# Developing Fly Ash for Use in Concrete: Overview of UK University Research

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# Forty Years Fly Ash Research at Dundee

## Main Researchers

Prof. R. K Dhir: 40 years

Dr. M. R. Jones: 28 years

Dr. M. J. McCarthy: 22 years

## Main Thrust of Research

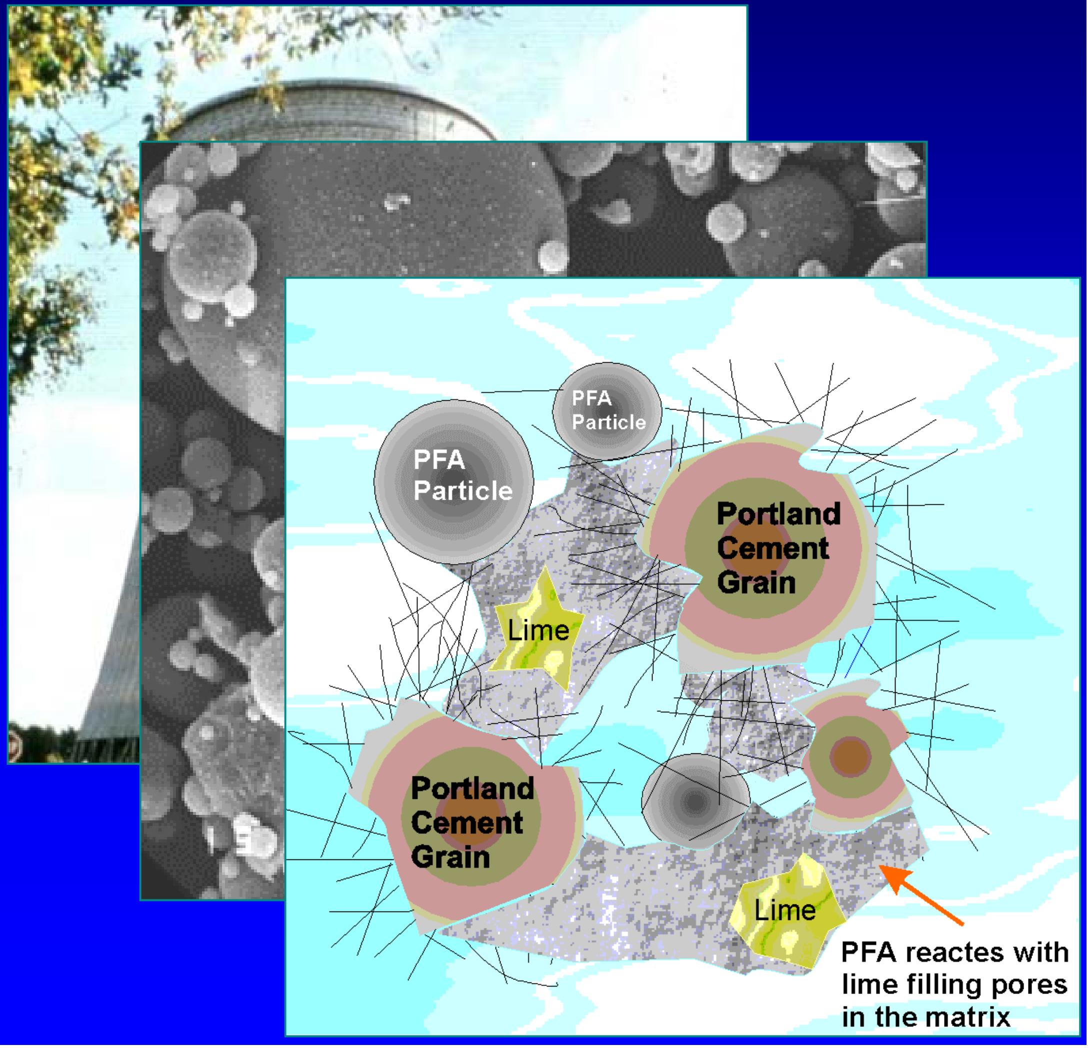
1. Developing simple Fundamental Concepts
2. Developing Challenging Fly Ash Applications
3. Dissemination of New Knowledge

# Main Thrust of Dundee Research

1. **Developing Simple Fundamental Concepts**
   - 1.1 Fly Ash
     - 1.1.1 BS 3892:Part 1 PFA
     - 1.1.2 EN 450 Fly Ash
     - 1.1.3 Conditioned/Lagooned Fly Ash
     - 1.1.4 Stockpiled/Landfilled Fly Ash
     - 1.1.5 Co- Combustion Fly Ash
   - 1.2 Enabling Low $CO_2$ Emission cements
     - 1.2.1 Low Energy Cements
     - 1.2.2 High Volume Fly Ash Cements
   - 1.3 High performance Fly Ash
2. **Developing Challenging Fly Ash Applications**
   - 2.1 General Use in Concrete
   - 2.2 High Performance Concrete
   - 2.3 Chloride resistant Concrete
   - 2.4 Minimising ASR with EN 450 / CFA
   - 2.5 Fly Ash Mortar
   - 2.6 Foam Concrete
   - 2.7 Sulfate resisting Grout
   - 2.8 Activated Sand
   - 2.9 Lime Stabilised Soils with Fly Ash
3. Multi Blend Cements with Fly Ash

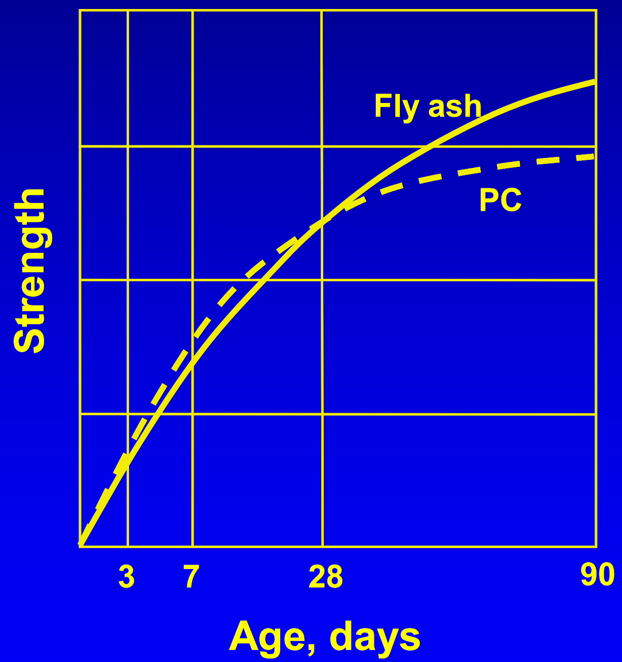
# 1.1 What is Fly Ash?

- **Fly Ash (FA) is the particulate materials produced at coal fired power stations.**
- **Spherical particles, in range < 1 μm to 150 μm.**
- **Pozzolanic materials, reacting with water and lime to form cementitious compounds.**

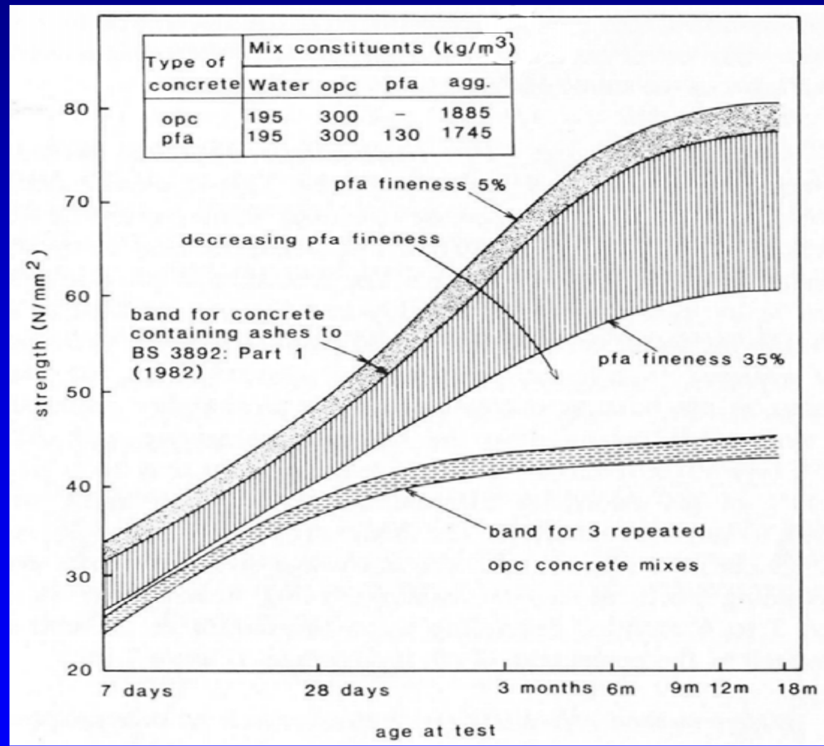


# 1.1.1 Fly Ash: All Grades and BS3892, Part 1 PFA

## Strength Development with Age




**Designed at equal 28 day strength**




**Strength development with additional fly ash in concrete mixes**

## Enhanced long-term strength development

# Standards

1965: BS 3892. FA as fine aggregate.

1982: BS 3892,Part1. FA as cement component.

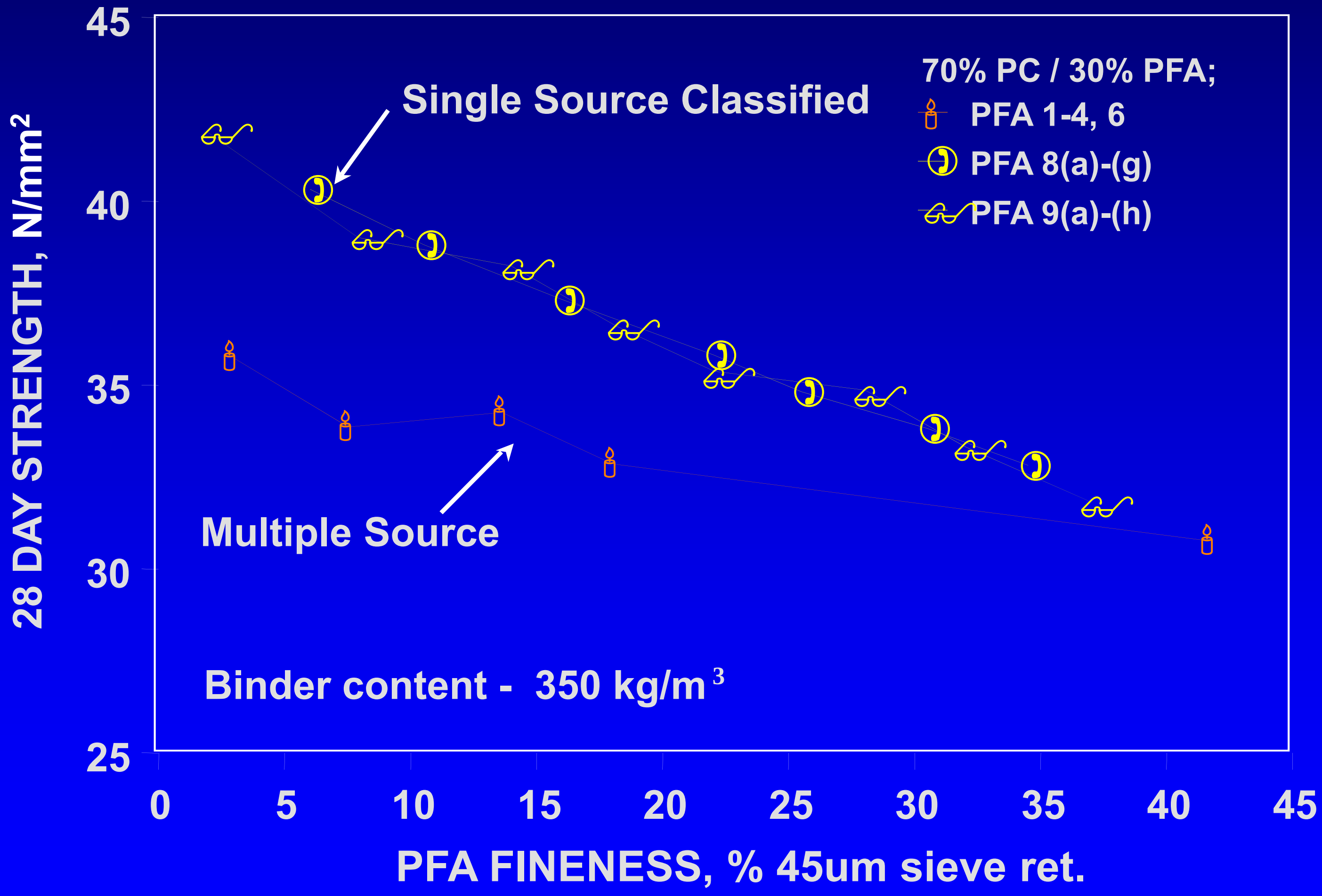
1995: BS EN 450. Wide range FA, in particular fineness, as cement component.

2000: BS EN 197-1. Wide range materials as cement component.

2005: BS EN 450 (revised). Includes co-combustion FA.

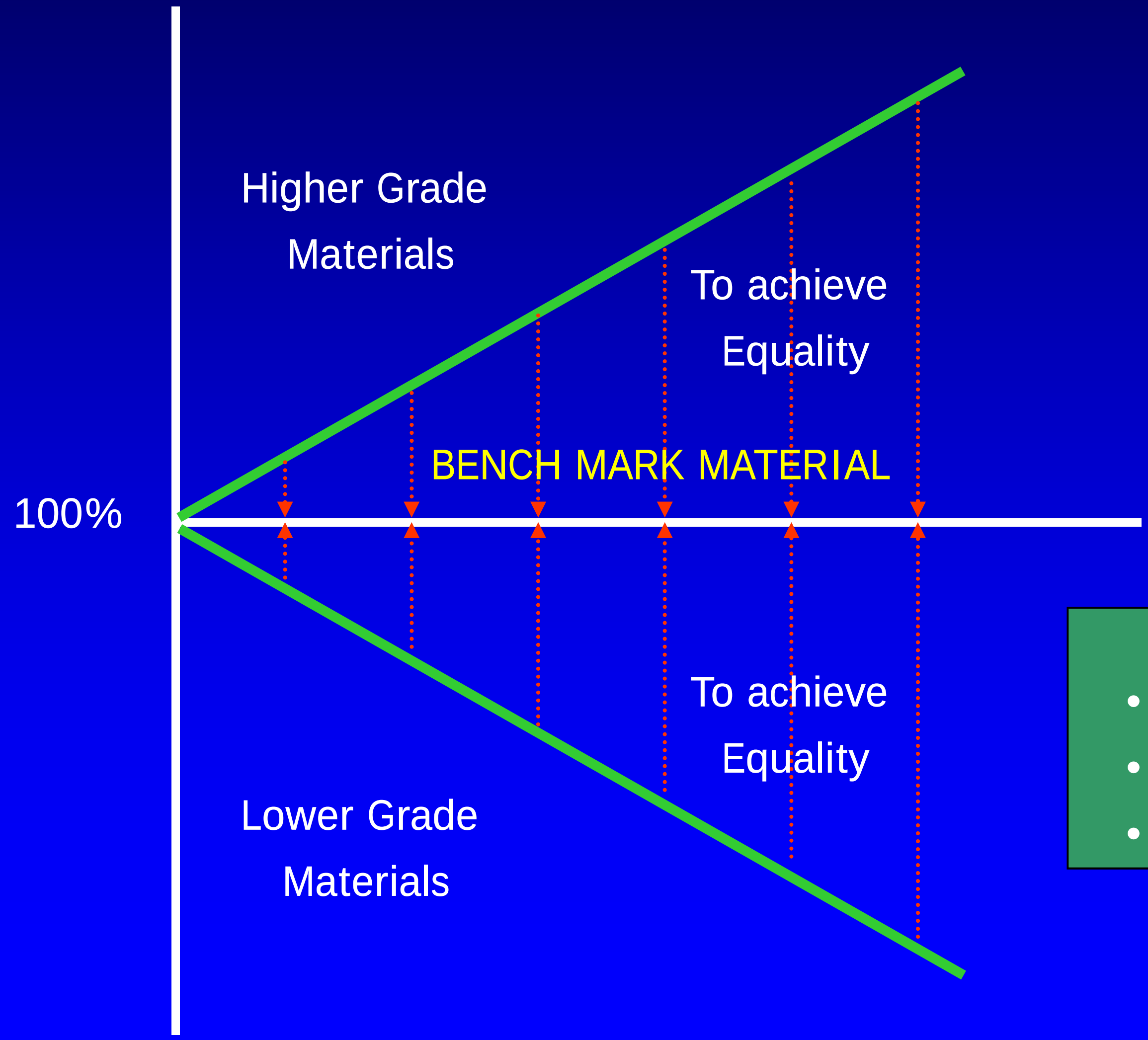
# 1.1.2 BS EN 450 Fly Ash

## Single and Multiple Sources



# 1.1.2 BS EN 450 Fly Ash

Appropriate and Sustainable use of PFA, based on Equal Performance

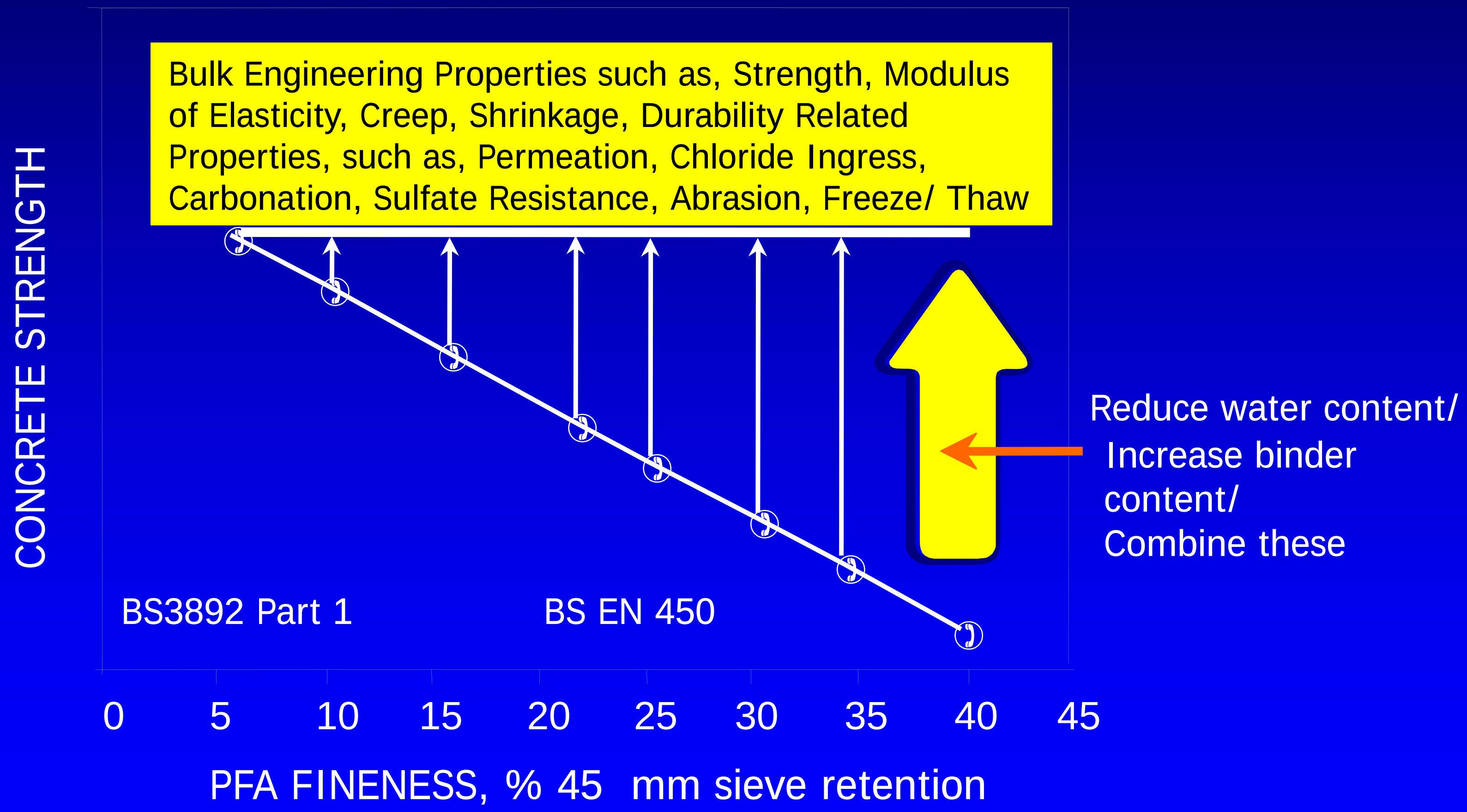



Important Considerations

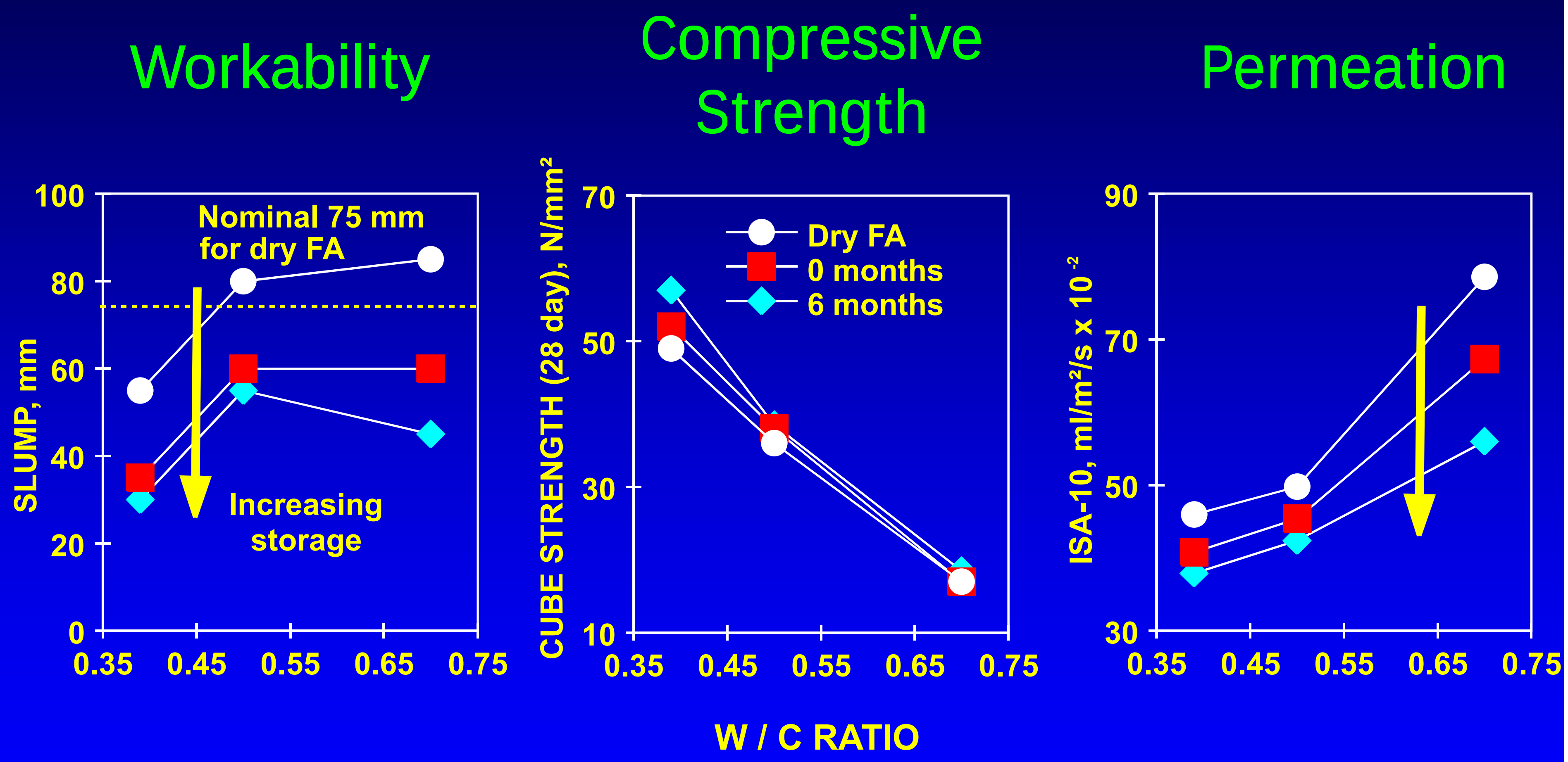
- Mix Design
- Cost
- Performance

# 1.1.2 BS EN 450 Fly Ash

## Achieving Equal Performance



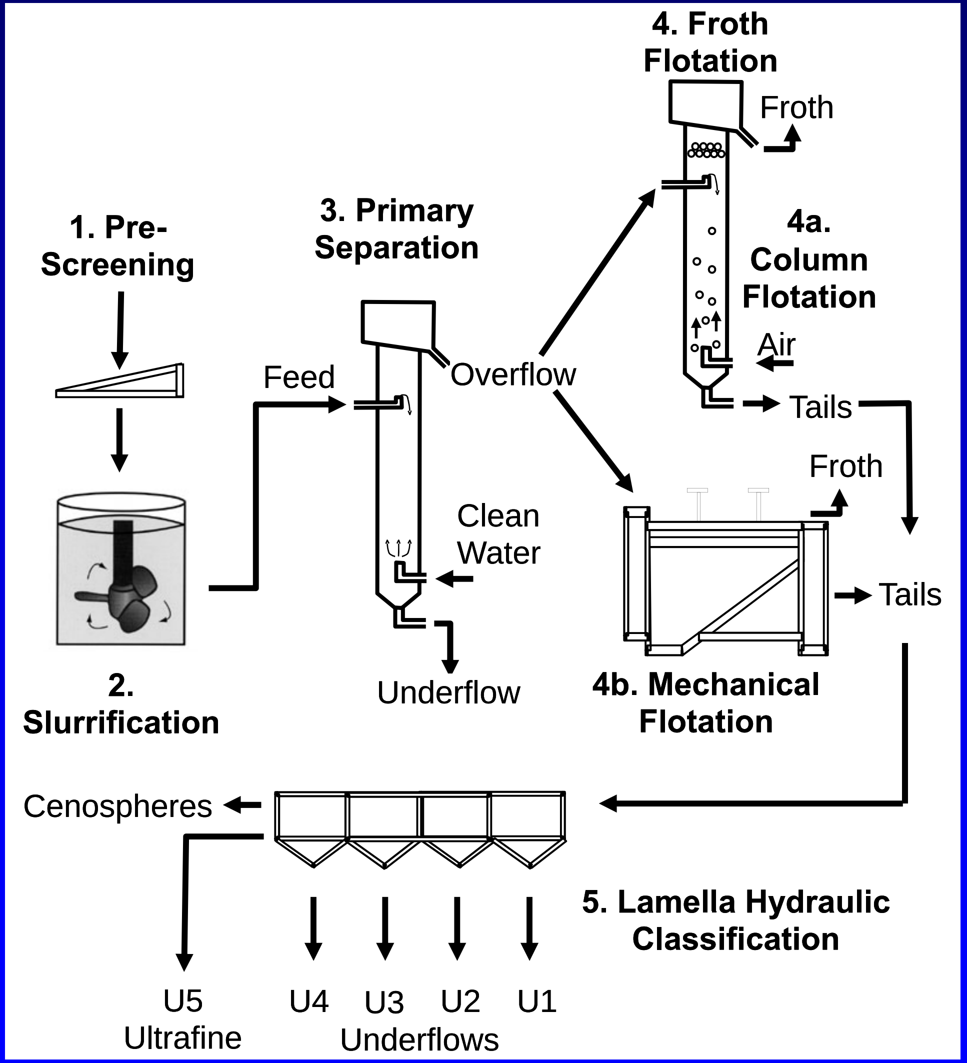
# 1.1.3 Conditioned and Lagooned Fly Ash




30% FA level
Fine FA (10% moisture)

# 1.1.4 Stockpiled and landfilled Fly Ash

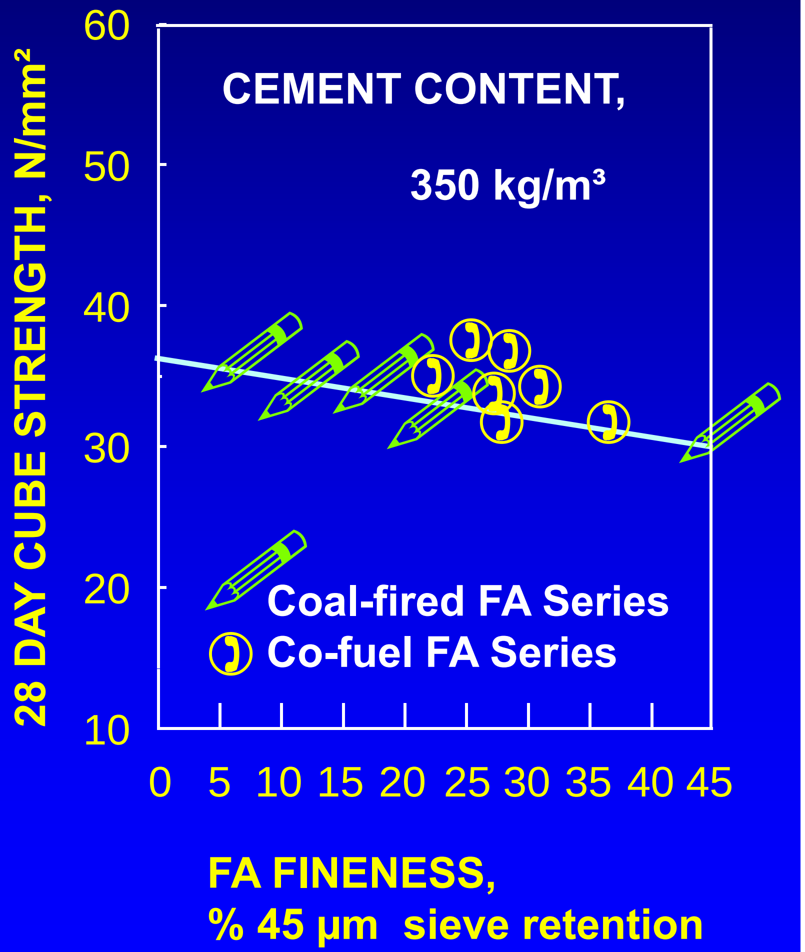
## Overview of Fly Ash Processing System



# 1.1.5 Co-Combustion Fly Ash

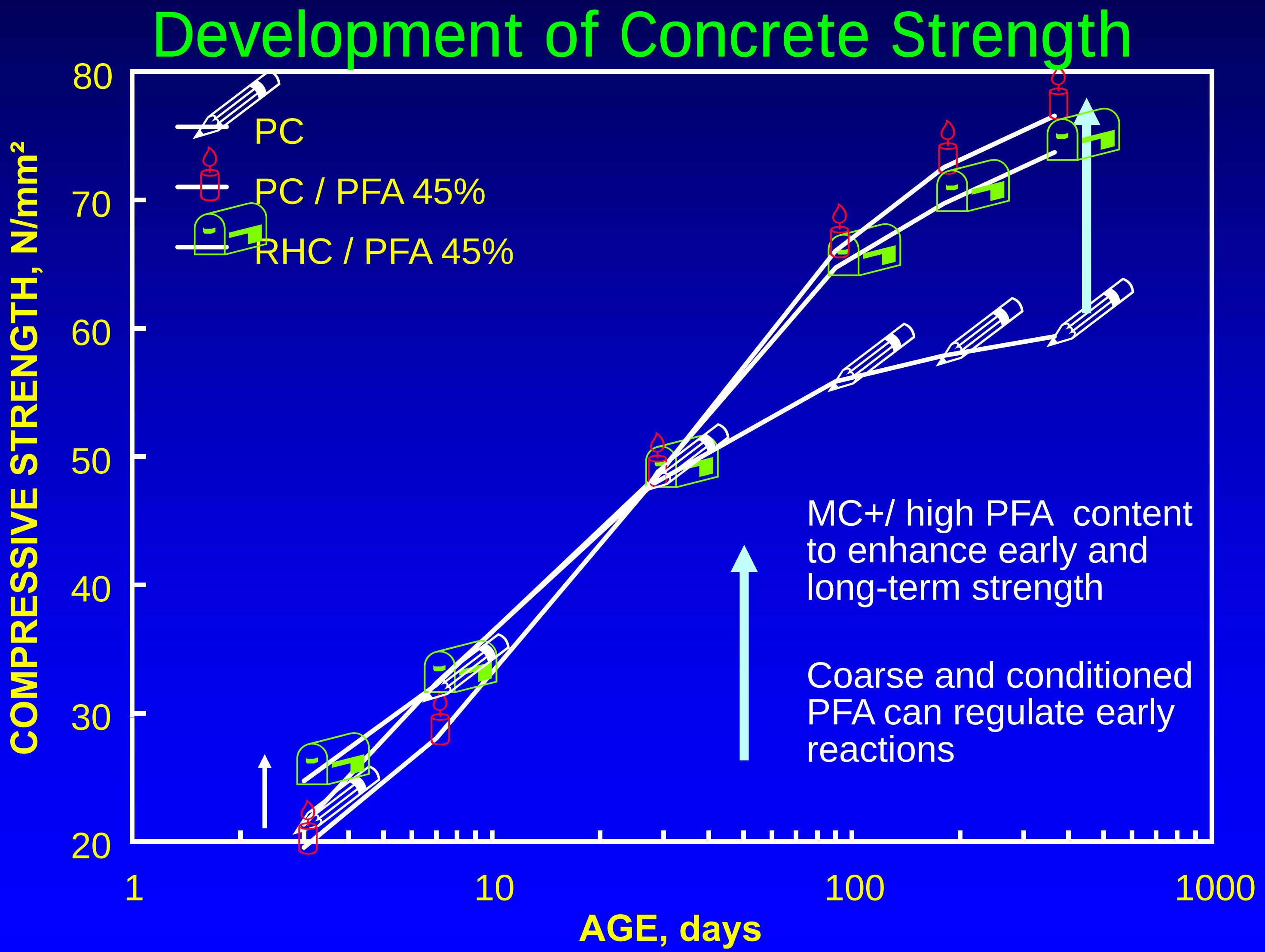
## Effect on Fly Ash and Concrete Strength

| CO-FUEL | FINENESS, % ret. 45 µm | | LOI, % | |
|---|---|---|---|---|
| | CA | CCA | CA | CCA |
| Meat/Bone Meal | 25.8 | 26.2 | 6.4 | 7.1 |
| Poultry Dung | 25.3 | 29.2 | 4.9 | 5.9 |
| Cocoa Shells | 23.0 | 21.1 | 4.0 | 4.2 |
| Sewage Sludge | 28.0 | 27.0 | 7.0 | 7.2 |



# Enabling Low $CO_2$ Emission Cements

# 1.2.1 Low Energy Cements




MC+ Mineralised Clinker

# 1.2.1 High Volume Fly Ash Cements

## Effect on Engineering Properties

| PROPERTY | DESIGN STRENGTH, $N/mm^2$ | CEMENT TYPE: PC | CEMENT TYPE: MC+/45FA |
|---|---|---|---|
| [1]Modulus of Elasticity, $kN/mm^2$ | | | |
| | 35 | 25.0 | 25.5 |
| | 50 | 28.5 | 29.0 |
| | 70 | 33.0 | 35.5 |
| [2]Drying Shrinkage, Microstrain | | | |
| | 35 | 490 | 465 |
| | 50 | 560 | 545 |
| | 70 | 600 | 600 |
| [1]Creep, Microstrain | | | |
| | 50 | 1200 | 600 |

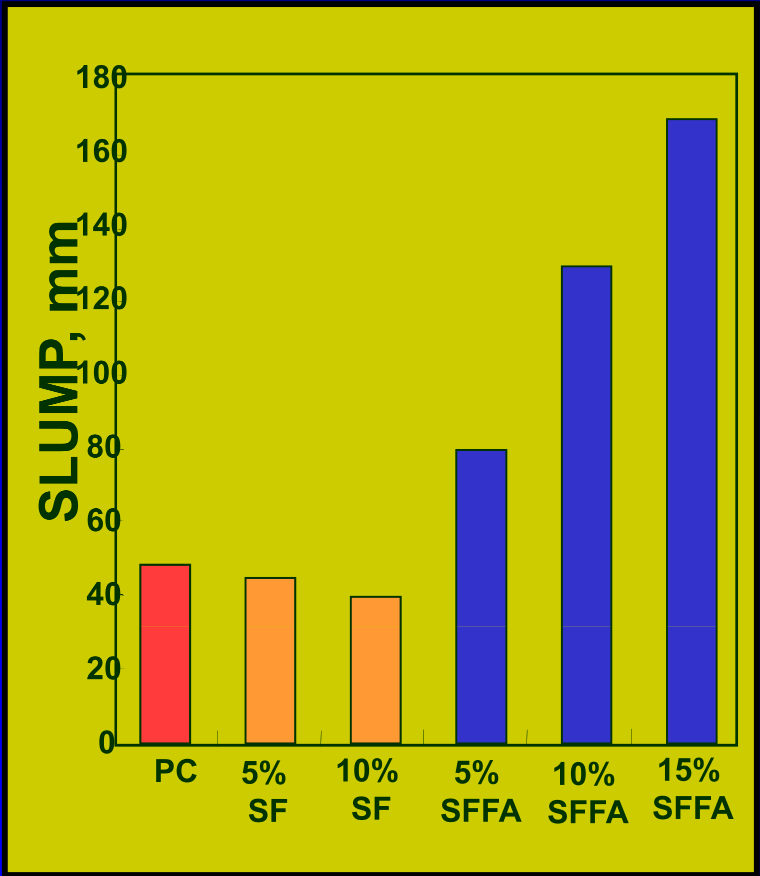
[1] test carried out at 28 days

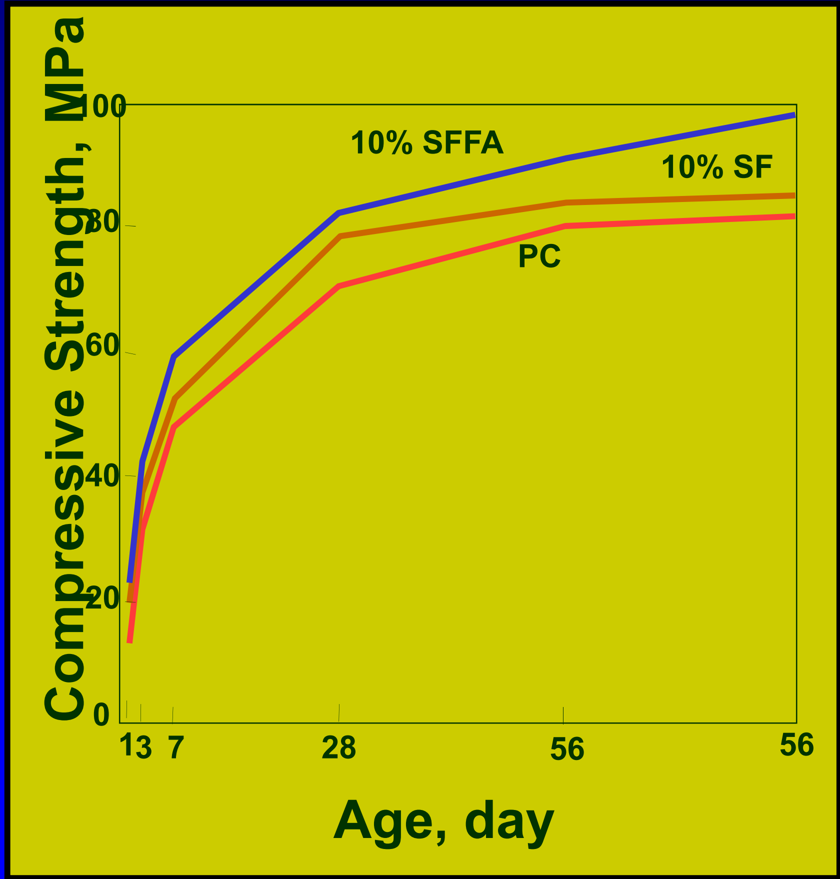
[2] 12 month result

**MC+ Mineralised clinker**

# High Performance Fly Ash

## **Improved** Fresh/Hardened Concrete Performance



# 2. Developing Challenging Fly Ash Applications in Concrete Construction

# 2.1 General Use in Concrete

- **Improved fresh properties**
- **Improved engineering properties**
- **Improved durability**

# 2.2 High Performance Concrete

| PROJECT | Year(s) | Location | Combination, % | Strength, N/mm2 | Main Requirement |
|---|---|---|---|---|---|
| Pacific First Centre | 1989 | United States of America | PC/FA9/SF6 | 124/56day | Ultra high long-term strength |
| Petronas Twin Towers | 1995 | Malaysia | PC/FA18/SF10 | 80 | High early and long-term strength |
| Tsing Ma Bridge | 1997 | Hong Kong | PC/FA25/SF5 | 50 | Chloride/ permeability resistance |
| Storebaelt Crossing | 1998 | Denmark | PC/FA10/SF5 | - | Chloride / sulfate / freeze-thaw |
| Bandra Worli Sealink | On-going | India | PC/FA25/SF7 | 60 | Chloride in marine exposure |
| Burj Dubai | 2004-2009 | United Arab Emirates | PC/FA25/SF7<br>PC/FA13/SF10 | 60<br>80 | Chloride / sulfate<br>Strength / workability |

# 2.3 Development of Chloride Resistant Concrete

**Chloride exposure classes (BS 8500)**

| | Class designation | Class description |
|---|---|---|
| | XD classes | Chlorides other than from sea water |
| Severity ↓ | XD1 | Moderate humidity |
| | XD2 | Wet, rare dry |
| | XD3 | Cyclic wet and dry |
| | XS classes | Chlorides from sea water |
| Severity ↓ | XS1 | Not in direct contact with sea water |
| | XS2 | Permanently submerged |
| | XS3 | Tidal, splash and spray zones |

**Designed w/c, water and cement contents for XS3 exposure**

| Cement Combination | W/C | Mix constituents, $kg/m^3$ | | | | | Estimete D $cm^2/s\times10^9$ | Estimate Strength $N/mm^2$ |
|---|---|---|---|---|---|---|---|---|
| | | Water | PC | FA | Total Cement | PC Savings | | |
| PC | 0.40 | 180 | 450 | – | 450 | – | 15.0 | 53 |
| 10% FA | 0.40 | 174 | 390 | 45 | 435 | 60 | 6.0 | 51 |
| 30% FA | 0.47 | 160 | 240 | 100 | 340 | 210 | 3.0 | 38 |
| 50% FA | 0.44 | 150 | 170 | 170 | 340 | 280 | 1.5 | 33 |

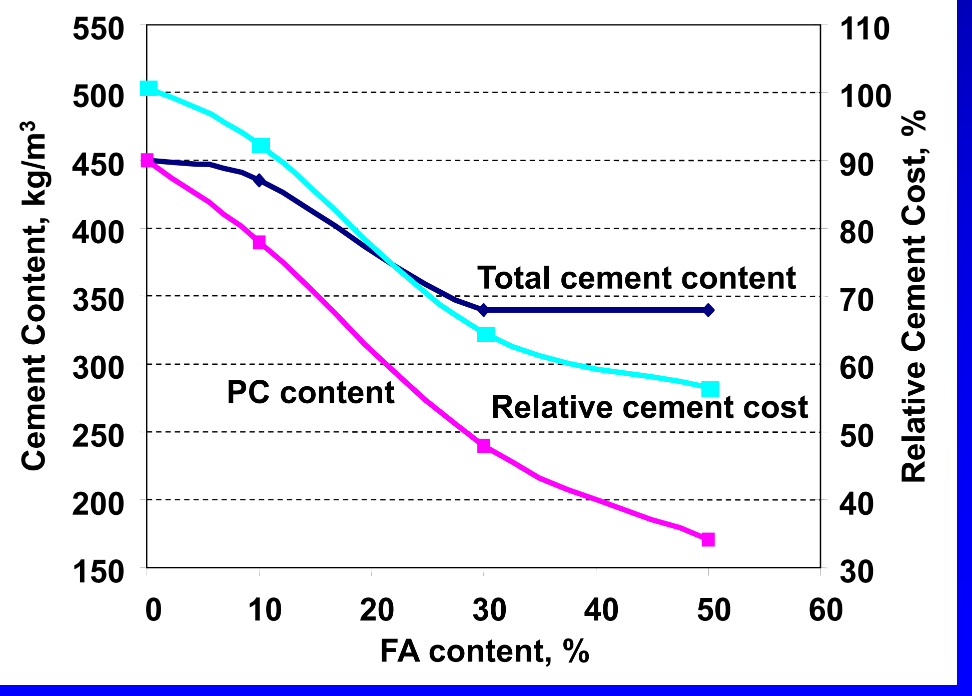
**FA cements grouping with respect to chloride exposure**

| | |
|---|---|
| Group 4 | CEM I, CEM I+(6%-20%)FA |
| Group 5 | CEM I+(21%-35%)FA |
| Group 6 | CEM I+(36%-55%)FA |

**Concrete required for XS3 with nominal cover = 50 + Δc**

| Cement Combination | Min. Strength | Max. w/c | Min. Cement $kg/m^3$ |
|---|---|---|---|
| PC (Group 4) | C50 | 0.40 | 380 |
| 10% FA (Group 4) | C50 | 0.40 | 380 |
| 30% FA (Group 5) | C35 | 0.50 | 340 |
| 50% FA (Group 6) | C30 | 0.50 | 340 |

***Relative cement cost analysis:***

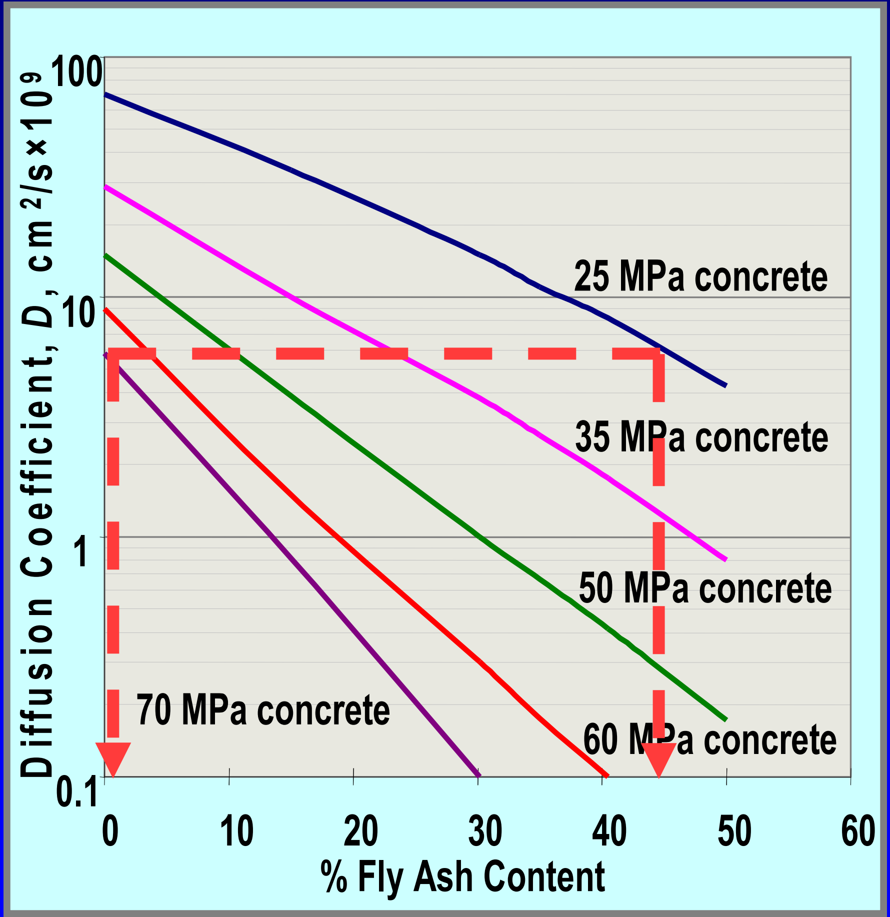



Assume Part 1 PFA price = 50% of PC price

RKD1

# Fly Ash: Durability of Concrete Improving Chloride Resistance

## Environmental and Economic Considerations




For equal chloride diffusion coefficient:

PC Concrete: 70 MPa

(w/c=0.30, PC=550kg/m$^3$, PFA=0kg/m$^3$)

PC55/FA45 Concrete: 25MPa

(w/c=0.60, PC=145kg/m$^3$, FA=125kg/m$^3$)

Potential for Cement Saving: 275 kg/m$^3$

**Slide 21**

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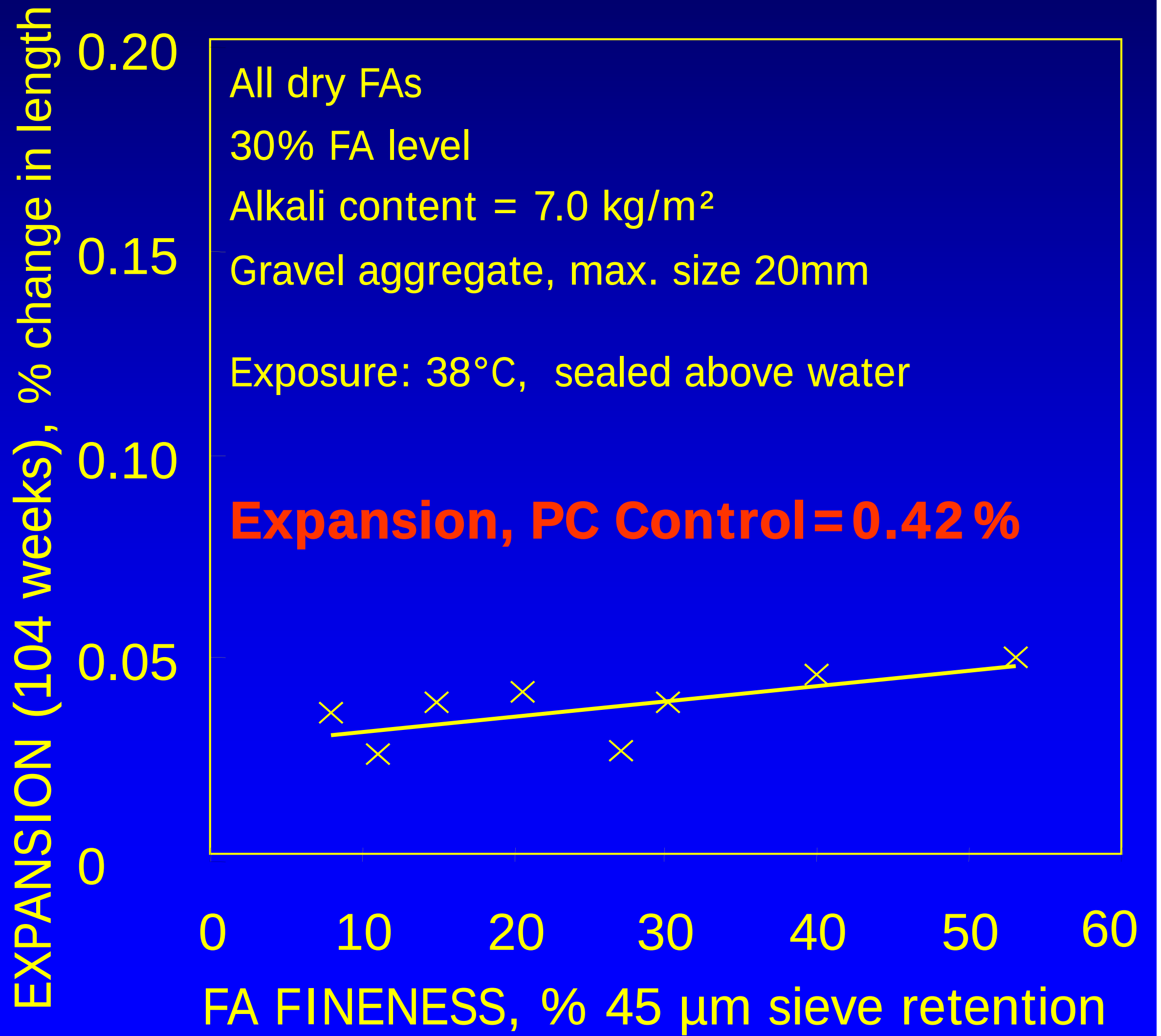
**RKD1** R K Dhir, 19/05/2009

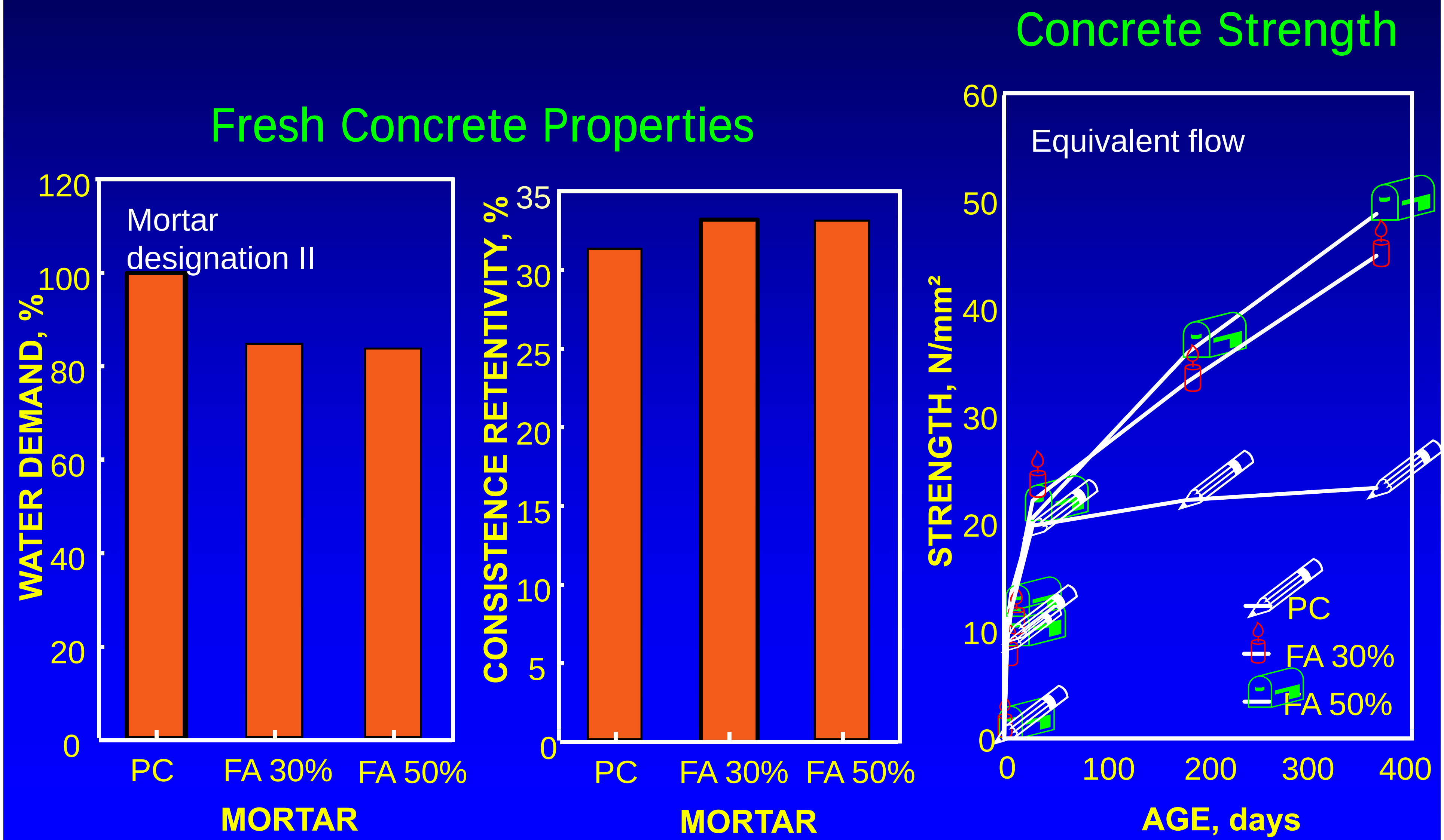
# 2.4 Minimising ASR with EN 450 FA/CFA

## Test Method – BS 812-123

## ASR Expansion of Concrete



# 2.5 Properties of Fly Ash Mortar

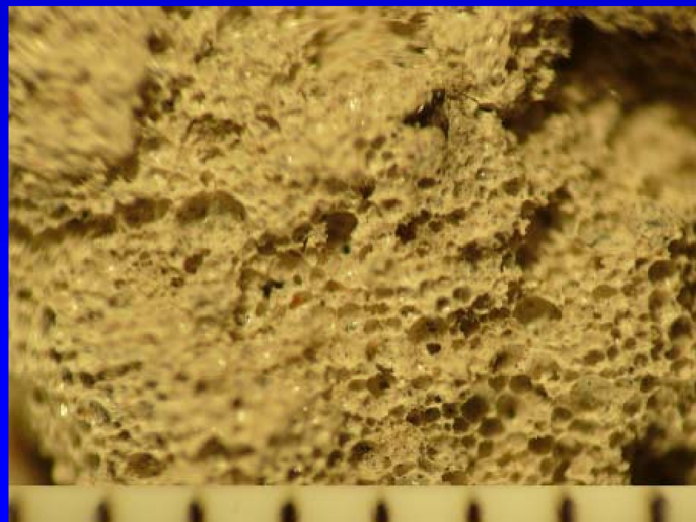


# 2.6 Foamed Concrete

| Foamed Concrete Mix[a] | Efflux Time, Second[b] | Cube Strength, N/mm² | | | | |
|---|---|---|---|---|---|---|
| | | 3 d | 7 d | 28 d | 56 d | 90 d |
| PC Ref | 50 | 1.2 | 1.4 | 1.7 | 1.9 | 1.9 |
| Raw Ash | 25 | 1.4 | 1.7 | 2.8 | 3.2 | 3.4 |
| U1 | 20 | 1.3 | 1.6 | 2.2 | 2.6 | 2.7 |
| U2 | 20 | 1.5 | 1.8 | 3.2 | 3.7 | 3.9 |

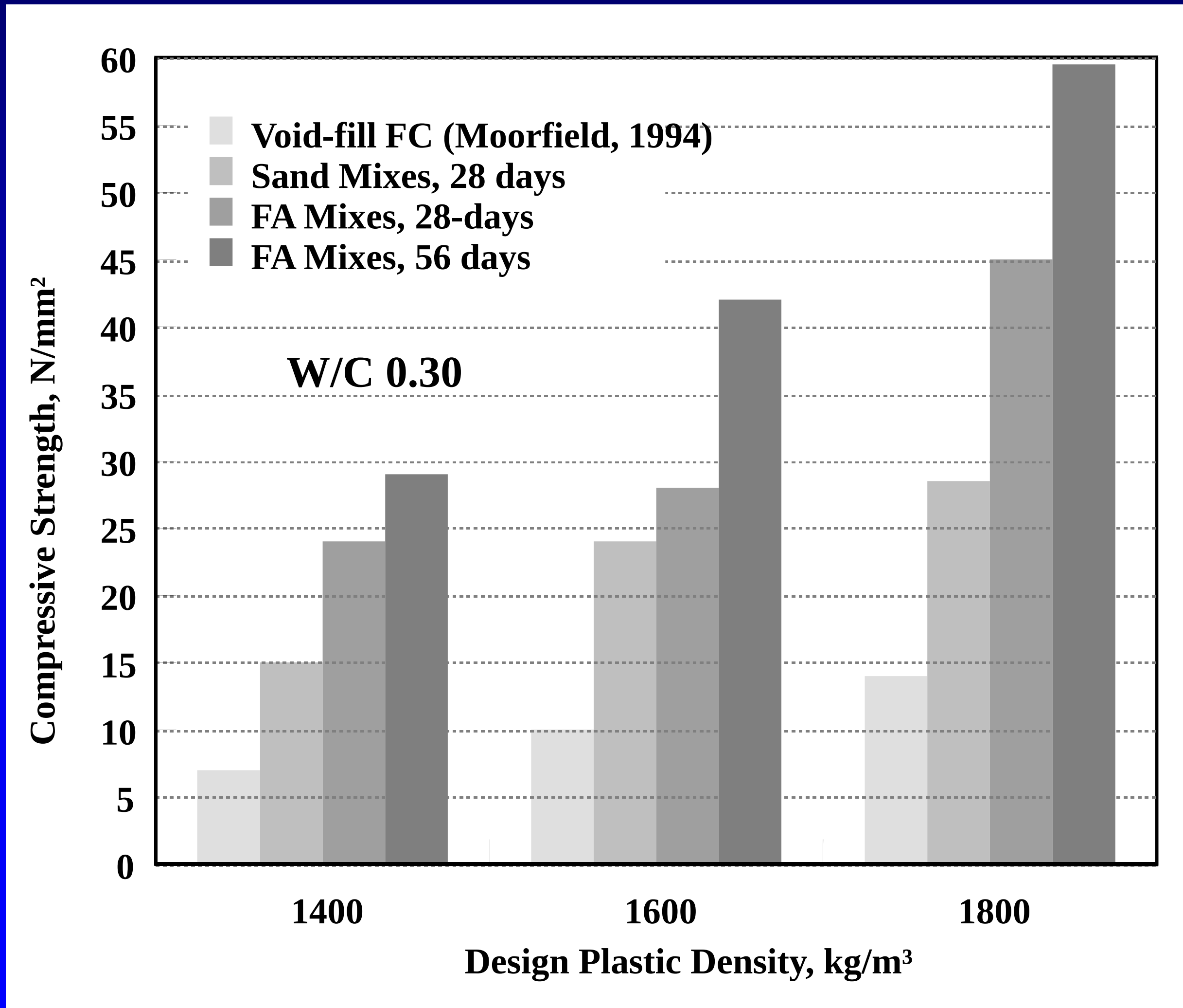
[a] Fly ash was used to replace sand at 50% by mass.

[b] <60 seconds: mix is flowing and self-compacting

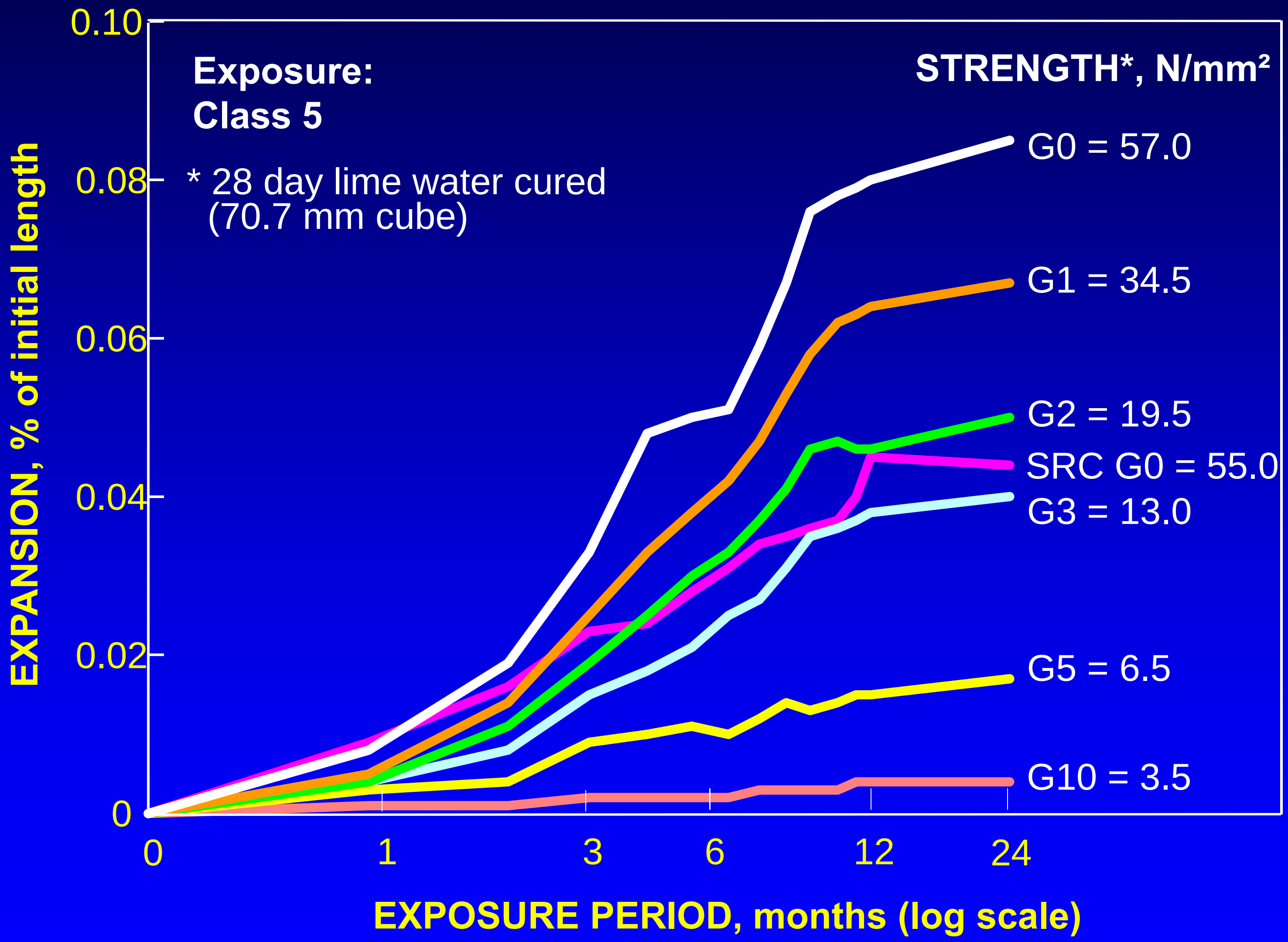


# 2.6 Foamed Concrete

## Effect of Fly Ash on Density/ Strength Relationship

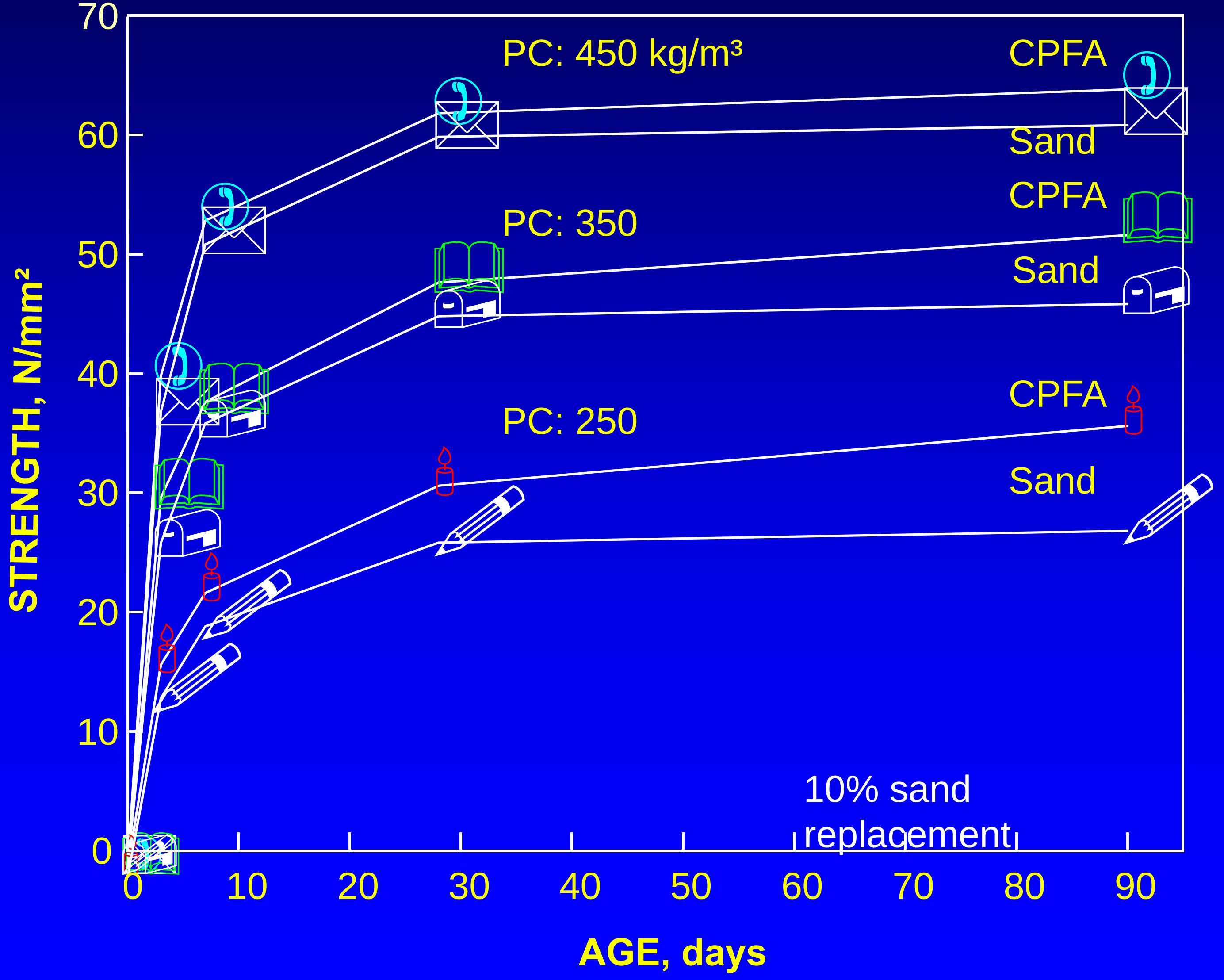


# 2.7 Sulfate Resisting Fly Ash Grout

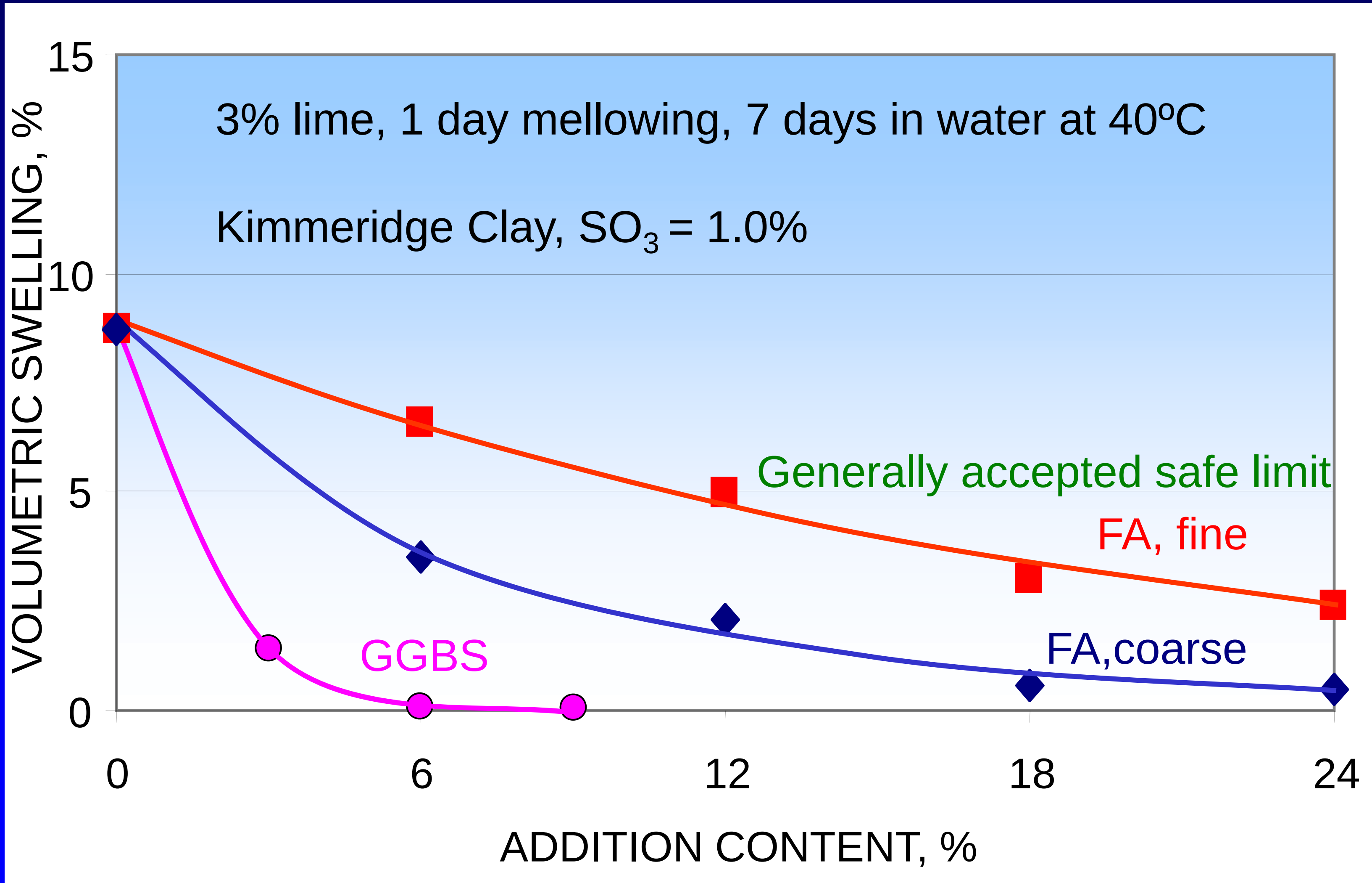


# 2.8 Conditioned Fly Ash Activated Sand

## Strength Performance



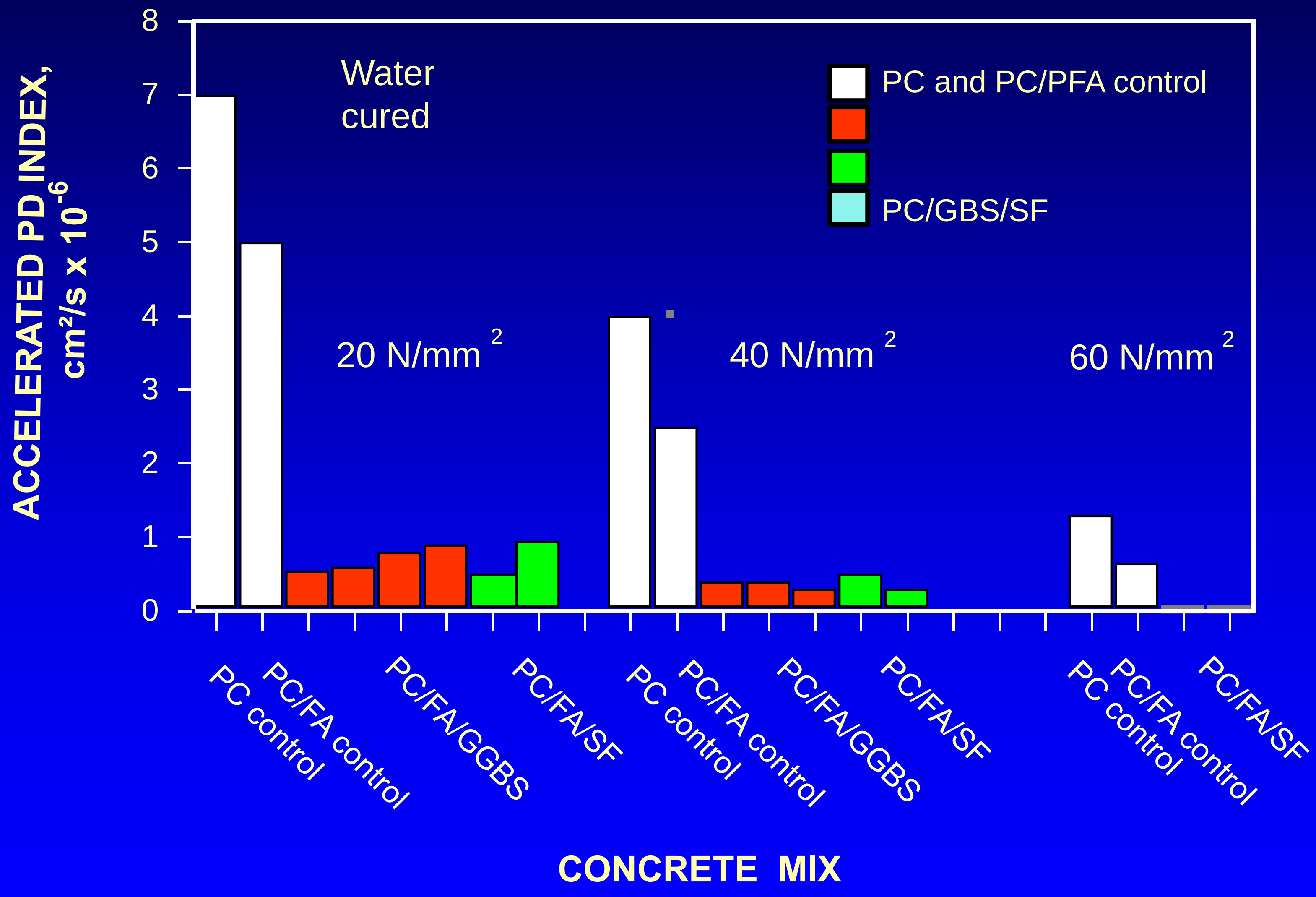
# 2.9 Lime Stabilization of Soils with Fly Ash



# 3. Multi-Blended Cements with Fly Ash

| CEMENT | STRENGTH N/mm$^2$ | | |
|---|---|---|---|
| | **w/c 0.65** | **w/c 0.55** | **w/c 0.45** |
| PC / 30%FA | 22.5 | 29.0 | 39.5 |
| PC / 25%FA / 5%LS | 22.0 | 28.0 | 39.0 |
| PC / 25%FA / 5%MK | 23.5 | 30.5 | 42.0 |
| PC / 25%FA / 5%SF | 25.0 | 33.0 | 45.0 |

# 3. Multi-Blended Cements with Fly Ash



# Concluding Remarks

The CTU model of working in partnership with all the stakeholders, including government and industry, has made it possible for University research to be innovative and practical and thereby facilitate maximising the use of fly ash as a valuable resource in concrete construction and, in so doing, it can claim to be a major player in enabling sustainable use of cement in concrete construction, in terms of reducing significantly its carbon footprint and enhancing concrete durability.