Micromechanics and Complementary Energy of Fibers Embedded in a Low-Energy CSA Cement Matrix

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http://www.flyash.info/
Purpose of Study

- Evaluate interfacial bond and complementary energy of reinforcing fibers
  - Embedded in a calcium sulfoaluminate (CSA) matrix
    - Commercially available CSA
    - CSAB produced from CCBs
  - Embedded in silicate-based Portland matrix

- Evaluation Tools:
  - Single-fiber pullout test
    - Simulates fibre bridging-pullout mechanism during fracture process
  - Scanning electron microscope
Importance of Fibers

- Delay and contain cracking

- Bridge cracked parts of the matrix
  - Delaying sudden global failure

- Post-cracking stage behavior of fibers
  - Composite will carry increasing loads
    - Pullout resistance
  - Transfer of stress to matrix
    - Bond stress
      - < bond strength
    - Multiple cracking
Fiber-reinforced composites (FRC)

- Part of the tensile force is resisted by the matrix
  - Balance is taken by the fibers
- Shearing stress bond
  - Transmission of forces at the interface
- Toughness = total energy (mJ) absorbed prior to complete failure
  - Crack resistance capability of concrete
  - Primarily dictated by the mechanisms of fiber pullout
Introduction

• Mechanisms of fiber pullout
  o Fiber-matrix interface debonding
  o Post-debonding friction
  o Fiber fracture/rupture
  o Stress redistribution
  o Fiber pullout

• Primary Mode of Failure
  o Fiber rupture or debonding/pullout
Introduction

- Cement-Fiber Interfacial Bond
  - Mechanical interlocking
  - Chemical Reaction
  - Principal factor governing load transfer is shear strength of interfacial bond
PVA Fiber Channel
PVA Fiber Channel

0.07 mm
Polypropylene Fiber Channel
Introduction

- **Engineered cementitious composites (ECC)**
  - Fiber-reinforced material
  - Deformation behavior analogous to that of metals
    - After first cracking
      - Pseudo strain-hardening
      - Multiple cracking

- **Multiple Cracking**
  - Requires steady-state crack extension
  - Can be evaluated in terms of **COMPLEMENTARY ENERGY**
    - Energy needed to propagate the crack
    - Graphically is the area to the left of the $\sigma – \delta$ relation up to peak stress
    - The mechanism to link interfacial bond to composite fracture behavior
Low Energy/Low CO2 Cement

- Calcium Sulfoaluminate (CSA) Cement

- Gypsum or anhydrite is milled with the clinker to “activate” ettringite formation

- Main cementitious phases are:
  - $\mathrm{C}_4\mathrm{A}_3\dot{\mathrm{S}} \ [\mathrm{Ca}_4\mathrm{Al}_6\mathrm{O}_{12}(\mathrm{SO}_4)]$ a.k.a. Klein’s compound
  - $\mathrm{C}_2\mathrm{S} \ [\mathrm{Ca}_2\mathrm{SiO}_4]$
  - (Minor) $\mathrm{C}_4\mathrm{AF} \ [\mathrm{Ca}_4(\mathrm{Al}_x\mathrm{Fe}_{1-x})\mathrm{O}_{10}]$ where $0 < x < 0.7$

- Ettringite is the main cementitious phase:
  $$\mathrm{C}_4\mathrm{A}_3\dot{\mathrm{S}} + 2\mathrm{C}\dot{\mathrm{S}}\mathrm{H} + \mathrm{H}_2\mathrm{O} \rightarrow \mathrm{C}_6\dot{\mathrm{A}}\dot{\mathrm{S}}_3 \cdot 32\mathrm{H}_2\mathrm{O} + 2\mathrm{AH}$$

- Belite hydration can provide additional long-term strength
## Laboratory Cement Formulations

<table>
<thead>
<tr>
<th>Component</th>
<th>CSAB#1</th>
<th>CSAB#2</th>
<th>CSAB#4 HS</th>
<th>CSAB#4 MS</th>
<th>CSAB#4 LS</th>
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</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>39.1</td>
<td>46.0</td>
<td>29.6</td>
<td>24.6</td>
<td>13.7</td>
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<tr>
<td>Bauxite</td>
<td>15.0</td>
<td>15.2</td>
<td>30.2</td>
<td>25.0</td>
<td>13.9</td>
</tr>
<tr>
<td>FBC Spent Bed(^1)</td>
<td>13.0</td>
<td>13.1</td>
<td>19.6</td>
<td>16.3</td>
<td>9.0</td>
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<tr>
<td>Class C Fly Ash</td>
<td>6.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>-</td>
<td>12.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gypsum(^2)</td>
<td>13.3</td>
<td>12.8</td>
<td>20.6</td>
<td>17.1</td>
<td>31.7</td>
</tr>
<tr>
<td>Ultra Fine Ash(^3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17.1</td>
<td>31.7</td>
</tr>
<tr>
<td>Total CCBs</td>
<td>33.1</td>
<td>38.8</td>
<td>40.2</td>
<td>50.5</td>
<td>72.4</td>
</tr>
</tbody>
</table>

\(^1\)Byproduct of fluidized bed combustion (FBC) of coal

\(^2\)Gypsum and Ultra Fine Ash are milled with the clinker; percentage is calculated on a mass basis of the cement product

\(^3\)Ultra Fine Ash is a processed material from ponded Class F fly ash
XRD Analysis of Cement Clinkers
Single-Fiber Pullout Test

- **Test Setup**
  - 2 kN (450 lbf) load cell
  - Displacement rate of 0.02 mm/s
  - Fiber-free length ~ 1 mm
  - Embedded depth: 6 mm

- **Fibers embedded in a paste plug**
  - Diameter: 8mm
  - Length: 25 mm
  - w:c = 0.45
**Fiber Types**

- **Copper-Coated Steel Fiber**
  - Low carbon, drawn wire (Type-I)
  - Purpose:
    - Primary Reinforcement

- **Polypropylene Fiber**
  - Macro-synthetic
  - Purpose:
    - Secondary Reinforcement
    - Control plastic shrinkage
    - Control plastic settlement cracking

- **Polyvinyl-Alcohol Fiber**
  - Purpose:
    - Control plastic shrinkage
    - Thermal cracking
    - Abrasion resistance
  - Advantage: Molecular bond
Interfacial Bond

PEAK LOAD & ENERGY CONSUMPTION (TOUGHNESS)
Polyvinyl Alcohol (PVA) Fiber
Polypropylene Fiber
Copper-Coated Steel Fibers

Magnification:

400x

Magnification:

500x

Magnification:

2000x
Matrix: Ordinary Portland Cement

Peak Load (N) vs. Energy Consumption (mJ)

- **PVA**
- **PP**
- **Steel**

<table>
<thead>
<tr>
<th>Time (Days)</th>
<th>Peak Load (N)</th>
<th>PVA</th>
<th>PP</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>10</td>
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<td>21</td>
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<td>56</td>
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Images:
- **PVA**
- **PP**
- **Steel**

28-days
Matrix: Commercial CSA Cement

- **Peak Load (N)**
- **Energy Consumption (mJ)**

![Graphs showing Peak Load and Energy Consumption over time for PVA, PP, and Steel](image)

- **PVA**
- **PP**
- **Steel**

28-days
Matrix: CAER CSAB Cement

Peak Load (N)

Energy Consumption (mJ)

Time (Days)

PVA
PP
Steel

28-days
Complementary Energy

ABILITY TO FORM A DAMAGE TOLERANT COMPOSITE
Damage Tolerant Composites

- **Single Crack (no fibers)**
  - Unstable crack spreading
  - Immediate formation of macroscopic crack

- **Multiple Cracking**
  - Pseudo strain-hardening
    - Series of microscopic fracture events
    1. Applied load shared by bridging fibers
    2. Load transferred through interface back to matrix
    3. Matrix may crack again if enough load is transferred
    4. Repeat process
      - Formation of sub-parallel cracks of approximate equal spacing
  - Composite strain > matrix failure strain
Complementary Energy

\[ C = \sigma_0 \delta_0 - \int_0^{\delta_0} \sigma(\delta) \, d\delta \]

\( \sigma_0 \) and \( \delta_0 \)

maximum bridging stress

For Steady-State Crack Extension:

\[ C \geq J_0 \]
Matrix: OPC

Complementary Energy

Complementary Energy (mJ) vs. Time (Days)

- PVA
- PP
- Steel
Matrix:
Commercial CSA Cement
Complementary Energy

Complementary Energy (mJ)
Time (Days)
PVA
PP
Steel
Matrix: CAER
CSA Cement
Complementary Energy

![Graph showing complementary energy over time for different materials (PVA, PP, Steel).]
### Conclusions

<table>
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<th>Ductility of Interfacial Zone</th>
<th>Copper-Coated Steel Fibers</th>
<th>Complementary Energy</th>
</tr>
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<td>OPC &gt; Comm. CSA &gt; CAER CSAB</td>
<td>Highest overall peak load values and energy consumption</td>
<td>Damage tolerant behavior prefers a $\sigma - \delta$ relation with large complementary energy or area</td>
</tr>
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<td></td>
<td>PP fibres highest sustained toughness value during pullout</td>
<td></td>
</tr>
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<td>CCB-Fabricated Cement</td>
<td>Achieved the highest peak loads and toughness values</td>
<td></td>
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Questions???