# Low-$CO_2$ Cements based on Calcium Sulfoaluminate

Keith Quillin BRE

# About BRE

- **Over 80 years as a leading authority on the built environment**
- **Much of work has underpinned UK Government policy, building regulations, codes and standards etc.**
- **Numerous programmes on cement and concrete**
  - **Durability and service life**
  - **Blended Portland cements**
  - **Alternative cements**
  - **Structural**
- **National and international reputation for knowledge and quality**
- **Privatised in 1997 - Now owned by the BRE Trust**
- **Have run a number of programmes on low $CO_2$ cements funded by DETR, DTI, Carbon Trust and Technology Strategy Board with industry support, as well as on a commercial basis**

# The Impact of Construction

- A big industry
  - *10% GDP in UK*
- major consumer of land and raw materials
  - *90% (260 million tonnes) of non-energy minerals*
- dust, noise and heavy transport
- major user of energy and producer of green house gases
- waste
  - *70 million tonnes in UK*
  - *13 million tonnes wasted on site*

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# Our need for Concrete

- Most widely used and important construction material
- whole family of materials that can be tailored to almost any use
- made from locally available raw materials

but:

  - Largest component of waste stream (53%)
  - Aggregate extraction is land-hungry
  - Cement is intensive energy user and greenhouse gas producer

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# Concrete – An economic material

- The quantity of concrete poured in the UK per annum shows that it is a viable economic material. (Currently circa 40 million tonnes p.a.)
- The supply chain is generally considered to be lean and focused on price and delivery. A low margin, bulk supply business.

# Factors Influencing the “$CO_2$-Efficiency” of Concrete.

1. The total embodied $CO_2$ content of the clinker, which is the sum of its raw-materials $CO_2$ and fuel-derived $CO_2$ emissions during manufacture.

2. The composition of the cement (binder), considering the total embodied $CO_2$ content of each of its components.

3. The cement content of the concrete that is ultimately manufactured and must perform to a given specification.  (We neglect any embodied $CO_2$ in aggregates, etc.)

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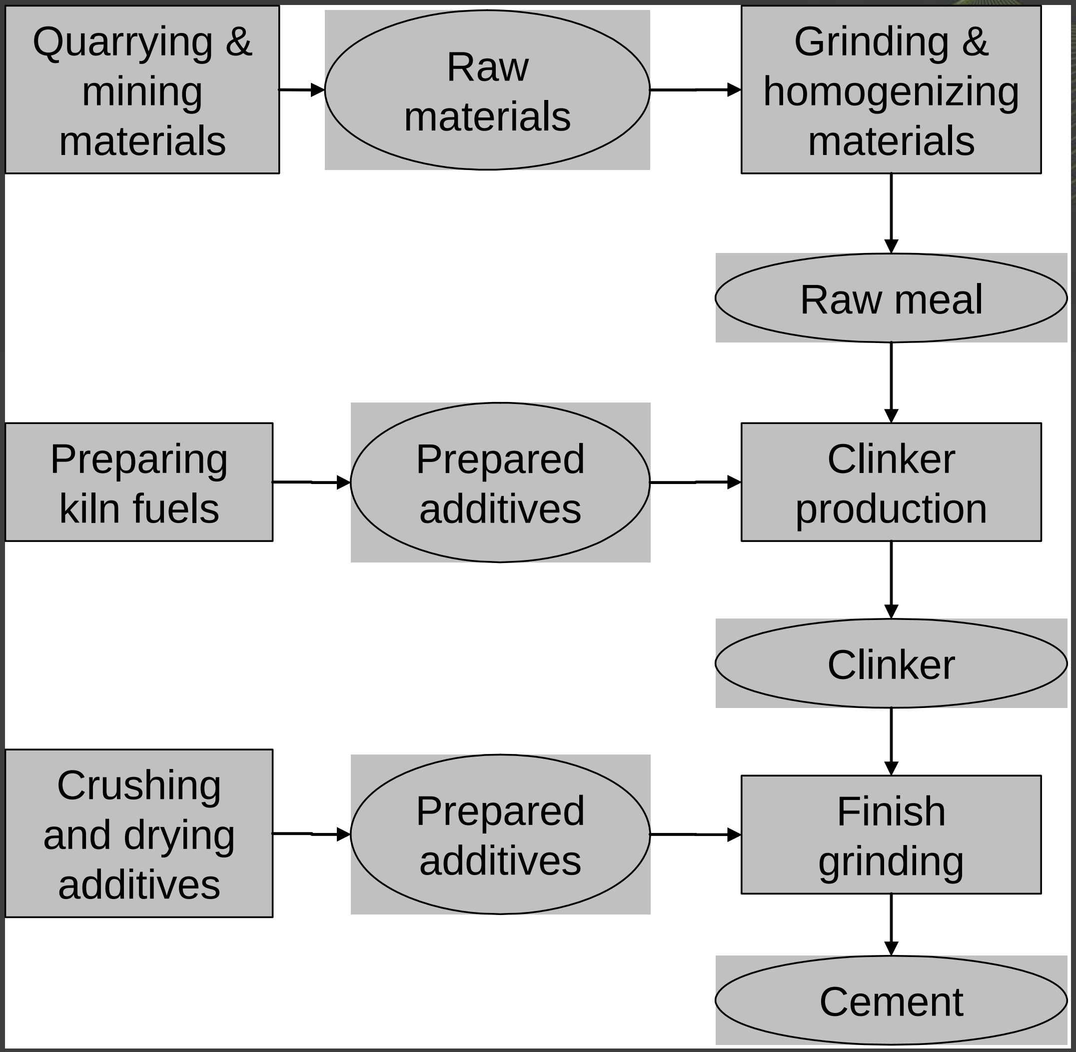
# Cement manufacture

- Portland cement clinker manufactured by heating intimate mixture of limestone and clay, generally in rotary kiln.
- Manufacture is intrinsically energy intensive and produces large amounts of $CO_2$.
- Manufacturing $CO_2$ emissions are the sum of 2 or 3 contributions:
  - The decarbonation of limestone by the reaction $CaCO_3 = CaO + CO_2$
  - Energy used in heating the kiln to decarbonate limestone and to form components such as alite and belite.
  - Energy used in grinding the clinker

# Cement manufacture

Schematic representation of cement manufacturing process[i]




[i] M Taylor, Global energy use, $CO_2$ emissions and the potential for reduction in the cement industry, Cement Energy Efficiency Workshop, Organised by IEA and WBCSD, Paris, September 2006

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# Energy consumption and $CO_2$ production in Portland cement manufacture

- Cement manufacture requires a large amount of energy
  - Clinker formation - approx. 1750kJ/Kg
  - Thermal losses
  - Consumption of electricity
  - Total of approx. 3600KJ/Kg
- $CO_2$ produced in decarbonation of $CaCO_3$ and in burning fuel
  - ~1.7 billion tonnes cement produced per annum
  - ~1 tonne of $CO_2$/tonne cement produced
  - 0.08 tonnes $CO_2$/tonne concrete (based on all concrete produced)
  - Up to 8% global $CO_2$ production (2% in UK)
- Also need to consider through-life $CO_2$ emissions from structure

# Theoretical Heat Balance for OPC Manufacture

*(Assumes dry limestone and clay as kiln feed; analysis based on Lea, 3rd Edn., p126)*

| Kiln section | Temperature range | Process | Heat required, kJ/g (GJ/t) of clinker |
|---|---|---|---|
| Preheater | 20 – 900° C | heating raw feed to 900° C | +1.53 |
| " | about 450° C | dehydration of clays | +0.17 |
| " | 20 – 900° C | cooling $CO_2$ and $H_2O$ | - 0.59 |
| Calciner | about 900° C | dissociation of calcite | +1.99 |
| " | about 900° C | reactions of dehydrated clays | - 0.04 |
| Rotary Kiln | 900 –1400° C | heating feed from 900 to 1400° C | +0.52 |
| " | 900 –1400° C | formation of clinker phases | - 0.31 |
| Clinker cooler | 1400 – 20° C | cooling of clinker to 20° C | - 1.51 |
| | | Net heat required: | +1.76 |

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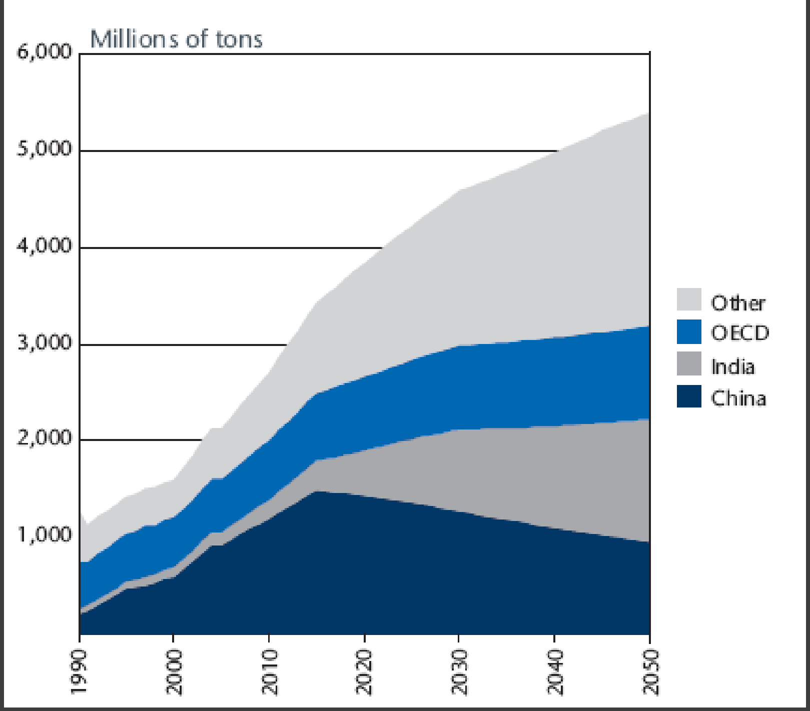
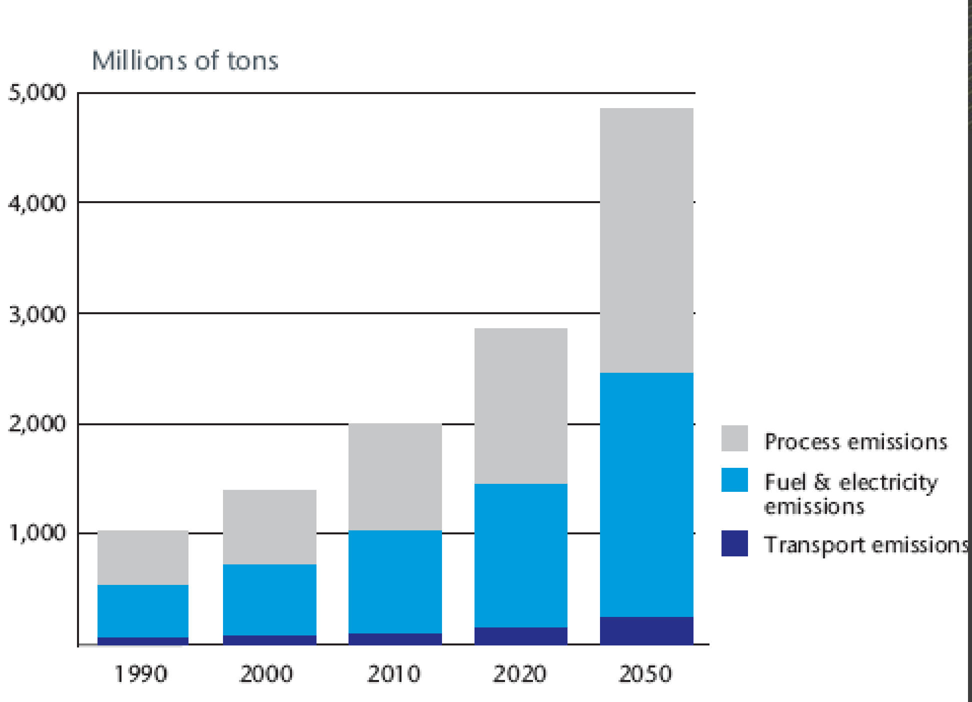
# Projections for global cement manufacture and $CO_2$ emissions to 2050 (industry data)




Predicted growth in global cement demand (million tonnes p.a)

Currently ~2 billion tonnes pa

Rising to over 5 billion tonnes pa by 2050

Cement-related $CO_2$ emissions (no change in current practices)

If best practice implemented globally $CO_2$ emissions would rise to 2.4–2.7 billion tonnes pa.

~5 billion tonnes pa if current practices remain

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# Cement Production and Associated $CO_2$ Emissions

| | Production (%) | $CO_2$ emissions (%) |
|---|---|---|
| Africa | 2.4 | 2.0 |
| Latin America | 5.9 | 4.7 |
| North America | 5.1 | 5.5 |
| Middle East | 7.1 | 6.7 |
| OECD Pacific | 6.3 | 4.3 |
| Eastern Europe and Former Soviet Union | 4.7 | 4.1 |
| Europe | 9.4 | 6.9 |
| Other Asia | 8.6 | 8.2 |
| India | 5.9 | 5.9 |
| China | 44.7 | 51.8 |
| **Total** | **100** | **100.0** |

# Approaches to energy conservation and reduced $CO_2$ emissions

- Ongoing process improvements
- Use of wastes as fuels
- Use of waste materials as raw feed
- Fluxes and mineralisers to reduce clinkering temperatures
- More efficient use of cement
- Use of additions (e.g. pfa and ggbs)
- Alternative cements
- Capture of $CO_2$ emissions
- Recarbonation

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# Cement Manufacture

- 1 tonne $CO_2$/tonne cement often quoted
  - Industry data indicate 0.83 tonnes of $CO_2$/tonne Portland cement
  - 0.51 tonnes $CO_2$/tonne for decarbonation of limestone for PC
- Fuel-derived $CO_2$ emissions will diminish slowly for purely economic reasons.
- Cannot address decarbonation without changing composition of the cement

# Cementing Systems of Potential Interest for General and Widespread Application

- Limestone-based cements:
  - Calcium silicate cements (portland cements; belite & alinite cements)
  - Lime-pozzolan cements (includes portland-pozzolan cements & hydraulic limes)
  - Calcium aluminosilicate cements (based on CAS glasses or blast furnace slags)
  - Calcium aluminate cements (based principally on CA)
  - Calcium sulfoaluminate cements (based principally on $C_4A_3\$$)
  - Various combinations of the above systems
- Non limestone-based cements:
  - Alkali activated pozzolans (e.g. “Geopolymers”)
  - Calcium sulfate cements (“plasters”, etc.)
  - Mg-based cements

# What is a low $CO_2$ cement?

- A low $CO_2$ cement can be defined as one which:
  - Releases less $CO_2$ from decarbonation of raw materials during manufacture than PC

  And/or

  - Releases less $CO_2$ from energy use in manufacture than PC

  - It could also be one which reabsorbs significantly more $CO_2$ during use in a concrete or mortar than PC
    - *It may be possible to design concrete made using Portland cement to facilitate carbonation.*

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# Requirements for low carbon cements

In addition to low net $CO_2$ emissions:

- Economic to produce
- Readily available raw materials
- Ease of use in concrete
  - Properties of wet concrete
  - Strength development
- Suitable physical properties
- Durability and chemical resistance
- No problems with by-products, emissions, leachates etc
- Others?

(Ease of use in concrete through Durability and chemical resistance:) Comparable or better than PC?

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# Apart from strength, what other performance-related parameters should we compare?

- Robustness with respect to:
  - Impurities in the cement-manufacturing process
  - Temperature and water-content variations in the fresh concrete
  - Admixtures or impurities in the concrete
  - Curing of the concrete
  - Surface finishing

- Durability with respect to:
  - Dissolution in pure water, or in dilute acids or bases, salt solutions, etc.
  - Attack by atmospheric gases (especially $CO_2$)
  - Protection of embedded reinforcement (steel, glass, etc.)
  - Time, humidity and temperature-dependent phase changes that can cause strength loss.
  - Paste volume changes that can cause cracking (e.g. due to changes in T or RH)
  - Reactions between the cement paste and the aggregates that can cause cracking
  - Excessive creep (generally a function of RH).

***Such data are far from complete for most systems other than OPCs***

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# Data on Portland cement concrete

- There is a huge database of performance information on PC concrete:
  - Decades of use backed by research
  - Relationships between composition (cement content, water: cement ratio, aggregate type etc) and performance
  - Long term durability
- Provides strong foundation for codes and standards, guidance etc.
- This information is NOT applicable to new cements
- Similar data and guidance is essential if alternative cements are to be used by inherently cautious industry
- Major barrier to uptake

# Exposure categories for concrete from EN206 and BS8500

| Group | Class | Description |
|---|---|---|
| No risk of corrosion | X0 | • Concrete without reinforcement or embedded metal: All exposures except freeze/thaw, abrasion or chemical attack.<br>• Concrete with reinforcement or embedded metal: Very dry |
| Carbonation-induced corrosion | XC1 | Dry or permanently wet |
| | XC2 | Wet, rarely dry |
| | XC3/XC4 | Moderate humidity or cyclic wet and dry |
| Chloride-induced corrosion resulting primarily from de-icing salts | XD1 | Moderate humidity |
| | XD2 | Wet, rarely dry |
| | XD3 | Cyclic wet and dry |
| Corrosion induced by chlorides from sea water | XS1 | Exposed to airborne salt but not in direct contact with sea water |
| | XS2 | Permanently submerged |
| | XS3 | Tidal, splash and spray zones |
| Freeze-thaw attack | XF1 | Moderate water saturation without de-icing agent |
| | XF2 | Moderate water saturation with de-icing agent |
| | XF3 | High water saturation, without de-icing agent |
| | XF4 | High water saturation, with de-icing agent or sea water |
| Chemical attack | XA1 | Slightly aggressive chemical environments |
| | XA2 | Moderately aggressive chemical environments |
| | XA3 | Highly aggressive chemical environments |

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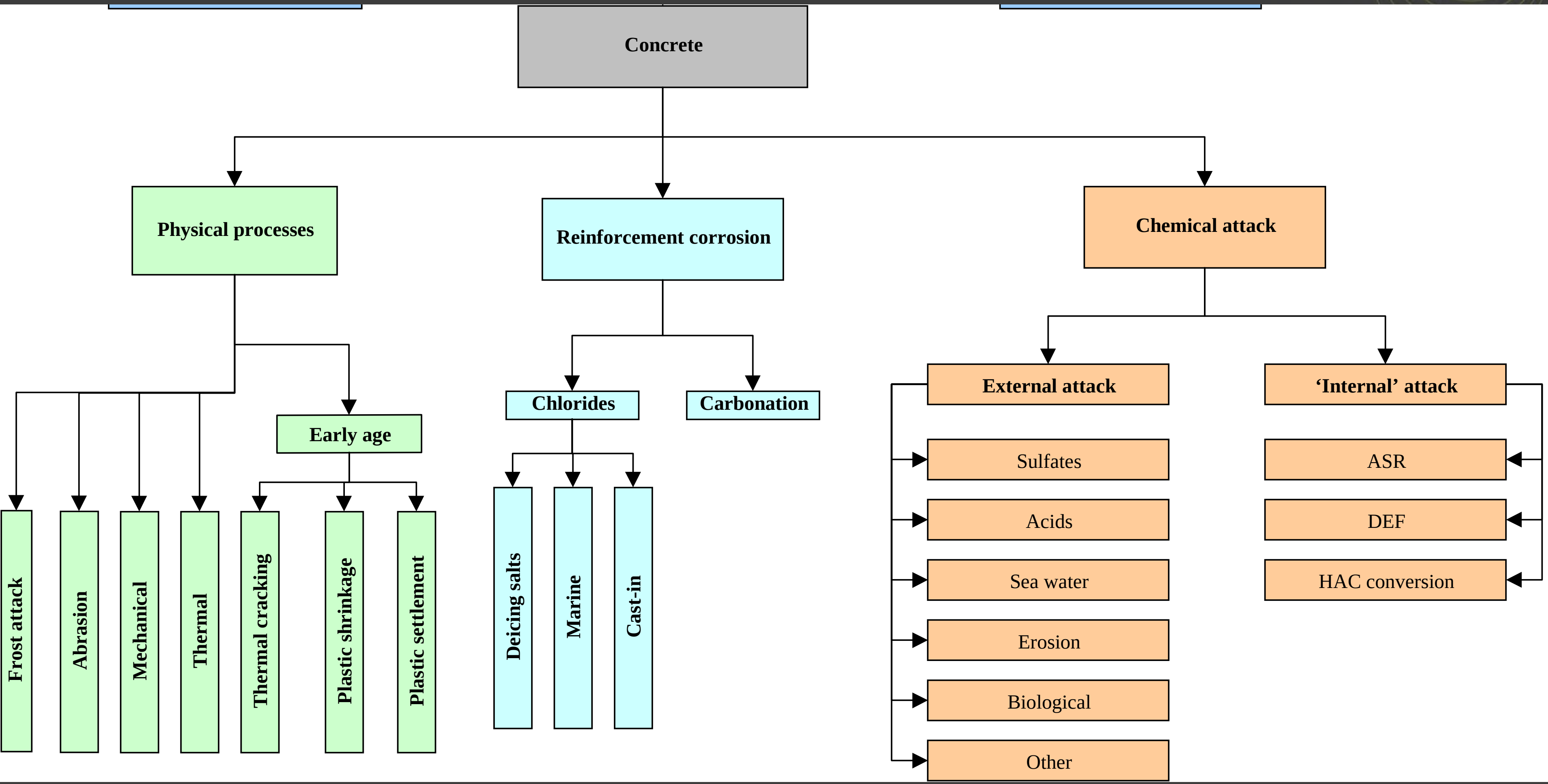
# Deterioration processes affecting concrete



Sometimes steel corrodes........

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# Carbonation induced corrosion

# Background to the BRE-Carbon Trust project (2004-6)

- Managed by Building Research Establishment.
- Funded partly by the UK Carbon Trust and partly by and Industrial Consortium:
  - Lafarge
  - Cemex
  - Castle Cement
  - Marshalls
  - CRH
  - Fosroc

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# Background to the BRE-Carbon Trust project (2004-7)

- Technical Objective:

  "To facilitate a step change reduction in $CO_2$ emissions from cement manufacture within the UK and Europe by encouraging the development and implementation of low $CO_2$-producing cements based on calcium sulfoaluminate and belite"

  Focusing on concrete technology:

  - Investigating effects of composition on properties
  - Properties of wet concrete
  - Strength development with time
  - Robustness and durability

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# Belite-calcium sulfoaluminate cements

- $C_2S$, lower CaO than $C_3S$ and produced at lower T
- But slower hydration than $C_3S$
- Activate $C_2S$ or add reactive component – e.g. $C_4A_3s$ (also low $CO_2$)
- Benefits:
  - Up to 50% reduced $CO_2$ from calcination - More if activation of pfa and ggbs considered
  - (Rapid) early age strength development mainly due to $C_4A_3s$ hydration (to form ettringite)
  - Long-term strength development due to $C_2S$ hydration
  - Good chemical resistance and durability
  - Reduced $NO_x$ emissions

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# Belite-calcium sulfoaluminate cements

- Manufactured on commercial scale in China since 1970's
  - NOT produced as low carbon cements
  - Production >1 million tonnes per annum
  - Considerable experience in China of using these cements in structural and non-structural concrete
  - UK use as special cement
- Manufacturing process similar to that of Portland cement
  - Mixture of limestone, bauxite and $CaSO_4$
  - Heated to 1300 - 1350$^{o}$C

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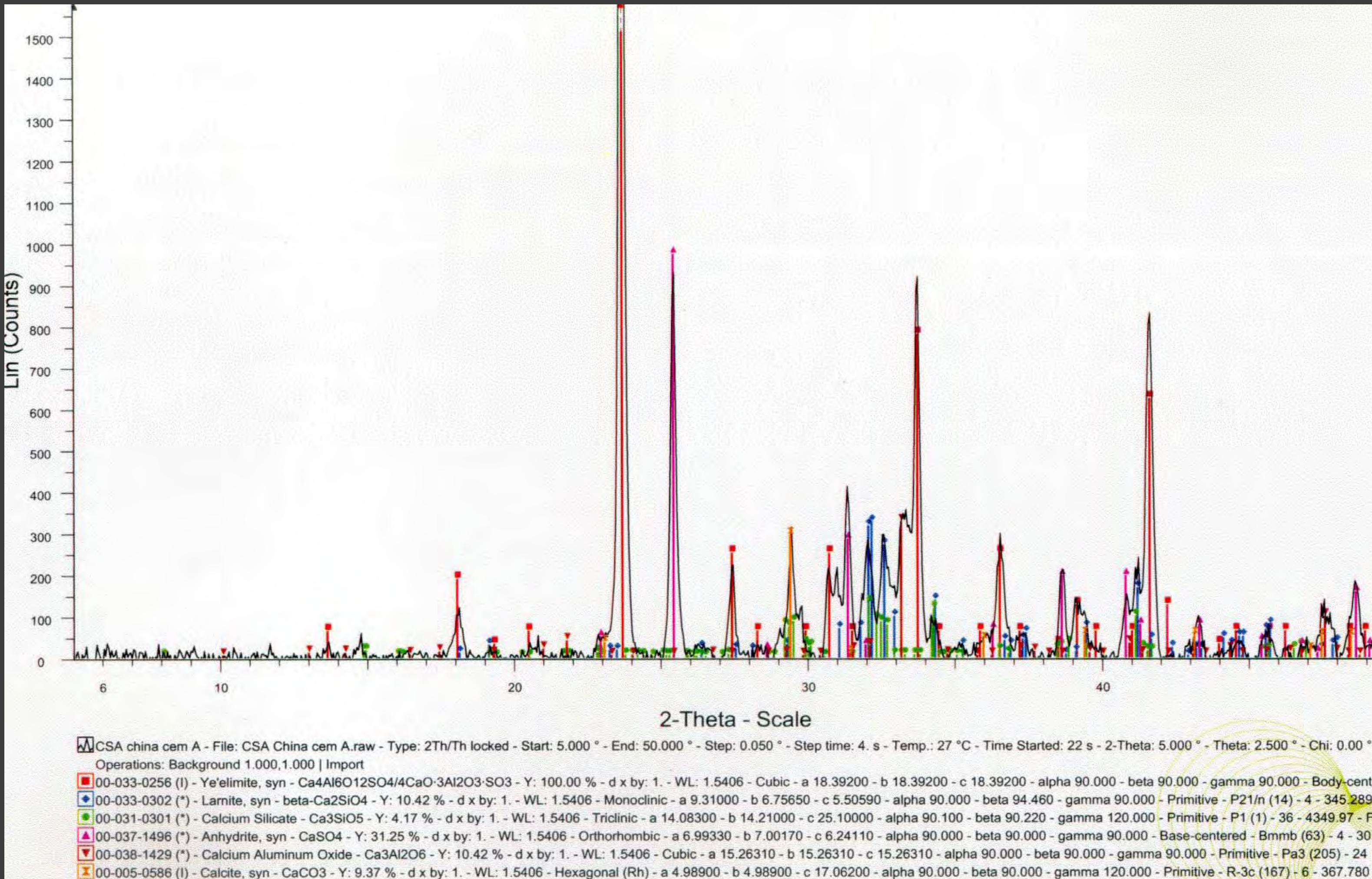
# Estimated cement phase compositions

| | Amount in clinker | | | | | | |
|---|---|---|---|---|---|---|---|
| **Oxide/ compound** | **525[a] (China)** | **SAC[a] (China)** | **Barnstone (B2)[b]** | **CSA[c] (Mehta - 3)** | **CSA[c] (Mehta - 5)** | **50PC:50 ggbs** | **PC** |
| **CaO** | 42 | 40.92 | 47 | 48.3 | 51.8 | | |
| **$SiO_2$** | 8.35 | 11.16 | 9.9 | 8.7 | 15.7 | | |
| **$Al_2O_3$** | 25.6 | 24.41 | 33.2 | 18.4 | 13.1 | | |
| **$Fe_2O_3$** | 2.84 | 2.29 | 1 | 13.2 | 5 | | |
| **$SO_3$** | 13.8 | 14.66 | 7.9 | 11.4 | 14.4 | | |
| **MgO** | 2.01 | 2.89 | | | | | |
| | | | | | | | |
| **Cs** | 12.9 | 14.7 | 0.1 | 15 | 20 | 0.75 | 1.5 |
| **$C_4A_3s$** | 47.5 | 45.8 | 59.9 | 20 | 20 | | |
| **$C_2S$** | 23.9 | 32.0 | 22.2 | 25 | 45 | 8.25 | 16.5 |
| **$C_3S$** | | | 8.2 | | | 32 | 64 |
| **$C_3A$** | | | | | | 1.75 | 3.5 |
| **$C_{12}A_7$** | | | 4.9 | | | | |
| **Cc** | | | | | | 1.25 | 2.5 |
| **$C_4AF$** | 8.64 | 7.0 | 3 | 40 | 15 | 4.75 | 9.5 |
| **$CO_2$ from decarb*** | **51.5** | **54.1** | **60.8** | **59.0** | **61.2** | **50** | **100** |

# Estimated cement phase compositions – cements from China

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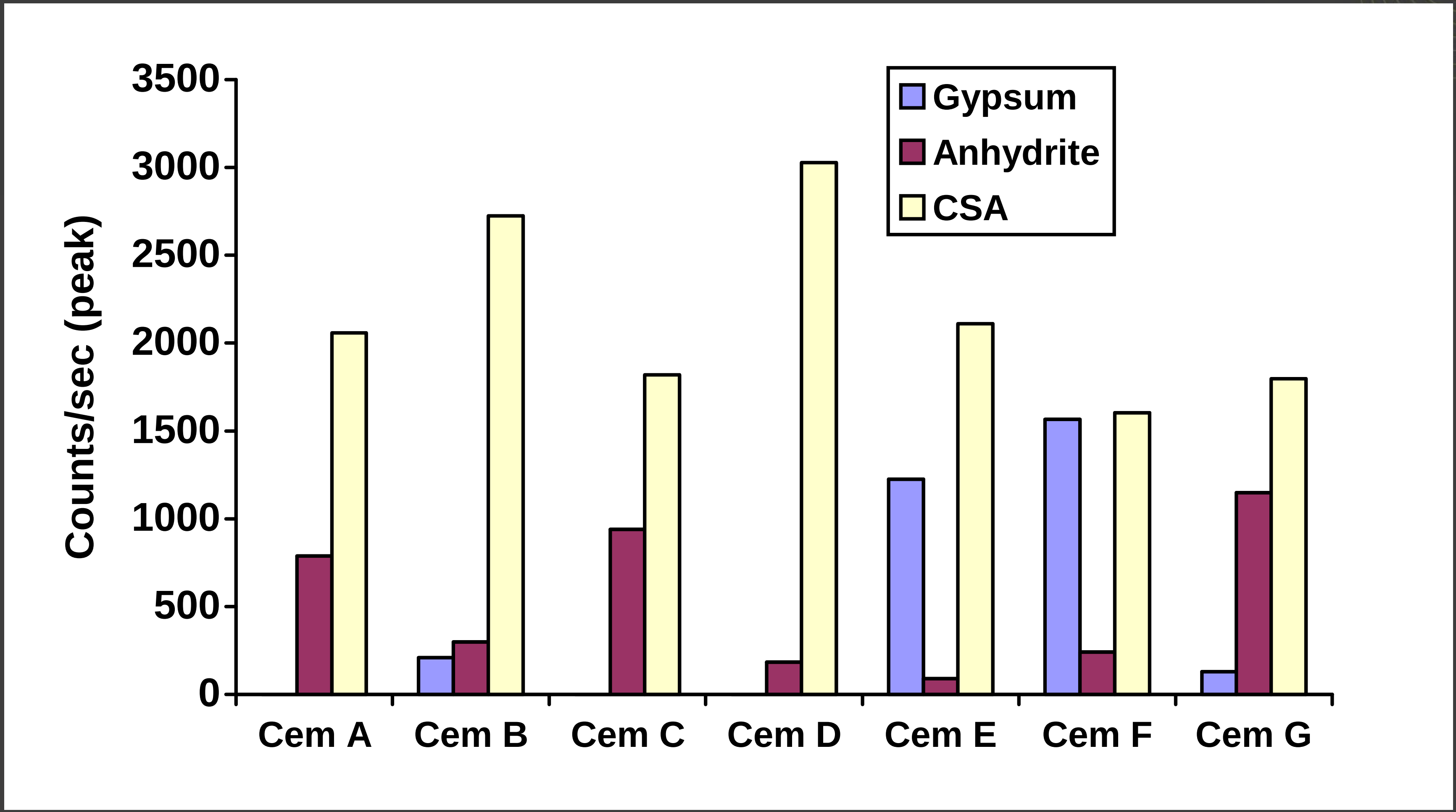
# Estimated cement phase compositions – cements from China



# Two different approaches based on CSA

- CSA-rich clinkers blended with ggbs, pfa, calcium sulfate and other non-clinker ingredients:

- Belite-CSA-ferrite clinkers which can be made in conventional OPC kilns *(Lafarge BCSAF cements)*

- Strength development associated with formation of a calcium sulfoaluminate hydrate known as ettringite ($6CaO.Al_2O_3.3SO_3.32H_2O$)

- $CO_2$ savings 25% - 80% relative to neat PC but depends on:
  - *composition*
  - *raw materials availability*
  - *use of cement replacements*

# Blended CSA cements

- Lafarge Barnstone CSA (B2) mainly used
- Cements sourced from China used in other programmes
- Blended with different proportions of
  - Ggbs
  - Anhydrite
  - Lime
  - Pfa
  - Limestone
- Studies have included compressive strength development and durability to 2 years for concretes
- ~70-80% reduction in $CO_2$ emissions from decarbonation compared to neat PC

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# Binder compositions used in concrete tests

| BINDER COMPOSITIONS (kg/m$^3$) | | | | | | | % $CO_2$ (decarb) | |
|---|---|---|---|---|---|---|---|---|
| | Total kg/m$^3$ | PC | B2 | Slag | Anhydrite | Lime | | Binder Remark |
| ix 1 | 300 | 0 | 300 | 0 | 0 | 0 | 60% | B2 only |
| ix 2 | 300 | 0 | 150 | 150 | 0 | 0 | 30% | 50% B2; 50% ggbs |
| ix 3 | 300 | 300 | 0 | 0 | 0 | 0 | 100% | PC only |
| ix 4 | 300 | 150 | 0 | 150 | 0 | 0 | 50% | 50 % PC; 50% ggbs |
| ix 5 | 300 | 0 | 120 | 150 | 30 | 0 | 24% | 40% B2; 10% Anhydrite; 50% ggbs |
| ix 6 | 300 | 0 | 90 | 150 | 60 | 0 | 18% | 30% B2; 20% Anhydrite; 50% ggbs |
| ix 7 | 300 | 0 | 114 | 150 | 30 | 6 | 23% | 38% B2; 10% Anhydrite; 2% Lime; 50% ggbs |
| ix 8 | 300 | 0 | 144 | 150 | 0 | 6 | 29% | 48% B2; 2% lime; 50% ggbs |
| ix 9 | 300 | 0 | 84 | 150 | 60 | 6 | 17% | 28% B2; 20% Anhydrite; 2% lime; 50% ggbs |

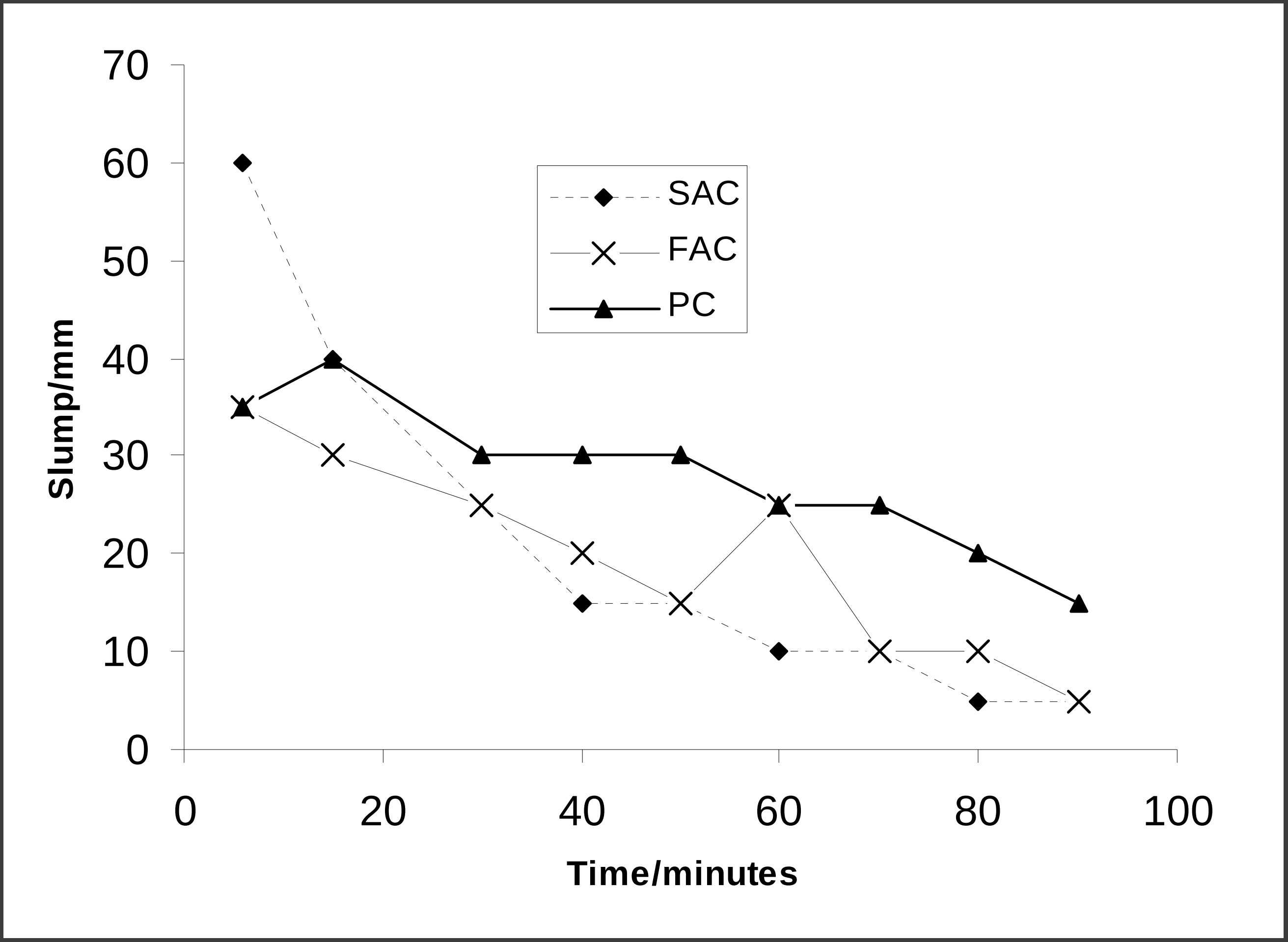
The OPC used for comparison was a CEM I - 42.5R.

“%$CO_2$ decarb” represents RM-$CO_2$ as a percentage of that of the OPC

# Concrete – observations on fresh properties

- Premature stiffening (5 -1 0 minutes).
- Rework of concrete produced small periods of workability.

# Concrete – observations on fresh properties




Slump against time for CSA and PC concrete

# Concrete – observations on hardened concrete

- Standard curing regime – 24 hours under damped hessian.
- Thereafter in standard water immersion curing.

- Cubes left in the dedicated water tank developed a sticky white slimy deposit on their surfaces, which could be scraped off easily.
- The deposit was analysed and found to be ettringite.

- Hardened concrete failed in compression tests conventionally.

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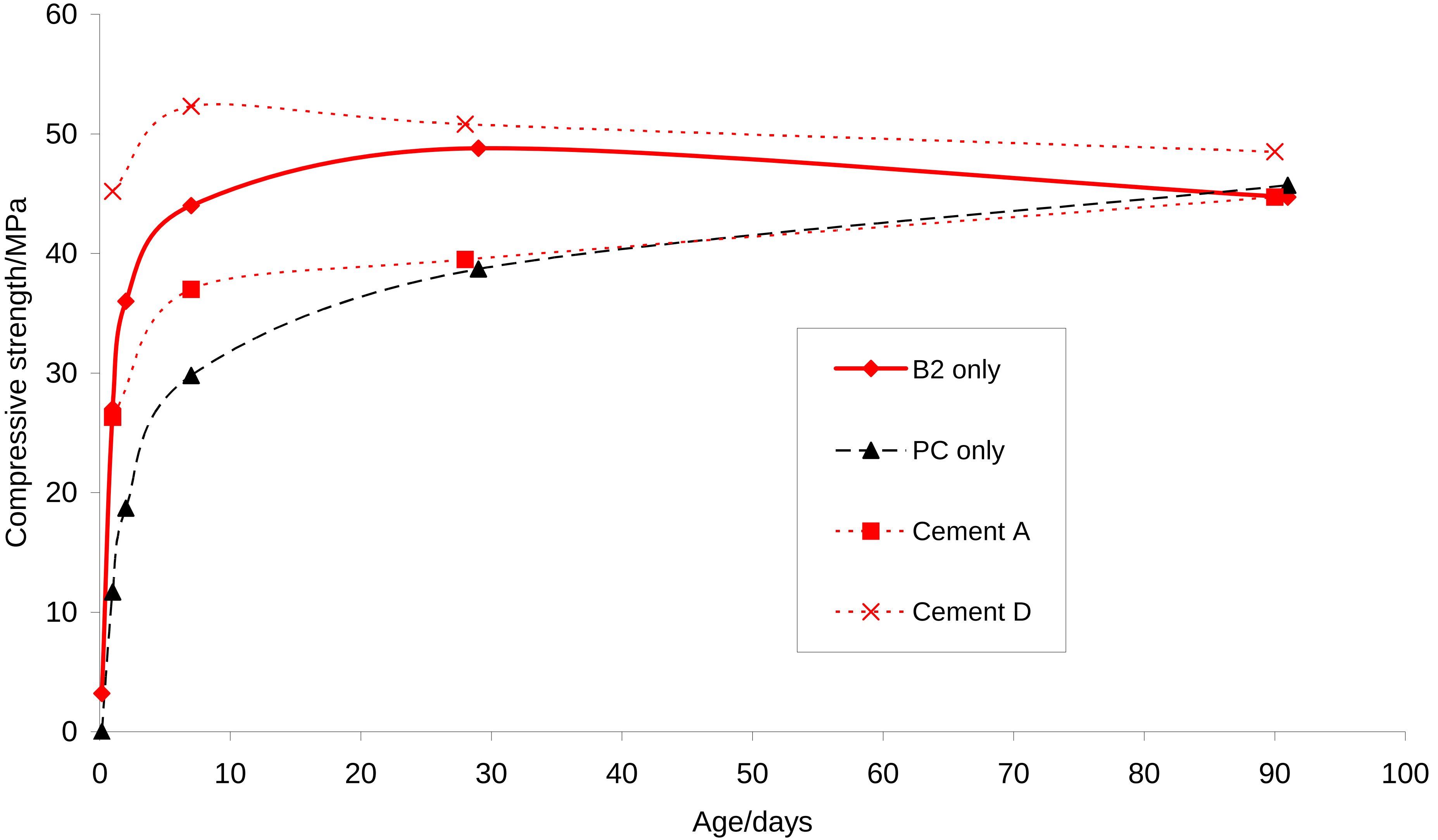
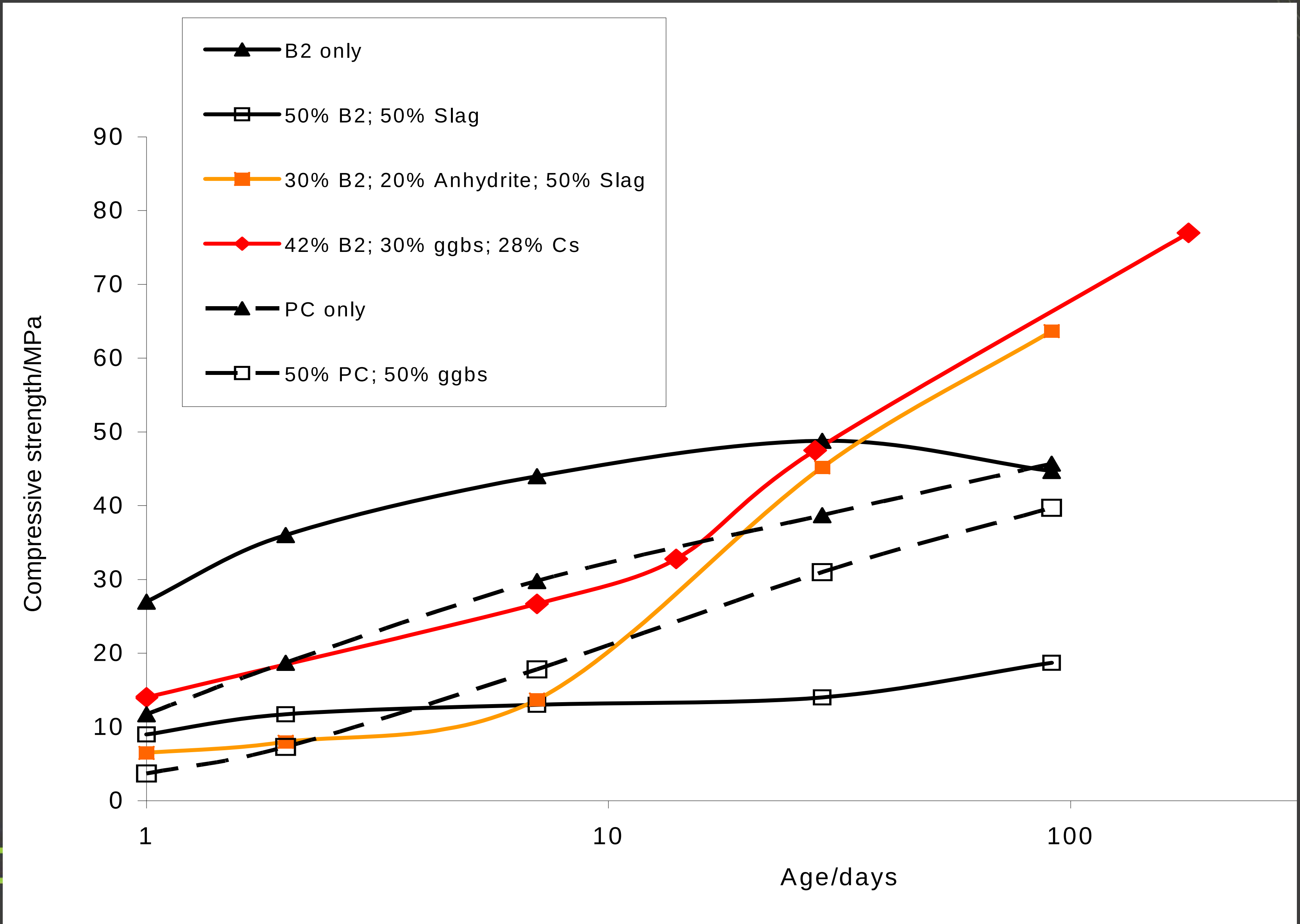
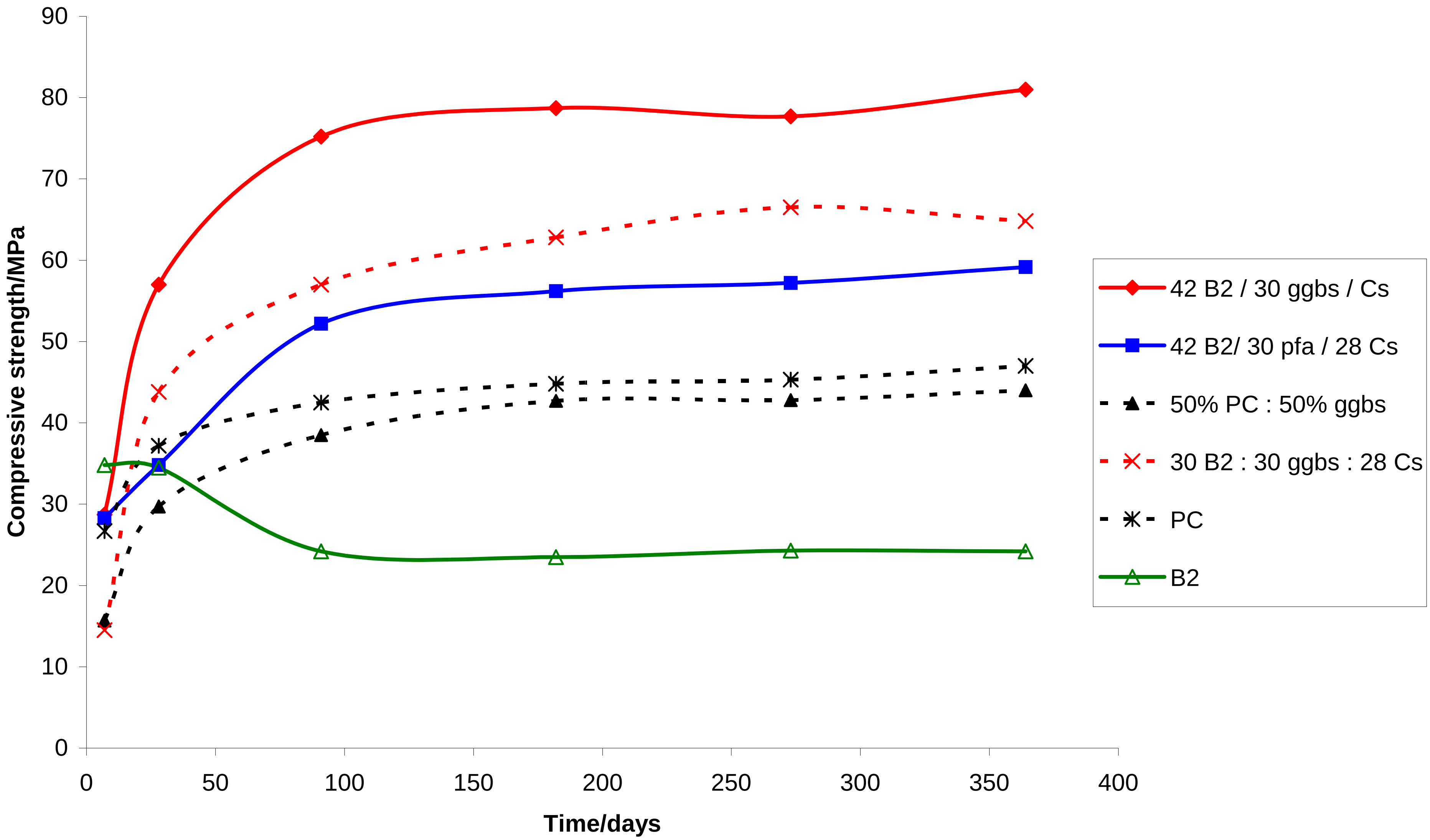
# Compressive strength development in neat CSA concrete (cement content = 300kg/m$^3$; w/c = 0.55)



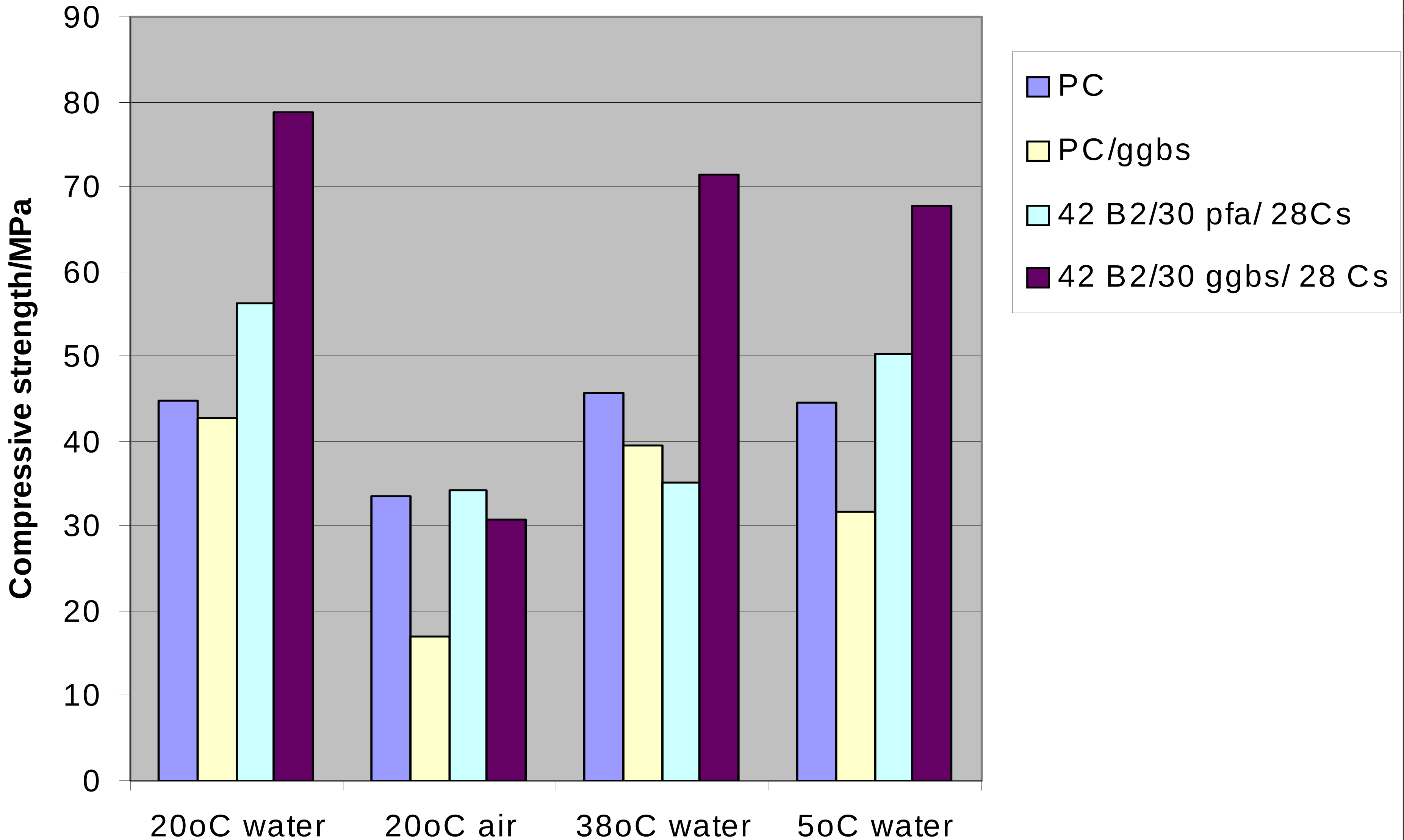
# Compressive strength development in blended CSA concrete (cement content = 300kg/m$^3$; w/c = 0.55)



# Compressive strength development in concretes made using B2/ggbs/Cs and B2/pfa/Cs blends (cement content = 300kg/m$^3$; w/c = 0.55)



# Compressive strength at 180 days



# Effect of temperature and curing on strengths:

The mix design used was the same for all tests, with only the cement composition changed.
The total binder content was 300kg/m$^3$ throughout.
The free water: binder ratio was 0.55. No additives were used.

| | Neat PC (A05/5135) | | | |
|---|---|---|---|---|
| Mix number | 5135 | 5135 | 5135 | 5135 |
| **Age/days** | **20°C water** | **20°C air** | **38°C water** | **5°C water** |
| **7** | 26.7 | | | |
| **28** | 37.2 | 30.2 | 36.5 | 30.0 |
| **91** | 42.5 | | | |
| **182** | 44.8 | 33.5 | 45.7 | 44.5 |

| | 42 B2: 30 ggbs: 28 Cs (A05/5140-5142) | | | |
|---|---|---|---|---|
| Mix number | 5140 | 5141 | 5141 | 5142 |
| **Age/days** | **20°C water** | **20°C air** | **38°C water** | **5°C water** |
| **7** | 28.7 | | | |
| **28** | 57.0 | 31.8 | 47.8 | 38.5 |
| **91** | 75.2 | | | |
| **182** | 78.7 | 30.7 | 71.5 | 67.8 |

| | 50PC: 50 ggbs (A05/5136) | | | |
|---|---|---|---|---|
| Mix number | 5136 | 5136 | 5136 | 5136 |
| **Age/days** | **20°C water** | **20°C air** | **38°C water** | **5°C water** |
| **7** | 15.67 | | | |
| **28** | 29.67 | 16.17 | 33.17 | 17.33 |
| **91** | 38.50 | | | |
| **182** | 42.67 | 17.00 | 39.50 | 31.67 |

| | 42 B2: 30 pfa: 28 Cs (A05/5143-5145) | | | |
|---|---|---|---|---|
| Mix number | 5143 | 5144 | 5144 | 5145 |
| **Age/days** | **20°C water** | **20°C air** | **38°C water** | **5°C water** |
| **7** | 28.3 | | | |
| **28** | 34.8 | 33.2 | 31.0 | 30.2 |
| **91** | 52.2 | | | |
| **182** | 56.2 | 34.3 | 35.2 | 50.3 |

# Carbonation depth by phenolphthalein test

- Depth in mm as measured on 75x75x200mm concrete prisms

- Accelerated carbonation
  - Specimens stored in water to 28 days followed by 28 days conditioning at 20° C and 65%RH prior to testing.

- Natural carbonation
  - Specimens not cured prior to exposure – carbonation rates for blends are therefore higher (especially unsheltered) than predicted from accelerated tests.

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# Carbonation depth by phenolphthalein test

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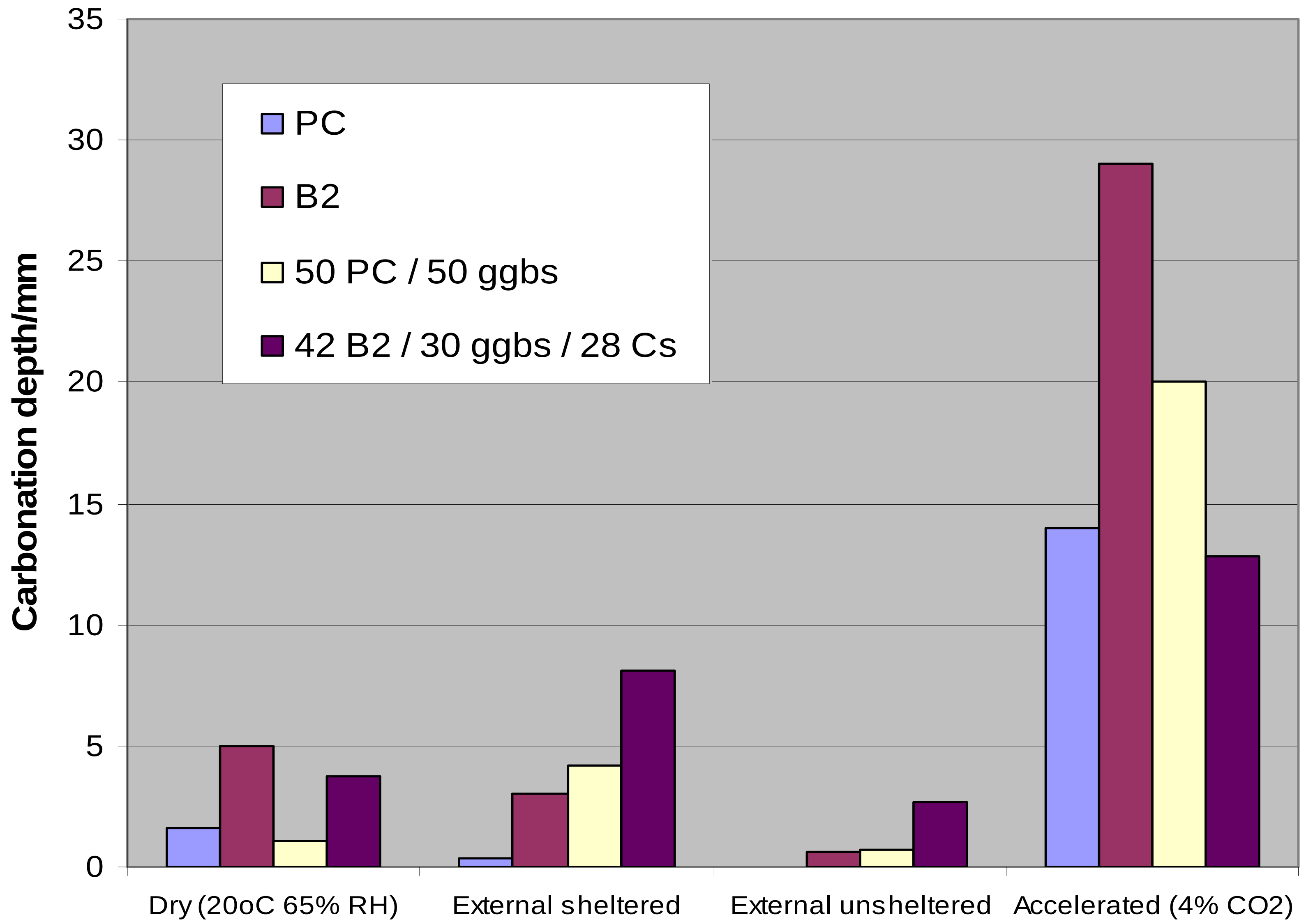
# Carbonation depth at 90 days



# Concrete expansion under water

Expansion on storage in water has been monitored for periods of up to 365 days using 75x75x200mm prisms which were cast with inserts to facilitate measurement. Mix designs are as with compressive strength and carbonation. Specimens were demoulded at 24 hours (initial measurement) and stored in water at 20$^{o}$C.

| Mix | Expansion at 182 days (%) | Expansion at 273 days (%) | Expansion at 365 days (%) |
|---|---|---|---|
| Neat B2 (A05/5134) | 0.041 | 0.046 | 0.058 |
| Neat PC (A05/5135) | 0.008 | 0.020 | 0.025 |
| 50% PC: 50% ggbs (A05/5136) | 0.017 | 0.023 | 0.023 |
| 30% B2: 50% ggbs: 20% anhydrite (A05/5139) | 0.048 | 0.065 | 0.079 |
| 42% B2: 30% ggbs: 28% anhydrite (A05/5142) | 0.014 | 0.021 | 0.12 |
| 42% B2: 30% pfa: 28% anhydrite (A05/5142) | 0.024 | 0.029 | 0.032 |

# Principal results of concrete test

- On its own, CSA-rich clinker is not a good activator for conventional SCMs
- However, combinations of CSA with calcium sulfate (but not with lime) show good strength development properties when combined with GGBS.
- Concrete tests of this type of blend show no significant expansion in water over 9 months and a rate of carbonation higher than OPC but not extreme.
- Theoretical $CO_2$ savings can be > 70% vs. pure OPC.

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# Precast trial – paver manufacture

- 30% B2 / 50% ggbs / 20% Cs used
- Preliminary laboratory work identified suitable admixture to control setting
- Produce Concrete Block Paving in a standard production environment
  - Produce concrete in production sized forced action pan mixer
  - Hold concrete in holding hopper
  - Convey concrete to block plant via belt-feed
  - Vibro-compact concrete in a block machine to form Concrete Block Paving
  - Cure the produced CBP in standard curing chambers at 27$^{o}$C & 85% humidity)

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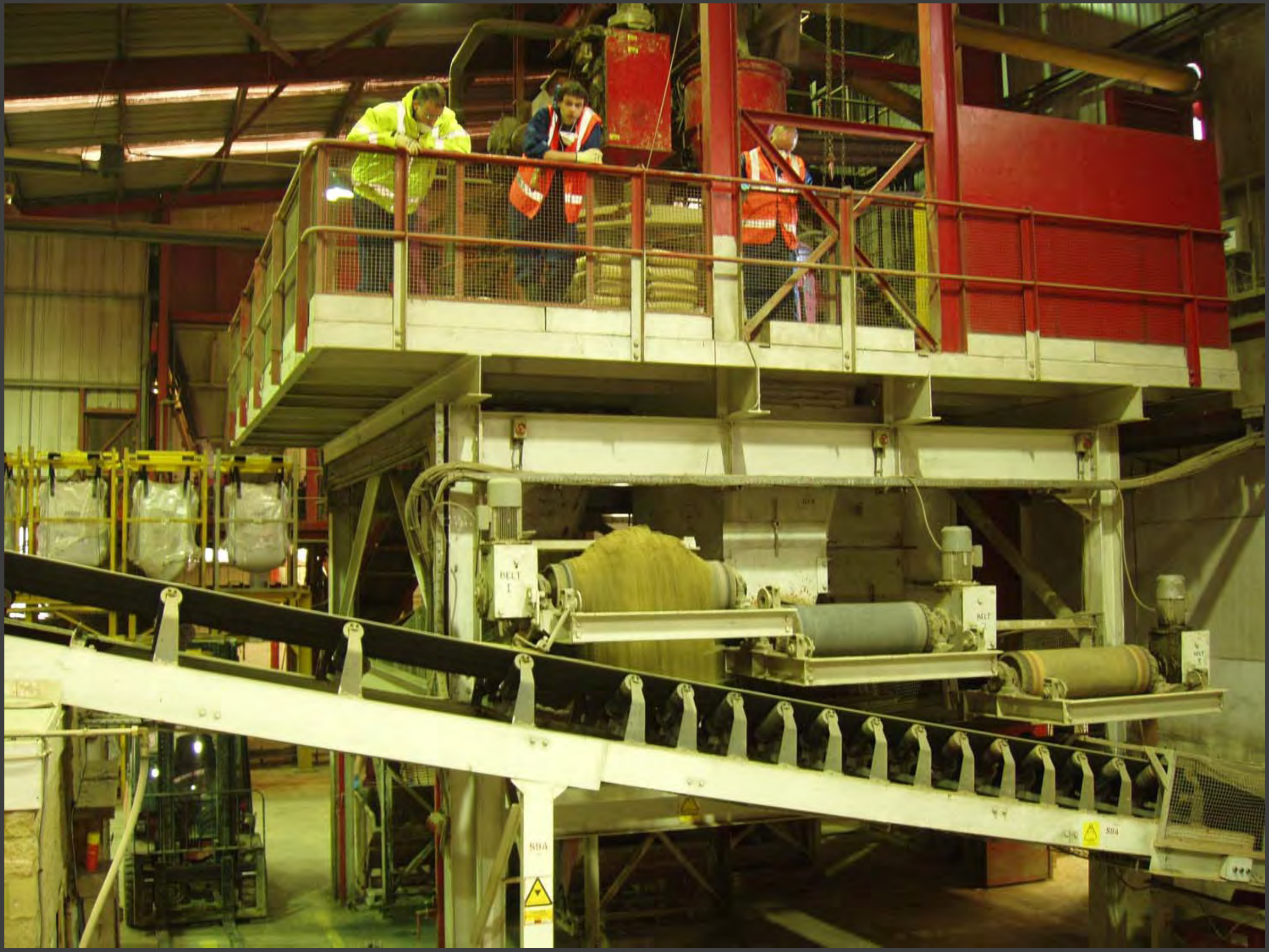
# Paving Blocks made from the CSA/slag/anhydrite blend
**(courtesy of Ian Ferguson, Marshalls, UK)**



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# Paving Blocks made from the CSA/slag/anhydrite blend
**(courtesy of Ian Ferguson, Marshalls, UK)**

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# Precast trial – paver manufacture

- Finished product subjected to conformance testing to BS EN 1338:
  - Strength
  - Water Absorption
  - Polishing (Polished Paver Value)
  - Skid Resistance (Unpolished Skid Resistance Value)
  - Abrasion (Wide Wheel Abrasion)
  - Durability (Freeze / Thaw)

- Trial went very well
  - Wear, freeze/thaw, slip risk and wear resistance were all excellent
  - Nice buff colour!

# Lafarge Central Research novel Belite-CSA-Ferrite (BCSAF) cements

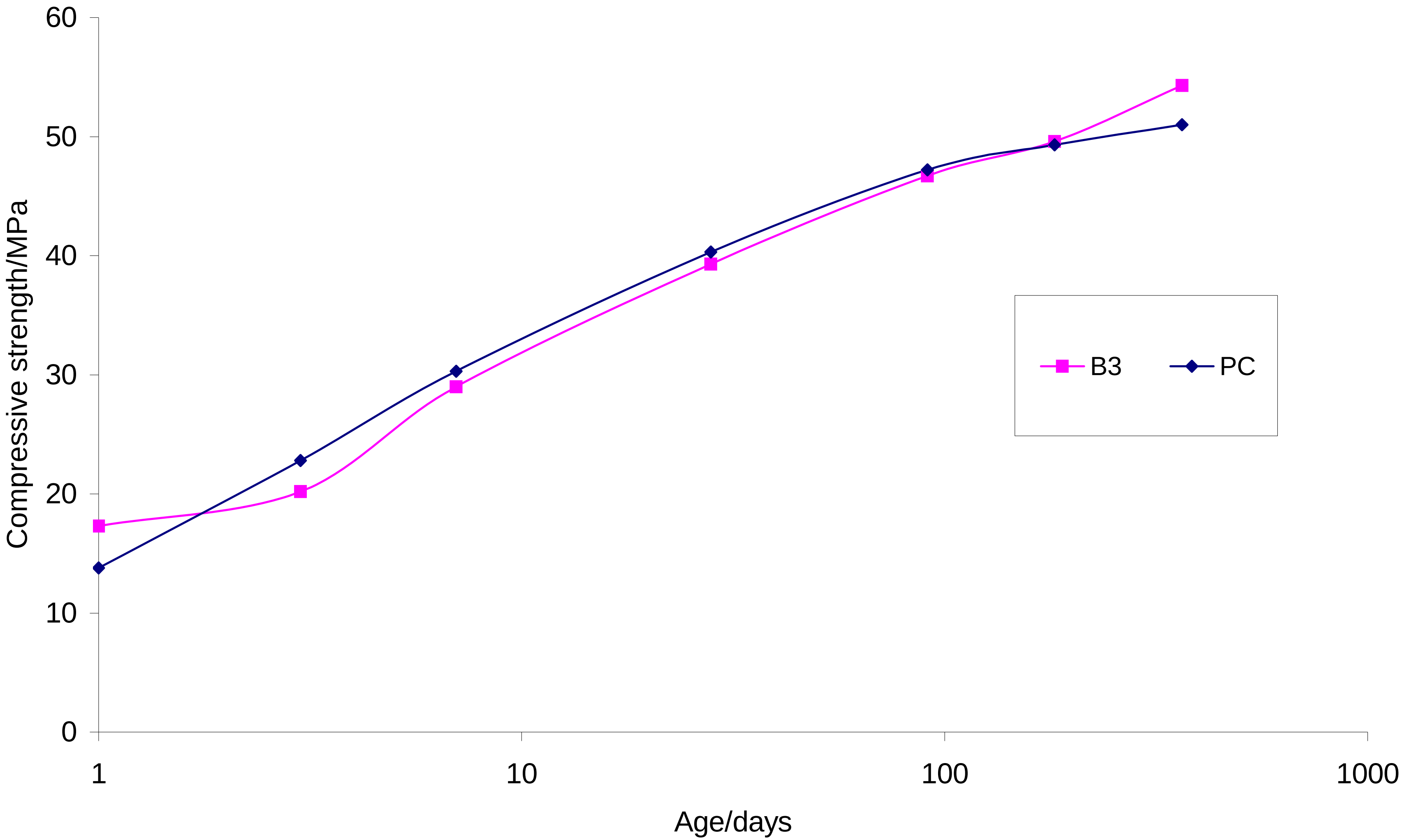
- LCR approach was to attempt to produce clinkers that would perform at least as well as those claimed in the Mehta patent but based on realistic raw materials.

- Certain combinations of minor elements allowed significant activation of the belite phase.

- The ferrite phase also appears to be somewhat reactive, as was previously reported by Mehta.

bre

# BRE concrete data at w/c = 0.55, 300kg/m$^3$ for pilot batch of BCSAF (B3) compared to OPC (CEM I 42.5)



# BRE concrete data at w/c = 0.55, 300kg/m$^3$ for pilot batch of BCSAF (B3) compared to OPC (CEM I 42.5)

Initial durability tests:

- Freeze/thaw comparable to PC/pfa blends
- Reinforcement corrosion
- Sulfate attack
- Carbonation
- Dimensional stability

XRD shows that the following hydrates are present in carbonated concrete:

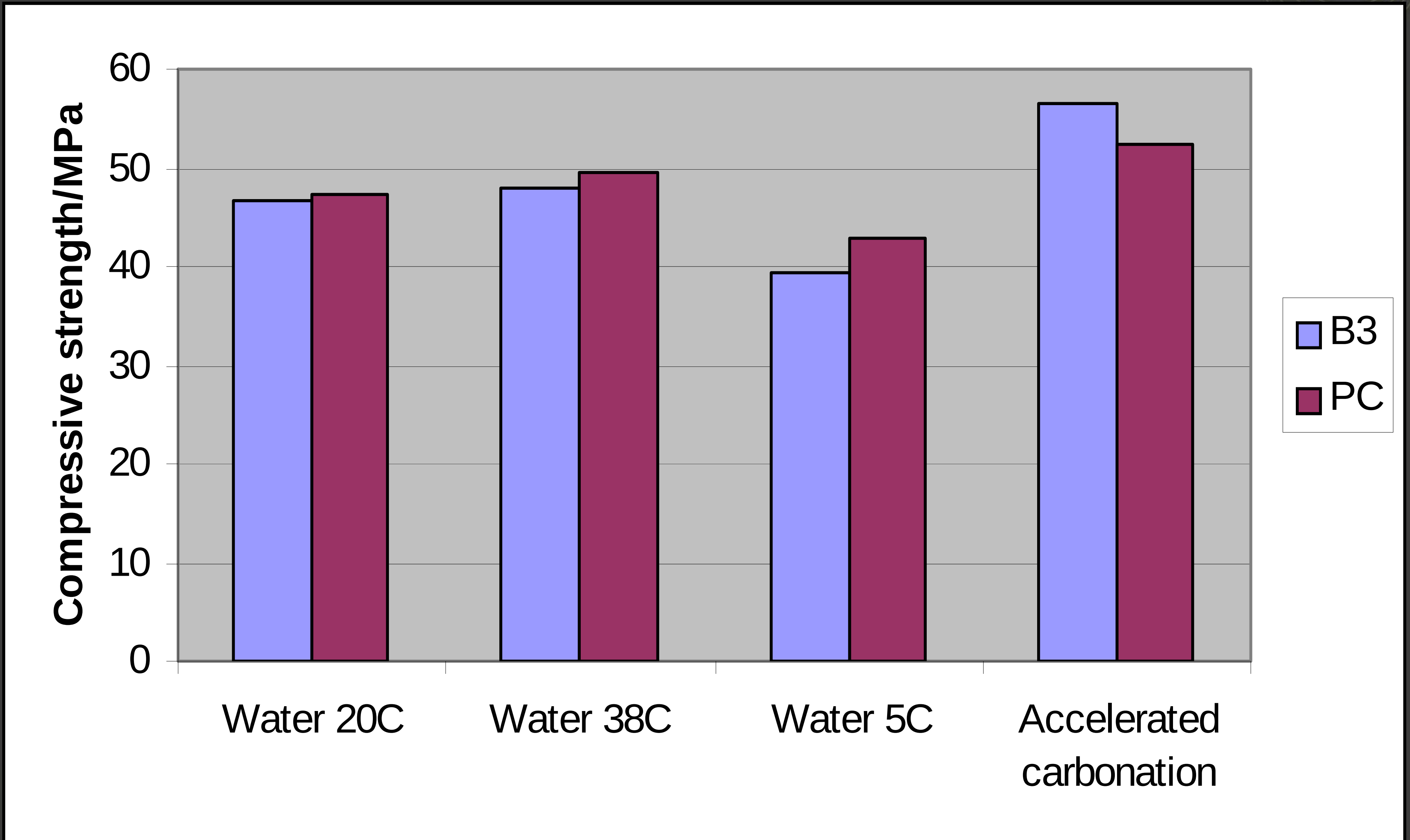
Ettringite

$C_4Ac_{0.5}H_{11.5}$

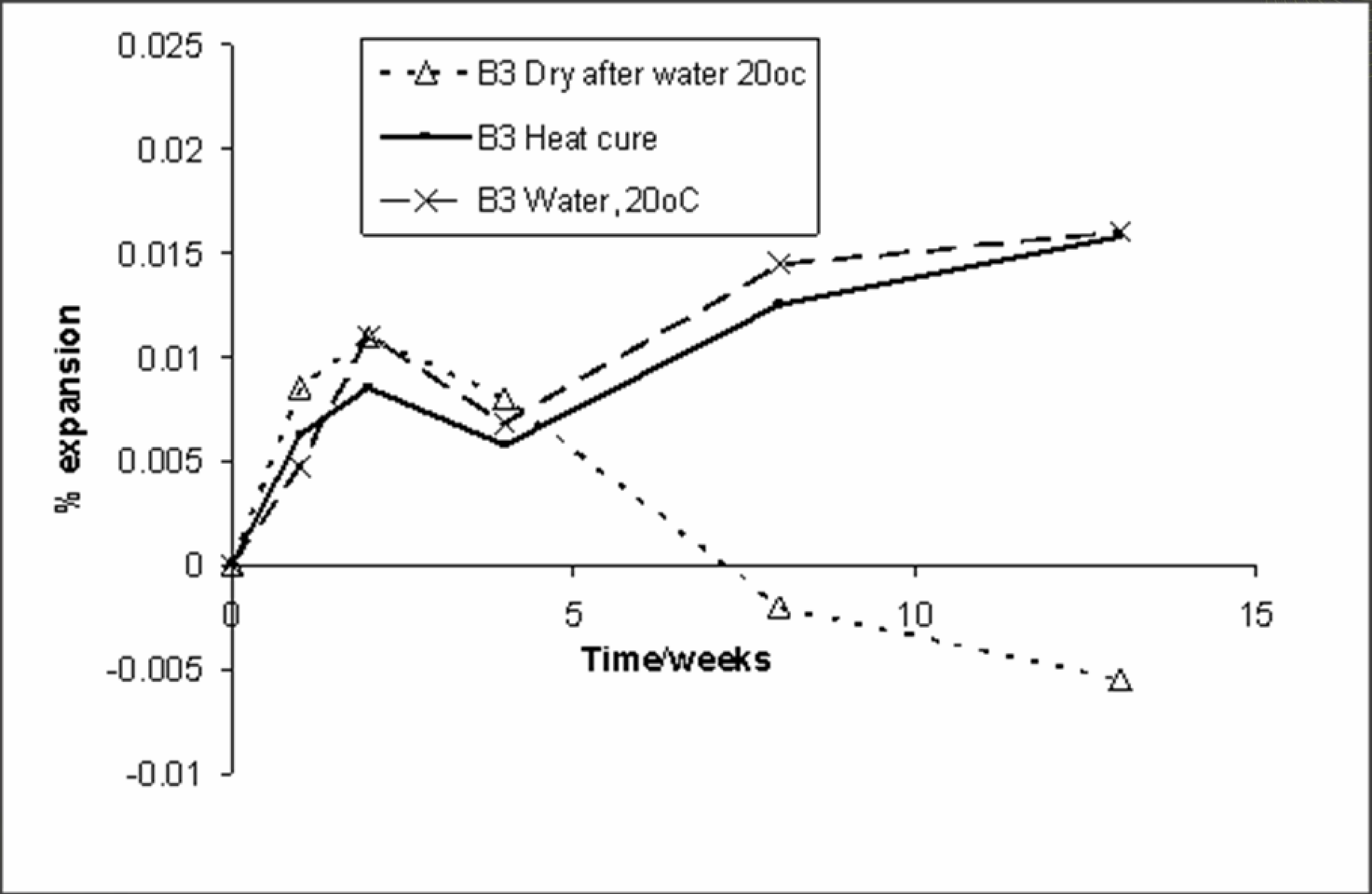
$C_4AcH_{11}$ or gypsum

Calcite and quartz are also present

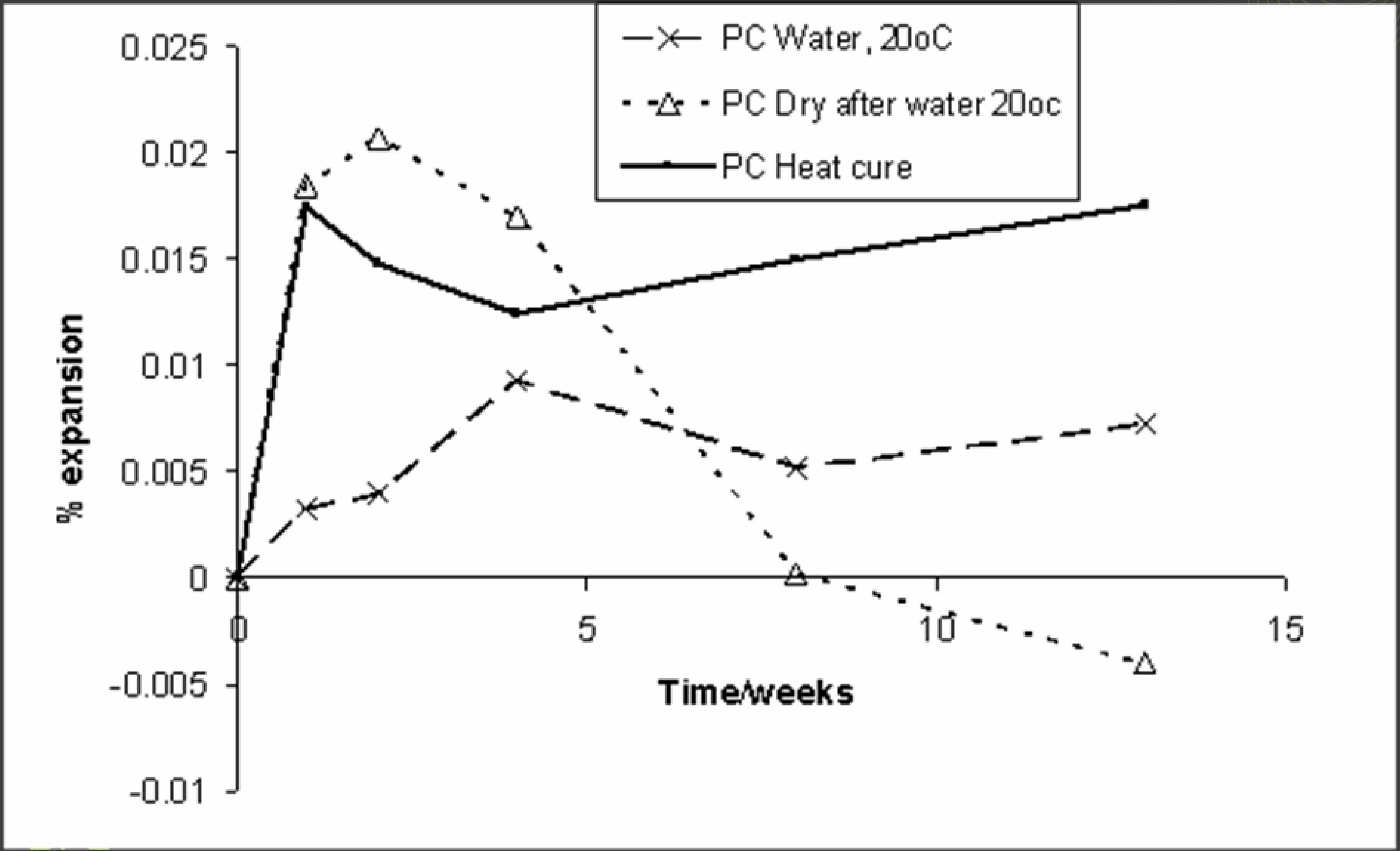
# Effect of curing/storage conditions on B3 concrete (after 91 days)



# Dimensional stability in B3 concrete



# Dimensional stability in PC concrete



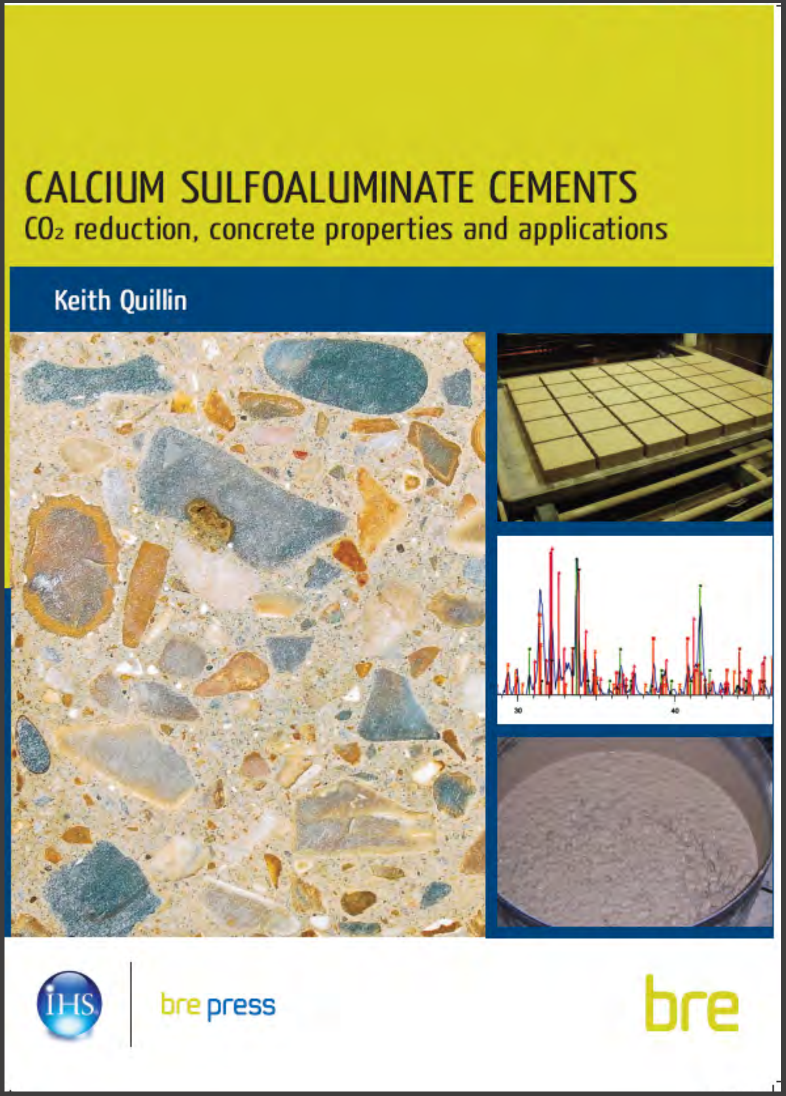
# CONCLUSIONS

- To have the potential to significantly reduce global $CO_2$ emissions from cement manufacture 'Low carbon' cements must:
  - Be able to produce concrete with appropriate physical and durability properties
  - Be based on widely available raw materials (even if the materials are available, transportation costs can be high).
- Cements based on $C_4A_3\check{S}$ plus ferrites, calcium sulfates and either GBFS or activated belite are a promising option. They can tolerate high sulfate contents and hydrate to form mainly ettringite, C-S-H & AFm phases.
- Significant reductions in $CO_2$ emissions relative to Portland cement
- Preliminary concrete tests of two alternative approaches to this have shown promising strength and durability results
- Much more work is needed to establish data for Codes and Standards etc.

bre

# ‘Calcium sulfoaluminate cements’, BR496

- Includes work on UK Carbon Trust-funded programme on belite-calcium sulfoaluminate cements
- Also includes earlier BRE work on CSA cements



# Acknowledgements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