Portland Cement Concrete

Durability

Durable: “Able to exist for a long time without significant deterioration.” (Webster’s New Collegiate Dictionary)

Durability: “The ability of a building or any of its components to perform its required function over an intended period of time.” (CSA S478 - 95)

Durability of PC Concrete: “The ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration.” (ACI Committee 201)

<table>
<thead>
<tr>
<th>Category</th>
<th>D.S.L.</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporary</td>
<td>Period Agreed</td>
<td>Non-permanent site huts</td>
</tr>
<tr>
<td></td>
<td>Up to 10 Years</td>
<td>Temporary exhibition buildings</td>
</tr>
<tr>
<td>Short Life</td>
<td>10 - 24 Years</td>
<td>Temporary classrooms</td>
</tr>
<tr>
<td>Medium Life</td>
<td>25 - 49 Years</td>
<td>Most industrial buildings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Most parking structures</td>
</tr>
<tr>
<td>Long Life</td>
<td>50 - 99 Years</td>
<td>Most residential, commercial buildings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Health &amp; education buildings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Parking structures below LL buildings</td>
</tr>
<tr>
<td>Permanent</td>
<td>100 Years Min.</td>
<td>Monumental or heritage buildings</td>
</tr>
</tbody>
</table>

Canadian Standards Association CSA S478 - 95
Guideline on Durability in Buildings
Portland Cement Concrete
Durability

How Long will Concrete Last?

Under Ideal Conditions: Virtually forever.

Under Normal Conditions: Depends on what it is exposed to (i.e. deterioration mechanism).

General Categories of Deterioration Mechanisms:

Chemical Attack
Physical Attack

How Does Deterioration Initiate?

Generally, surface attack of concrete is an extremely slow deterioration process.

In most cases, aggressive agents must enter the concrete to cause significant damage.

There are three primary transport mechanism that allow such penetration:

Absorption
Permeation
Diffusion
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Transport Properties

Absorption: Transport of liquids in unsaturated porous solids due to surface tension acting in capillaries.

Permeation: Movement of gases or liquids through a saturated porous medium due to a pressure gradient.

Diffusion: Transfer of mass by random motion of free molecules or ions in the pore solution due to a concentration gradient.

Absorption and Diffusion are affected in a similar manner - a denser paste acts to restrict movement.
Portland Cement Concrete

Durability

The single greatest difficulty related to durability research is predicting concrete behavior decades in the future based upon short-term laboratory tests.

<table>
<thead>
<tr>
<th>TABLE 18.1 Durability of Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical attack</td>
</tr>
<tr>
<td>Leaching and efflorescence (P)</td>
</tr>
<tr>
<td>Sulfate attack (P)</td>
</tr>
<tr>
<td>Alkali-aggregate reaction (A)</td>
</tr>
<tr>
<td>Acids and alkalis (P)</td>
</tr>
<tr>
<td>Corrosion of metals (R)</td>
</tr>
<tr>
<td>Physical attack</td>
</tr>
<tr>
<td>Freezing and thawing (P, A)</td>
</tr>
<tr>
<td>Wetting and drying (P)</td>
</tr>
<tr>
<td>Temperature changes (P, A)</td>
</tr>
<tr>
<td>Wear and abrasion (P, A)</td>
</tr>
</tbody>
</table>

Portland Cement Concrete

Leaching

**Leaching** - the hydrolysis of cement paste components (particularly calcium hydroxide) by water flowing through the concrete.


*Soft Water* (Rain, Melting Snow & Ice) contains no calcium ions or other minerals. Readily dissolves calcium containing products.

The rate of leaching is dependent upon the amount of dissolved salts in the water and the temperature of the water.

Prevention:
- Minimize transport properties (low W/C, SCMs).
- Minimize calcium hydroxide content of hcp (SCMs).
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Leaching

Quality hcp

hcpp Subject to Severe Leaching
Portland Cement Concrete

Efflorescence

Alkali Silica Reaction (ASR) - chemical reaction between the soluble alkalis contained in the hcp and certain reactive forms of silica found in the aggregates.

<table>
<thead>
<tr>
<th>Reaction Step</th>
<th>Reaction</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Release of alkali ions from the cement during hydration</td>
<td>Increases the concentration of hydroxide ions in the pore solution</td>
</tr>
<tr>
<td>2</td>
<td>Initial hydrolysis of silicious fraction of the aggregate in the highly alkaline pore solution ([K(Na)OH + SiO_2 \rightarrow [K_2O(Na_2O)SiO_2H_2O] ) (amorphous alkali silicate gel)</td>
<td>Destroys aggregate integrity</td>
</tr>
<tr>
<td>3</td>
<td>Swelling of alkali silicate gel by inhibition of water.</td>
<td>Causes localized swelling internal pressure, and cracking</td>
</tr>
<tr>
<td>4</td>
<td>Liquafaction of alkali silicate gel by further inhibition of water</td>
<td>Expulsion of liquid gel through the cracks</td>
</tr>
</tbody>
</table>
Portland Cement Concrete
Alkali Silica Reaction
Portland Cement Concrete
Alkali Silica Reaction

Table 5-7. Some Potentially Harmful Reactive Minerals, Rock, and Synthetic Materials

<table>
<thead>
<tr>
<th>Alkali-silica reactive substances*</th>
<th>Alkali-carbonate reactive substances**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesite</td>
<td>Opal</td>
</tr>
<tr>
<td>Argillite</td>
<td>Opaline shales</td>
</tr>
<tr>
<td>Certain siliceous limestones and dolomites</td>
<td>Quartzites</td>
</tr>
<tr>
<td>Chaledonic cherts</td>
<td>Quartzizes</td>
</tr>
<tr>
<td>Chaledony</td>
<td>Cherts</td>
</tr>
<tr>
<td>Cristoblite</td>
<td>Rhodochrosite</td>
</tr>
<tr>
<td>Dacites</td>
<td>Sphene</td>
</tr>
<tr>
<td>Glassy or cryptocrystalline volcanics</td>
<td>Siliceous shales</td>
</tr>
<tr>
<td>Granite gneiss</td>
<td>Strained quartz</td>
</tr>
<tr>
<td>Graywackes</td>
<td>and certain other forms of quartz</td>
</tr>
<tr>
<td>Metagraywackes</td>
<td>Synthetic and natural siliceous glass</td>
</tr>
<tr>
<td></td>
<td>Tridymite</td>
</tr>
<tr>
<td></td>
<td>Calcite dolomites</td>
</tr>
<tr>
<td></td>
<td>Dolomite limestones</td>
</tr>
<tr>
<td></td>
<td>Fine-grained dolomites</td>
</tr>
</tbody>
</table>

Portland Cement Concrete
Alkali Silica Reaction

**TABLE 7.7 Forms of Reactive Silica in Rocks That Can Participate in Alkali–Aggregate Reaction**

<table>
<thead>
<tr>
<th>Reactive Component</th>
<th>Physical Form</th>
<th>Rock Types in Which It Is Found</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opal</td>
<td>Amorphous</td>
<td>Siliceous (opaline limestones, cherts, shales, flints)</td>
<td>Widespread</td>
</tr>
<tr>
<td>SiO2 glass</td>
<td>Amorphous</td>
<td>Volcanic glasses (rhyolite, andesite, dacite) and tuffs, synthetic glasses</td>
<td>Regions of volcanic origins: river gravels originating in volcanic areas; container glass</td>
</tr>
<tr>
<td>Cheleodony</td>
<td>Poorly crystallized quartz</td>
<td>Siliceous limestones and sandstones, cherts and flints</td>
<td>Widespread</td>
</tr>
<tr>
<td>Cristobolite</td>
<td>Crystalline</td>
<td>Opaline rocks, formed ceramics</td>
<td>Uncommon</td>
</tr>
<tr>
<td>Quartz</td>
<td>Crystalline</td>
<td>Quartzite, sands, sandstones, many igneous and metamorphic rocks (e.g., granites and schists)</td>
<td>Common, but reactive only if highly strained or microcrystalline</td>
</tr>
</tbody>
</table>
Portland Cement Concrete

Alkali Silica Reaction

Factors affecting reaction:

- nature of the reactive silica
- amount of reactive silica
- particle size of reactive material
- amount of alkalis available
- amount of moisture available

The time elapsed between concrete casting and the appearance of damage can vary significantly, depending upon the nature of the silica involved:

<table>
<thead>
<tr>
<th>Silica</th>
<th>Examples</th>
<th>Time to Obvious Distress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali-silica glass</td>
<td>Waste container glass</td>
<td>~1 year</td>
</tr>
<tr>
<td>Hydrolyzed amorphous silica</td>
<td>Opal, flint</td>
<td>~5 years</td>
</tr>
<tr>
<td>Aluminosilicate glass</td>
<td>Rocks of volcanic origin—rhyolites, dacites, pumice</td>
<td>5–10 years</td>
</tr>
<tr>
<td>Microcrystalline silica</td>
<td>Weathered quartzites</td>
<td>10–20 years</td>
</tr>
<tr>
<td>Layer silicates (expansion of layers)</td>
<td>Phyllites</td>
<td>30–40 years</td>
</tr>
</tbody>
</table>
Portland Cement Concrete

Alkali Silica Reaction

Amount of reactive silica:

![Graph showing amount of reactive silica](image1)

- Pessimum amount

Particle size of reactive silica:

![Graph showing particle size of reactive silica](image2)

- Increasing particle size
Portland Cement Concrete
Alkali Silica Reaction

Alkali content of cement:

![Graph showing the relationship between alkali content of cement and expansion.](image)

ASTM Limit

Ratio of reactive silica to alkali:

![Graph showing the relationship between reactive silica/alkali ratio and expansion.](image)
**Portland Cement Concrete**  
*Alkali Silica Reaction*

**Prevention:**

- Identify and avoid reactive aggregates.
- Limit the amount of alkalis available in the hcp:
  \[ \text{Na}_2\text{O} + 0.65 \text{K}_2\text{O} < 0.60 \]
- Add an SCM to the concrete mix.

**Effect of fly ash:**

![Graph showing expansion of concrete with different fly ash percentages over time.](image)
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Alkali Silica Reaction

Effect of SCMs:

[Graph showing the effect of various SCMs on expansion]

Effect of low alkali cement:

[Graph showing expansion over time with low alkali content]
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Alkali Silica Reaction

Detection – UV Fluorescence Technique
Portland Cement Concrete
Alkali Silica Reaction
Portland Cement Concrete

Alkali Silica Reaction

Fig. 1.10. Example of cracking due to ASR at the Hoover Dam, USA

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Alkali Silica Reaction
Portland Cement Concrete

Alkali Carbonate Reaction

*Alkali Carbonate Reaction (ACR)* - Expansive reactions involving carbonate rocks (dolomitic limestone) have also been observed.

Carbonate rocks susceptible to expansive reactions possess the following features:
- Very fine grained dolomite (small crystals)
- Contain considerable amounts of fine-grained calcite
- Abundant interstitial clay
- Dolomite and calcite crystals evenly dispersed in clay matrix

Sulphate Attack

*Sulphate Attack* - A chemical reaction between a sulfate ions and certain components of hcp.

Damage may include expansion and cracking of the concrete, as well as softening and disintegration of the paste.

**Primary Forms of Sulphate Attack**
- External sulphate attack
- Physical sulphate attack
- Thaumasite
- Internal sulphate attack (DEF)
- Waste/Sewage
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Sulphate Attack

Sulphate attack is a three step reaction:

1. Sulphates must first enter the concrete, usually from an outside source.
2. Sulphates react with CH to produce gypsum:
   \[ \text{CH} + \text{SO}_4^{2-} \rightarrow \text{CSH}_2 + 2\text{OH}^- \]
3. The gypsum reacts with the monosulphoaluminate in the hcp to form ettringite:
   \[ \text{C}_4\text{ASH}_{12} + 2\text{CSH}_2 + 16\text{H} \rightarrow \text{C}_6\text{AS}_3\text{H}_{32} \]

Steps 2 and 3 are both EXPANSIVE !!!
Portland Cement Concrete
Sulphate Attack
Prevention

C_{3}A Content

Relative rate of deterioration

C_{3}A content of cement
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**Sulphate Attack**

*Seawater* – though high levels of sulphates are present in seawater, sulphate attack is mitigated to some extent.

- Magnesium hydroxide chemically protects against sulphate attack.
- Gypsum and ettringite are more soluble in solutions containing chloride ions.

**Internal Sulphate Attack** – Delayed Ettringite Formation (DEF)

Curing at elevated temperatures destroys ettringite and the sulphate is absorbed by the C-S-H.

After cooling, the sulphate again becomes available to form ettringite, resulting in expansion and cracking.
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Acid Attack

**Acid attack** - a chemical reaction between an external source of acidic liquid and hcp and, in some cases, aggregates.

Attack Sequence:

Attack is normally limited to surface of concrete only. Progresses inward.

Dissolution of compounds soluble in the given acid takes place virtually instantaneously.

In most cases, this reaction forms insoluble calcium salts which build up and protect the concrete from further attack.

---

**Chemical Industry:**
- Hydrochloric Acid
- Sulfuric Acid
- Phosphoric Acid

**Food Industry:**
- Acetic Acid
- Lactic Acid
- Carbonic Acid

**Agriculture:**
- Ammonium Chloride
- Humic Acid
- Tannic Acid

**Natural:**
- High CO₂ Content Water (Carbonic Acid)
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Acid Attack
CIVE 202 – Construction Materials

Portland Cement Concrete
Acid Attack c/w Sulphate Attack

H₂SO₄
H₂O
H₂S

sewage

H₂S = Hydrogen Sulphide Gas
H₂SO₄ = Sulphuric Acid

Results in a combination of sulphuric acid and sulphate attack.
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Freezing & Thawing

Damage is induced by internal tensile stresses which are a direct result of repetitive cycles of freezing and thawing.

Freeze/thaw damage is through attrition - one cycle does very little damage, it takes many cycles before the damage adds up to significant levels.

**Contributing Factors:**
1. Expansion of water
   Just before freezing, volume increases 9%

2. Hydraulic Pressure
   All of the water in concrete does not freeze at the same time, but follows a gradual process as freezing begins in the larger cavities and progresses to successively smaller ones due to the effect of pore pressure.
   This produces a hydrostatic pressure as the expansion forces unfrozen water ahead of the freezing front.
   Magnitude of hydrostatic pressure is a function of:
   - Concrete’s resistance to flow
   - Distance to void boundary
   - Rate of freezing
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Freezing & Thawing

Graph showing temperature (°C) vs. pore radius (nm).

Images showing microstructural changes in concrete with freezing and thawing.
Typical Design Air Content = 3-10%

Design Spacing Factor: 0.23 mm max
Worst Case Scenario:

Lots of F/T Cycles
NOT Extremely Cold

Special Case:

Tidal Zone in Cold Climate
3. Solar Heating
Two-directional freezing at surface due to daily thawing from incident solar radiation.

4. Litvan's Model
A vapor pressure gradient is created between surface ice and super-cooled pore water. Induces movement of water toward surface.

A dense, impermeable surface layer will restrict this movement and potentially cause mechanical failure.

Deicer Salt Scaling
A major advantage of concrete in construction is its ability to withstand the ravages of fire. This is a direct result of concrete’s low rate of heat penetration.

Low rate of heat penetration due to:

- Low thermal conductivity.
- Heat is consumed by evaporation of water.
- Heat is consumed in decomposition of hydration products.
- Some aggregates also decompose and consume heat.
- Decomposed material has even lower thermal conductivity.
Water loss and shrinkage cause strength reduction and tensile stresses, resulting in cracking and spalling.

Still, concrete is much less susceptible than steel, which conducts heat rapidly, causing severe loss of structural integrity in beams and columns.

Core of element, including reinforcement, will remain at lower temperatures and be relatively unaffected at low exposure temperatures or times.
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Heat / Fire
An electrochemical attack mechanism affecting the reinforcing steel which results in a volume increase, thus inducing tensile stresses in the concrete.

Structural concrete requires steel reinforcement to carry the applied tensile stresses.

Concrete is normally capable of providing excellent protection to the steel and prevent it from corroding.
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Corrosion of Reinforcement

This protection is both physical and chemical in nature:

Physically: the concrete restricts ingress of the basic components required to initiate corrosion (water, oxygen, chlorides).

Chemically: the pore solution in concrete typically has a very high pH, which leads to the formation of a protective iron oxide film around the steel bar.

**Passivation Film**

Primary reasons for loss of protection:

**Physical:**
- Insufficient cover over reinforcement.
- High permeability concrete.
- Failure to protect concrete from chloride sources.
- Damage to concrete (cracking, spalling, scaling).
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Corrosion of Reinforcement

Primary reasons for loss of protection:

Chemical:
- Penetration of chlorides into concrete. Passivation layer is destroyed when chloride ion content reaches 0.2 – 0.4% in region adjacent to steel.
- Carbonation (due to CO₂ exposure) of concrete leads to a reduction in pH. Depassivation occurs as pH approaches 11.

Corrosion is an electrochemical process – it requires the formation of a cathode and an anode, with an electrical current flowing between them.
Corrosion of Reinforcement

**Anode:** Iron metallic atoms are oxidized to Fe$^{2+}$ ions, which dissolve into the surrounding solution, also producing electrons.

**Cathode:** Electrons are consumed and OH$^-$ ions are formed. Water and oxygen are required for this to occur.

Corrosion of steel in concrete produces two deleterious effects:

1. Reduction of the cross-sectional area of the steel at the anode.

2. Spalling or cracking of the concrete due to the expansion stresses created by rust formation.
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Corrosion of Reinforcement

Prevention in Design:
- Sufficient Cover
- Low Permeability Concrete
- Corrosion Inhibitors
- Corrosion-Resistant Reinforcement
- Zinc-Coated Steel
- Stainless Steel
- Epoxy-Coated Steel
- Fibre Reinforced Plastics
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Corrosion of Reinforcement

Typical Damage due to Corrosion

Corrosion Cracking

Spalling

Typical Damage due to Corrosion
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Corrosion of Reinforcement

Typical Damage due to Corrosion
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Corrosion of Reinforcement
**Portland Cement Concrete**

**Corrosion of Reinforcement**

Protection/Repair of Existing Structure:
- Remove, Clean, Replace
- Corrosion Inhibitors
- Cathodic Protection
  - Sacrificial Anode
  - Cancellation Current
- Protective Overlay
  - Waterproof Membrane
  - Watertight Concrete Overlay

**Surface Wear**

*Surface Wear* - Progressive mass loss from a concrete surface due to repetitive attrition cycles.

Surface wear is divided into three primary mechanisms:
- Abrasion
- Erosion
- Cavitation
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**Abrasion & Erosion**

**Abrasion** – Refers to dry attrition as another solid object moves along or rubs against the concrete surface.

Primarily relates to vehicular traffic or mechanical devices but can also occur in walls of silos or bins.

**Erosion** – Wear caused by the abrasive action of solid particles suspended in fluids.

Caused by the physical action of debris impacting, rubbing, rolling, and grinding against the concrete surface.

Common on canal linings, spillways and pipes for water or sewage transport.
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Cavitation

Cavitation – Loss of mass caused by the formation of vapor bubbles and their subsequent collapse due to sudden changes of direction in rapidly flowing water.

Requires:
- Rapid water flow (exceeding 12 m/s)
- Surface irregularities

At irregularities, water flow separates from concrete surface creating zone of lowered vapour pressure causing bubbles to form.

As bubbles move downstream to regions of normal pressure they collapse violently, creating a shock wave.

Shock wave can induce high tensile stresses in concrete if this occurs near the concrete surface.
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Cavitation
Portland Cement Concrete

Cavitation
Portland Cement Concrete

Sea Water

A special extreme case of durability where concrete is exposed to a combination of detrimental effects simultaneously.

Soluble salt content = 3.5% by mass

pH = 7.5 - 8.4

Typical ionic concentrations:

- $\text{Na}^+$: 11,000 mg/l
- $\text{Cl}^-$: 20,000 mg/l
- $\text{Mg}^{2+}$: 1,400 mg/l
- $\text{SO}_4^{2-}$: 2,700 mg/l

Deleterious Effects:

- **Leaching**: Constant exposure to seawater and/or flow
- **AAR**: Alkalis in seawater (if reactive aggregate is present)
- **Sulfate Attack**: chemical reaction + crystallization (W/D)
- **Acid Attack**: High CO$_2$ contents possible (pH < 7.5)
- **Freeze/Thaw**: Accentuated in tidal zone
- **Corrosion**: High Cl$^-$ content
- **Surface Wear**: flow, waves, sediment, floating objects
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Sea Water