.19	23.9	-	65.4	10.7	1.19
c2.74_0.59	-	23.9	65.4	10.7	0.59
c2.74_1.19	-	23.9	65.4	10.7	1.19

* The nomenclature of the mixtures is referred to $C_3S/C_4A_3\$=2.74$ and the second number is the w/s ratio.
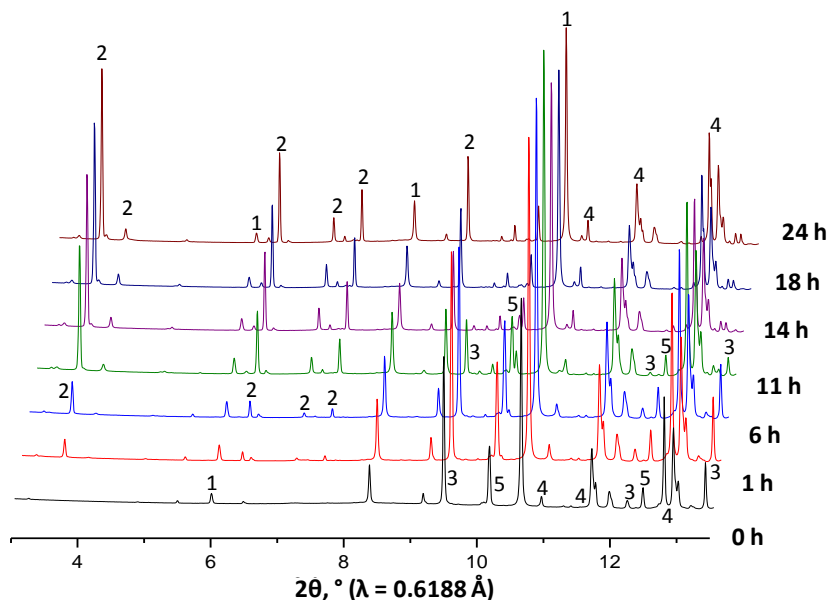
2.2 Methods

In-situ SXRPD investigations on the pastes were carried out at the Materials Science and Powder Diffraction (MSPD) beamline in the Spanish Synchrotron Light Source - ALBA at Barcelona (Spain). All patterns were collected in Debye-Scherrer (transmission) mode, utilizing a wavelength of 0.61878(3) Å selected with a doble-crystal Si(111) monochromator. The diffractometer is equipped with a MYTHEN detector especially suited for time-resolved experiments. Previously, all the anhydrous mixtures were mixed with ~20 wt% SiO_2 (99.5%, AlfaAesar) as an internal standard, and powder diffraction data were collected to obtain the initial phase assemblage (t_0), including amorphous and non-crystalline (ACn) content (A.G. De la Torre, Bruque, & Aranda, 2001). Pastes were ex-situ prepared (mixing with fresh twice-boiled water by hand for 2 min) and immediately poured into glass capillaries of 0.7 mm of diameter with a syringe. Afterward, they were sealed with grease to avoid any water loss. The capillaries were rotated during data collection to improve diffracting particle statistics. The data acquisition time was ~6 min per pattern to attain very good signal-to-noise ratio over the angular range 2–40° (2θ), with the aim to follow the hydration products formation.
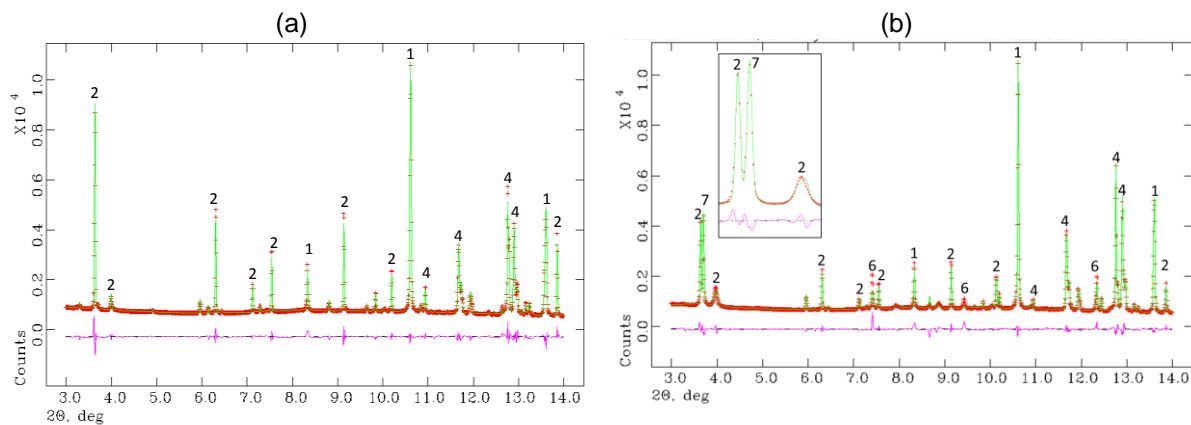
For *in-situ* IC, two grams of mixture with its corresponding mix water/solid ratio (Table 1) were prepared by internal mixing for 2 min using an Admix automatic device. The pastes were tested for heat evolution using a Thermometric TAM Air® 8 (TA Instruments) during 72 hours at 25 °C. The heat flow of three separate runs for each paste was recorded following ASTM C1679 – 13 methodology. No significant differences were observed between the three runs and the arithmetic mean was used.

3.   RESULTS AND DISCUSSION

The hydration mechanism of mixtures of pure phases was studied during the first 24 hours. The effect of w/s ratio and ye'elimite polymorphism jointly with anhydrite on the alite hydration were studied. Figure 2 depicts the raw SXRPD patterns at different times of hydration of c2.74_1.19 mixtures. Figure 3 shows Rietveld plots of c1.37_1.32 and o1.37_1.32 mixtures after 24 hours of hydration, as representative examples.

Figure 2. In-situ SXRPD hydration evolution of c2.74_1.19. 1 (Quartz as internal standard), 2 (ettringite), 3 (pseudocubic ye'elimite), 4 (alite) and 5 (anhydrite).

Figure 3. Rietveld plots of (a) c2.74_1.19 and (b) o2.74_1.19 at 24 hours of hydration. 1 (Quartz as internal standard), 2 (ettringite), 4 (alite), 6 (stratlingite) and 7 (monosulfoaluminate).

Table 2, Table 3, Table 4 and Table 5 give RQPA including the ACn and free water (FW) contents determined by internal standard methodology. Figure 4 provides the full phase content evolution and heat flow curves of c2.74 and o2.74 at different w/b ratios. From all these Figures and Tables, two phenomena can be clearly described. On the one hand, the orthorhombic ye'elimite mixture has totally reacted at 5 hours of hydration independently of w/b ratio. While in pastes prepared with the pseudo-cubic ye'elimite has only partially reacted during the same time. This is in agreement with Cuesta et al (Cuesta, Álvarez-Pinazo, et al., 2014) and Jansen et al (Jansen et al., 2017) where orthorhombic ye'elimite with gypsum or anhydrite reacted at a higher speed than cubic one. On the other hand, alite did not start to react until ye'elimite was completely consumed, independently of the polymorphism. The main crystalline hydration products of these systems were AFt, monosulfoaluminate and stratlingite.

Moreover, the phase assemblage was not strongly affected by water-to-solid ratio or polymorphism of ye'elimite.

Table 2. RQPA results (wt%) of the in-situ hydration study of c2.74_0.59.

Phases / Age (h)	$C_4A_3\$$	C$	AFt	C_2ASH_8	C_3S	ACn+FW
0	15.8	6.8	-	-	38.1	39.3
1	13.9	6.3	2.2	-	38.1	39.5
2	13.3	6.2	2.7	-	38.1	39.6
3	12.4	6.2	3.4	-	38.1	39.9
4	11.1	6.0	4.5	-	38.0	40.3
6	8.4	5.4	7.8	0.4	38.0	40.1
8	4.2	3.9	14.1	0.4	38.0	39.3
10	1.7	2.4	18.4	0.5	38.0	39.1
14	1.0	2.0	20.6	0.6	37.7	38.1
18	0.1	1.0	24.1	0.7	35.8	38.3
24	-	0.2	26.8	1.1	33.6	38.3
47	-	-	27.8	1.8	31.3	38.9

Table 3. RQPA results (wt%) of the in-situ hydration study of c2.74_1.19.

Phases / Age (h)	$C_4A_3\$$	C$	AFt	AFm	C_2ASH_8	C_3S	ACn+FW
0	11.4	5.0	-	-	-	27.6	55.9
1	10.2	4.6	1.7	-	-	27.6	55.9
2	9.5	4.5	2.1	-	-	27.6	56.2
3	9.1	4.5	2.4	-	-	27.6	56.4
4	8.9	4.5	2.7	-	-	27.6	56.3
6	8.4	4.5	2.9	-	-	27.6	56.6
8	7.3	4.3	4.1	-	-	27.6	56.8
10	3.5	2.9	9.6	-	-	27.6	56.4
14	0.3	0.9	15.9	0.2	0.2	27.1	55.3
18	-	0.3	18.7	0.3	0.2	26.7	53.8
24	-	0.2	19.7	0.3	0.3	24.5	54.9
47	-	-	19.2	0.3	5.2	21.9	52.9

Table 4. RQPA results (wt%) of the in-situ hydration study of o2.74_0.59.

Phases Age (h)	$C_4A_3\$$	C$	AFt	AFm	C_2ASH_8	C_3S	ACn+FW
0	13.3	6.6	-	-	-	37.6	42.5
1	13.0	6.5	2.5	-	-	37.6	40.5
2	12.4	6.5	3.1	-	-	37.6	40.4
3	12.2	6.4	3.2	-	-	37.5	40.6
4	12.1	6.4	3.4	-	-	37.5	40.7
7	1.2	4.9	10.6	5.5	-	36.7	41.0
10	0.9	3.3	10.6	6.0	5.6	33.8	40.5
12	-	3.2	10.7	6.7	5.8	33.8	40.2
16	-	3.1	10.8	7.4	6.1	33.0	39.6
24	-	2.5	10.9	8.3	6.5	32.6	39.2
47	-	1.0	13.1	10.8	7.4	27.1	40.6

Table 5. RQPA results (wt%) of the in-situ hydration study of o2.74_1.19.

| Phases Age (h)	$C_4A_3\$$	C$	AFt	AFm	C_2ASH_8	C_3S	ACn+FW
0	9.7	4.8	-	-	-	27.3	58.2
1.5	8.9	4.6	0.9	-	-	27.3	58.2
3	8.7	4.6	1.1	-	-	27.3	58.3
4	6.6	4.4	1.9	1.6	-	27.3	58.2
5	1.4	3.6	5.4	4.0	-	27.3	58.3
7	-	2.8	6.8	5.2	3.4	26.0	55.8
10	-	2.8	6.8	5.2	4.1	25.1	55.9
12	-	2.8	7.0	5.4	4.6	25.1	55.1
16	-	2.3	8.4	6.0	4.8	25.1	53.3
24	-	2.0	8.8	6.5	5.1	24.3	52.3
47	-	0.6	11.7	8.7	8.0	17.2	53.8

Figure 4. Heat flow and mineralogical in-situ hydration evolution of (a and c) c2.74 and (b and d) o2.74. In each plot, the left-hand vertical axis shows the rate of heat release, and the right-hand vertical axis shows the weight percent amount of the phases. Black line: Heat flow, blue diamond: $C_4A_3\$$, yellow triangle: $C\$$, red square: C_3S, purple asterisk: ettringite, light blue circle: monosulfoaluminate and green cruise: C_2ASH_8.

The isothermal calorimetric curves, Figure 4 (black line), present a strong peak within the first 25 minutes (0.4 hours) since mixing, known as the induction period. This peak is clearly associated with the dissolution (heat of wetting of the cement), and hydration of ye'elimite to form ettringite (purple asterisk) (Cuesta, Álvarez-Pinazo, et al., 2014; Jansen et al., 2017). The hydration of orthorhombic and pseudo-cubic ye'elimite was published elsewhere (Cuesta, Álvarez-Pinazo, et al., 2014) and the total heat evolved after 7 days was ~570 and ~550 J/g, respectively. The higher amount of heat released by the samples with the orthorhombic polymorph at 25 minutes corroborates the quicker reactivity of that phase when compared with the samples pseudo-cubic polymorph in spite of the amount of water. At 15 h, when both ye'elimites have completely reacted, the total heat released for c2.74 and o2.74 were ~70 and ~200 J/g respectively, Figure 5. While independently of the w/b used, the cumulative heat displayed after 48 hours, were about ~200 and ~230 J/g by c2.74 and o2.74 respectively.

During the induction peak a small amount of AFt crystallized without the dissolution of anhydrite, as previously reported (Cuesta, Álvarez-Pinazo, et al., 2014; Jansen et al., 2017; Pelletier-Chaignat et al., 2011). Monosulfoaluminate was not detected in the pseudo-cubic ye'elimite mixtures. However, in o2.74 mixtures, the precipitation of AFt increased considerably jointly with monosulfoaluminate co-precipitation, Figure 4 (Table 2, Table 3, Table 4 and Table 5).The raise of water/binder ratio from 0.59 to 1.19 did not affected the mixtures with orthorhombic ye'elimite. However, in the mixture with the pseudo-cubic form, both alite dissolution and precipitation of stratlingite are enhanced, were larger amounts of stratlingite were precipitated. This may be justified by the availability of water.

It is noticeable that crystalline portlandite and gibbsite were not detected in the first 48 h of hydration in any system (c2.74 and o2.74). The lack of precipitation of CH was expected and it is associated to the enhanced hydration of $C_4A_3\$$ that favors the early-ettringite formation (Hargis, Kirchheim, Monteiro, & Gartner, 2013; Péra & Ambroise, 2004; Winnefeld & Barlag, 2009). Moreover, the lack of crystalline AH₃

is associated with the formation of stratlingite (1) (Trauchessec, Mechling, Lecomte, Roux, & Le Rolland, 2015; Winnefeld & Lothenbach, 2016).

$$C_3S + AH_3 + 6H \longrightarrow C_2ASH_8 + CH \qquad (1)$$
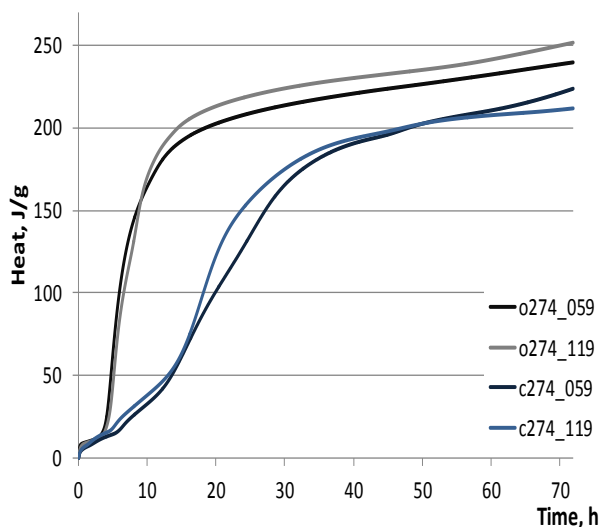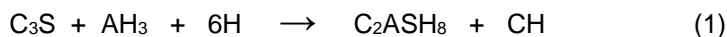
Figure 5. Total heat (cumulative) release curves of c2.74 and o2.74.

The pseudo-cubic ye'elimite mixtures produced higher amounts of ettringite than orthorhombic ye'elimite samples, under similar hydrating conditions. This is due to orthorhombic ye'elimite presents a higher kinetic of hydration than pseudo-cubic ye'elimite, consequently when orthorhombic ye'elimite reacts with the anhydrite, which is slowly dissolved, favors the jointly formation of AFt and monosulfoaluminate.

4. CONCLUSIONS

C_3S hydration was influenced by the kinetic of ye'elimite dissolution and reaction, and it began to react after ye'elimite reacted completely. In mixtures with orthorhombic and pseudo-cubic ye'elimite, alite depletion started after 10 and 20 hours respectively, since orthorhombic ye'elimite reacts faster than the pseudo-cubic polymorph. The main products from alite reaction were stratlingite and C-S-H gel. The formation of calcium hydroxide (as portlandite or amorphous) was not detected, as expected. The increase of w/s ratio also affected the kinetic of hydration of alite. The mixtures with orthorhombic ye'elimite and higher w/s ratio presented, after 48 hours, a higher hydration degree. Consequently, higher amounts of C-S-H (as amorphous phase) and stratlingite were obtained. The mixtures with pseudo-cubic ye'elimite, even after 48 hours of hydration, presented high amounts of non-reacted C_3S. Moreover, the main hydration product from the reaction of alite is stratlingite, while in the orthorhombic ye'elimite mixtures, the main phase is also amorphous C-S-H gel.

5. REFERENCES

Bullerjahn, F., Boehm-Courjault, E., Zajac, M., Ben Haha, M., & Scrivener, K. (2019). Hydration reactions and stages of clinker composed mainly of stoichiometric ye'elimite. *Cement and Concrete Research*, *116*, 120–133. https://doi.org/10.1016/J.CEMCONRES.2018.10.023

Chen, I. A., & Juenger, M. C. G. (2011). Synthesis and hydration of calcium sulfoaluminate-belite cements with varied phase compositions. *Journal of Materials Science*, *46*(8), 2568–2577. https://doi.org/10.1007/s10853-010-5109-9

Chitvoranund, N., Lothenbach, B., Winnefeld, F., & Hargis, C. W. (2017). Synthesis and hydration of alite-calcium sulfoaluminate cement. *Advances in Cement Research*, *29*, 101–111. Retrieved from http://dx.doi.org/10.1680/jadcr.16.00071

Cuberos, A. J. M., De la Torre, A. G., Alvarez-Pinazo, G., Martín-Sedeño, M. C., Schollbach, K., Pöllmann, H., & Aranda, M. A. G. (2010). Active iron-rich belite sulfoaluminate cements: clinkering and hydration. *Environmental Science Technology*, *44*(17), 6855–6862. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20701316

Cuesta, A., Álvarez-Pinazo, G., Sanfélix, S. G., Peral, I., Aranda, M. A. G., & De la Torre, A. G. (2014). Hydration mechanisms of two polymorphs of synthetic ye'elimite. *Cement and Concrete Research*, *63*, 127–136. https://doi.org/10.1016/j.cemconres.2014.05.010

Cuesta, A., De la Torre, A. G., Losilla, E. R., Peterson, V. K., Rejmak, P., Ayuela, A., … Aranda, M. A. G. (2013). Structure, atomistic simulations, and phase transition of stoichiometric yeelimite. *Chemistry of Materials*, *25*(9), 1680–1687. https://doi.org/10.1021/cm400129z

Cuesta, A., De la Torre, A. G., Losilla, E. R., Santacruz, I., & Aranda, M. A. G. (2014). Pseudocubic crystal structure and phase transition in doped ye'elimite. *Crystal Growth and Design*, *14*(10), 5158–5163. https://doi.org/10.1021/cg501290q

De la Torre, A. G., Bruque, S., & Aranda, M. A. G. (2001). Rietveld quantitative amorphous content analysis. *Journal of Applied Crystallography*, *34*(2), 196–202. https://doi.org/10.1107/S0021889801002485

De la Torre, A. G., Londono-Zuluaga, D., Zea-Garcia, J. D., García-Maté, M., Álvarez-Pinazo, G., Aranda, M. A. G., … Tobon, J. I. (2018). X-ray diffraction , cements and environment , three worlds in one . *MATEC Web of Conferences*, *149*(CMSS-2017), 01003. https://doi.org/https://doi.org/10.1051/matecconf/201814901003

Duvallet, T., Zhou, Y., Robl, T. L., & Andrews, R. (2014). Synthesis and Characterization of High-Iron Alite-Calcium Sulfoaluminate-Ferrite Cements Produced from Industrial By-Products. *Coal Combustion and Gasification Products*, *6*(1), 29–34. https://doi.org/10.4177/CCGP-D-14-00007.1

Gartner, E. (2004). Industrially interesting approaches to "low-CO2" cements. *Cement and Concrete Research*, *34*(9), 1489–1498. https://doi.org/10.1016/j.cemconres.2004.01.021

Gartner, E., & Sui, T. (2017). Alternative cement clinkers. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2017.02.002

Hargis, C. W., Kirchheim, A. P., Monteiro, P. J. M., & Gartner, E. (2013). Early age hydration of calcium sulfoaluminate (synthetic ye'elimite, C4A3s) in the presence of gypsum and varying amounts of calcium hydroxide. *Cement and Concrete Research*, *48*, 105–115. https://doi.org/10.1016/j.cemconres.2013.03.001

Hargis, C. W., Telesca, A., & Monteiro, P. J. M. (2014). Calcium sulfoaluminate (Ye'elimite) hydration in the presence of gypsum, calcite, and vaterite. *Cement and Concrete Research*, *65*, 15–20. https://doi.org/10.1016/j.cemconres.2014.07.004

Hu, Y., Li, W., Ma, S., Wang, Q., Zou, H., & Shen, X. (2018). The composition and performance of alite-ye'elimite clinker produced at 1300 °C. *Cement and Concrete Research*, *107*(5), 41–48. https://doi.org/10.1016/j.cemconres.2018.02.009

Jansen, D., Spies, A., Neubauer, J., Ectors, D., & Goetz-Neunhoeffer, F. (2017). Studies on the early hydration of two modifications of ye'elimite with gypsum. *Cement and Concrete Research*, *91*, 106–116. https://doi.org/10.1016/j.cemconres.2016.11.009

June, J., Politecnica, U., Marroccoli, M., Pace, M. L., Telesca, A., & Valenti, G. L. (2010). Synthesis of Calcium Sulfoaluminate Cements From Al2O3 -Rich By-products from Aluminium Manufacture. In *Second International Conference on Sustainable Construction Materials and Technologies*.

Khessaimi, Y. E., Hafiane, Y. E., Smith, A., Trauchessec, R., Diliberto, C., & Lecomte, A. (2018). Solid-state synthesis of pure Ye'elimite. *Journal of the European Ceramic Society*, *38*, 3401–3411. https://doi.org/10.1016/j.jeurceramsoc.2018.03.018

Koga, G. Y., Albert, B., Roche, V., & Pereira Nogueira, R. (2018). On the intrinsic passivating ability of Belite-Ye'elimite-Ferrite towards carbon steel: A straightforward comparison with ordinary Portland cement. *Corrosion Science*. https://doi.org/10.1016/J.CORSCI.2018.11.012

Li, X., Xu, W., Wang, S., Tang, M., & Shen, X. (2014). Effect of SO3 and MgO on Portland cement clinker: Formation of clinker phases and alite polymorphism. *Construction and Building Materials*, *58*, 182–192. https://doi.org/10.1016/j.conbuildmat.2014.02.029

Liu, X. C., Li, B. L., Qi, T., Liu, X. L., & Li, Y. J. (2009). Effect of TiO2 on mineral formation and properties of alite-sulphoaluminate cement. *Materials Research Innovations*, *13*(2), 92–97. https://doi.org/10.1179/143307509X435178

Londono-Zuluaga, D., Tobon, J. I., Aranda, M. A. G., Santacruz, I., & De la Torre, A. G. (2017). Clinkering and hydration of Belite-Alite-Ye´elimite cement. *Cement and Concrete Composites*, *80*, 333–341. https://doi.org/10.1016/j.cemconcomp.2017.04.002

Lu, L., Chang, J., Cheng, X., Liu, H., & Yuan, R. (2005). Study on a cementing system taking alite-calcium barium sulphoaluminate as main minerals. *Journal of Materials Science*, *40*(15), 4035–4038. https://doi.org/10.1007/s10853-005-2005-9

Lu, X., Zhengmao, Y., Wang, S., Du, P., Li, C., & Xin, C. (2018). Study on the preparation and properties of belite-ye'elimite-alite cement. *Construction & Building Materials*, *182*, 399–405. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2018.06.143

Ludwig, H.-M. M., & Zhang, W. (2015). Research review of cement clinker chemistry. *Cement and Concrete Research*, *78*, 24–37. https://doi.org/10.1016/j.cemconres.2015.05.018

Pelletier-Chaignat, L., Winnefeld, F., Lothenbach, B., Saout, G. Le, Müller, C. J., & Famy, C. (2011). Influence of the calcium sulphate source on the hydration mechanism of Portland cement-calcium sulphoaluminate clinker-calcium sulphate binders. *Cement and Concrete Composites*, *33*(5), 551–561. https://doi.org/10.1016/j.cemconcomp.2011.03.005

Péra, J., & Ambroise, J. (2004). New applications of calcium sulfoaluminate cement. *Cement and Concrete Research*, *34*(4), 671–676. https://doi.org/10.1016/j.cemconres.2003.10.019

Pérez-Bravo, R., Álvarez-Pinazo, G., Compana, J. M., Santacruz, I., Losilla, E. R., Bruque, S., & De la Torre, A. G. (2014). Alite sulfoaluminate clinker: Rietveld mineralogical and SEM-EDX analysis. *Advances in Cement Research*, *26*(1), 10–20. https://doi.org/10.1680/adcr.12.00044

Puertas, F., Blanco-Varela, M. T., & Giménez-Molina, S. (1995). Kinetics of the Thermal decomposition of C4A3s in air. *Cement and Concrete Research*, *25*(3), 572–580.

Scrivener, K. L., John, V. M., & Gartner, E. (2018). Eco-efficient cements: Potential, economically viable solutions for a los-CO2, cement-based materials industry. *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2018.03.015

Senff, L., Castela, A., Hajjaji, W., Hotza, D., & Labrincha, J. A. (2011). Formulations of sulfobelite cement through design of experiments. *Construction and Building Materials*, *25*(8), 3410–3416. https://doi.org/10.1016/j.conbuildmat.2011.03.032

Trauchessec, R., Mechling, J. M., Lecomte, A., Roux, A., & Le Rolland, B. (2015). Hydration of ordinary Portland cement and calcium sulfoaluminate cement blends. *Cement and Concrete Composites*, *56*, 106–114. https://doi.org/10.1016/j.cemconcomp.2014.11.005

Winnefeld, F., & Barlag, S. (2009). Influence of calcium sulfate and calcium hydroxide on the hydration of calcium sulfoaluminate clinker. *ZKG International*, (12), 42–53.

Winnefeld, F., & Barlag, S. (2010). Calorimetric and thermogravimetric study on the influence of calcium sulfate on the hydration of ye'elimite. *Journal of Thermal Analysis and Calorimetry*, *101*, 949–957. https://doi.org/10.1007/s10973-009-0582-6

Winnefeld, F., & Lothenbach, B. (2016). Phase equilibria in the system Ca4Al6O12SO4 – Ca2SiO4 – CaSO4 – H2O referring to the hydration of calcium sulfoaluminate cements. *RILEM Technical Letters*, *1*, 10–16.

Zhao, J., & Chang, J. (2017). Crystallographic Analysis of Sr-Bearing Ye'elimite. *Journal of Inorganic and Organometallic Polymers and Materials*, *27*(6), 1–9. https://doi.org/10.1007/s10904-017-0631-8