Cementos belíticos y sulfobelíticos

* a way for reducing CO$_2$ emissions

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Monday, 13 September 2010
Outline

1. Introduction to cement industry environmental problem

2. Searching for sustainable materials and processes

3. Methodology (mainly at Universidad de Málaga)

4. Laboratory active belite cements

5. Laboratory active belite sulfoaluminate cements

6. Conclusions
Industrial production of Ordinary Portland Cement

**Dry process**

**Quarry**

**Raw materials:**
- Limestone (Ca)
- Clays (Al, Si)
- Feldspars
- Fe₂O₃ (iron ore / rust)

**1450°C**

**Rawmix mill**

**Kiln**

**Gypsum and additions**

**Cement mill(s)**
<table>
<thead>
<tr>
<th>Clinker</th>
<th>CCN</th>
<th>Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate (CaO)₃ · SiO₂</td>
<td>C₃S</td>
<td>45-75%</td>
</tr>
<tr>
<td>Dicalcium silicate (CaO)₂ · SiO₂</td>
<td>C₂S</td>
<td>7-32%</td>
</tr>
<tr>
<td>Tricalcium aluminate (CaO)₃ · Al₂O₃</td>
<td>C₃A</td>
<td>0-13%</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite (CaO)₄ · Al₂O₃ · Fe₂O₃</td>
<td>C₄AF</td>
<td>0-18%</td>
</tr>
<tr>
<td>Gypsum CaSO₄ · 2 H₂O</td>
<td></td>
<td>2-10%</td>
</tr>
</tbody>
</table>

**Typical constituents of Portland cement**

Cement chemists notation under CCN.

<table>
<thead>
<tr>
<th>Cement</th>
<th>CCN</th>
<th>Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium oxide, CaO</td>
<td>C</td>
<td>61-67%</td>
</tr>
<tr>
<td>Silicon oxide, SiO₂</td>
<td>S</td>
<td>19-23%</td>
</tr>
<tr>
<td>Aluminum oxide, Al₂O₃</td>
<td>A</td>
<td>2.5-6%</td>
</tr>
<tr>
<td>Ferric oxide, Fe₂O₃</td>
<td>F</td>
<td>0-6%</td>
</tr>
<tr>
<td>Sulfate</td>
<td>S</td>
<td>1.5-4.5%</td>
</tr>
</tbody>
</table>
### Table 1  Typical engineering properties of OPC-based structural concrete$^{157}$

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>35 MPa</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>6 MPa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>3 MPa</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>28 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.18</td>
</tr>
<tr>
<td>Tensile strain at failure</td>
<td>0.001</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>$10 \times 10^{-6} \degree \text{C}^{-1}$</td>
</tr>
<tr>
<td>Ultimate shrinkage strain</td>
<td>0.5–0.1%</td>
</tr>
<tr>
<td>Density—normal</td>
<td>2300 kg m$^{-3}$</td>
</tr>
<tr>
<td>Density—lightweight</td>
<td>1800 kg m$^{-3}$</td>
</tr>
</tbody>
</table>

### Table 4  Typical properties of construction materials$^{13,26,158}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Density/ kg m$^{-3}$</th>
<th>Tensile strength/MPa</th>
<th>Elastic modulus/GPa</th>
<th>Co-efficient of thermal expansion/10$^{-6}$ °C$^{-1}$</th>
<th>Thermal conductivity / W m$^{-1}$ K$^{-1}$</th>
<th>Energy requirement/ GJ m$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium—pure</td>
<td>2800</td>
<td>100</td>
<td>70</td>
<td>23</td>
<td>220</td>
<td>360</td>
</tr>
<tr>
<td>Aluminium—alloy</td>
<td>2800</td>
<td>300</td>
<td>70</td>
<td>23</td>
<td>125</td>
<td>360</td>
</tr>
<tr>
<td>Steel—mild</td>
<td>7800</td>
<td>300</td>
<td>210</td>
<td>12</td>
<td>50</td>
<td>300</td>
</tr>
<tr>
<td>Steel—high strength</td>
<td>7800</td>
<td>1000</td>
<td>210</td>
<td>11</td>
<td>45</td>
<td>—</td>
</tr>
<tr>
<td>Glass</td>
<td>2500</td>
<td>60</td>
<td>65</td>
<td>6</td>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>Wood—soft</td>
<td>350</td>
<td>50</td>
<td>5.5</td>
<td>—</td>
<td>0.2–0.6</td>
<td>—</td>
</tr>
<tr>
<td>Wood—hard</td>
<td>700</td>
<td>100</td>
<td>10</td>
<td>—</td>
<td>0.2–0.6</td>
<td>—</td>
</tr>
<tr>
<td>Plastic (polystyrene)</td>
<td>1000</td>
<td>~50</td>
<td>~3</td>
<td>72</td>
<td>0.1</td>
<td>—</td>
</tr>
<tr>
<td>Rock (granite)</td>
<td>2600</td>
<td>~20</td>
<td>~50</td>
<td>7–9</td>
<td>3</td>
<td>—</td>
</tr>
<tr>
<td>Concrete</td>
<td>2300</td>
<td>3</td>
<td>~25</td>
<td>10</td>
<td>3</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Green house gases: CO$_2$, etc.

$\text{CaCO}_3 \xrightarrow{\Delta} \text{CaO} + \text{CO}_2$

0.54 Tons / ton of clinker

The overall CO$_2$ emissions of cement industry (~ 0.98 T) are $\approx 6\%$ of all anthropogenic carbon dioxide release

Other emissions: $\sim 0.34$ T from fuel burning
$\sim 0.10$ T from electricity

Cement industry contributes to the global warming of the planet in $\approx 4\%$
FACTS & Key figures - CO₂ and Cement production

**Worldwide cement production**  
~ 2.5 Gt (2005)

**Cement sector CO₂ emissions (2005)**  
~ 1.8 Gt CO₂/year

~ 4% of total CO₂ emissions  
~ 11% of industrial emissions  
(nearly half from China)

**Emissions (2005) differ substantially between regions** (McKinsey 2009)

- Germany: 0.63 t CO₂/t cement
- North America: 0.81 t CO₂/t cement
- Russia: 0.90 t CO₂/t cement
- World average: 0.79 t CO₂/t cement
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5. Laboratory active belite sulfoaluminate cements

6. Conclusions
2. Searching for sustainable materials and processes for reducing CO₂ emissions

2.1. Addition of mineralizers and/or fluxes, to enhance burnability and/or decrease the firing temperature.

2.2. Partial replacement of clinker by an active hydraulic compound (blended cements).

2.3. The use of (slightly) different mineralogical systems to decrease the burning temperature and/or to obtain highly reactive constituents.

Industrially interesting approaches to “low-CO₂” cements

Ellis Gartner*

Lafarge Laboratoire Central de Recherche, 95 Rue du Montmurier, St. Quentin Fallavier 38291, France
2.1. Mineralizers / fluxes (as an example)

Sulfates, chlorides, carbonates, phosphates, fluorides, fluorosilicates etc...

Phosphogypsum (PG) as raw material: \( \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{Na}_2\text{SiF}_6 \)

- 1200°C ⇒ 0.4 % CaO\text{free}
- Alite & belite ⇒ low crystal sizes
- ⊲ liquid phase: ⊲ porosity ⊲ grinding
- High mechanical strength 28 days
- Valorization of waste materials

Kacimi et al., J. Hazardous Mat. 2006
2.2. Partial replacement of clinker by an active hydraulic compound

As an example: Pozzolanic based cements

Pozzolanic reaction

\[ A_xS_y + mCH + nH \rightarrow C - S - H + C - A - H \]

Product of OPC hydration

POZZOLAN + LIME + WATER \Rightarrow \text{calcium silicate hydrates} + \text{calcium aluminate hydrates}

The hydration of alite with silica fume (S) gives 1.76 times much C-S-H / C_3S consumed

\[ C_3S + 0.76S + 7.04H \Rightarrow 1.76C_{1.7}SH_4 \]

Up to a reduction of 43\% of CO_2 emitted from raw materials (compared to pure C_3S) could be obtained.

2.3. Alternative mineralogical systems

Alkaline activation of fly ashes

Alkaline activation of slags

They will be treated in other lectures

(among other systems)
<table>
<thead>
<tr>
<th>Cement compound</th>
<th>Raw materials used</th>
<th>Quantity of CO₂ generated (g of raw material per g of CO₂)</th>
<th>Quantity of CO₂ generated (g of raw material per ml of CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (magnesia, periclase)</td>
<td>Magnesite</td>
<td>1.092</td>
<td>3.91</td>
</tr>
<tr>
<td>C (calcia, quicklime)</td>
<td>Limestone</td>
<td>0.785</td>
<td>2.63</td>
</tr>
<tr>
<td>C₃S (alite)</td>
<td>Limestone + silica</td>
<td>0.578</td>
<td>1.80</td>
</tr>
<tr>
<td>β-C₃S (belite)</td>
<td>Limestone + silica</td>
<td>0.511</td>
<td>1.70</td>
</tr>
<tr>
<td>C₃A (tricalcium aluminate)</td>
<td>Limestone + alumina</td>
<td>0.489</td>
<td>1.50</td>
</tr>
<tr>
<td>C₄AF (calcium aluminoferrite)</td>
<td>As above + iron oxide</td>
<td>0.362</td>
<td>1.29</td>
</tr>
<tr>
<td>NS (sodium metasilicate)</td>
<td>Soda + silica</td>
<td>0.361</td>
<td>—</td>
</tr>
<tr>
<td>CA (monocalcium aluminate)</td>
<td>Limestone + alumina</td>
<td>0.279</td>
<td>0.83</td>
</tr>
<tr>
<td>C₄A₃S (calcium sulfoaluminate)</td>
<td>As above + anhydrite</td>
<td>0.216</td>
<td>0.56</td>
</tr>
</tbody>
</table>

CO₂ emissions relationship between

**OPC**
(ordinary Portland cement; based on alite, and others)

&

**BSA**
(belite sulfoaluminate cements; based on belite, C₄A₃S, and others)
2.3. Alternative mineralogical systems

1.- ‘Active’ belite Portland cements:
To decrease the LSF from 98 to 71 leads to a 11% reduction of CO₂ emissions (less calcite as raw material). Furthermore, extra reduction (close to 3%) may be attained from burning at lower temperatures (1350 °C instead of 1450 °C) since less fuel is needed.

2.- ‘Active’ iron-rich belite sulfoaluminate cements:
Plus the above described savings:
~ 10% from substituting alite by belite (smaller LSF)
~ 5 % from burning the clinker at 1300 °C (fuel saving)
~ 15% from partial substitution of CaCO₃ by CaSO₄.
Therefore, more than 30% of CO₂ emissions savings can be obtained.

<table>
<thead>
<tr>
<th>Estimated phase composition</th>
<th>belite</th>
<th>ye’elimite</th>
<th>ferrite</th>
<th>others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>51</td>
<td>29</td>
<td>19</td>
<td>&lt;1</td>
</tr>
<tr>
<td>C₂S</td>
<td>C₄A₃S</td>
<td>C₄AF</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.3. Alternative mineralogical systems

a) High-belite cements: \( \downarrow \) LSF: higher C\(_2\)S less C\(_3\)S
b) Sulfoaluminate based cements: C\(_4\)A\(_3\)S

Table 2
Chemical analysis and mineralogical composition of the clinkers

<table>
<thead>
<tr>
<th>Oxide (%)</th>
<th>Type of clinker</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OPC</td>
</tr>
<tr>
<td><strong>Chemical analysis</strong></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>67.30</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>19.54</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>8.19</td>
</tr>
<tr>
<td>Fe(_2)O(_3)</td>
<td>3.94</td>
</tr>
<tr>
<td>SO(_3)</td>
<td>(-)</td>
</tr>
<tr>
<td>Other</td>
<td>1.03</td>
</tr>
<tr>
<td><strong>Mineralogical composition</strong></td>
<td></td>
</tr>
<tr>
<td>C(_2)S</td>
<td>65(^a) (67(^b))</td>
</tr>
<tr>
<td>C(_3)S</td>
<td>7 (13)</td>
</tr>
<tr>
<td>C(_3)A</td>
<td>15 (11)</td>
</tr>
<tr>
<td>C(_4)AF</td>
<td>12 (7)</td>
</tr>
<tr>
<td>C(_4)A(_3)S</td>
<td>(-)</td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^a\) From Bogue analysis.
\(^b\) From X-ray and chemical analysis.

Fig. 2. Development of compressive strength of OPC, HFBC and SFAB cements.

Problem:
Low early mechanical strengths

Industrial trial production of low energy belite cement

C.D. Popescu \(^a\), M. Muntean \(^b\), J.H. Sharp \(^c\)

Cement & Concrete Composites 25 (2003) 689–693
Burning at 1250 °C

The fly ash is blended with powdered calcium carbonate in a \( \frac{CaO}{SiO_2} = 2 \) ratio and the resultant mix named FC\(_2\)

Two raw mixtures noted FC\(_2\)P\(_{10}\) and FC\(_2\)P\(_{15}\) prepared by adding 10 and 15 % of phosphogypsum to FC\(_2\)

respectively.

Semi-quantitative estimation of the identified crystalline phases

<table>
<thead>
<tr>
<th></th>
<th>T= 1.250 °C</th>
<th>T= 1.350 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC(<em>2)P(</em>{10})</td>
<td>FC(<em>2)P(</em>{15})</td>
</tr>
<tr>
<td>β-C₃S</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>C₄A.3S</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>C₃A</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>C₄AF</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>C₃AS</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>CaO</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

+++: Abundante/Abundant; ++: Moderado/Moderate; +: Poco/Little; -: Trazas/Traces

Obtención de cementos belíticos de sulfoaluminatos a partir de residuos industriales

MATER CONSTRUCC. Vol. 53, nº 270, 2003
Activation of belite clinkers

⇒ Higher mechanical strength at early ages

Ordinary Portland clinker component. Mechanical strength at later ages.

Hydraulically non-active.

β

γ

≤ 500ºC

780-860ºC

690ºC

1160ºC

1425ºC

Hydraulically very active.

α-forms stabilisation by oxides such as Na₂O, SO₃, BaO and K₂O.

✓ Quenching.
✓ Chemistry stabilisation.
High-belte cements - Quenching

↓ LSF: higher C$_2$S less C$_3$S

✓ **Decrease** CO$_2$ emissions in the decomposition of calcite (8%).
✓ The optimum clinkerization temperature is roughly 100 °C lower.
✓ Belite based concretes are more durable.

Quenching ↑ mechanical strength 3000 K/min vs. 100 K/min in belite cements (at 28 days)

Wolter, Cement International 2005
Belite sulfoaluminate cements # 1

**Raw materials**
Calcite (Ca)
bauxite (Al)
Fluidized bed combustion (FBC) (Ca, Si, Al & S)
Fly ash (Al, Si)
Red mud (Al, Si & Fe)

**Advantages**
✓ Easier to grind (↓ liquid phase ↑ porosity)
✓ ↓ synthesis temperature
✓ ↓ CO₂ emissions
✓ Used (valorization) of waste materials
✓ ↓ porosity on hydrated samples ⇒ durability

**Thermal treatment:** 2h @ 1150-1300ºC

<table>
<thead>
<tr>
<th>Mixture</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>M7</th>
<th>M8</th>
<th>M9</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₄A₃S</td>
<td>52.50</td>
<td>49.70</td>
<td>41.70</td>
<td>43.16</td>
<td>42.70</td>
<td>39.54</td>
<td>41.61</td>
<td>38.01</td>
<td>41.30</td>
</tr>
<tr>
<td>C₂S</td>
<td>34.80</td>
<td>39.00</td>
<td>40.10</td>
<td>34.30</td>
<td>33.10</td>
<td>43.07</td>
<td>43.70</td>
<td>45.53</td>
<td>39.43</td>
</tr>
</tbody>
</table>

Flue Gas Desulfuration (FGD) gypsum

**Potential mineralogical clinker compositions (main phases)**

Valenti et al., W3-11.2, 12th ICCC, Montreal 2007
Canonico et al., W3-11.4, 12th ICCC, Montreal 2007

<table>
<thead>
<tr>
<th>CSA</th>
<th>OPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength on mortar, MPa&lt;sup&gt;(h)&lt;/sup&gt;</td>
<td>(3h)</td>
</tr>
<tr>
<td>6.1</td>
<td>23.9</td>
</tr>
<tr>
<td>Compressive strength on concrete, MPa&lt;sup&gt;(h)&lt;/sup&gt;</td>
<td>(5h)</td>
</tr>
<tr>
<td>9.0</td>
<td>30.1</td>
</tr>
</tbody>
</table>

M7
M8

Valenti et al., W3-11.2, 12th ICCC, Montreal 2007
Canonico et al., W3-11.4, 12th ICCC, Montreal 2007
Belite sulfoaluminate cements #2

<table>
<thead>
<tr>
<th>Estimated phase composition</th>
<th>belite</th>
<th>ye’elimite</th>
<th>ferrite</th>
<th>others</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>51</td>
<td>29</td>
<td>19</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Clinkering temperature

= 1300ºC

Abstract

Clinkers based principally on belite, calcium sulfoaluminate and calcium aluminoferrite were made at 1300ºC from a raw mix based on limestone, kaolinite, gypsum and haematite. The inclusion of dopants stabilized belite in the α-form, which led to a greater hydraulic reactivity. Cements made from such clinkers with 8-12% gypsum were more easily grindable than OPC and offered potential CO₂ emissions reductions of 20-30% in manufacturing, while giving performance not far from that of OPC. It is

Li et al., TH3-15.3, 12th ICCC, Montreal 2007
Belite sulfoaluminate cements # 2

Fig. 2: Strength development of BCŠAF micromortars vs. OPC

Fig. 6. Semiquantitative XRD analyses of hydrating BCŠAF pastes

Li et al., TH3-15.3, 12th ICCC, Montreal 2007
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Round robin on Rietveld quantitative phase analysis of Portland cements


**Synchrotron powder diffraction data, $\lambda=0.44$ Å**
We are using a similar approach (but with synchrotron and CuKα_{1,2} radiations)
We are using a similar approach (but with synchrotron and CuKα₁,₂ radiations)
Convert the divergent X-ray beam from a tube in line focus position to an intense beam that focuses onto the goniometer circle.

Laboratory X-ray Powder data collection
In-situ hydration

Application laboratory of PANalytical (Almelo, The Netherlands) $\lambda=1.5418\ \text{Å}$
Flat sample

Convert the divergent X-ray beam from a tube in line focus position to an intense beam that focuses onto the goniometer circle.
Synchrotron X-ray Powder data collection

*In-situ* hydration

Image plate detector: two data collection strategies

![Diagram](image)

- **Transmission**
  - Cement + Water
  - \( W/C = 0.5 \)

- **BM08 beam line @ ESRF**
  - \( \lambda = 0.6888 \) Å
  - Debye Scherrer configuration
  - Flat sample

- **X-Rays**
  - Slits
  - Sample
  - 2D single pattern
  - Translating mode

- **Radiation**
  - \( \beta \)
In situ synchrotron powder diffraction study of active belite clinkers

Ángeles G. De la Torre, Khadija Morsli, Mohammed Zahir and Miguel A.G. Aranda


Why an in-situ study?

- Clinkering process for belite clinkers is not well known
- Polymorphic transformations at high temperature
- Liquid appearance temperature(s)
- Influence of minor elements in these reactions

Selected compositions

<table>
<thead>
<tr>
<th>sample</th>
<th>K₂O/ %</th>
<th>Na₂O/ %</th>
<th>SO₃/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_ref</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bel_10K</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bel_15Na</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>Bel_05K05Na</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Bel_10S10K</td>
<td>1.0</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Bel_10S05K05Na</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Clinkerization process for an ordinary Portland Clinker

700-900ºC Decarbonation (CO₂)

900-1300ºC free lime, Al & Fe rich phases and silicates

1300-1450ºC liquid phase + silicates

Quenching Phase stabilisation + subcooled liquid
Thermo-diffractometric data collection

Data collection
ESRF (Grenoble)
ID31 diffractometer
\( \lambda = 0.3007 \, \text{Å} \)
Debye Scherrer configuration
Capillaries were spun
Angular range 2.5-30° (in 2\( \theta \))
15 minutes per run
3 runs for a single pattern

Real temperature was checked by Pt peak positions

Parabolic mirror furnace
(3 halogen lamps)

Samples were heated from 900 to 1450°C
Halogen lamps

Ceramic holder
Reference belite clinker (B_ref) on heating

Free lime (CaO ■) 9.6(2)wt%
(1) Primary formation of C₄AF (★)

Free lime (CaO ■) 4.2(1)wt%
(3) Formation of C₃A (○)
(4) Crystal size growth of C₄AF (★)
B_ref on heating (continuing)

1300°C

(5) Melting of C₃A (○) & C₄AF (★) → Liquid phase (□)

(6) $\alpha'_H$-C₂S(△) + CaO → C₃S (▲)

Free lime (CaO ■) 0.0wt%

1350°C

(7) $\alpha'_H$-C₂S → α-C₂S(●)

C₃S (▲)
Liquid phase (B_ref) on heating

Melting
Forming/sinterization
Formation

- C₄AF
- C₃A

<table>
<thead>
<tr>
<th>Temperature</th>
<th>C₄AF/</th>
<th>C₃A/</th>
</tr>
</thead>
<tbody>
<tr>
<td>920 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1055 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1180 °C</td>
<td>16</td>
<td>8</td>
</tr>
</tbody>
</table>
| 1300 °C     | 16.7(3) | 6.2(2) | 1180°C

Nominal composition
Active belite clinker $1.0\%$ $K_2O$ (B$_{10K}$) on cooling

<table>
<thead>
<tr>
<th>B$_{1.0K}$</th>
<th>$\alpha$-C$_2$S</th>
<th>$\alpha'$-C$_2$S</th>
<th>$\alpha''$-C$_2$S</th>
<th>C$_3$S</th>
<th>C$_4$A</th>
<th>C$_4$AF</th>
<th>CaO</th>
<th>Liquid phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1200^\circ C$</td>
<td>--</td>
<td>75.4(1)</td>
<td>--</td>
<td>--</td>
<td>6.0(2)</td>
<td>14.0(2)</td>
<td>4.6(1)</td>
<td>--</td>
</tr>
<tr>
<td>$1440^\circ C$</td>
<td>72.7(1)</td>
<td>--</td>
<td>--</td>
<td>7.3(2)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>20.0</td>
</tr>
<tr>
<td>$1308^\circ C$</td>
<td>72.9(1)</td>
<td>--</td>
<td>--</td>
<td>7.1(2)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>20.0</td>
</tr>
<tr>
<td>$1310^\circ C$</td>
<td>72.4(1)</td>
<td>--</td>
<td>--</td>
<td>7.6(2)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>20.0</td>
</tr>
<tr>
<td>$1238^\circ C$</td>
<td>--</td>
<td>70.7(2)</td>
<td>--</td>
<td>9.3(2)</td>
<td>3.3(2)</td>
<td>5.6(3)</td>
<td>--</td>
<td>11.1</td>
</tr>
<tr>
<td>$1175^\circ C$</td>
<td>--</td>
<td>70.6(1)</td>
<td>--</td>
<td>9.4(2)</td>
<td>3.3(2)</td>
<td>6.2(3)</td>
<td>--</td>
<td>10.5</td>
</tr>
<tr>
<td>$1055^\circ C$</td>
<td>--</td>
<td>60.2(1)</td>
<td>10.3(2)</td>
<td>9.5(2)</td>
<td>3.5(1)</td>
<td>6.5(3)</td>
<td>--</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Diagram showing X-ray diffraction patterns for cooling from $1400^\circ C$ to RT.

- RT
- $1400^\circ C$
- $1350^\circ C$
- $1300^\circ C$
- $1250^\circ C$
- $1200^\circ C$
- $1100^\circ C$
- $1055^\circ C$
We have carried out a similar *in situ* type of study for belite sulfoaluminate clinkering, to be reported very soon.
Outline

1. Introduction to cement industry environmental problem

2. Searching for sustainable materials and processes

3. Methodology (mainly at Universidad de Málaga)

4. Laboratory active belite cements

5. Laboratory active belite sulfoaluminate cements

6. Conclusions