Alternative Test

Mehta and Gjørv proposed a test method to capture strength loss:

- 0.5” cement paste cubes
- 4% Na$_2$SO$_4$ solution is circulated
- pH is maintained constant at 7.2 by buffering solution with sulfuric acid
- Change in cube strength is measured

Alternative Test

A calcium aluminate cement after 63 days exposure.

A calcium sulfoaluminate cement after 28 days exposure.

Alternative Test

Results after 9 weeks exposure.

Design to Avoid Sulfate Damage

Susceptibility to sulfate damage is related to:

- Cement composition
- Concrete permeability
- Sulfate concentration
- Associated cation
- pH

Can control these
# ACI Recommendations

## Table 2.3—Requirements to protect against damage to concrete by sulfate attack from external sources of sulfate

<table>
<thead>
<tr>
<th>Severity of potential exposure</th>
<th>Water-soluble soluble sulfate (SO₄)⁺⁺</th>
<th>Sulfate (SO₄)⁺⁺ in water, ppm</th>
<th>w/cm by mass, max.†‡</th>
<th>Cementitious material requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 0 exposure</td>
<td>0.00 to 0.10</td>
<td>0 to 150</td>
<td>No special requirements for sulfate resistance</td>
<td>No special requirements for sulfate resistance</td>
</tr>
<tr>
<td>Class 1 exposure</td>
<td>&gt; 0.10 and &lt; 0.20</td>
<td>&gt; 150 and &lt; 1500</td>
<td>0.50‡</td>
<td>C 150 Type II or equivalent§</td>
</tr>
<tr>
<td>Class 2 exposure</td>
<td>0.20 to &lt; 2.0</td>
<td>1500 to &lt; 10,000</td>
<td>0.45‡</td>
<td>C 150 Type V or equivalent§</td>
</tr>
<tr>
<td>Class 3 exposure</td>
<td>2.0 or greater</td>
<td>10,000 or greater</td>
<td>0.40‡</td>
<td>C 150 Type V plus pozzolan or slag§</td>
</tr>
<tr>
<td>Seawater exposure</td>
<td>—</td>
<td>See Section 2.4</td>
<td>See Section 2.4</td>
<td></td>
</tr>
</tbody>
</table>

* Sulfate expressed as SO₄ is related to sulfate expressed as SO₃, as given in reports of chemical analysis of portland cements as follows: SO₃% x 1.2 = SO₄%.
† ACI 318, Chapter 4, includes requirements for special exposure conditions such as steel-reinforced concrete that may be exposed to chlorides. For concrete likely to be subjected to these exposure conditions, the maximum w/cm should be that specified in ACI 318, Chapter 4, if it is lower than that stated in Table 2.3.
‡ These values are applicable to normalweight concrete. They are also applicable to structural lightweight concrete except that the maximum w/cm ratios 0.50, 0.45, and 0.40 should be replaced by specified 28 day compressive strengths of 26, 29, and 33 MPa (3750, 4250, and 4750 psi) respectively.
§ For Class 1 exposure, equivalents are described in Sections 2.2.5, 2.2.6, and 2.2.9. For Class 2 exposure, equivalents are described in Sections 2.2.5, 2.2.7, and 2.2.9. For Class 3 exposure, pozzolan and slag recommendations are described in Sections 2.2.5, 2.2.8, and 2.2.9.
## Cement Composition: ASTM C 150

<table>
<thead>
<tr>
<th>Type</th>
<th>Use</th>
<th>C$_3$S</th>
<th>C$_2$S</th>
<th>C$_3$A</th>
<th>C$_4$AF</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>General</td>
<td>45-55</td>
<td>20-30</td>
<td>8-12</td>
<td>6-10</td>
<td>no limits on 4 principal components</td>
</tr>
<tr>
<td>II</td>
<td>general/ mod sulfate resistance/ mod heat of hydration</td>
<td>40-50</td>
<td>25-35</td>
<td>5-7</td>
<td>6-10</td>
<td>C$_3$A$\leq$8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C$_3$A+C$_3$S$\leq$58%</td>
</tr>
<tr>
<td>III</td>
<td>High early strength</td>
<td>50-65</td>
<td>15-25</td>
<td>8-14</td>
<td>6-10</td>
<td>C$_3$A$\leq$15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>more finely ground</td>
</tr>
<tr>
<td>IV</td>
<td>Low heat of hydration</td>
<td>25-35</td>
<td>40-50</td>
<td>5-7</td>
<td>12</td>
<td>C$_3$S$\leq$35%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C$_3$A$\leq$7%, C$_2$S$&gt;40%$</td>
</tr>
<tr>
<td>V</td>
<td>High sulfate resistance</td>
<td>40-50</td>
<td>25-35</td>
<td>0-4</td>
<td>10-20</td>
<td>C$_3$A$\leq$5%</td>
</tr>
</tbody>
</table>
Cement Composition

Type I General Use Vs. Type V High Sulfate Resistance

Type I - 14.1% C₃A
W/C = 0.50

Type V - 1.2% C₃A
W/C = 0.51

After immersion in sulfate solution for 5 years

Courtesy of BRE
Cement Composition: Strength Loss

<table>
<thead>
<tr>
<th>Type</th>
<th>Na</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2900</td>
<td>3900</td>
</tr>
<tr>
<td>5</td>
<td>4900</td>
<td>5900</td>
</tr>
<tr>
<td>10</td>
<td>6900</td>
<td>7900</td>
</tr>
<tr>
<td>15</td>
<td>8900</td>
<td>9900</td>
</tr>
</tbody>
</table>

Average compressive strength (psi) vs. Time of exposure (weeks)
Cement Composition: $\text{C}_3\text{A}$
Permeability: w/c

Type V High Sulfate Resistance after 12 years

Type V Cement  
W/C = 0.65

Type V Cement  
W/C = 0.39
Permeability: w/c

- Time (years)
- Expansion (%)

- w/c = 0.42
- w/c = 0.47
- w/c = 0.49
- w/c = 0.53
- w/c = 0.57
- w/c = 0.62
- w/c = 0.67
Permeability: w/c

<table>
<thead>
<tr>
<th>w/c</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>1</td>
</tr>
<tr>
<td>0.50</td>
<td>2</td>
</tr>
<tr>
<td>0.60</td>
<td>3</td>
</tr>
</tbody>
</table>

10,000 ppm sulfate Na$_2$SO$_4$ solution
Type I cement
Permeability: Aggregate

- In the presence of aggregate produces a region of lower density and greater microcrack concentration formed. This is the transition zone or interfacial transition zone (ITZ).
- “Weak link” in concrete
Use of SCMs

- fly ash=41.7% w/c=0.46 C3A=6.0%
- fly ash=25.0% w/c=0.49 C3A=5.7%
- fly ash=0% w/c=0.46 C3A=5.9%
Design to Avoid Sulfate Damage

- For concrete without SCMs, the w/c and C₃A content of the cement are the most important factors for avoiding sulfate-induced damage.

- For cement with C₃A < 8% and w/c between 0.37 and 0.71:

\[
\exp = \frac{0.0148(C_3A + 1)^{0.325} e^{0.94w_c\sqrt{T}}}{K_E}.
\]

- For cement with C₃A < 10% and w/c between 0.45 and 0.51:

\[
\ln(EXP) = -3.753 + 0.930T + 0.100\ln(T \times C_3A).
\]

Design to Avoid Sulfate Damage

To avoid damage by sulfate attack, specify:

- Appropriate cement Type (ASTM II or V)
- Appropriate w/c
- Supplementary cementing materials
  - 15% metakaolin
  - 35% slag
  - 6% silica fume
  - 20% Class F fly ash
- Good construction practices and curing
Design to Avoid Sulfate Damage

In some applications, the use of calcium aluminate cement may be considered

- Calcium aluminate (CA) cements are composed primarily of alumina (~40%) and lime (~40%), but also contain ferric or ferrous oxides (~15%), and fused silica (~5%)
- Principal cementitious phase is calcium aluminate (CA)
- CA hydration products include CAH$_{10}$, small quantities of C$_2$AH$_8$, and alumina gel (AH$_3$)
- In the presence of water, CAH$_{10}$ and C$_2$AH$_8$ transform (or convert) to C$_3$AH$_6$ and alumina gel
- CA cement possesses excellent sulfate resistance