BASF
The Chemical Company

The Concrete Life Cycle: Maintain to Sustain

Fred Goodwin

BASF Construction Chemicals (EB-N)

Beachwood OH

What is Concrete?

Concrete: “Instant rock”-just add water to make a hard wet sponge.

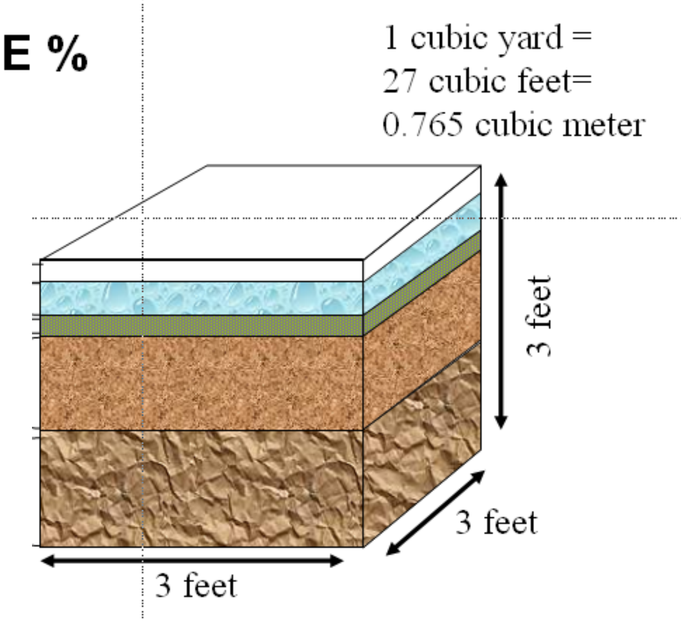
A composite of a binder (a mixture of hydraulic cement & water),

Aggregate (sand & rock),

and sometimes Admixtures

Proportions

VOLUME %



What is Concrete?

- Concrete is economical with a long life & low maintenance
- Concrete does not rot, corrode, or decay.
- Concrete can be molded or cast into almost any desired shape.
- Concrete is fire-safe & able withstand high temperatures.
- Concrete is resistant to wind, water, rodents, and insects.
- 12 BILLION cu meters per year globally
- ~1 cu yd / person / year in USA
- Revenue of top 100 Concrete Firms in US 2010 $6.9B
- >70 Billion cu meters placed in USA since 1930
  with ~10 Billion cu meters > 20 years old

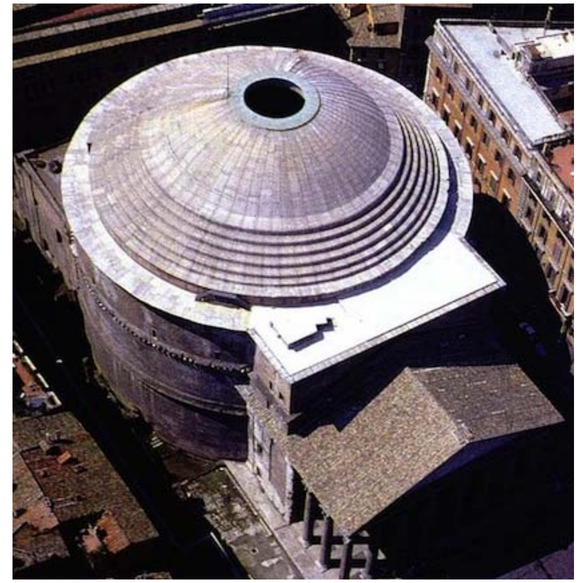
CONCRETE

Oldest Concrete Structures

An ancient Nabataea building

~6500 BC Syria

Yiftahel Israel ~8000 BC

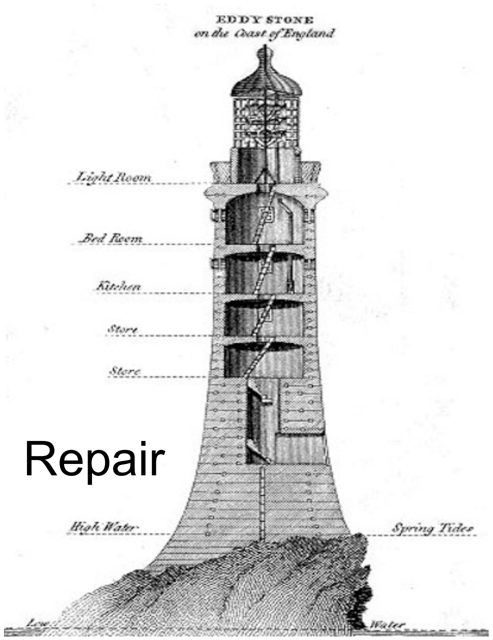


Cast in Place

The Pantheon

125 CE (AD)

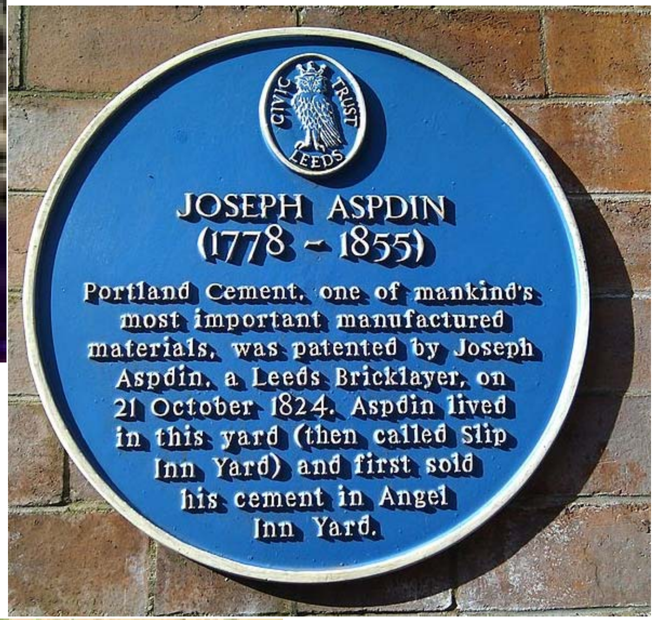
Great Pyramid of Giza ~2500BC



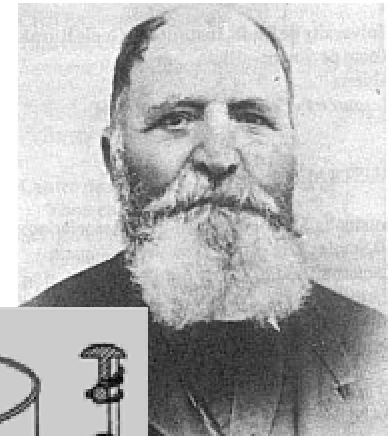
Eddystone Lighthouse 1793

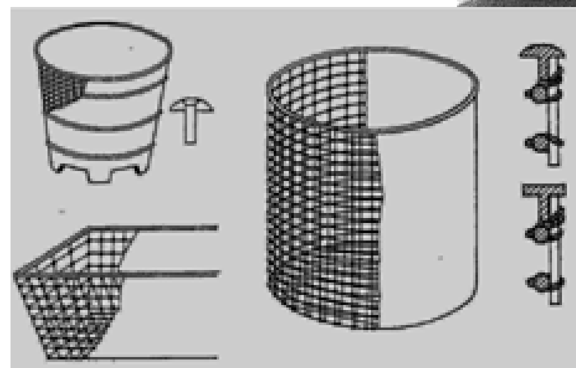
Lepenski Vir, Serbia ~5600 BC

Ward's Home 1875

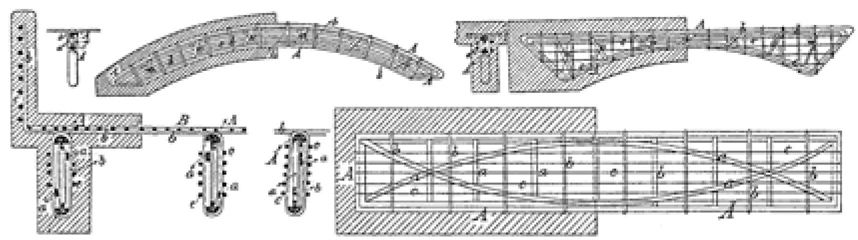


1824 Patent





Joseph Monier 1854



Steel Reinforcement







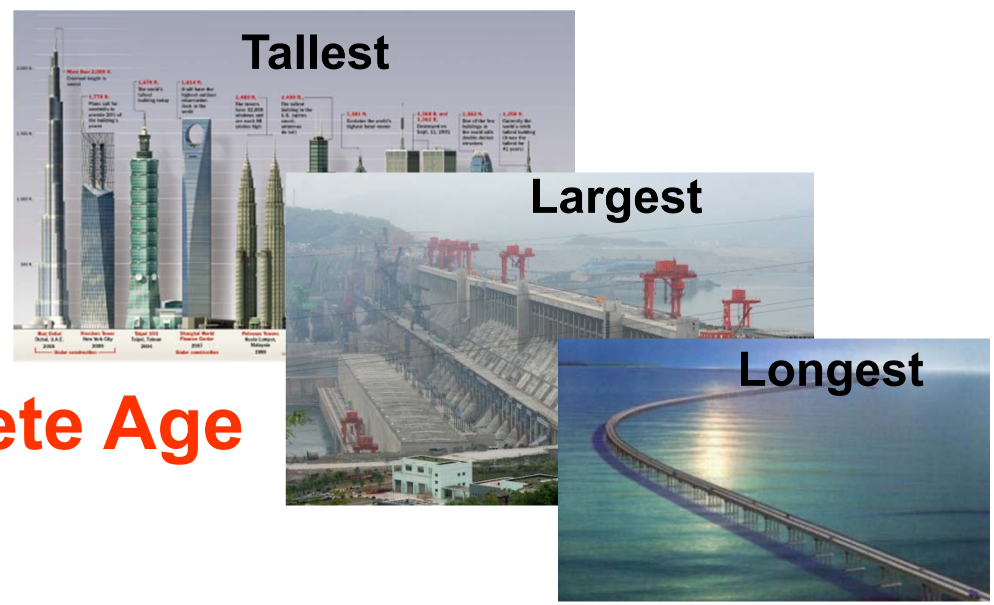
Wood Age →

Stone Age→

Masonry Age →

Steel Age →

Improved Construction Technology



Concrete Age

HOWEVER………

- The cost to owners for concrete repair, protection, and strengthening in US is $18 to $21B /yr (2004)

  htty://www.concrete.org/members/CRB04_Emmons-Sordyl.pdf

- The cost of corrosion of concrete reinforcement is > $125B / yr

  http://www.corrosioncost.com/infrastructure/highway/index.htm

- A 5 year infrastructure investment of $2.2 trillion is needed to return to quality of 1988 infrastructure

  http://www.asce.org/Infrastructure/Report-Card/Latest-News/




What Would it cost ($) to restore our infrastructure?

ASCE
American Society of Civil Engineers

ASCE Infrastructure Report

24 of the nation's leading civil engineers:

- **analyze hundreds of studies**
- **survey > 2,000 engineers**

Grades assigned on

- **condition and capacity**
- **funding versus need**
- **follow a traditional grading scale**

(e.g., if 77% of roads in > good condition = grade C=1980).

$2.2 Trillion = **$7,146** each person in US

TABLE A ★ 2009 Report Card for America's Infrastructure

Aviation	D
Bridges	C
Dams	D
Drinking Water	D-
Energy	D+
Hazardous Waste	D
Inland Waterways	D-
Levees	D-
Public Parks and Recreation	C-
Rail	C-
Roads	D-
Schools	D
Solid Waste	C+
Transit	D
Wastewater	D-

AMERICA'S INFRASTRUCTURE G.P.A.	D
ESTIMATED 5 YEAR INVESTMENT NEED	$2.2 TRILLION

NOTES Each category was evaluated on the basis of capacity, condition, funding, future need, operation and maintenance, public safety and resilience

A = Exceptional
B = Good
C = Mediocre
D = Poor
F = Failing

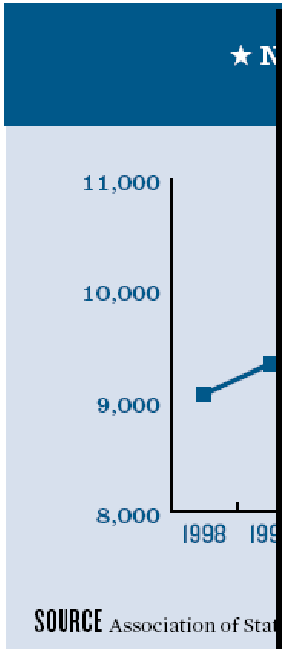
http://www.infrastructurereportcard.org/report-cards

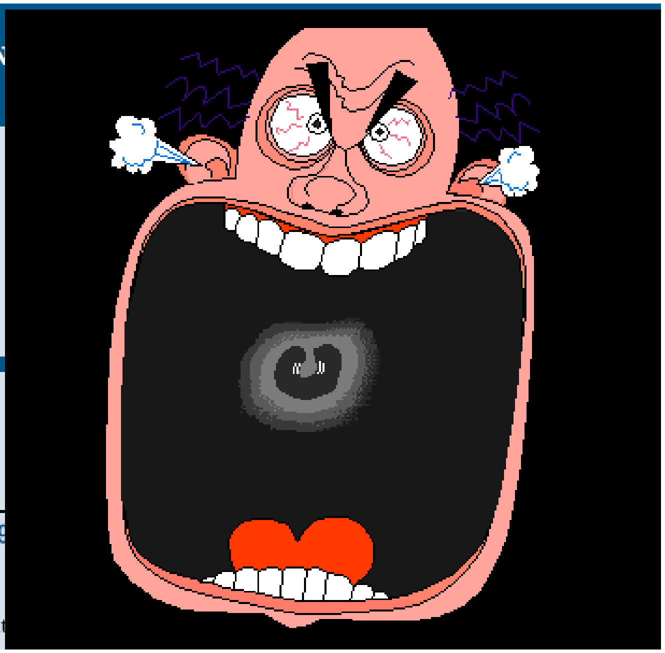
In 2009 >**26%** of the nation's bridges are rated structurally deficient or functionally obsolete.

Poor road conditions cost U.S. motorists **$67 billion** a year in repairs and operating costs – **$217 per person**. Americans spend **4.2** billion hours a year stuck in traffic, at a cost of $78.2 billion a year to the economy

State dam safety programs have identified more than 4000 **deficient dams**, with >**1800 high hazard**.

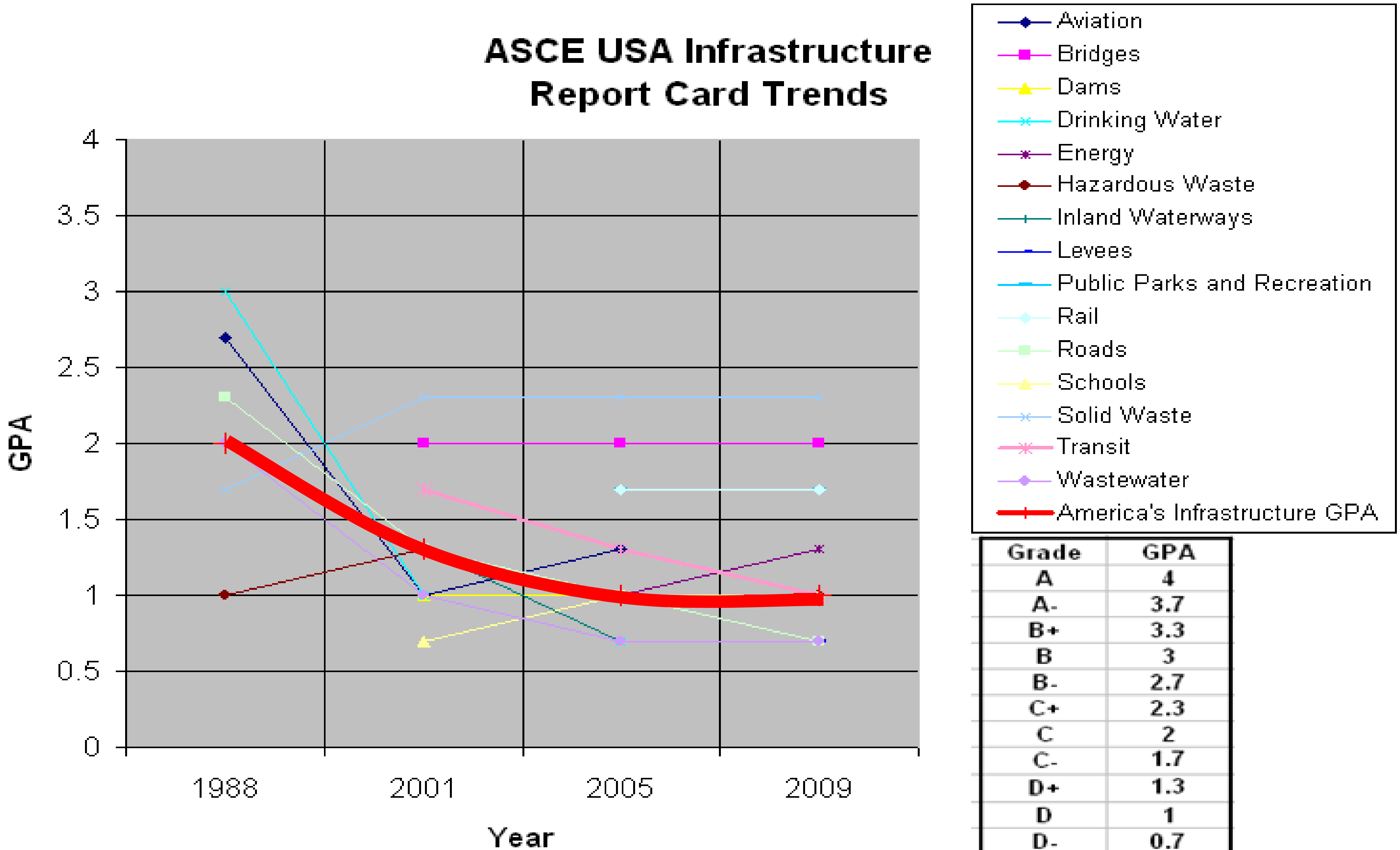
Of the 257 locks on 12,000 miles of waterways, nearly **50 percent** are functionally obsolete. By 2020 increase to ***80 percent***. The inland waterways system averages transportation savings~$10.67/ton vs other shipping methods





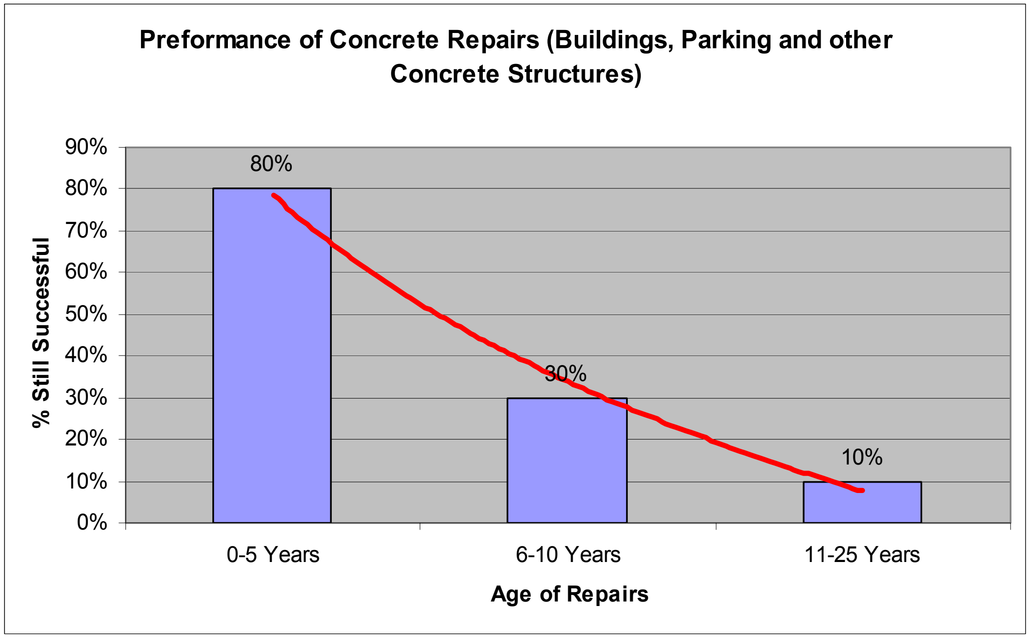
http://www.infrastructurereportcard.org/

http://www.asce.org/Infrastructure/Report-Card/Latest-News/



Grade	GPA
A	4
A-	3.7
B+	3.3
B	3
B-	2.7
C+	2.3
C	2
C-	1.7
D+	1.3
D	1
D-	0.7
F	0

How many repairs fail?



50% Successful Repairs Survival

215 useable case-histories

- 50% Successful and exhibiting no signs of deterioration.
- 25% Exhibiting evidence of deterioration, …not necessarily requiring remedial action.
- 25% Failure, clearly requiring remedial action.

http://projects.bre.co.uk/conrepnet/pages/default.htm

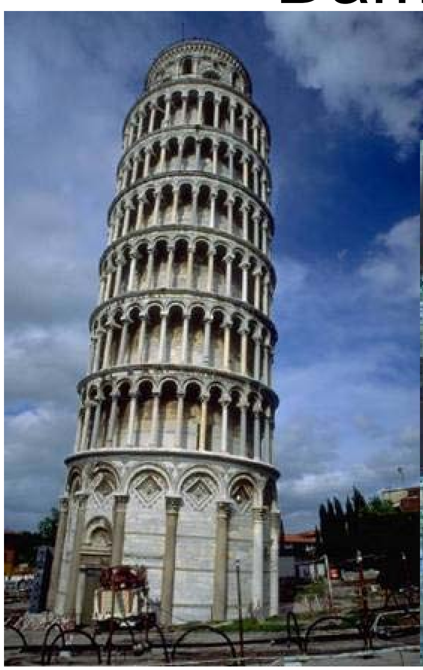
Why does concrete fail?

- **Concrete has (compared to other building materials)**
- **-low tensile strength** (~10% of compressive strength),
- **-low ductility** (it's brittle),
- **-low strength-to-weight ratio** (it's heavy),
- **-responds to environment** (it changes with time)
- **-has permeability**(ingress of deleterious materials)
- **-is susceptible to chemical attack**(acids, AAR, etc.)
- **-and it cracks.**
- **Steel corrodes**
  - Chloride, carbonation, and polarization interaction
  - Rust expands, causing cracking, spalling, and eventual failure

Why does concrete fail?

Concrete requires repair and strengthening due to the 3 D's

- Design and Construction Errors
- Deterioration
- Damage



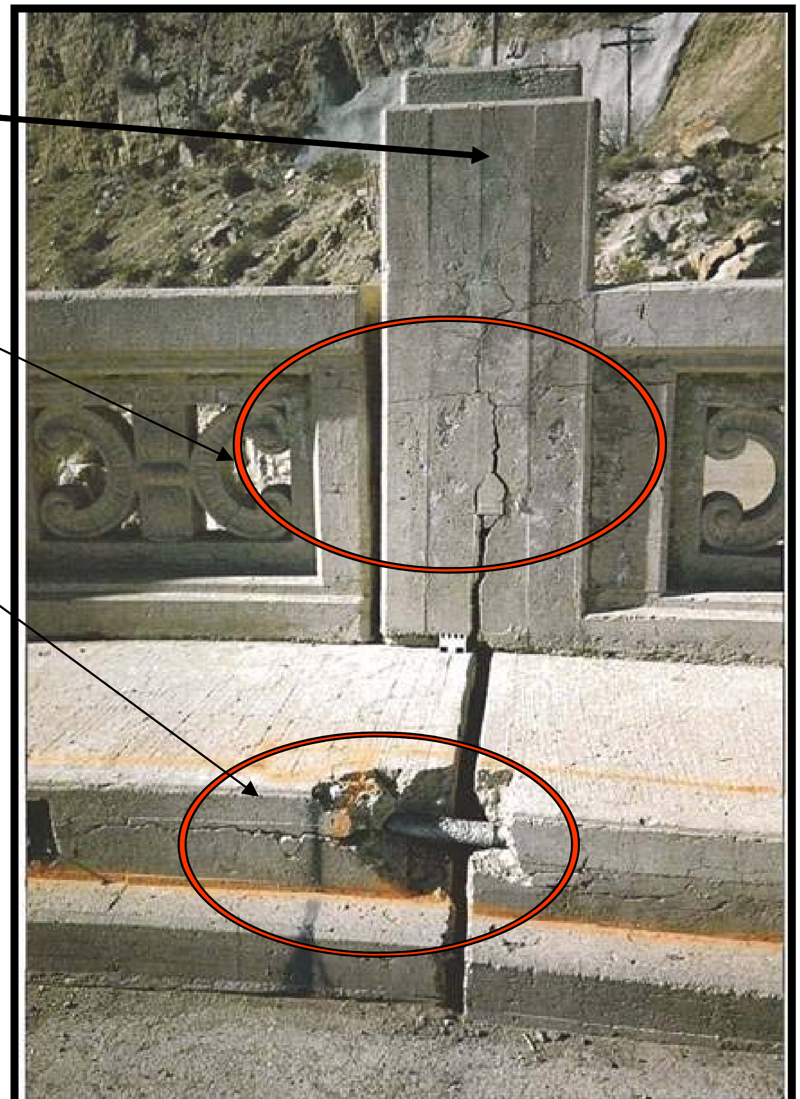
Why does concrete fail?

Combination of Effects

Deterioration

Design

Damage



Design

Why does concrete fail?

Poor Quality Concrete	Poor Structural Design	Poor Workmanship	Environment
Low strengths and high permeability due to high w/c ratio	Insufficient depth of concrete cover in thin architectural element	Honeycombing due to insufficient compaction	Reinforcement corrosion in tidal zone on 25 year old jetty
Concrete too stiff to flow around congested rebar	Cracking due to cyclic thermal movement	Drying shrinkage cracking due to insufficient or poorly timed curing	Widespread corrosion due to carbonation on 1960's tower block
Freeze thaw damage due to specified entrained air not present	Cracking due to repeated, but not excessive, mechanical loading	Settlement cracking over rebar due to over-vibration of concrete	Rebar corrosion from many years of deicing salt usage
ASR cracking due to reactive aggregates being used	Excessive damage due to minor seismic event	Low strengths due to water addition / re-tempering on site	Freeze thaw surface scaling due to many years of extreme exposure
		Rebar visible 2mm from surface on underside of cast-in-place roof slab	Fire damage due to vehicle collision in tunnel
		[illegible]nsufficient cove[illegible]e t[illegible]ovement [illegible]	Acid [illegible]ack on concrete in [illegible]

Do unto your future before it does unto you!

Design

Concrete Mix Rules of Thumb

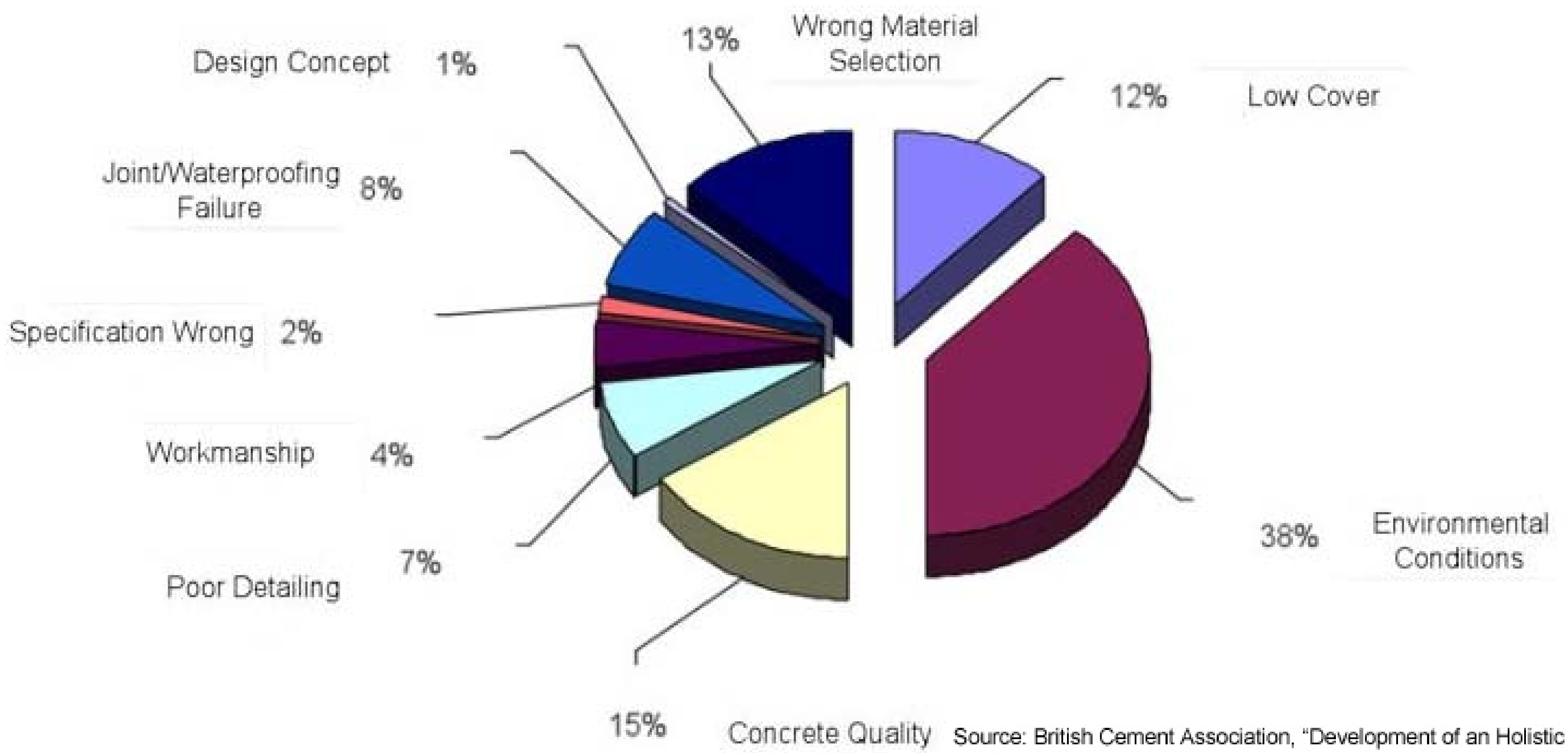
- Cement
  - as cement content ↑, strength ↑, shrinkage ↑, cost ↑
- Sand
  - as sand content ↑, workability ↑, finishability ↑, shrinkage ↑
- Stone
  - as stone content ↑, workability ↓, finishability ↓, shrinkage ↓
- Water or water to cement (w/c) ratio
  - as water ↑, workability ↑, shrinkage ↑ strength ↓, durability ↓
- Air content
  - as air content ↑, strength ↓, bleed ↓, freeze/thaw resistance ↑

Design

Category	Problem	Cause	Frequency	Consequence
Reinforcement chairs and ties	Reinforcement incorrectly shaped or sized	• Inadequate engineering design and documentation.	Frequent	Major
		• Incorrect scheduling.	Infrequent	Major
		• Incorrect fabrication on and off site.	Infrequent	Major
		• Damage during handling and after placement.	Infrequent	Minor
	Reinforcement in incorrect position	• Deformed bar chair.	Infrequent	Major
		• Inadequate reference lines.	Frequent	Major
		• Bar chairs missing or out of place.	Frequent	Major
		• Inappropriate bar chairs-shape, size, material.	Frequent	Major
		• Clashing reinforcement.	Frequent	Major
		• Reinforcement cage too heavy to adjust.	Infrequent	Major
		• Inaccessible location.	Frequent	Major
		• Negligent placement and fixing.	Frequent	Major
		• Ties missing and loose.	Frequent	Major
		• Reinforcement position altered after placement due to heavy treatment of other trades.	Infrequent	Minor
	Bar chairs too close to edge	• Placed over critical areas such as drip drains.	Frequent	Major
		• Displaced due to inappropriate bar chair.	Frequent	Minor
		• Displaced due to rough treatment.	Infrequent	Minor
	Ties too close to edge	• Ties bent out towards edge.	Frequent	Major
Conduits and inclusions clashing with reinforcement	Due to off-site problems	• Lack of coordination of services and structure.	Frequent	Major
		• Position not documented.	Frequent	Major
		• Lack of communication between consultants.	Frequent	Major
	Due to on-site problems	• Inadequate indication on site of correct position.	Frequent	Major
		• Careless placement of conduits.	Frequent	Major
		• Inadequate fixing of conduits in correct position.	Frequent	Major
Formwork	Formwork incorrectly positioned	• Incorrect setting out.	Infrequent	Major
		• Negligent positioning.	Infrequent	Major
		• Incorrect or inadequate drawings.	Infrequent	Major
		• Inadequate tolerances.	Infrequent	Major
	Contamination	• Inadequate cleaning out.	Frequent	Major
	Movement during placement of concrete	• Inadequate form thickness.	Infrequent	Major
		• Inadequate bracing.	Infrequent	Major

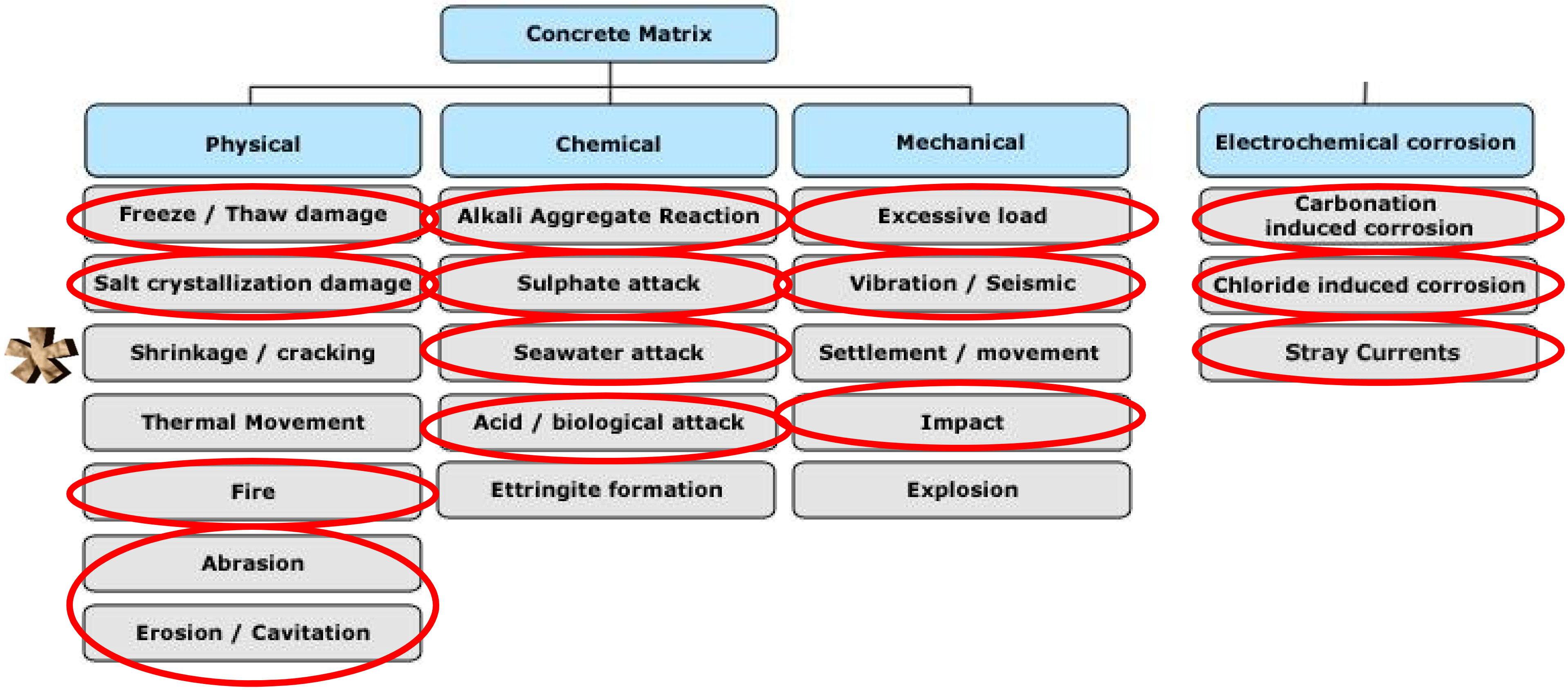
From "Site Investigation of Reinforcement Placement on Buildings and Bridges", M. Marosszeky, M. Chew; Concrete Durability: Corrosion Protection, Compilation 25 American Concrete Institute, this table shows that many concrete corrosion issues are preventable based on the results of 10,000 measurements of 17 structures.

Why does concrete fail?



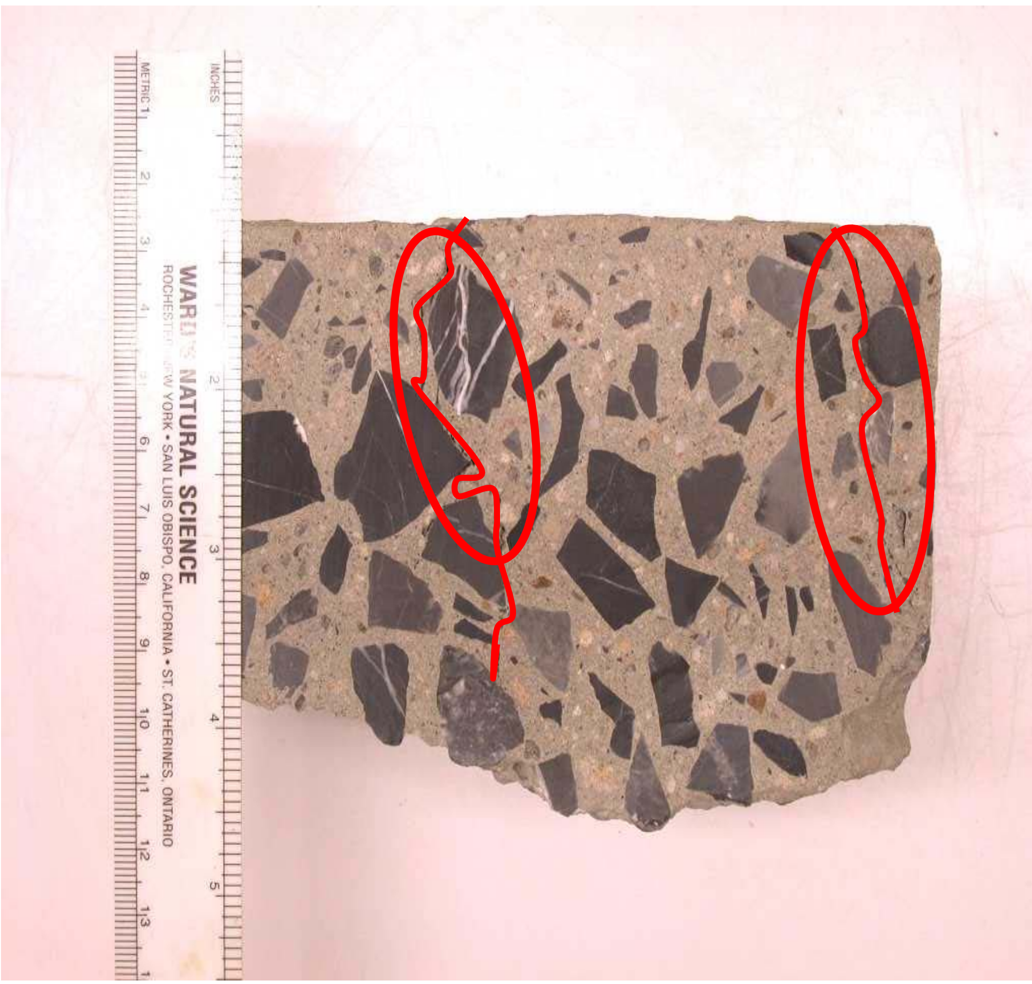
Source: British Cement Association, "Development of an Holistic Approach to Ensure the Durability of New Concrete Construction," Final Report to the Department of the Environment, BCA, Crowthorne, UK, October 1997

How does concrete fail?



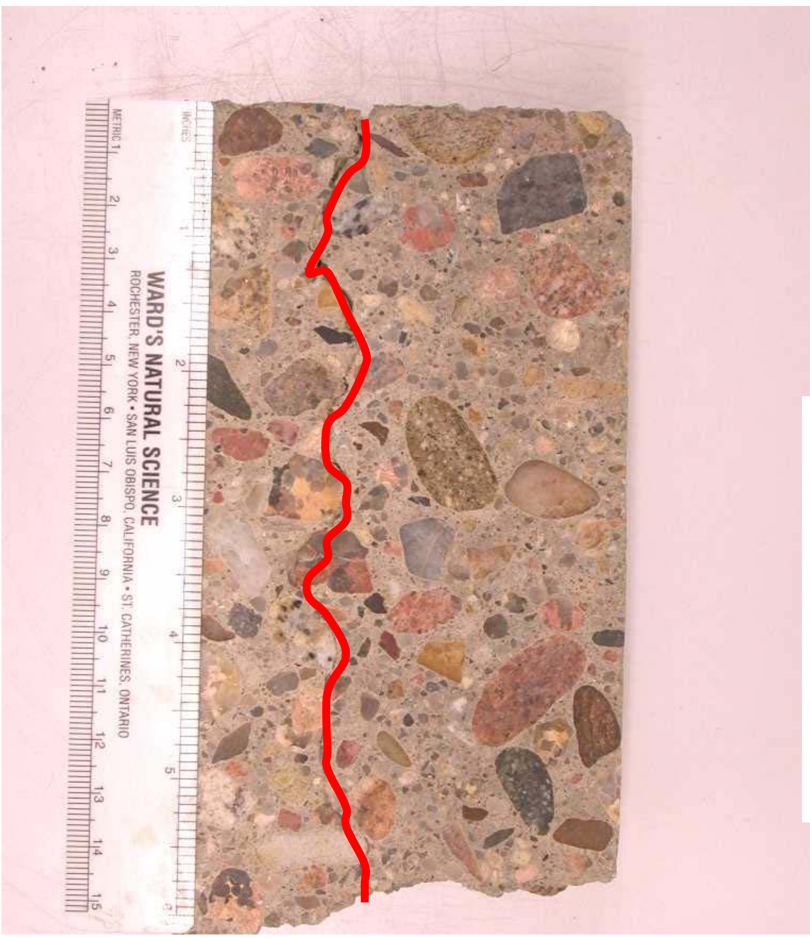
Shrinkage & Cracking

Plastic Shrinkage Cracking



Shrinkage & Cracking

Drying Shrinkage Cracking



The most common concrete repair failure

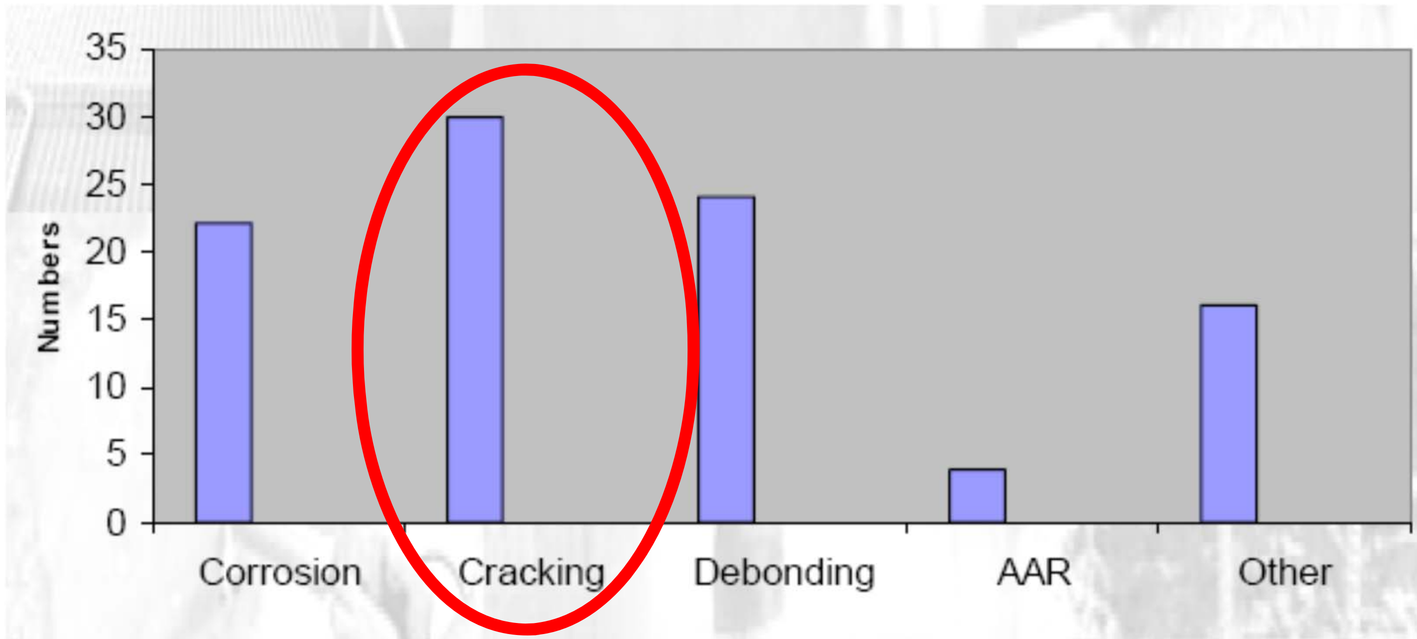


Figure 3. Modes of repair failures

Failures were ascribed to a variety of causes:

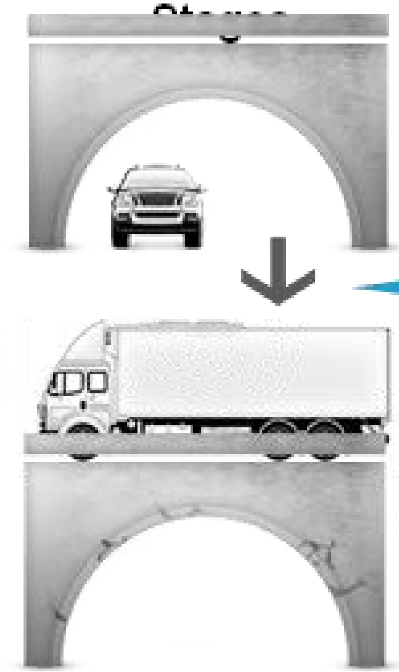
- incorrect diagnosis of the original cause of deterioration
- incorrect design of the repair and method of application
- selection of inappropriate material, and
- poor workmanship

http://projects.bre.co.uk/conrepnet/pages/default.htm

CONREPNET

Concrete Degradation

Enviromental Effects Stages



New structure with discontinuous cracks, microcracks and pores (essentially watertight)

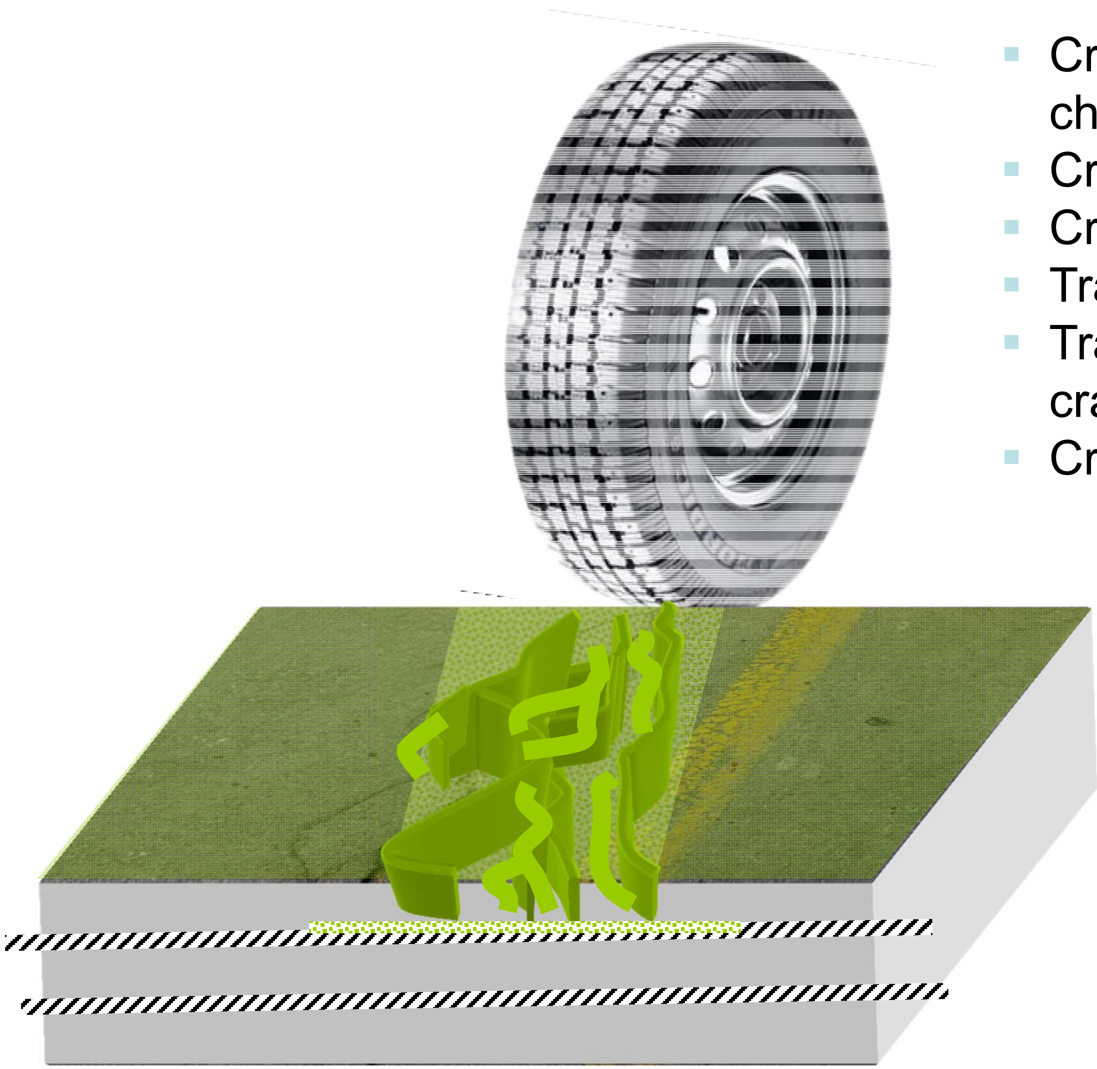
Thermal Cycling
Mechanical Loading

Cracks, microcracks and pores become more interconnected (loss of watertightness)

Ingress of
- **water**
- **Oxygen**
- **of Carbon Dioxide**
- **other aggressive agents**

Reinforcing steel corrosion, freeze-thaw damage, chemical attack.
Reduction in strength and stiffness

Cracking, spalling, mass loss



- Cracks provide a freeway for chlorides (reduced cover)
- Cracks catch salts (dry and wet)
- Cracks are a salt collection reservoir
- Traffic grinds the powder
- Traffic pumps the salty fluid along the crack
- Cracks tend to widen
  - Hydraulic pressure
  - Freezing - thawing cycles
  - Stress relief

Concrete Sustainability Hub
Massachusetts Institute of Technology
77 Massachusetts Avenue
MIT Room 1-372
Cambridge MA 02139

Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements

April 2012

Mehdi Akbarian
Franz-Josef Ulm

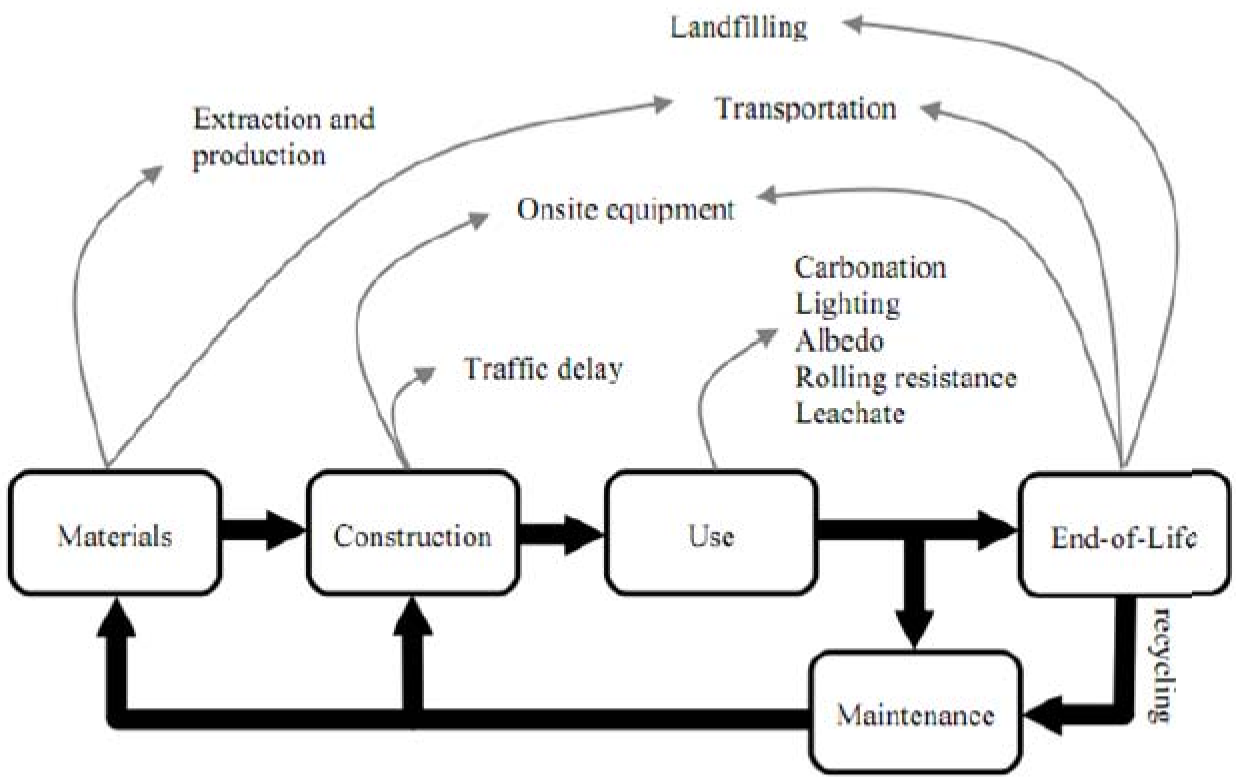
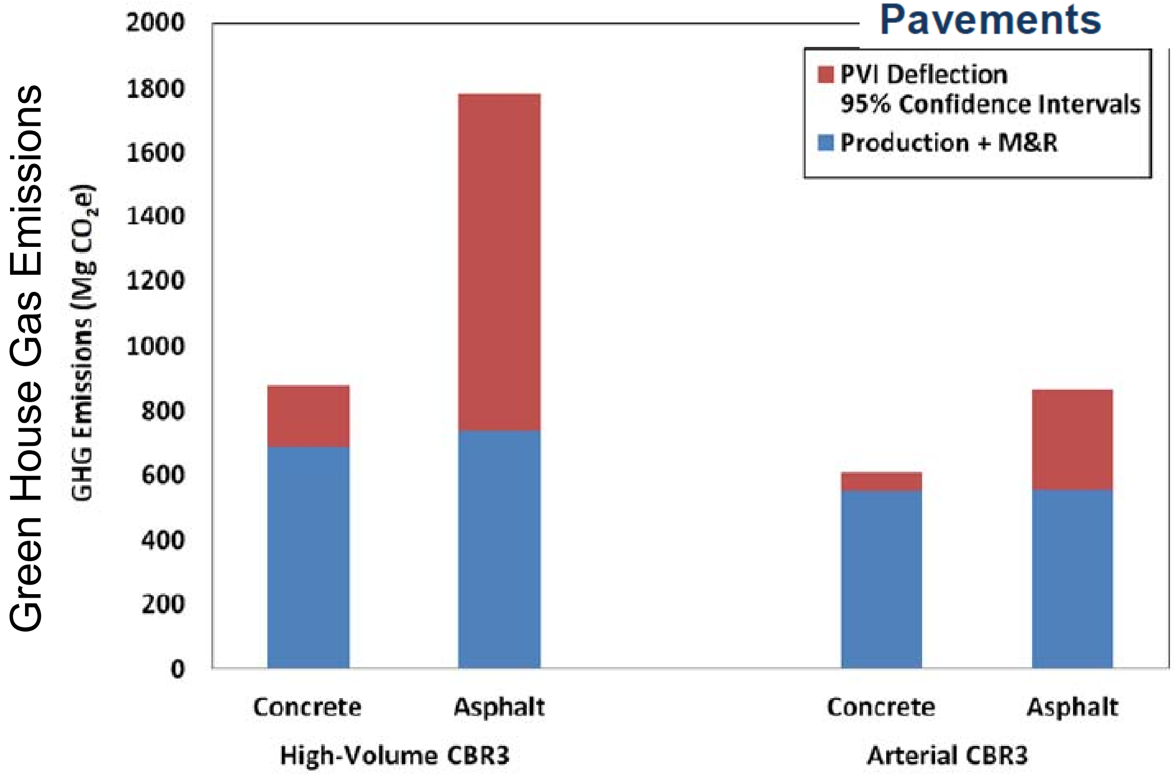


Figure 7-2: Suggested system boundaries (including life-cycle phases and components) for pavement LCA [39].

Scenario Name (CBR 3)	GHG: Production+M&R (tons CO_2e)	Design Life (years)	Traffic Volume (AADT)	Functional Unit
High Vol. – Concrete	688	50	50,000	2 lane-km
High Vol. – Asphalt	738	50	50,000	2 lane-km
Arterial – Concrete	554	50	15,000	2 lane-km
Arterial - Asphalt	555	50	15,000	2 lane-km

Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements



Blue is environmental impact of production, construction, maintenance and repair(~=).

Red is "Pavement Vehicle Interaction" or the "friction" of traffic over 50 years (Less Is Better, concrete wins)

Figure 7-3: Use of model predicted values in an LCA. Production and M&R values are extracted from [3]. Impact of PVI deflection is shown for 50 years lifetime at the 95% confidence interval.

Concrete Sustainability Hub
Massachusetts Institute of Technology
77 Massachusetts Avenue
MIT Room 1-372
Cambridge MA 02139

Methods, Impacts, and Opportunities in the Concrete Building Life Cycle

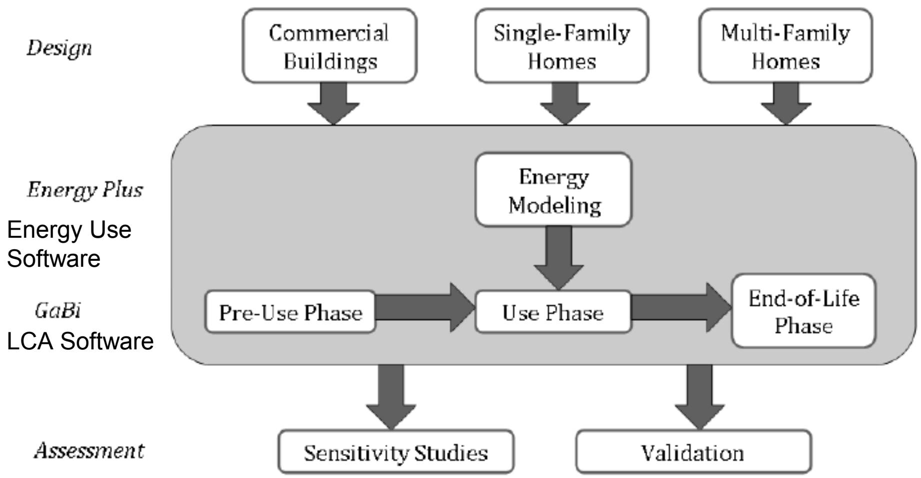
John Ochsendorf
Leslie Keith Norford
Dorothy Brown
Hannah Durschlag
Sophia Lisbeth Hsu
Andrea Love
Nicholas Santero
Omar Swei
Amanda Webb
Margaret Wildnauer

Massachusetts Institute of Technology

concrete sustainability hub

Research Report R11-01
Department of Civil and Environmental Engineering

Concrete Sustainability Hub
Massachusetts Institute of Technology
77 Massachusetts Avenue
MIT Room 1-372
Cambridge MA 02139



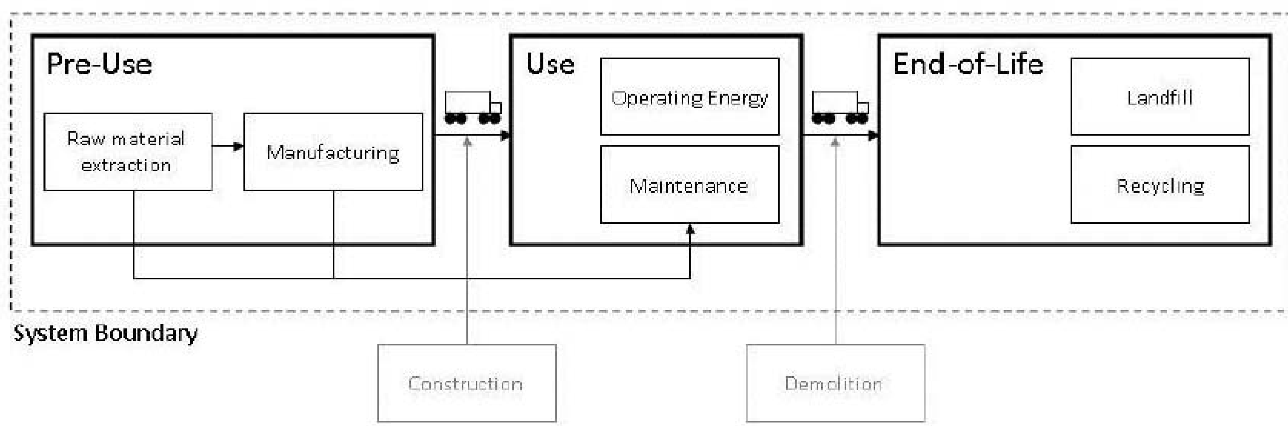


Figure 2.3 – Building LCA system boundary used in this study

Concrete Sustainability Hub
Massachusetts Institute of Technology
77 Massachusetts Avenue
MIT Room 1-372
Cambridge MA 02139

Methods, Impacts, and Opportunities in the Concrete Building Life Cycle

Massachusetts Institute of Technology

CSH concrete sustainability hub

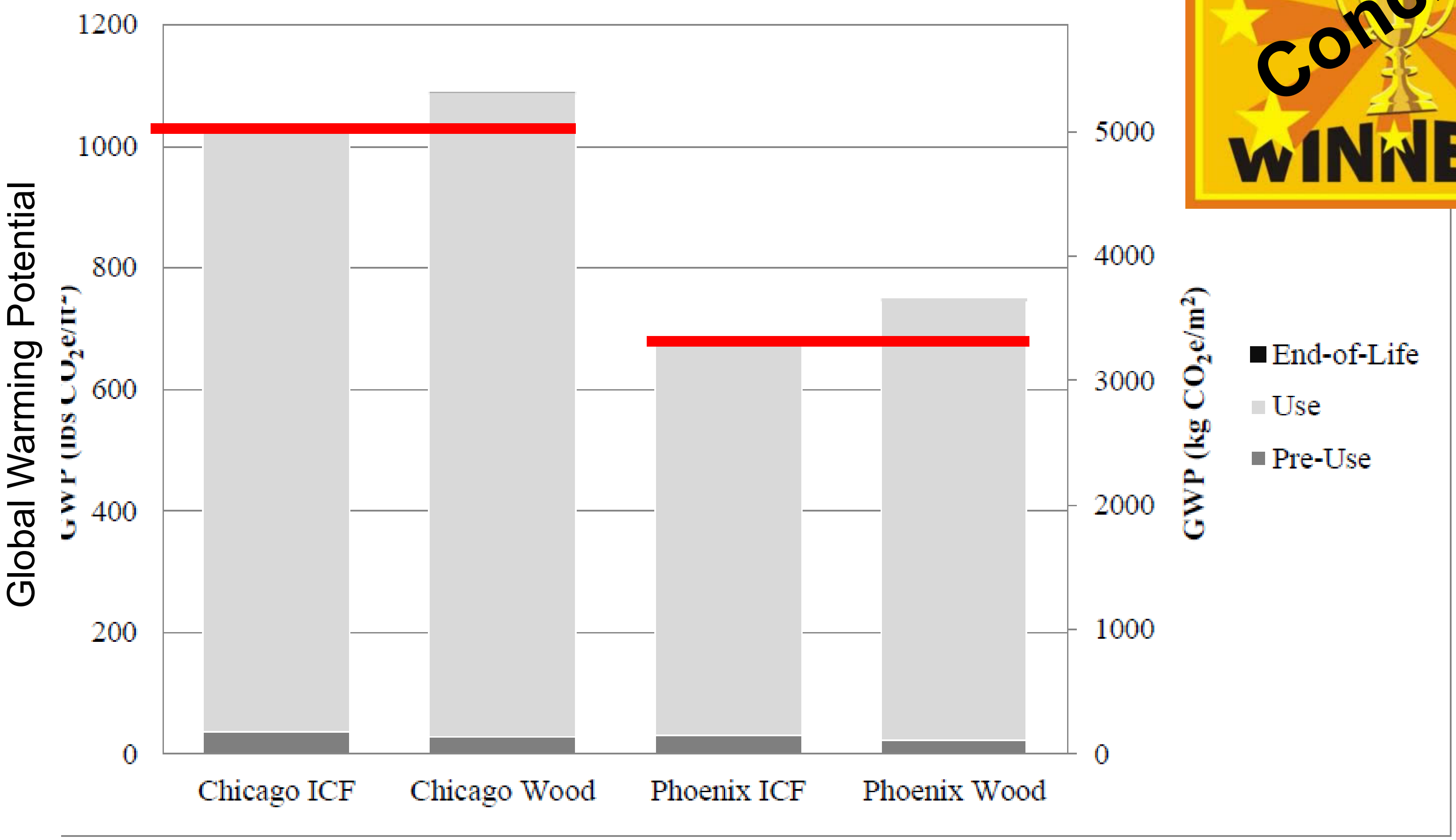


Figure 3.11 – GWP normalized by gross floor area over a 75-year lifespan for single-family houses of average air tightness separated by phase

Single Family Residential 75 Year Global Warming Potential (GWP) Insulated Concrete Forms vs, Stick Construction in two climates

Concrete Sustainability Hub
Massachusetts Institute of Technology
77 Massachusetts Avenue
MIT Room 1-372
Cambridge MA 02139

Methods, Impacts, and Opportunities in the Concrete Building Life Cycle

Massachusetts Institute of Technology

CSH concrete sustainability hub

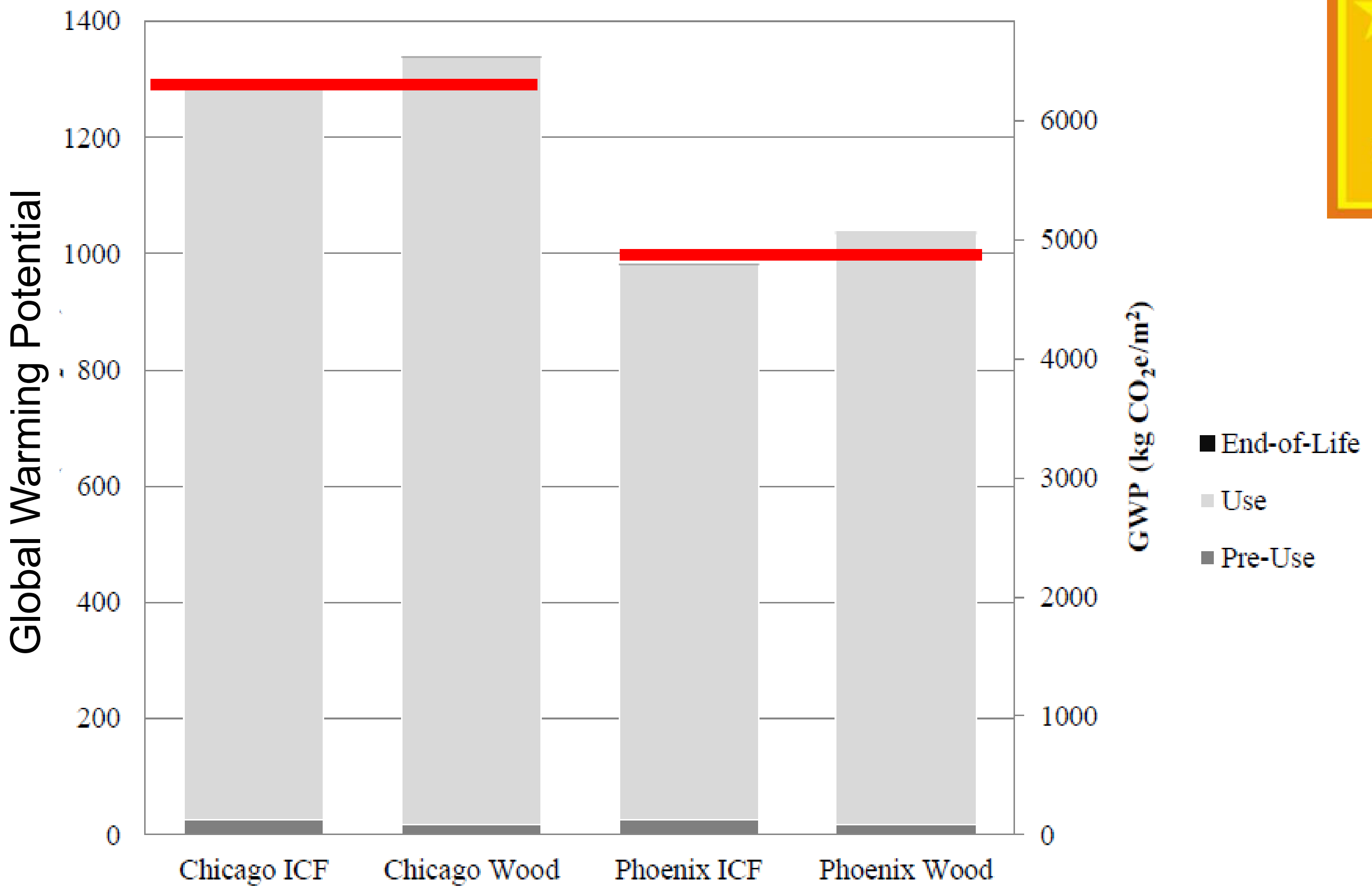


Figure 3.27 – GWP normalized by gross floor area over a 75-year lifespan for multi-family buildings of average air tightness separated by phase

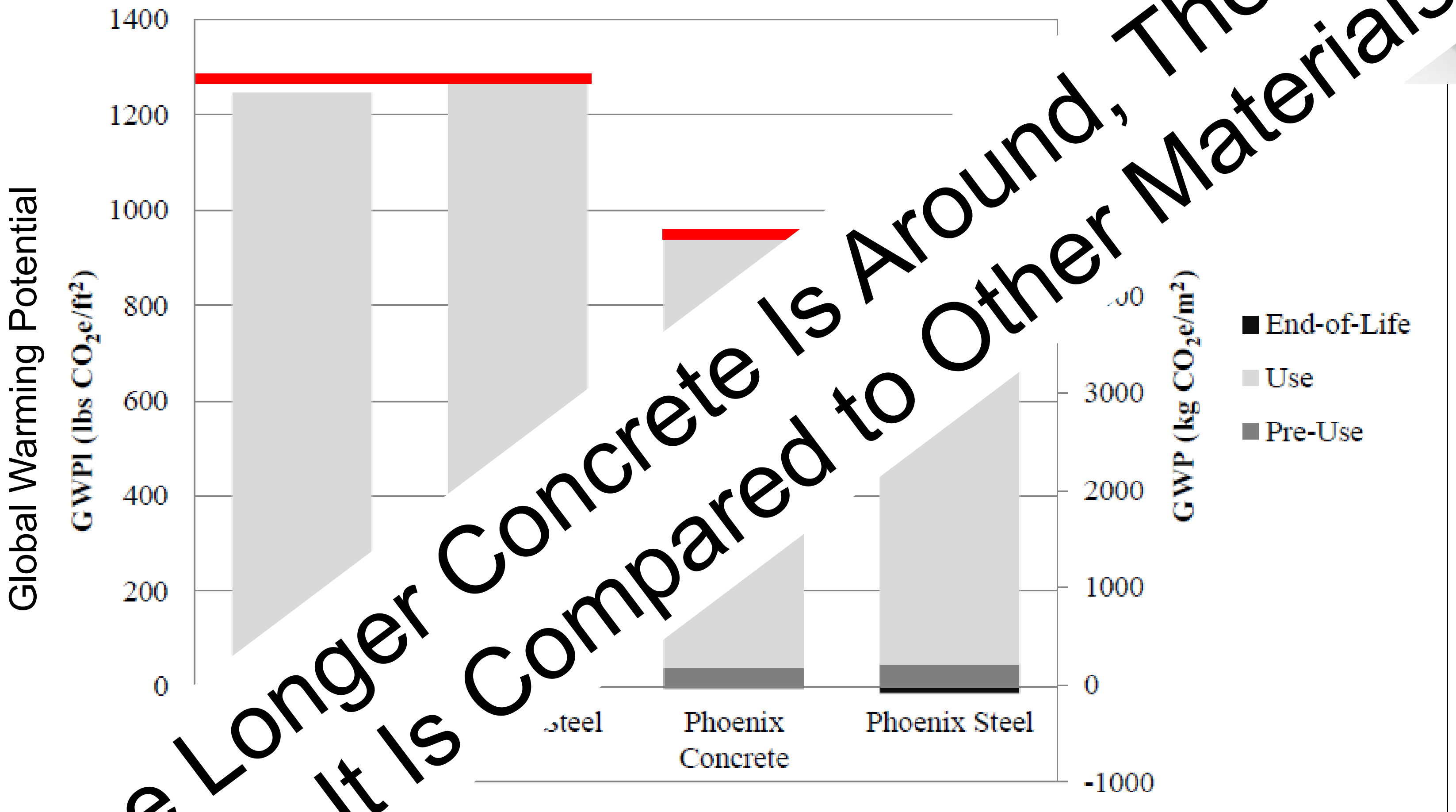
Multi Family Residential 75 Year Global Warming Potential (GWP) Insulated Concrete Forms vs. Stick Construction in two climates

Concrete Sustainability Hub
Massachusetts Institute of Technology
77 Massachusetts Avenue
MIT Room 1-372
Cambridge MA 02139

Methods, Impacts, and Opportunities in the Concrete Building Life Cycle

Massachusetts Institute of Technology

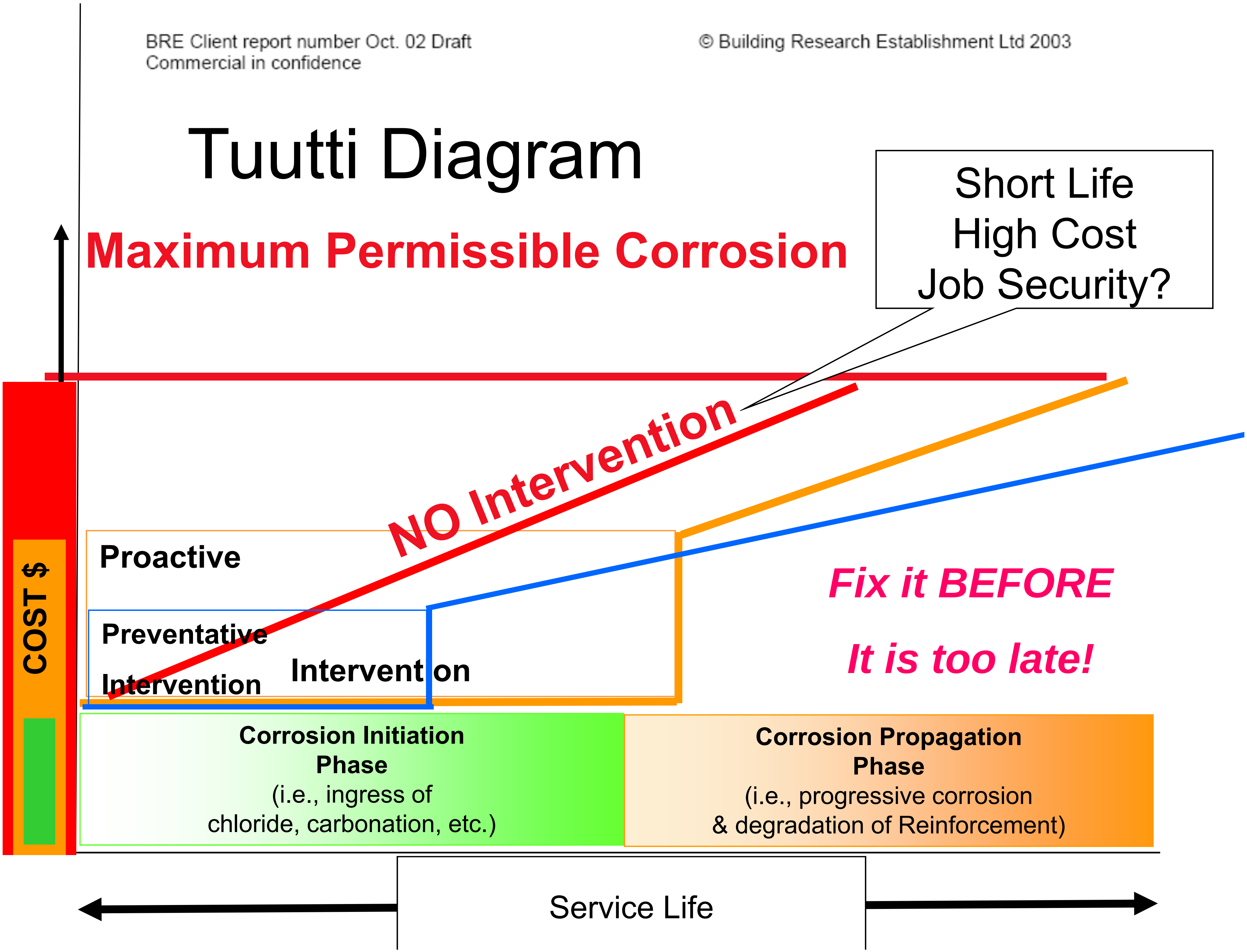
CSH concrete sustainability hub



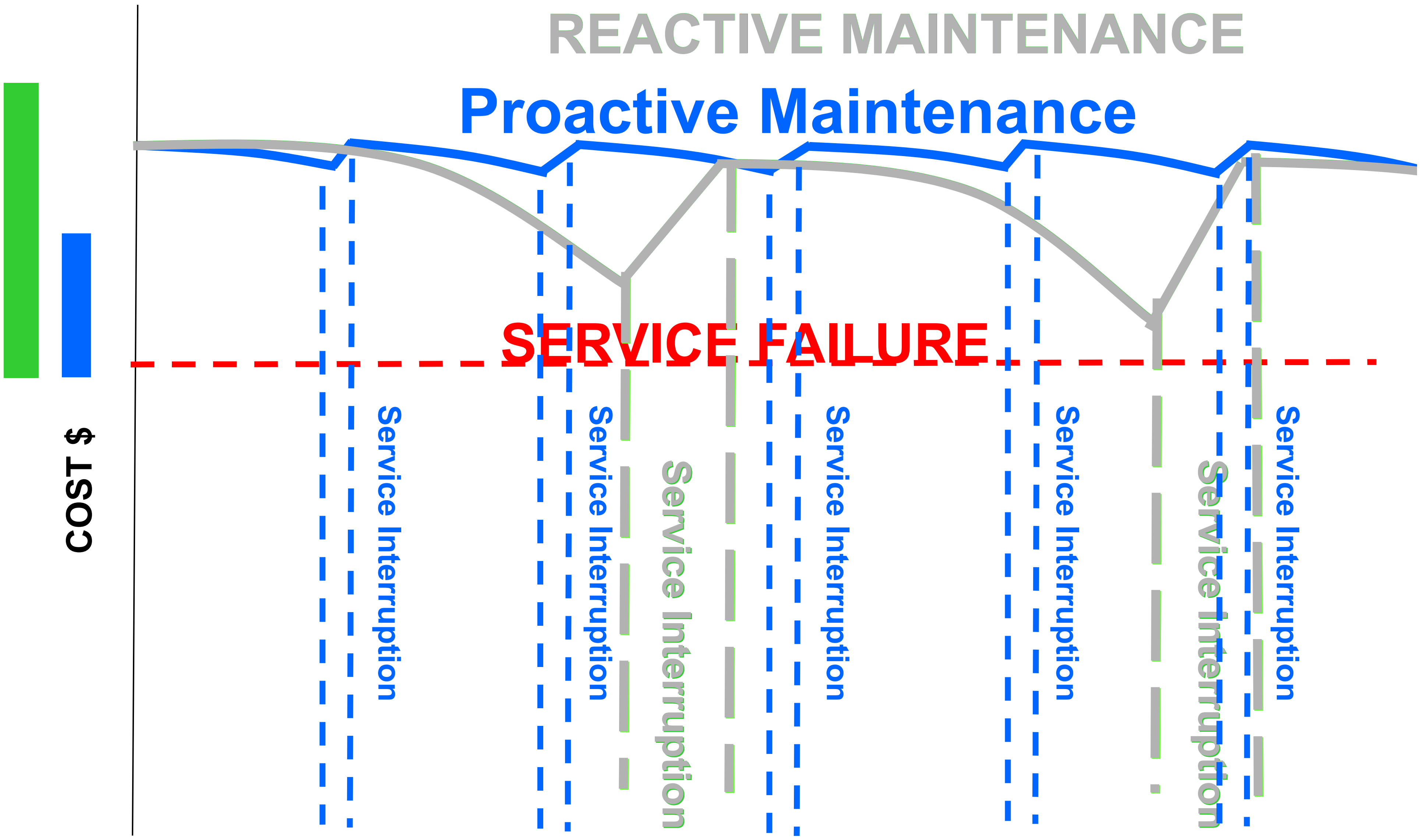
The Longer Concrete Is Around, The Better It Is Compared to Other Materials

...ized by gross floor area over a 75-year lifespan for commercial buildings separated

G... ...ing Potential for Commercial Buildings with Concrete vs. Steel Co... ...ion over 75 Year Life Span


BRE Client report number Oct. 02 Draft
Commercial in confidence
© Building Research Establishment Ltd 2003
Tuutti Diagram
Short Life
High Cost
Job Security?
Maximum Permissible Corrosion
NO Intervention
Proactive
Preventative
Intervention
Intervention
Fix it BEFORE
It is too late!
COST $
Corrosion Initiation
Phase
(i.e., ingress of
chloride, carbonation, etc.)
Corrosion Propagation
Phase
(i.e., progressive corrosion
& degradation of Reinforcement)
Service Life

Tuutti Repair Diagram



The BIGGEST ROI for concrete repair:

De Sitter's Law of Fives

$1 spent Monitoring =

$5 spent on Preventative Maintenance Before Corrosion Initiation =

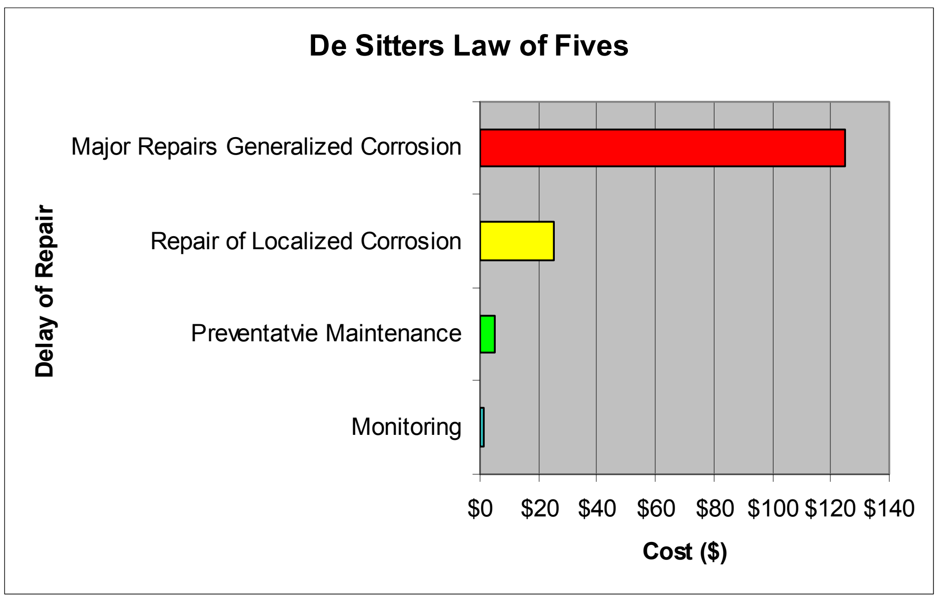
$25 spent on Repair and Maintenance after Localized Corrosion Initiation =

$125 spent on Repair & Replacement after Generalized Corrosion

Pay Me NOW

OR

Pay Me LATER



BRE Client report number Oct. 02 Draft
Commercial in confidence

What to Do?

New Construction

- Usually you inherit the problem, but….
  - Design!!!
  - Place reinforcement with proper cover depth (>1½”)
  - Use low W/C
  - Use appropriate admixtures (Air, AAR, SO3, etc.)
  - Proper consistency and well consolidated
  - Properly cure the concrete
  - i.e., good trade practice
    - **Details,** Details, Details, Details……

What to Do?

Existing construction

- Ok, you inherit the problem
  - Address problems early in the life cycle
  - Find the cause of problems and fix
  - Address cracks
    - Assume all cracks are likely to move
    - If structural, get help!
  - Keep water out & Protect from chemical attack
    - Coatings, water repellants
    - Drainage
  - Know when to walk away

Compromises

Cracking Resistance

- Creep
- Tensile Strength
- Modulus
- Bond Strength
- Length Change
- Thermal Expansion
- Flexural Strength

Durability

- Cracking Resistance
- Freeze Thaw Resistance
- Scaling resistance
- Chloride Ion Permeability
- Sulfate Resistance
- Chemical Resistance
- Abrasion Resistance

Economics

- **Repair or Replace?**
- **Material Cost**
- **Installed Cost**
- **Service Life**

Application Constraints

- **Environmental Considerations**
- **Utilities**
- **Surface Preparation Options**
- **Access**
- **Return to Service Time**
- **Orientation of Application**
- **Volume of Material to be Used**

Serviceability

- **Time to Usage**
- **Compatibility**
- **Esthetics**
- **Strength**

Service Conditions

- **Chemical Resistance**
- **Moisture Intrusion**
- **Abrasion Resistance**
- **Cleanability**

Environmental Conditions

- **Exposure Temperature**
  - **Freeze/Thaw**
  - **High Temperature**
  - **Thermal Shock**
- **Reinforcement Protection**

Blue Print for the Industry

Vision 2020
A Vision for the Concrete Repair, Protection and Strengthening Industry

1. **Mechanism for industry cooperation**
2. **Speed process of document creation**
3. **Create repair code**
4. **Performance based specifications**
5. **Improve cracking resistance**
6. **Worker friendly materials and methods**
7. **Performance modeling system**
8. **Industry strategic research plan**
9. **Increase industry professionals**
10. **Better contract documents**
11. **Owner education tools**
12. **Condition assessment standards**
13. **Special repair systems**
14. **Sustainability (2011)**
15. **Profession & Publicity (2011)**

Questions ?

Fred Goodwin, FICRI, FACI
Fellow Scientist
BASF Construction Chemicals

THANK

YOU !

BASF
The Chemical Company