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Internal Curing of High Performance Concrete Bridge Decks and its Effects on Performance, Service Life and Life-Cycle Cost

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Introduction

→ Presentation overview

1. High Performance Concrete Bridge Decks – Issues and Solutions
2. Effect of Internal Curing on Concrete Performance
3. Case Study – Highway Bridge Deck
4. Service Life Modelling
5. Life Cycle Cost Modelling
6. Environmental Impact

– Part 1 –

HPC Bridge Decks

(Issues and Solutions)

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HPC bridge decks
→ Benefits and challenges

- According to the US Federal Highway Administration, most DOTs use HPC for highway bridges, to benefit from:
    - high strength, low permeability, long spans, thin sections …

- FHA reports that the main causes of deterioration in bridge decks are:
    1. Shrinkage cracking (>100,000 bridges in USA)
    2. Rebar corrosion

- Cost to upgrade all concrete bridges:
    - $ 80-100 billion (USA)
    - $ 8-10 billion (Canada)

Confederation bridge

Prince-Edward Island, Canada

(13 km long, opened in 1997)

HPC bridge decks
→ Reinforcement corrosion

- Corrosion cracking due to de-icing salt contamination is a common problem in concrete bridges and parking structures.

- Solutions investigated at NRC:
  - Low-permeability concrete
  - Corrosion inhibitors
  - High-performance steels

Vachon Bridge, Laval, Canada, 1996
(before rehabilitation, after 22 years of service)

Laurier-Taché Parking Garage, Hull, Canada, 2004
(before rehabilitation, after 29 years of service)

HPC bridge decks
→ Restrained shrinkage

- Shrinkage cracking due to restraint of movement is also a common problem in concrete bridges and parking structures.

- Solutions investigated at NRC:
  - Internal curing with LWA
  - Shrinkage-reducing admixtures
  - Supplementary cementing materials

Vachon bridge, Laval, Canada, 1996
(a few days after rehabilitation)

Laurier-Taché Parking Garage, Hull, Canada, 2004
(a few weeks after rehabilitation)

HPC bridge decks

→ Underlying causes

1) Chemical shrinkage
   - Volume of hydrated cement < Volume of water + cement
   - Occurs in cement-based concrete (typical value for OPC = 7% by vol.)
2) Self-desiccation
   - Internal drying due to lack of water to hydrate all cement particles
   - Occurs more often in high-strength concrete due to low w/c (< 0.42)
3) Drying shrinkage
   - External drying when ambient RH is lower than concrete RH
   - Occurs more often in normal concrete due to high permeability
4) Cooling
   - Loss of heat to the environment, accumulated due to cement hydration
   - Occurs more in high-strength concrete due to high cement content
5) Other causes

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– Part 2 –

Effect of Internal Curing on Concrete Performance

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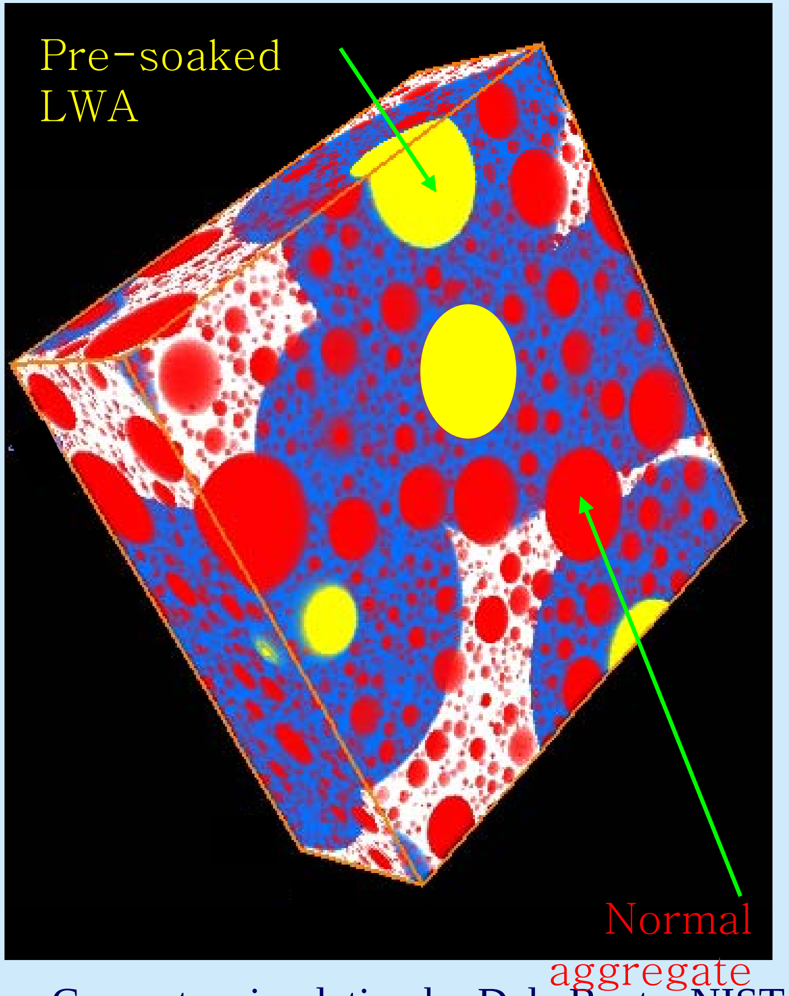
Internal curing
→ Definition

- IC consists of providing curing water to concrete from inside, by using:
  - pre-soaked porous LWA, or
  - super-absorbent polymers, or
  - saturated wood fibers.

- IC can compensate for chemical shrinkage, reduce self-desiccation, and improve cement hydration, which may result in:
  - reduced early-age cracking,
  - higher concrete strength and stiffness,
  - reduced permeability and rebar corrosion.

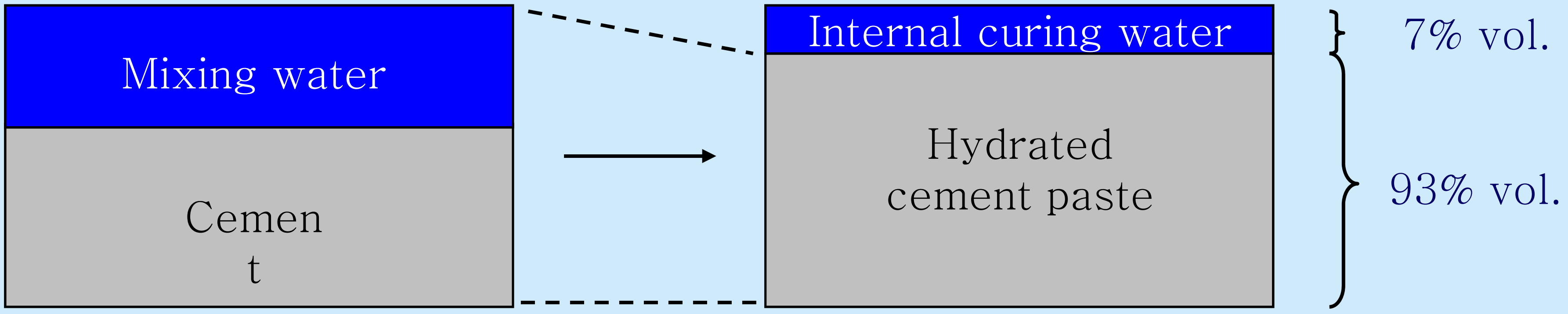


Computer simulation by Dale Bentz, NIST

Effect of internal curing
→ Chemical shrinkage

1) Chemical shrinkage

- Can be compensated by internal curing.



Mixing water

Cement

Internal curing water

Hydrated
cement paste

7% vol.

93% vol.

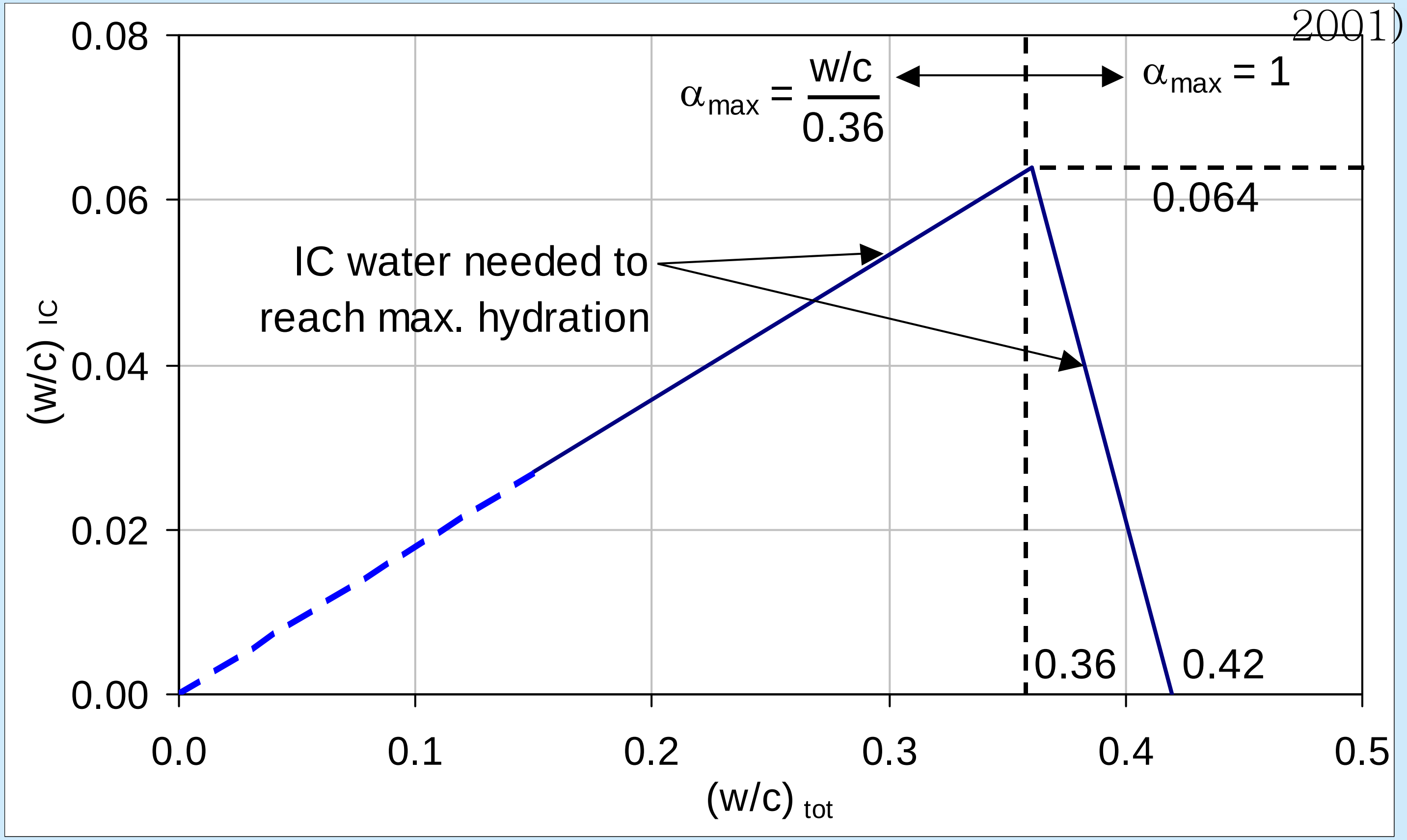
Proportions
before hardening

Proportions
after hardening

Effect of internal curing

→ Chemical shrinkage

(Jensen & Hansen 2001)



$$M_{LWA} = \frac{M_C\, C_S\, \alpha_{max}}{S_{LWA}\, \phi_{LWA}}$$

M_{lwa} = dry mass of LWA

M_c = mass of cement

C = chemical

α_{max} = hydration degree

S_{lwa} = saturation degree

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Effect of internal curing
→ Desiccation & shrinkage

2) Self-desiccation

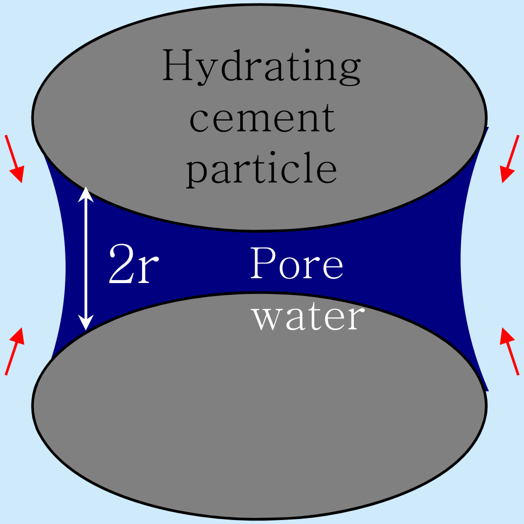
3) Drying shrinkage

Can be reduced by internal curing (higher RH),

Can also be reduced by use of SRA (lower γ).

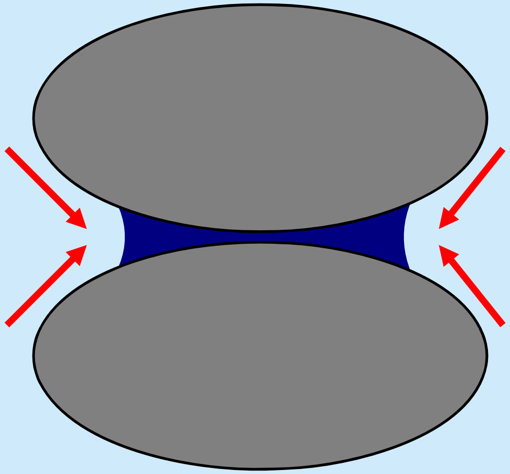
$$\boxed{\sigma_{cap} = \frac{2\gamma}{r} = \frac{-\ln(RH)RT}{V_m}}$$

Kelvin–Laplace equation



High RH

Surface tension forces pulling on particles (γ)



Low RH

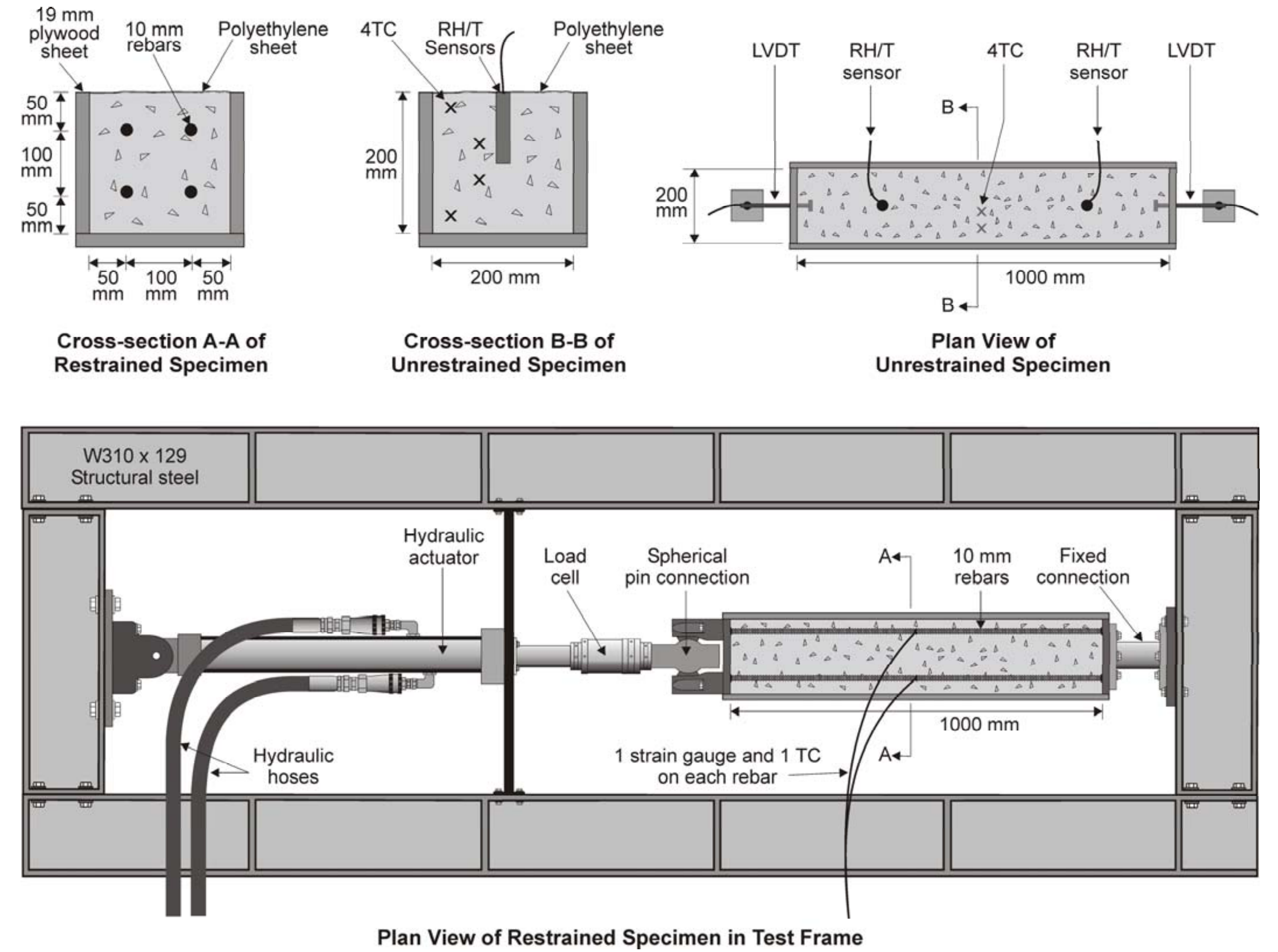
Effect of internal curing
→ Previous testing at NRC

- **Control concrete** (referred to as Mix-0)
  - Cement/sand/coarse aggregate ratio: 1:2:2
  - Water/cement ratio: 0.34
  - Cement content: 445 kg/m^3 (ASTM type I)

- **LWA-modified concretes**
  - Same as above, plus:
  - Normal sand partly replaced by saturated LWA (15% absorption capacity)
    - 6% sand replacement (Mix-L)
    - 12% sand replacement (Mix-M)
    - 20% sand replacement (Mix-H)

Effect of internal curing

→ Restrained shrinkage testing



Cross-section A-A of Restrained Specimen

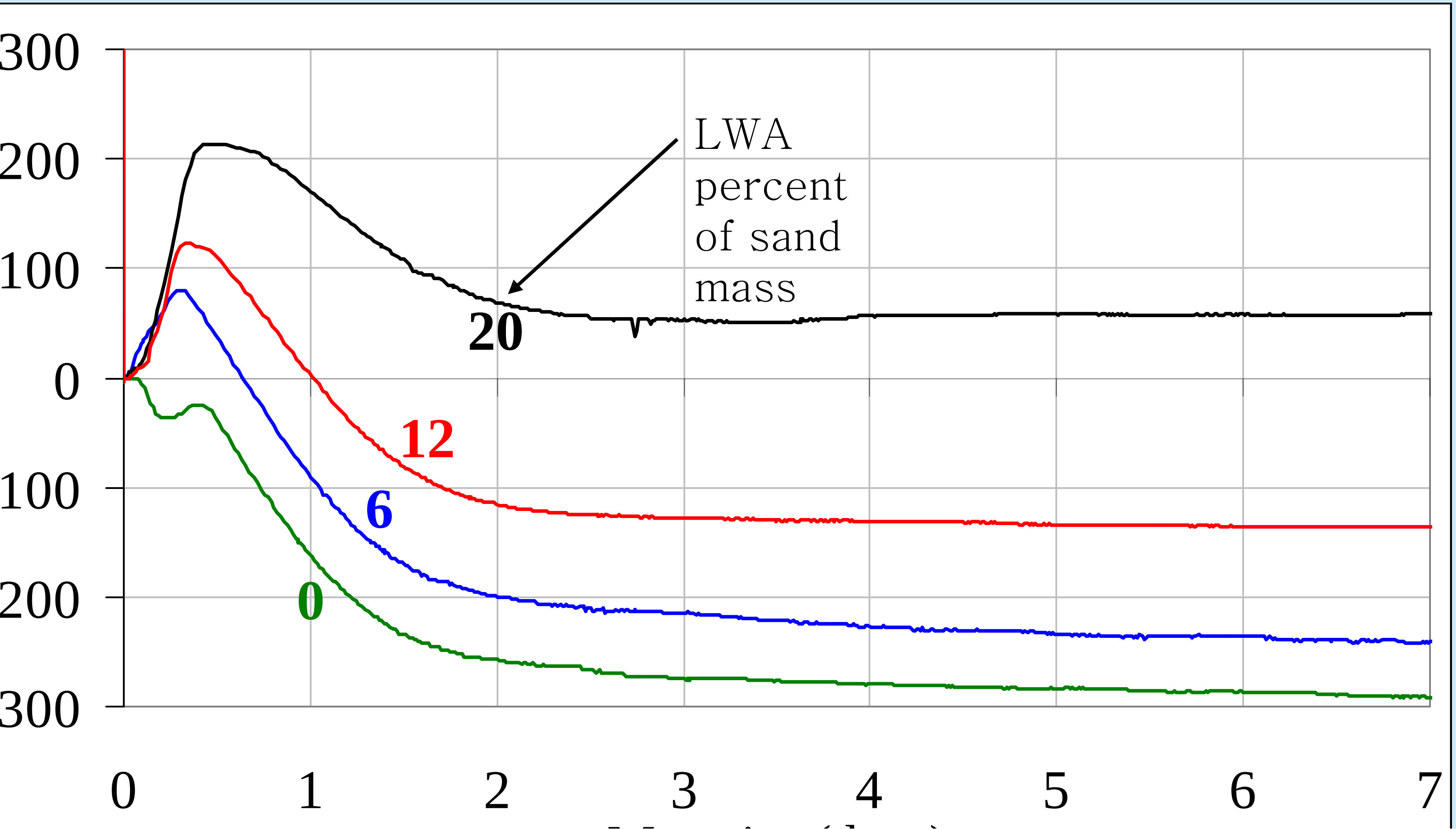
Cross-section B-B of Unrestrained Specimen

Plan View of Unrestrained Specimen

Plan View of Restrained Specimen in Test Frame

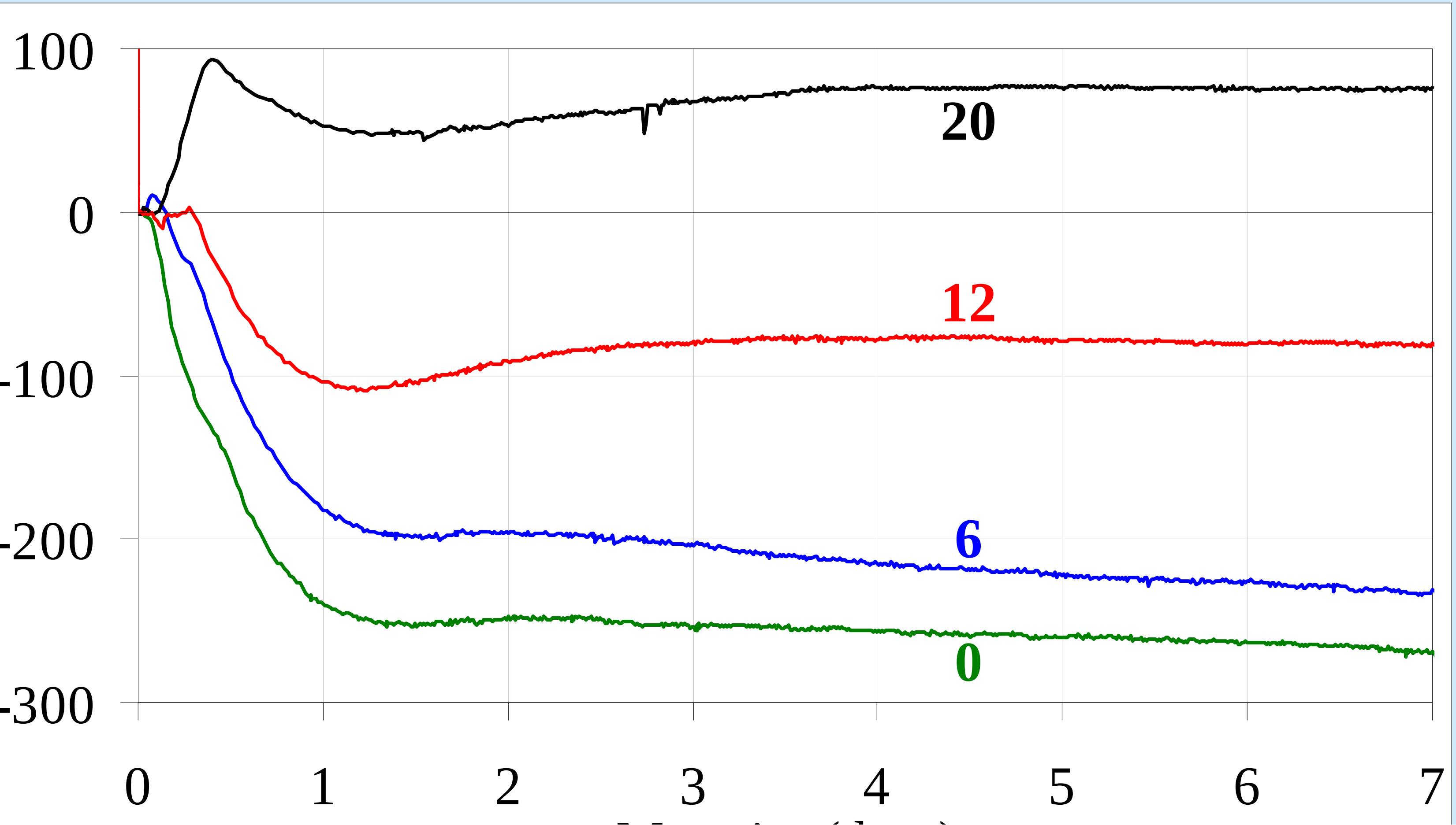
Effect of internal curing

→ Total strain



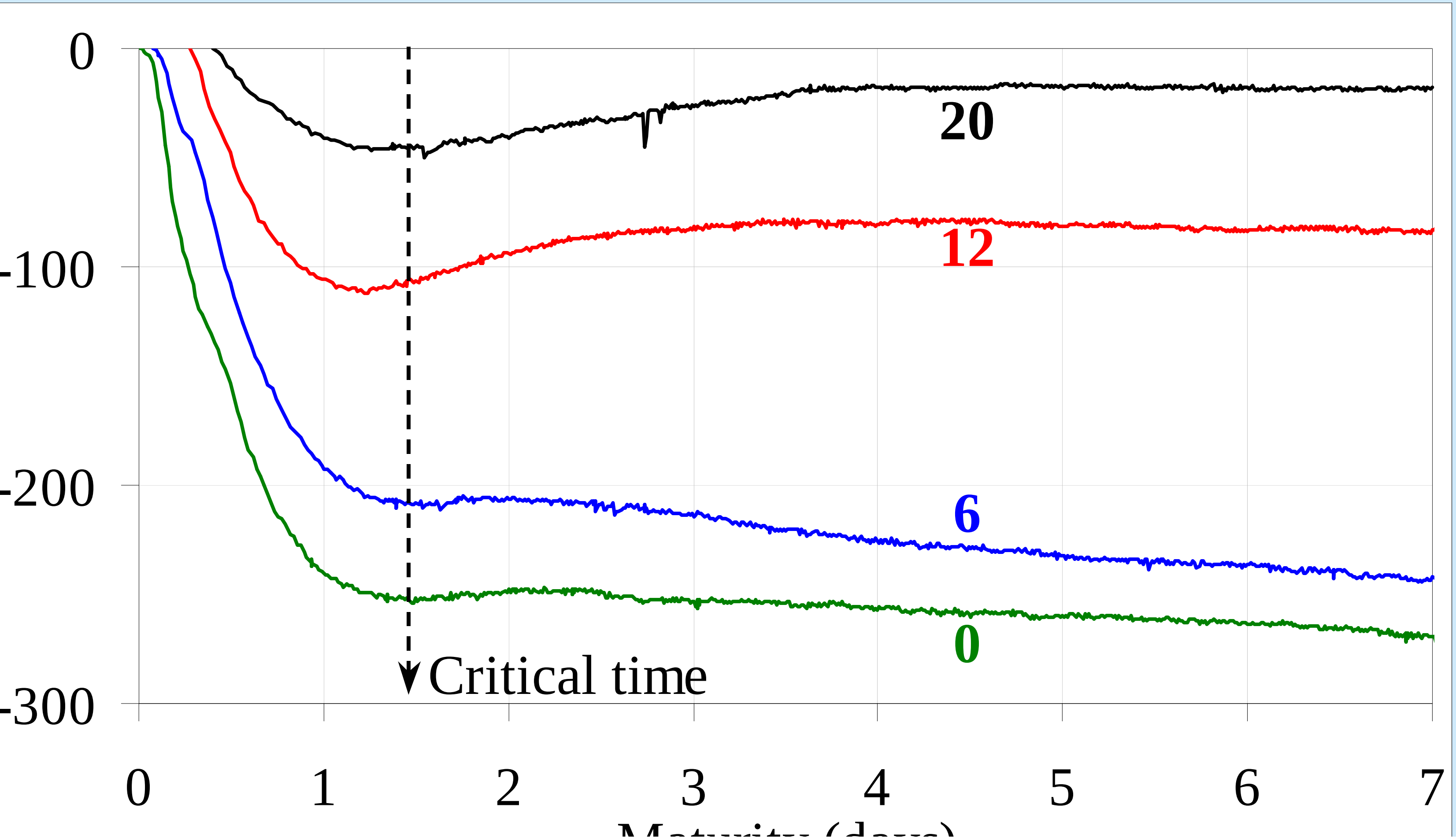
Effect of internal curing

→ Autogenous shrinkage strain



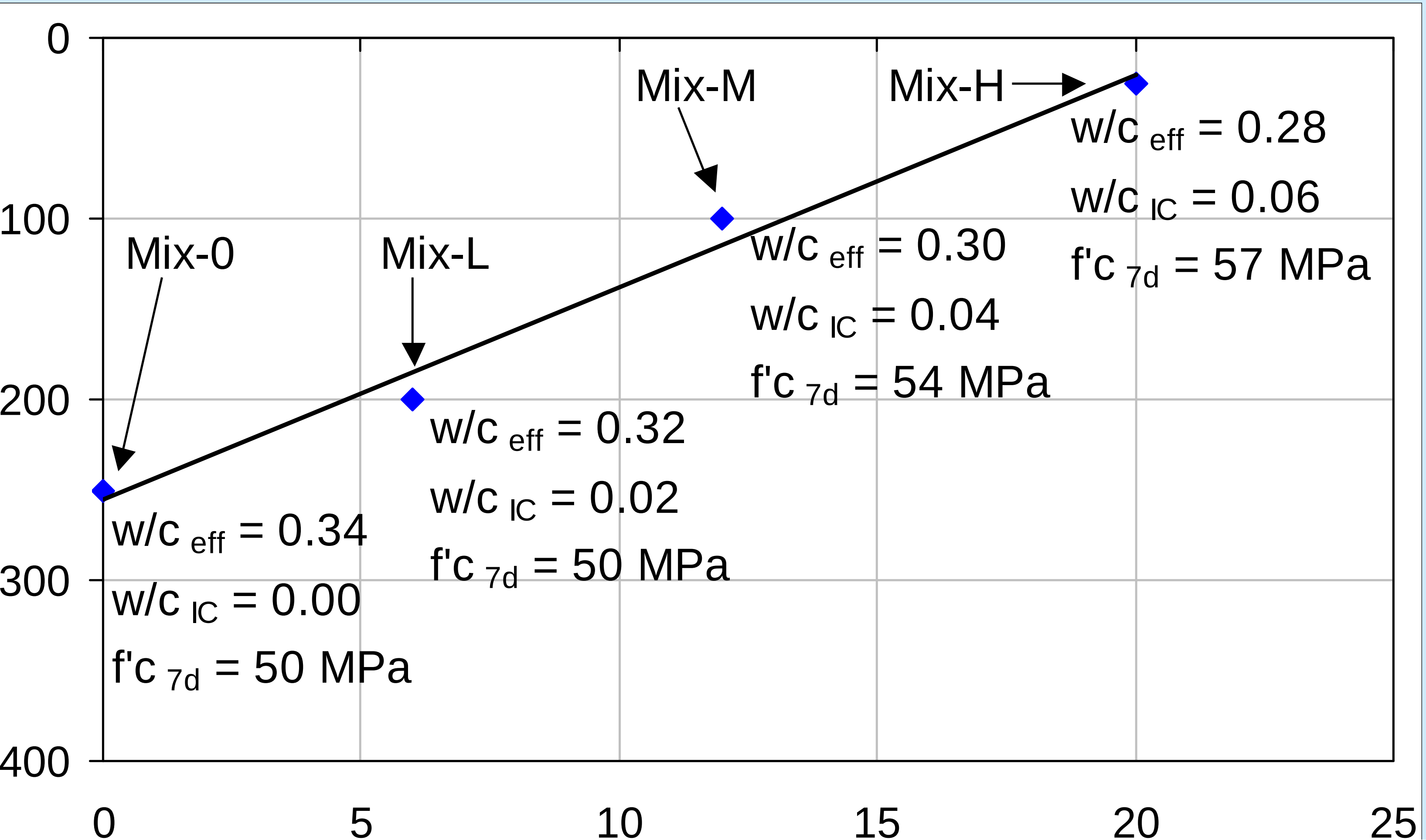
Effect of internal curing

→ Net shrinkage strain



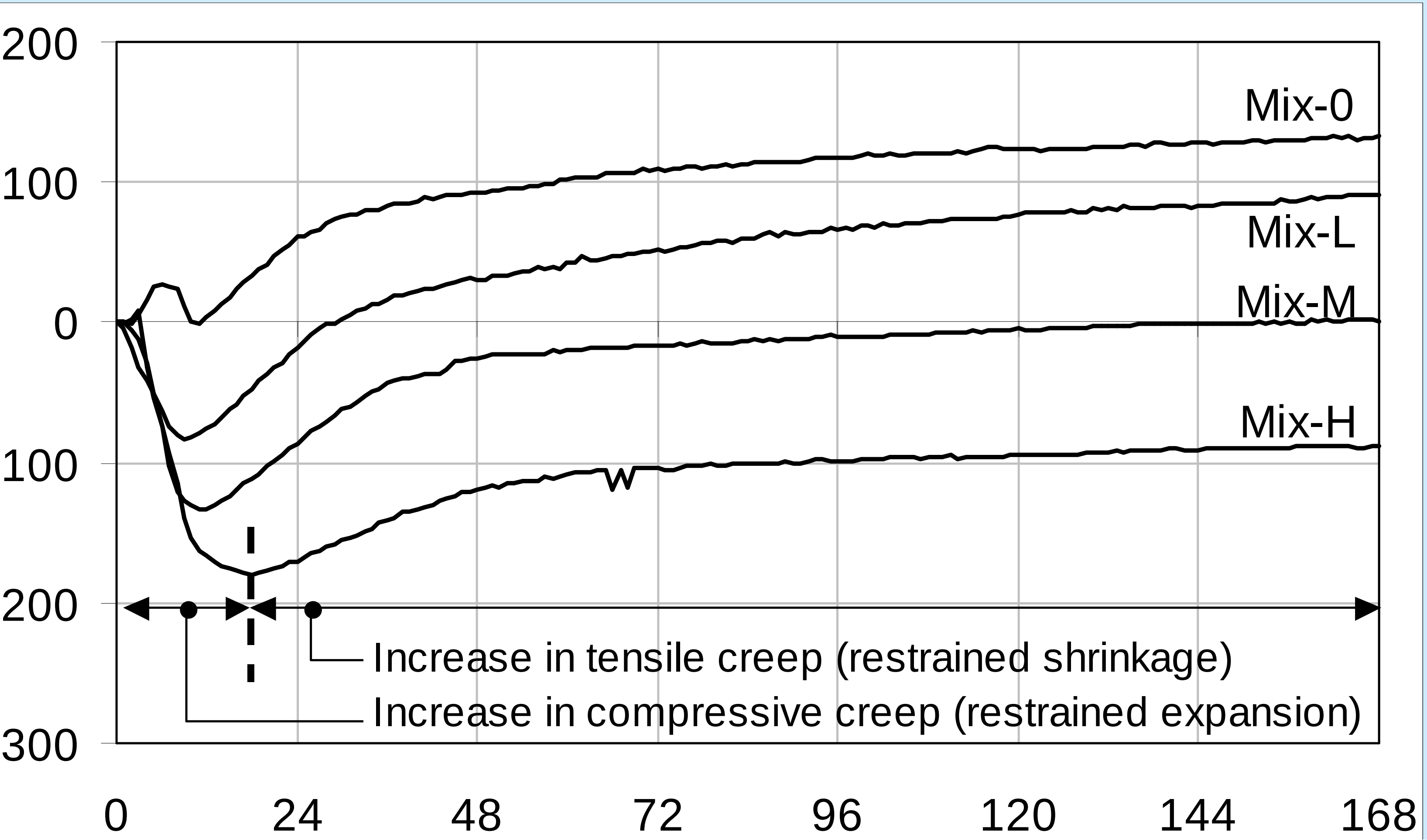
Effect of internal curing

→ Requirement to avoid shrinkage



Effect of internal curing

→ Basic creep strain

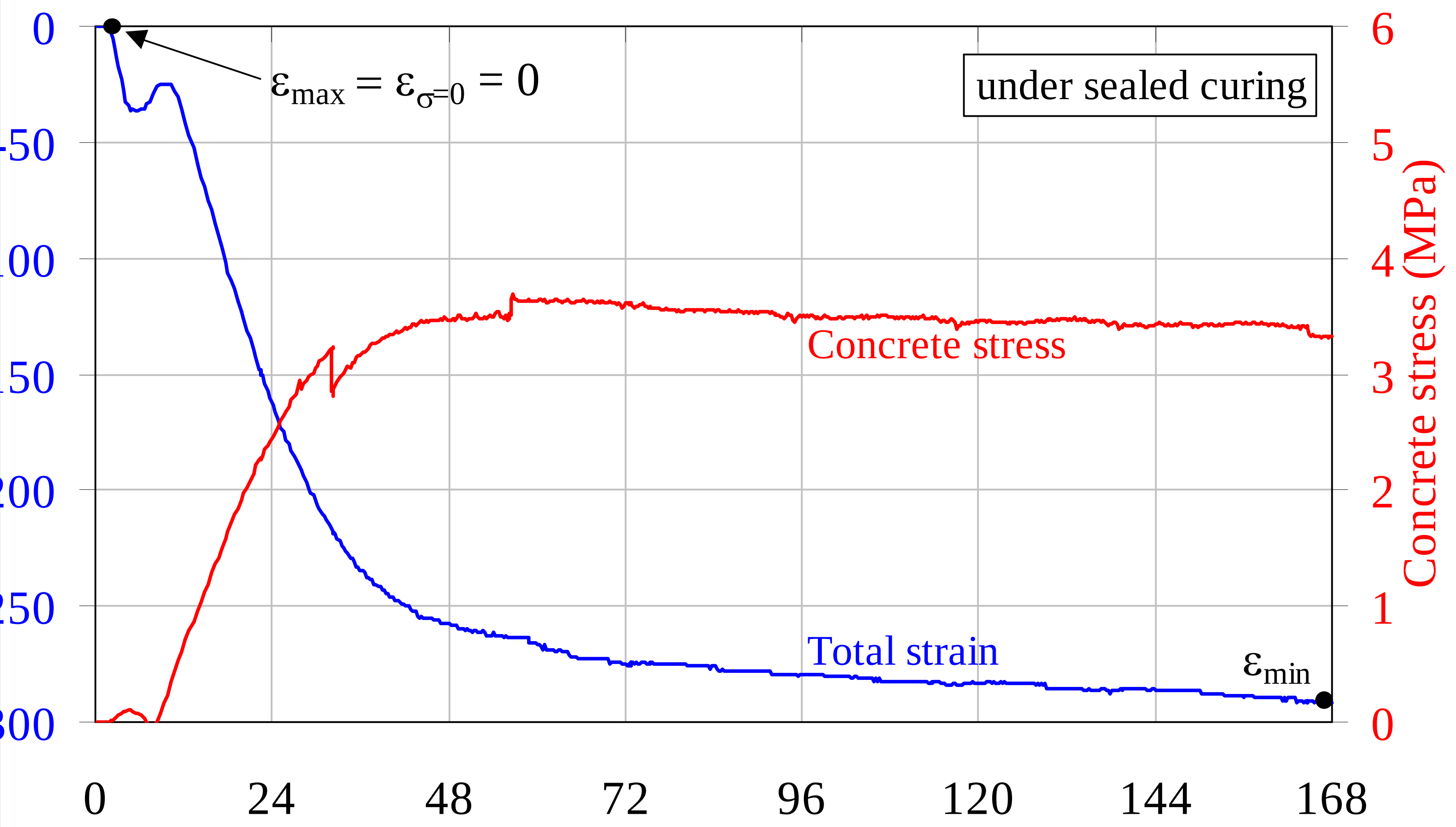


Increase in tensile creep (restrained shrinkage)

Increase in compressive creep (restrained expansion)

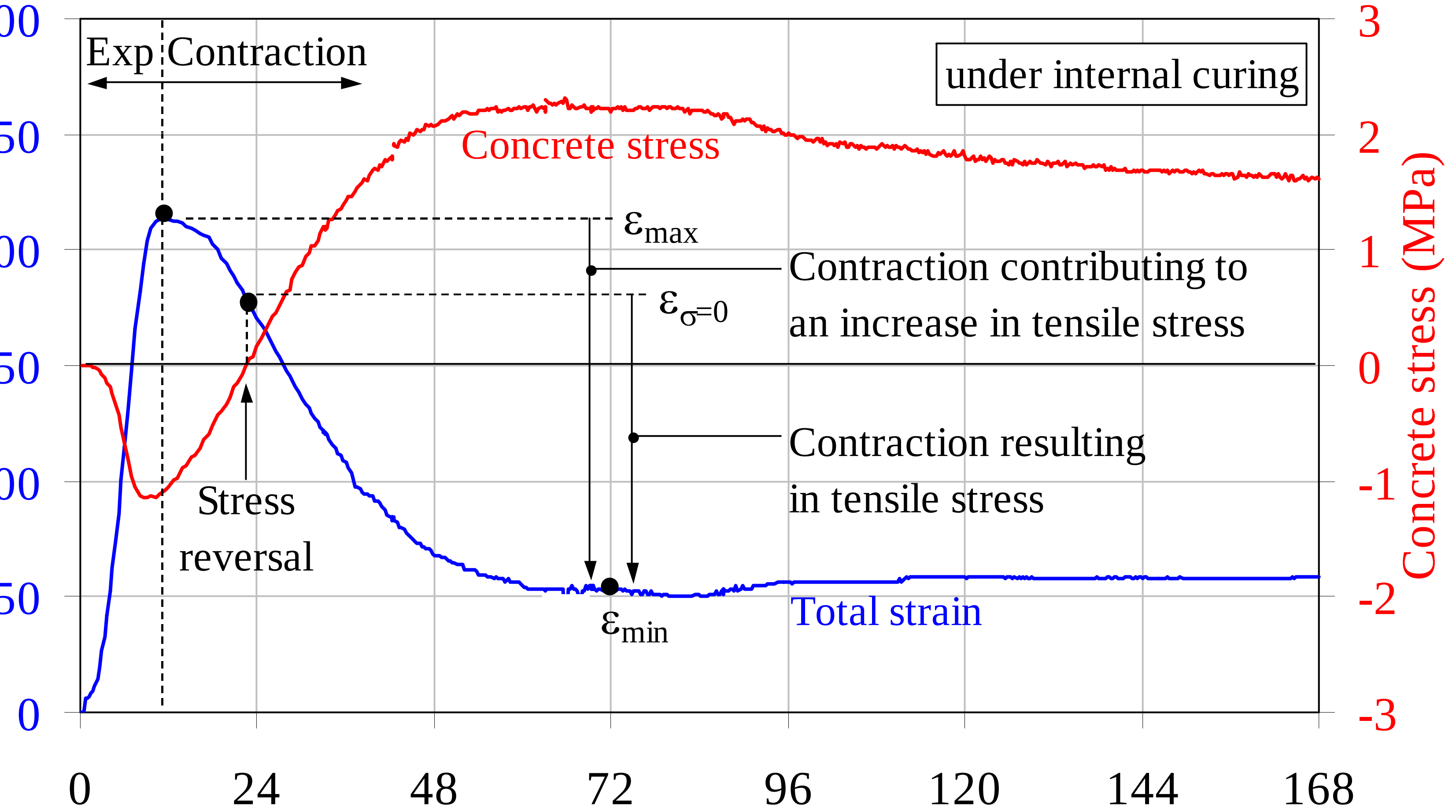
Effect of internal curing

→ Tensile stress



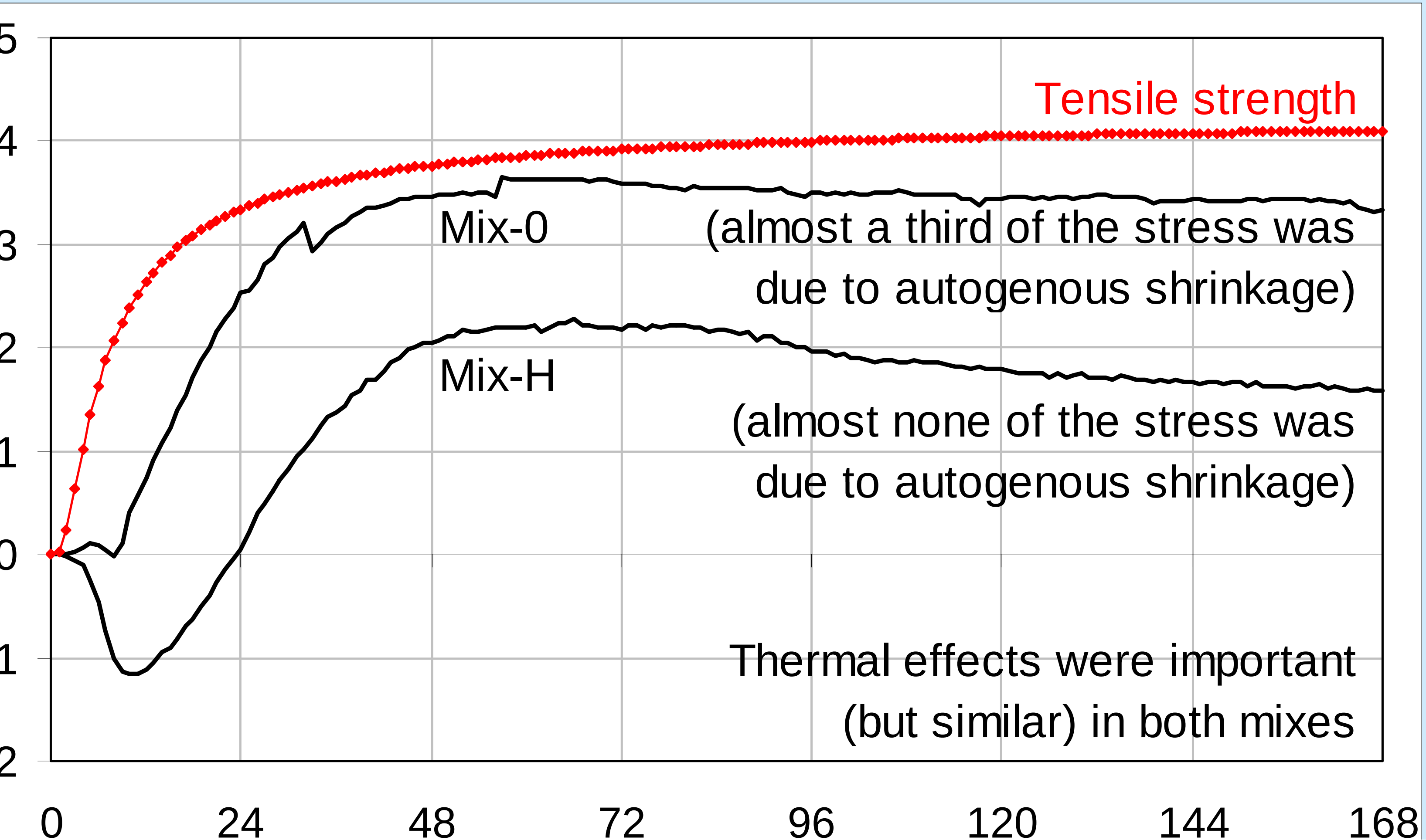
Effect of internal curing

→ Tensile stress



Effect of internal curing

→ Tensile stress



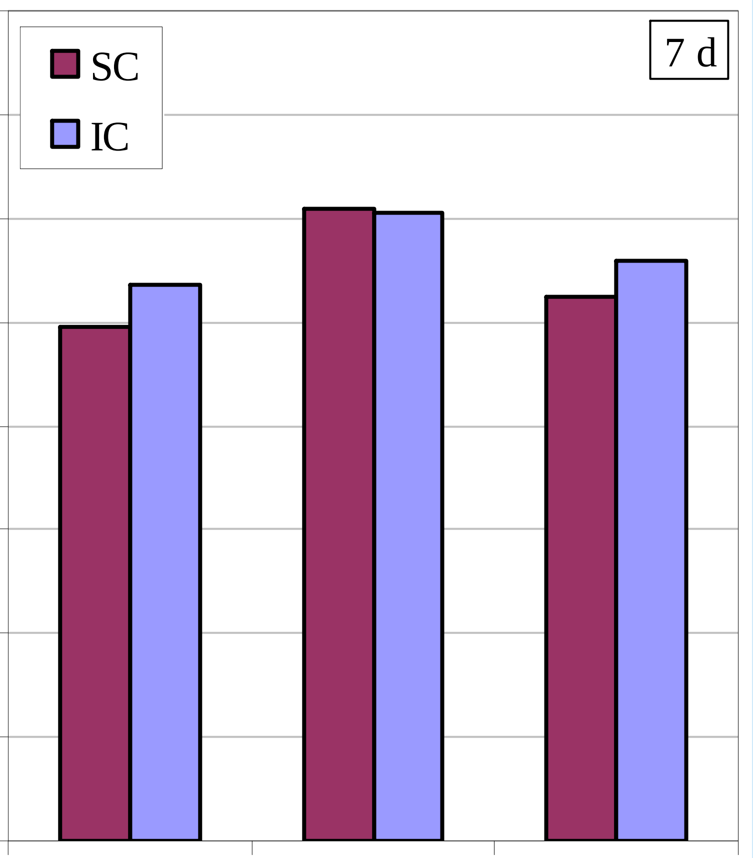
(almost a third of the stress was due to autogenous shrinkage)

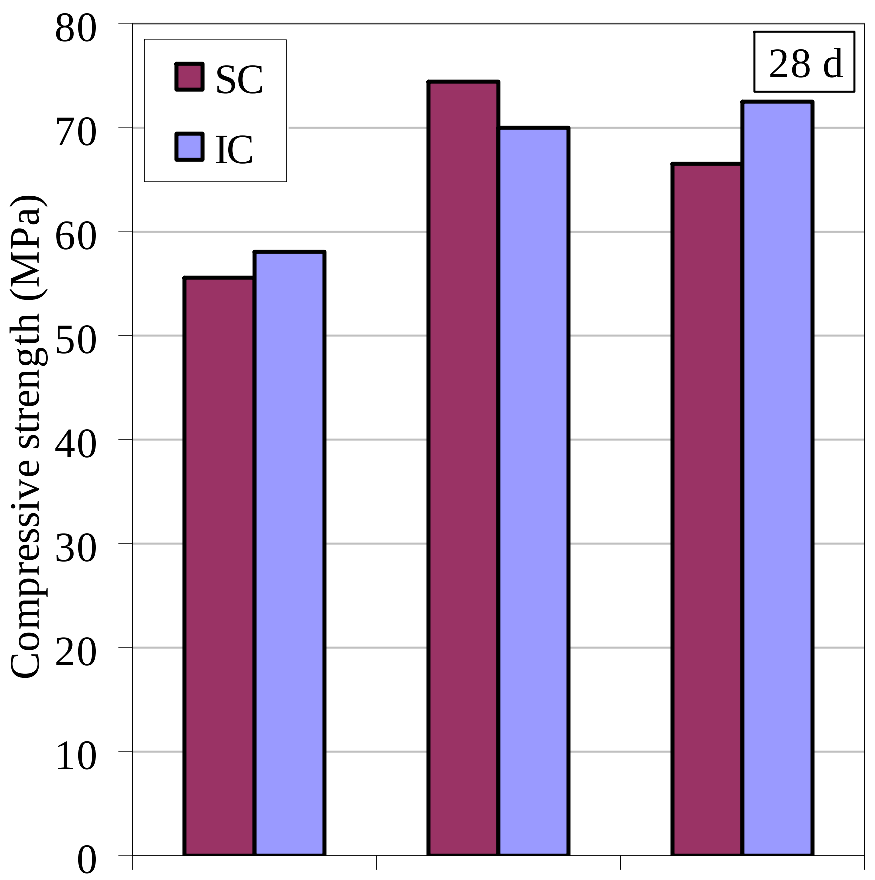
(almost none of the stress was due to autogenous shrinkage)

Thermal effects were important (but similar) in both mixes

Effect of internal curing

→ Compressive strength





Effect of internal curing
→ Field demonstration

Project description:

- Large-scale paving project in Hutchins, Texas (Villarreal & Crocker 2007)
- 190 000 m^3 of internally-cured concrete

Main field observations:

1. Marginal pavement cracking
2. 7-day flexural strengths > 90% of required 28-day flexural strength
3. Compressive strengths of air-cured cylinders = those of wet-cured cylinders

Main conclusions:

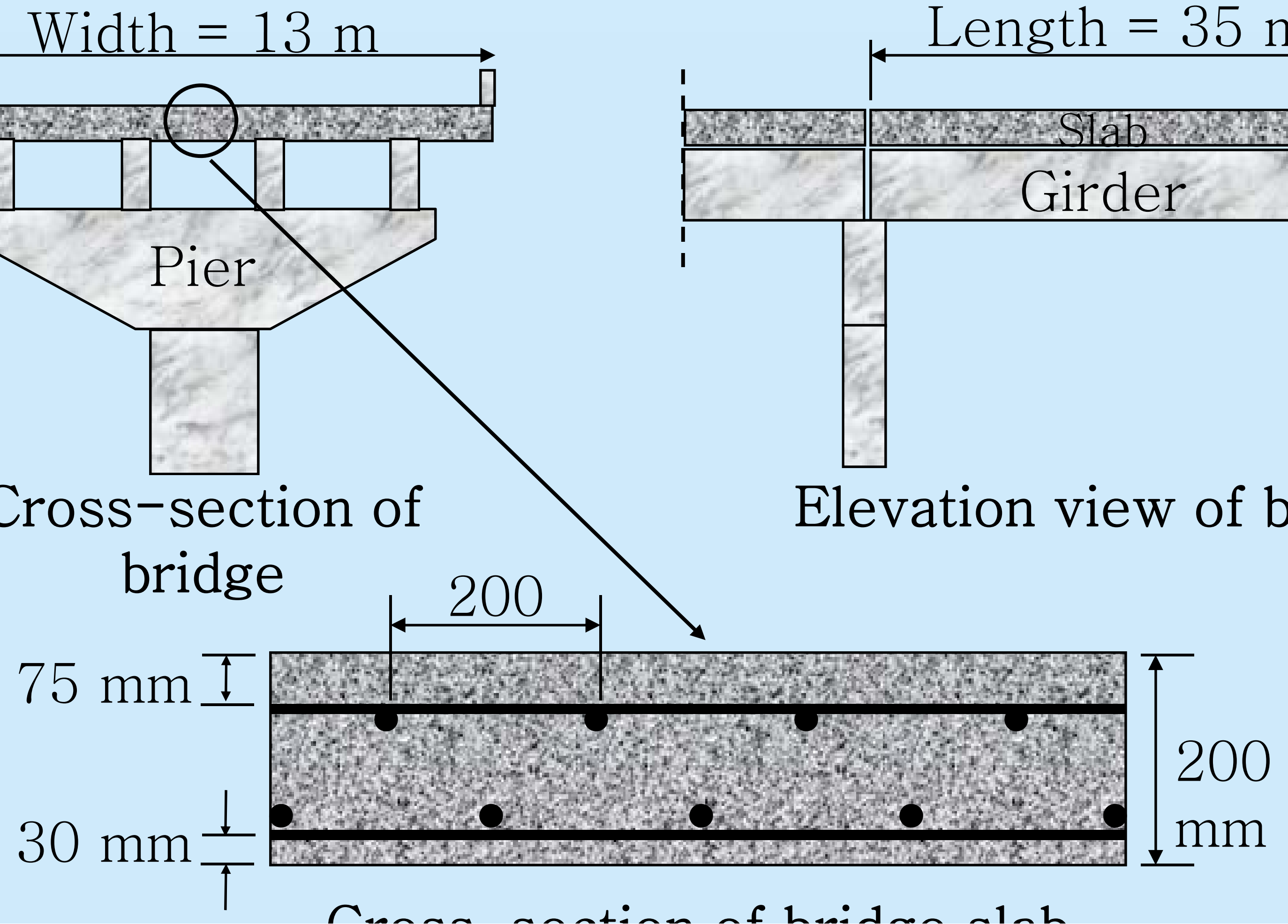
1. Internal curing can reduce shrinkage cracking significantly,
2. Cement hydration is more complete due to internal curing,
3. Internally-cured concrete is less sensitive to poor external curing practices or

– Part 3 –

Case Study – Highway Bridge Deck

Case Study

→ Highway Bridge Deck



Cross-section of bridge

Elevation view of bridge

Cross-section of bridge slab

Case Study

→ Concrete mix formulations

Bridge deck	Initial cracking	Water (kg/m³)	Cement (kg/m³)	SCM (%)	w/cm	LWA (kg/m³)	Cost ($/m³)
NC	No	140	350	0	0.40	0	$450
HPC	Yes	160	450	25	0.35	0	$600
HPC-IC	No	160	450	25	0.35	200	$625
VHPC-IC	No	160	525	25	0.30	200	$750

costs 75$/ton (vs. $15/ton for normal sand).

of 200 kg/m³ of LWA and long-distance transportation (e.g. 600

nly increase the in-place cost of concrete by approximately

Case study

→ Exposure conditions

osure conditions (all deck options):

Surface chlorides: 9 kg/m^3 (typical of severe conditions in Canada)

Corrosion threshold: 0.7 kg/m^3 (typical for normal steel
einforcement)

Corrosion rate: 0.5 μA/cm^2 (typical moderate value in concrete)

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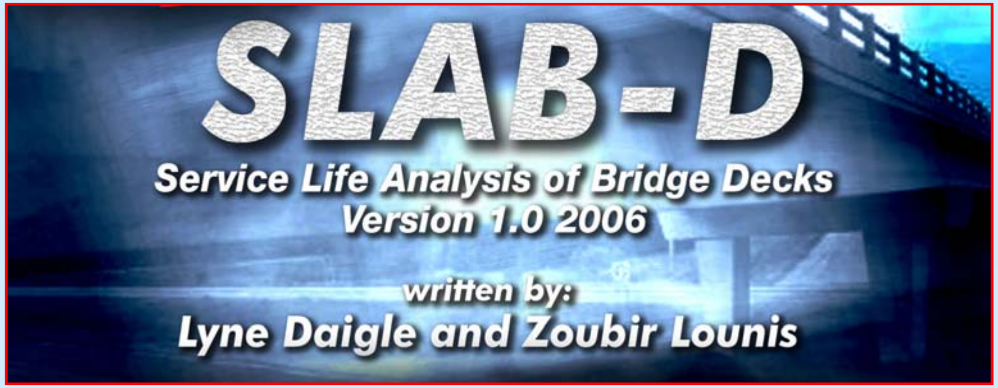
– Part 4 –

Service Life Modelling of Bridge Deck



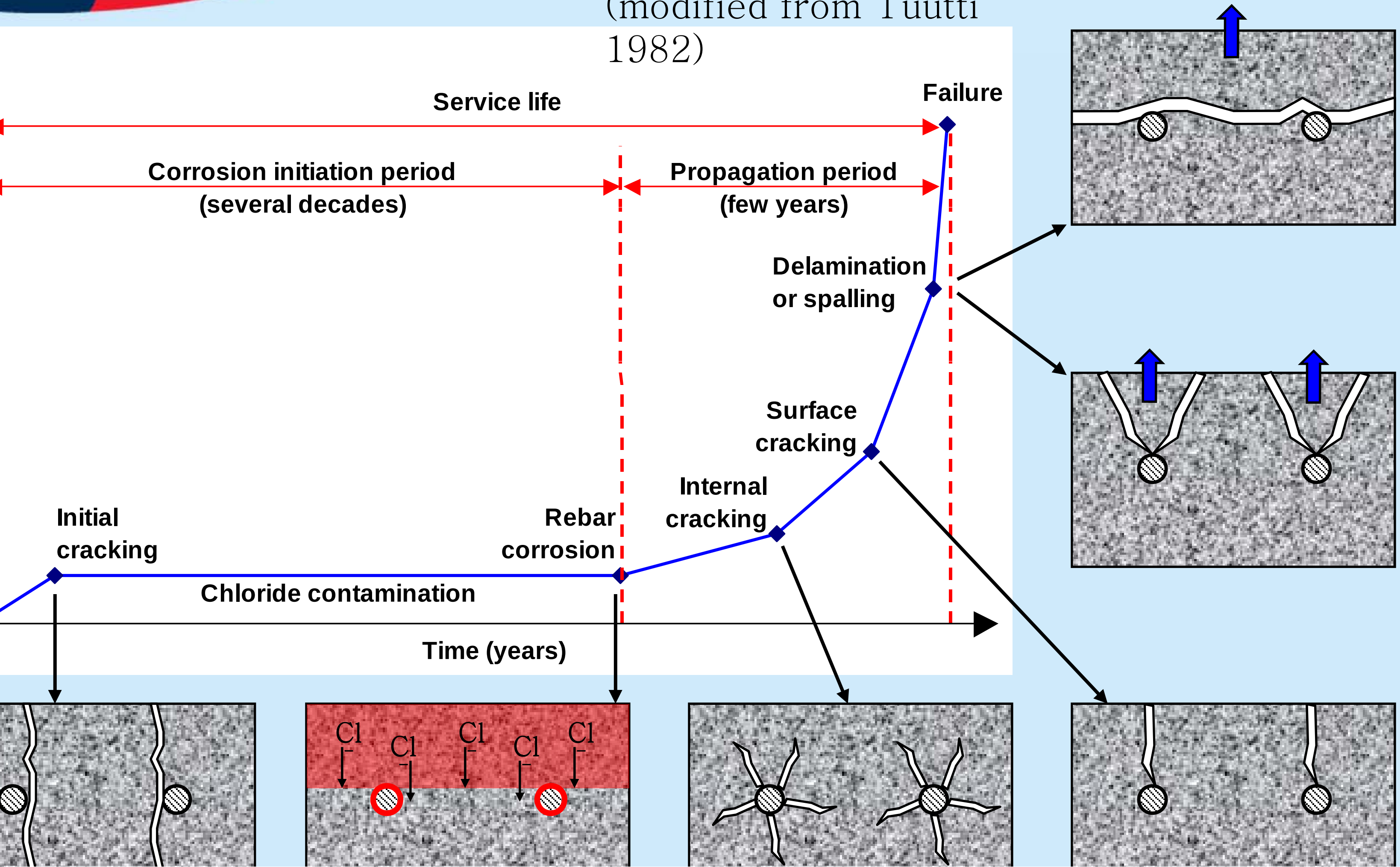
SLAB-D

Service Life Analysis of Bridge Decks
Version 1.0 2006

written by:
Lyne Daigle and Zoubir Lounis

Service life modelling

→ Two-phase damage model



(modified from Tuutti 1982)

Service life

Failure

Corrosion initiation period
(several decades)

Propagation period
(few years)

Delamination
or spalling

Surface
cracking

Internal
cracking

Initial
cracking

Rebar
corrosion

Chloride contamination

Time (years)

Service life modelling

→ Chloride diffusion in concrete

k's 2nd law of diffusion:
ank 1975)

$$x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D_C\;t}}\right)\right]$$

C = chloride concentration
C_s = surface chloride content
D_c = chloride diffusion coefficient
x = depth in concrete
t = time of exposure

loride diffusion coefficient:
ulfiza et al. 2003)

$$g\ D_C = -3.9\,(w/c)^2 + 7.2\,(w/c) - 14.0$$ (no SCMs)

$$D_C = -3.0\,(w/c)^2 + 5.4\,(w/c) - 13.7$$ (with SF / Slag)

Service life modelling

→ Cl diffusion in cracked concrete

ect of cracking on
ride penetration
eared approach):

$$= D_c + \frac{w_{cr}}{s_{cr}} D_{cr}$$

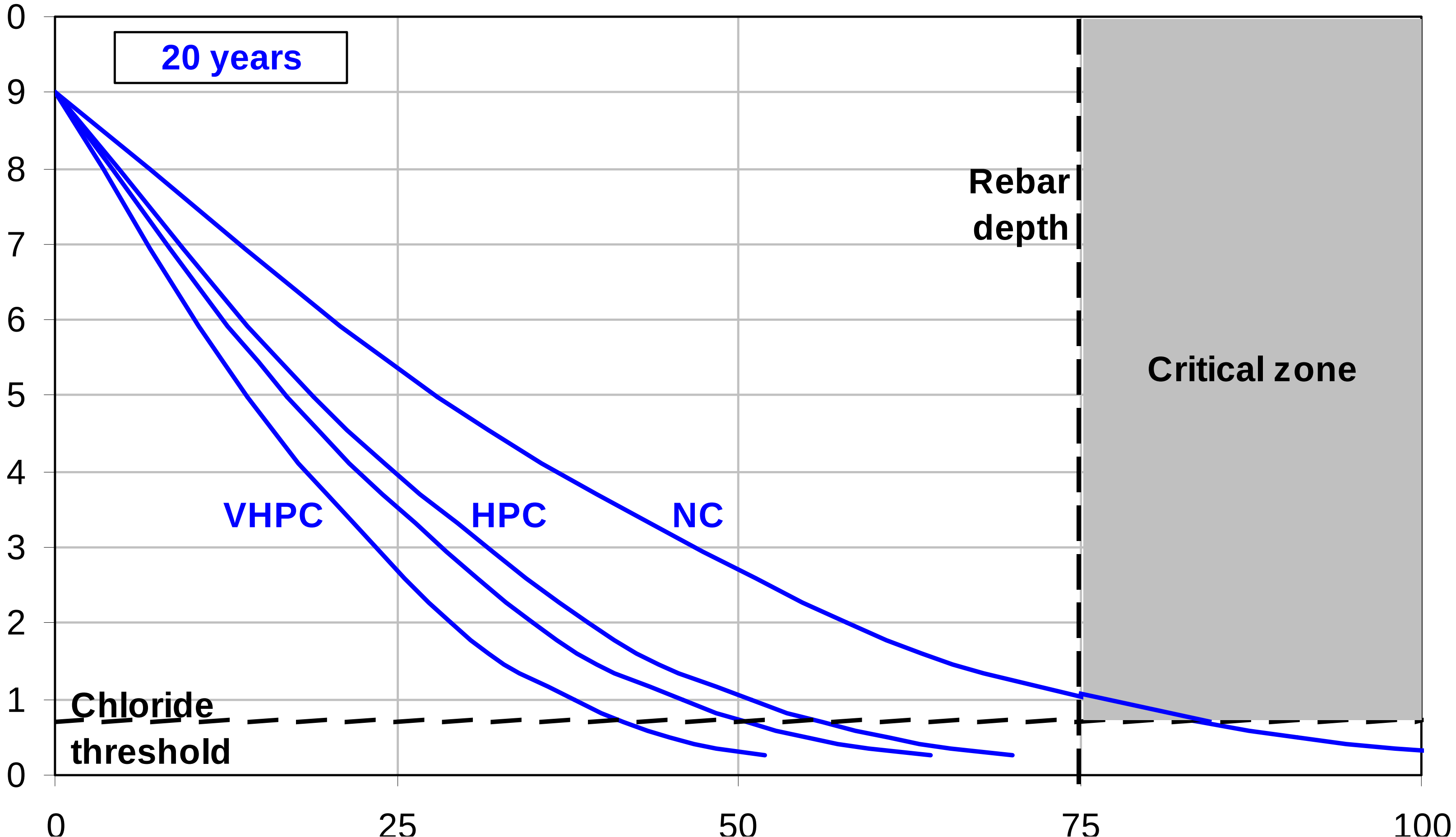
Bridge deck	w/cm (actual)	D_c (m^2/s)	D_{app} (m^2/s)
NC	0.40	18×10^{-13}	18×10^{-13}
HPC (cracks)	0.35	6.6×10^{-13}	8.1×10^{-13}
HPC-IC	0.35	6.6×10^{-13}	$^*6.6 \times 10^{-13}$
VHPC-IC	0.30	4.4×10^{-13}	$^*4.4 \times 10^{-13}$

* Conservative estimate

liffusion in cracks: 5×10^{-10}

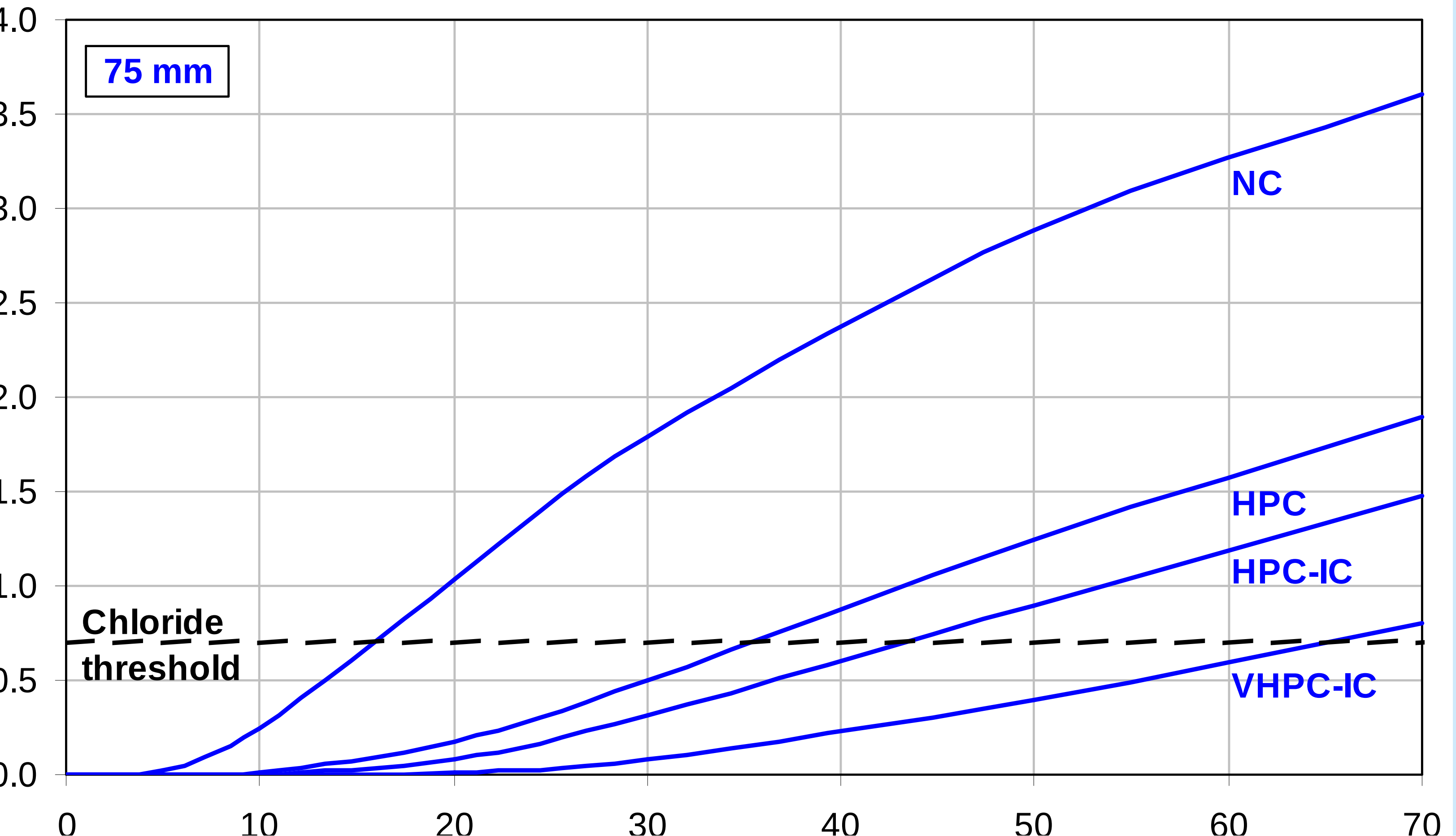
Service life modelling

→ Chloride profile after 20 years

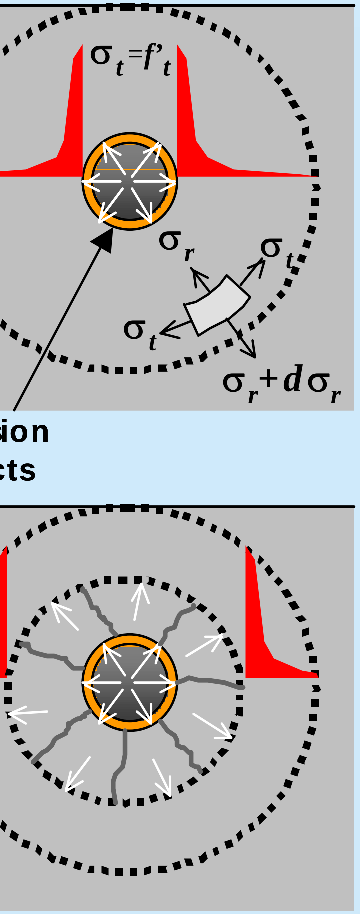


Service life modelling

→ Chloride ingress at rebar level



Service life modelling
→ Corrosion induced damage



-wall cylinder

Propagation time for each damage level:
(from onset of corrosion to initial cracking, surface cracking and spalling)

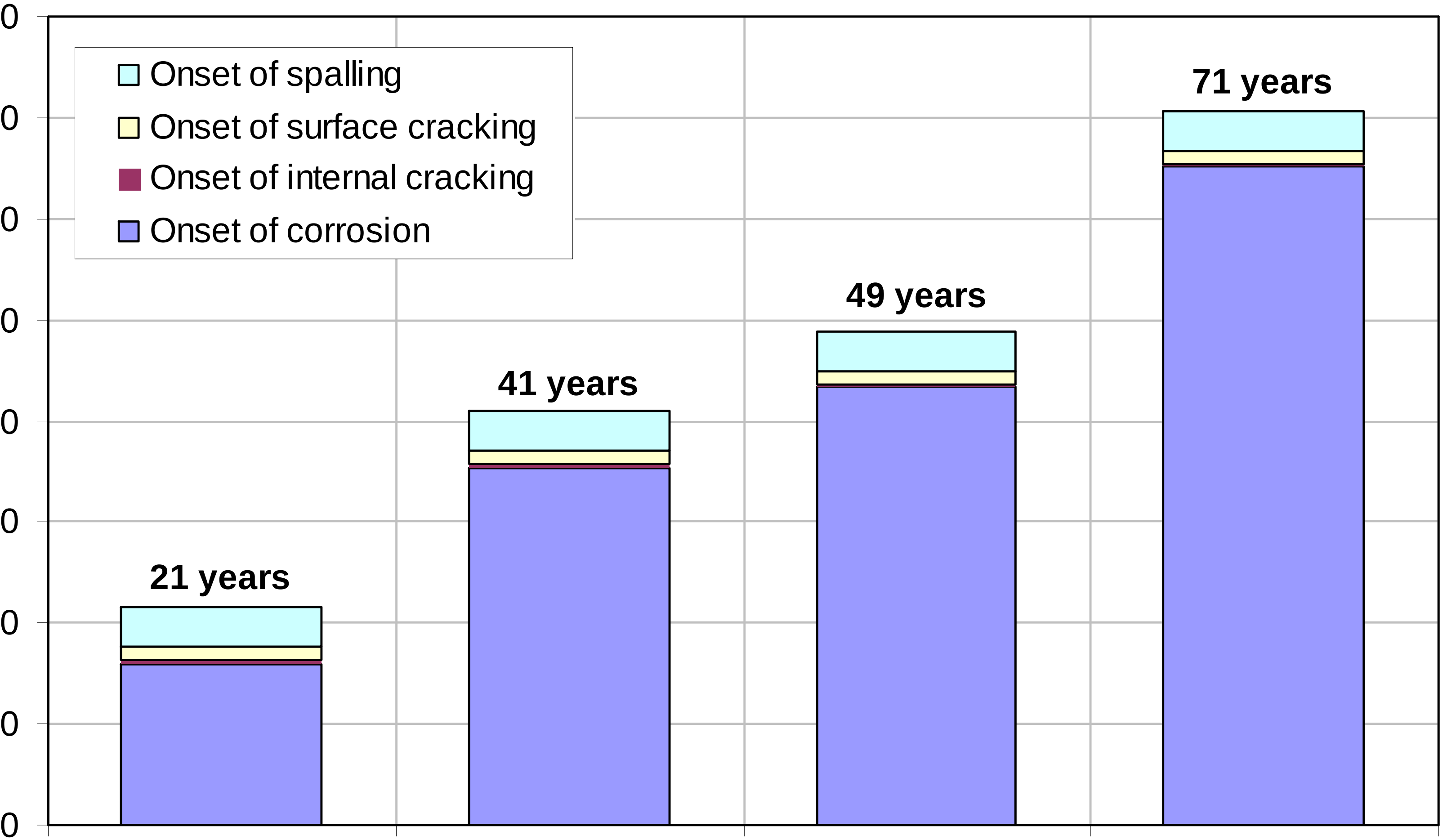
$$t_p = \frac{\pi\, d\,(\Delta d)}{2\,S\,j_r\left[\dfrac{1}{\rho_r} - \dfrac{\alpha}{\rho_s}\right]}$$

where:

d = rebar diameter
S = rebar spacing
j_r = rust production rate
ρ_r = rust density
ρ = steel density

Service life modelling

→ Average SL prediction



Service life modelling

→ Reliability analysis

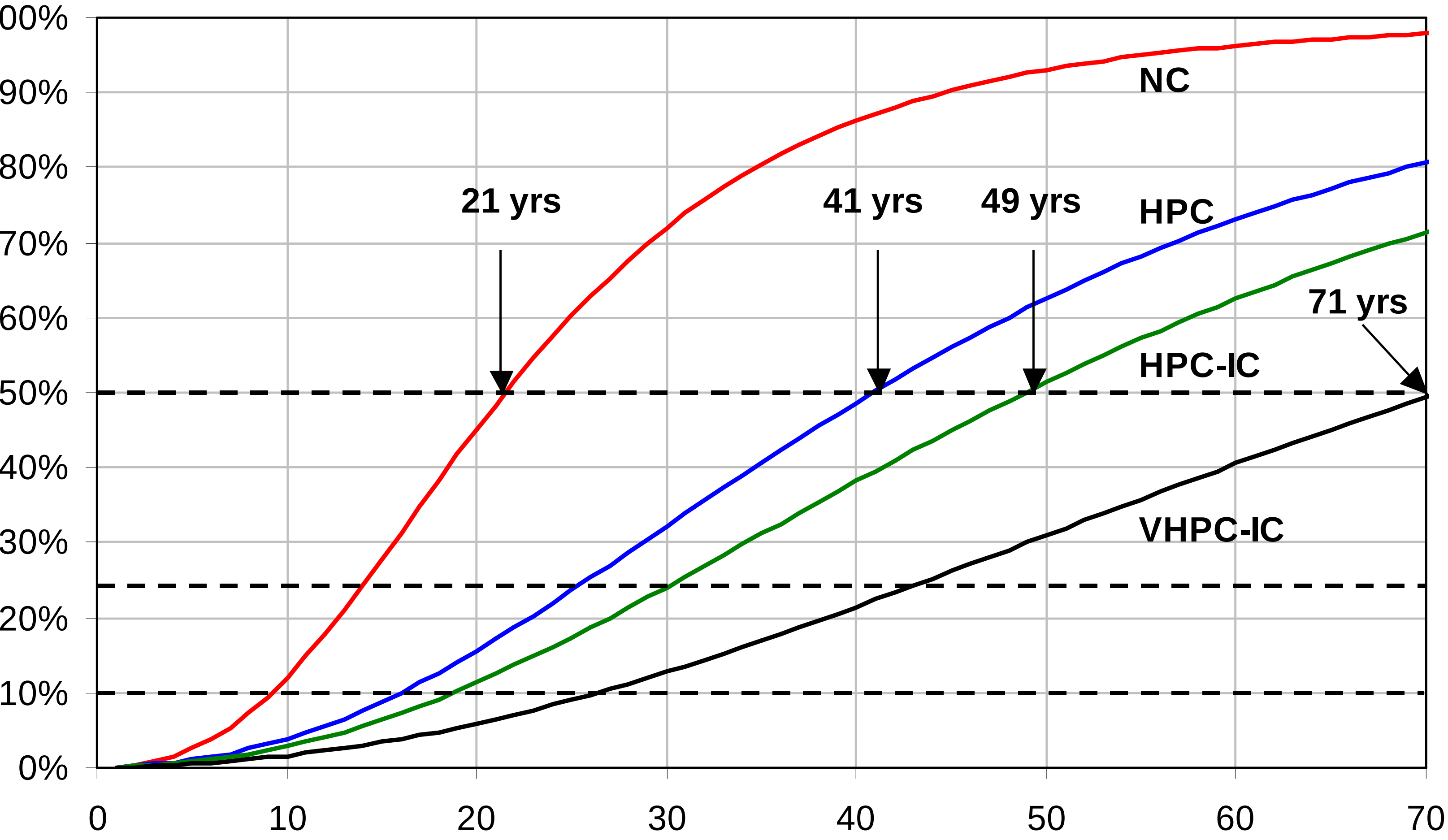
liability analysis takes into account variability and certainty

nput parameters (properties, dimensions, environmental ditions, etc.)

Model parameter	Average	COV
Surface chlorides	9 kg/m^3	30 %
Diffusion coefficient -NC -HPC -HPC-IC -VHPC-IC	 18 x 10^{-13} m^2/s 8.1 x 10^{-13} m^2/s 6.6 x 10^{-13} m^2/s 4.4 x 10^{-13} m^2/s	30 %
Cover depth	75 mm	30 %
Chloride threshold	0.7 kg/m^3	30 %
Corrosion rates	0.5 μA/cm^2	30 %

Service life modelling

→ Probability of spalling



Service life modelling

→ Assessment of deck condition

ndition state	Description (from AASHTO guidelines)
1	The surface of the deck has no patched area and no spalls in the deck surface.
2	The combined distress area (existing patches, delam. and spalling) of the deck is less than 10%.
3	The combined distress area of the deck is between 10% and 25%.
4	The combined distress area of the deck is between 25% and 50%.
5	The combined distress area of the deck is more than 50%.

this case study:

- 10 % distress area: major repair
- 25% distress area: major repair
- 50% distress area: deck replacement

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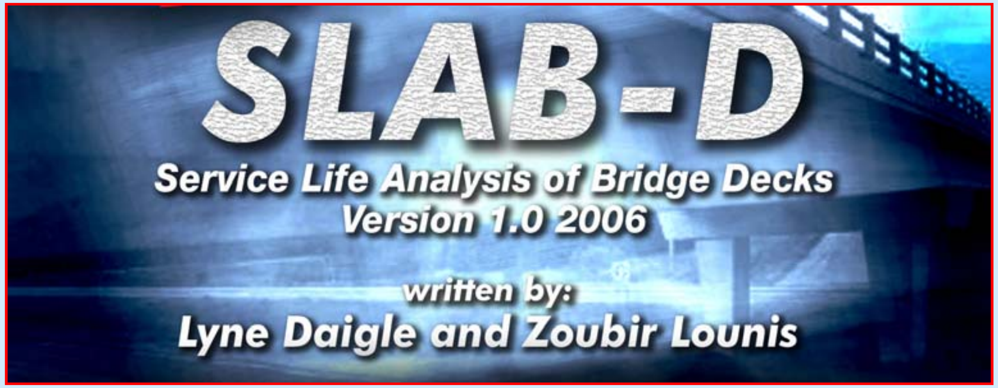
– Part 5 –

fe Cycle Cost Modelling of Bridge Deck



SLAB-D

Service Life Analysis of Bridge Decks
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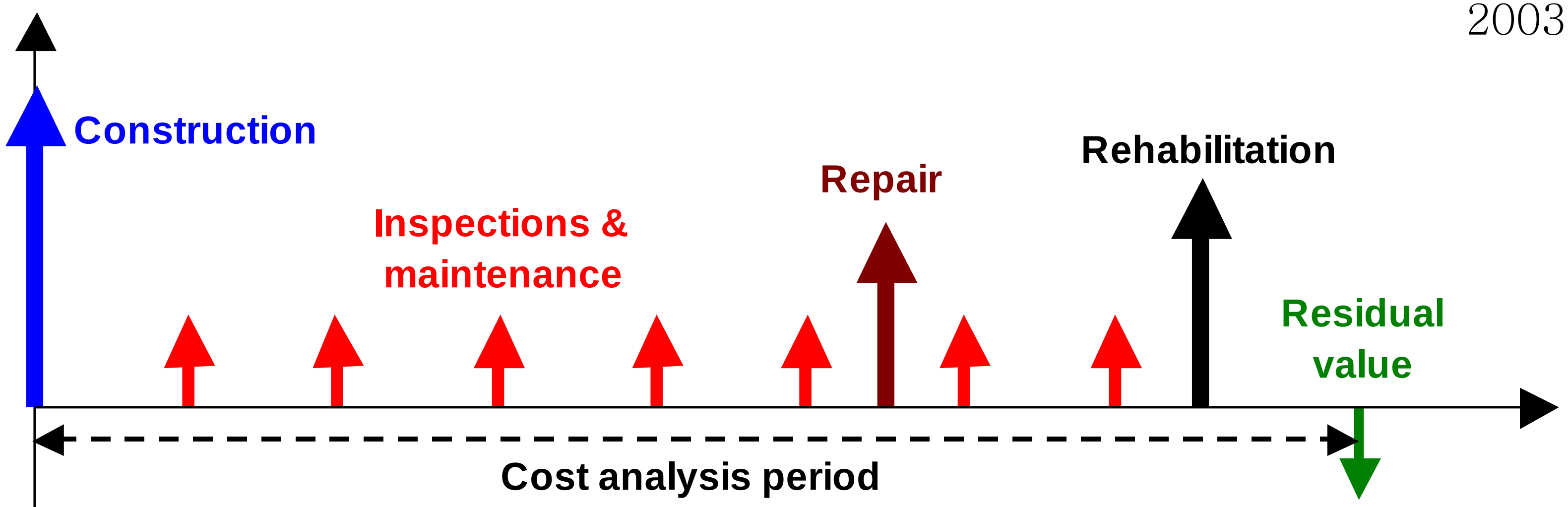
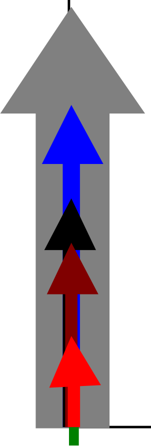
Life cycle cost modelling
→ Present value approach

(Grant et al. 1990; Hawk 2003)





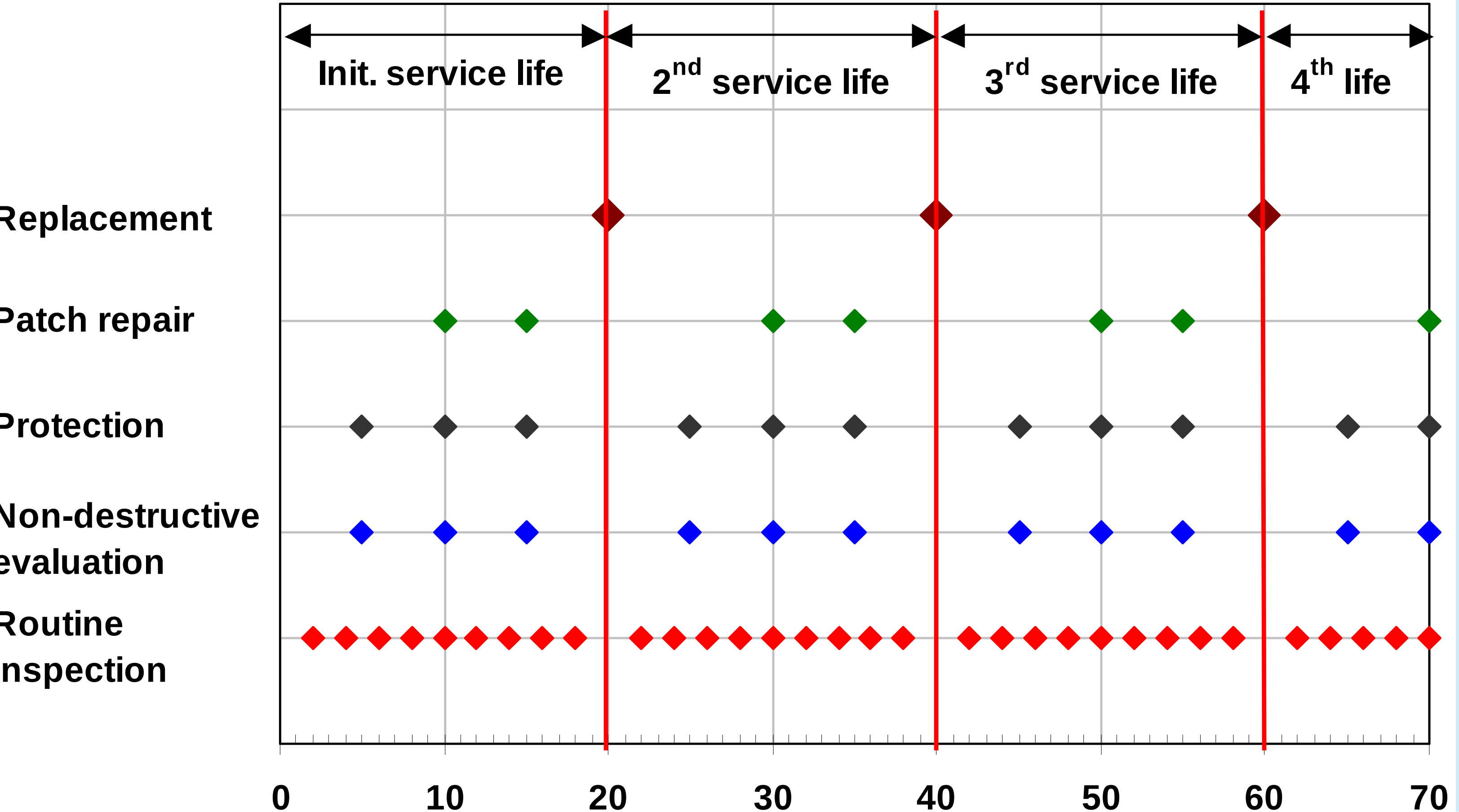
$$PVLCC = C_0 + \sum_{t_i=1}^{T} \frac{C_i}{(1+r)^{t_i}} - \frac{R_v}{(1+r)^T}$$

(r=3%)

(T=70 yrs)

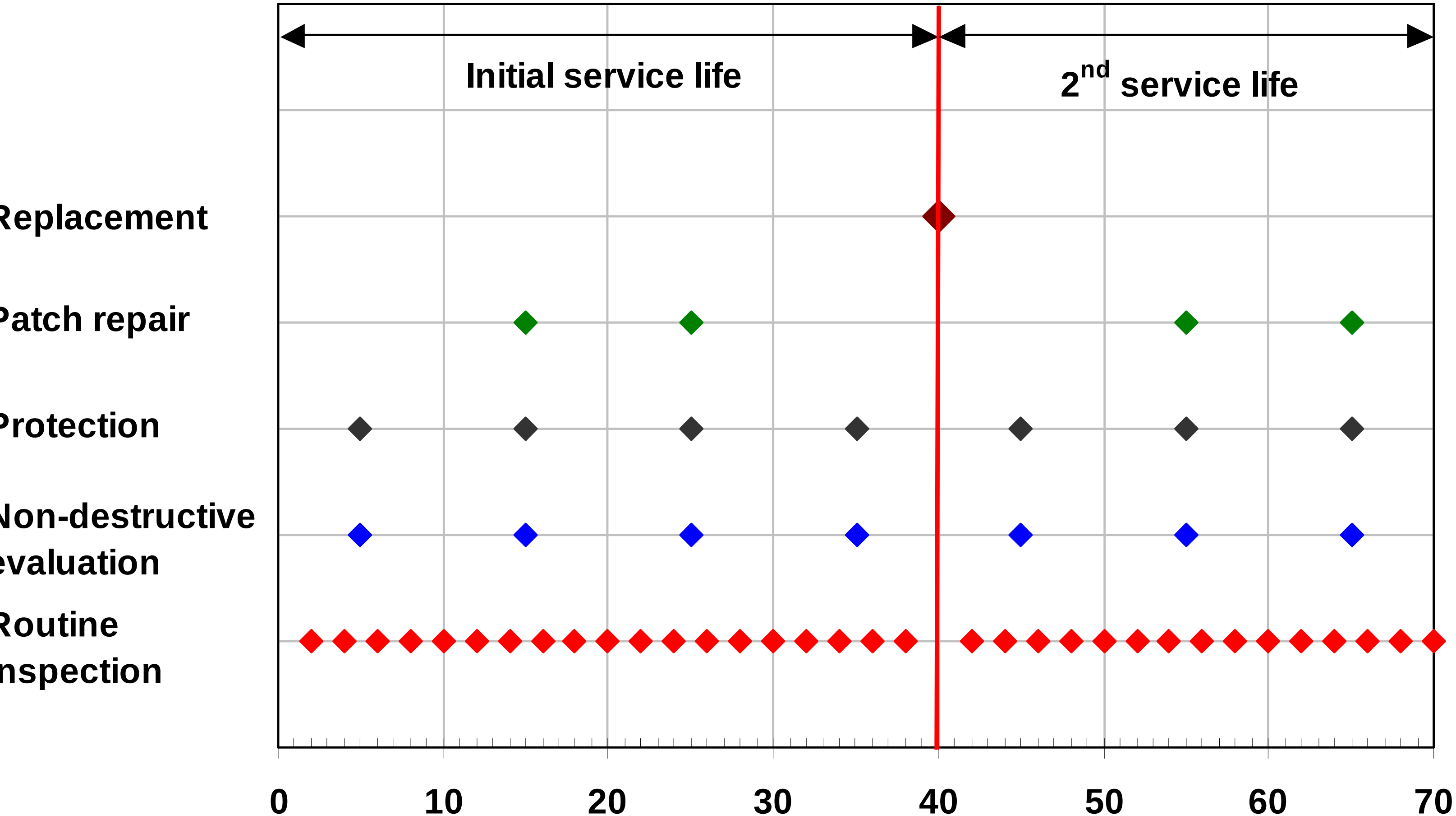
Life cycle cost modelling

→ Maintenance of NC deck



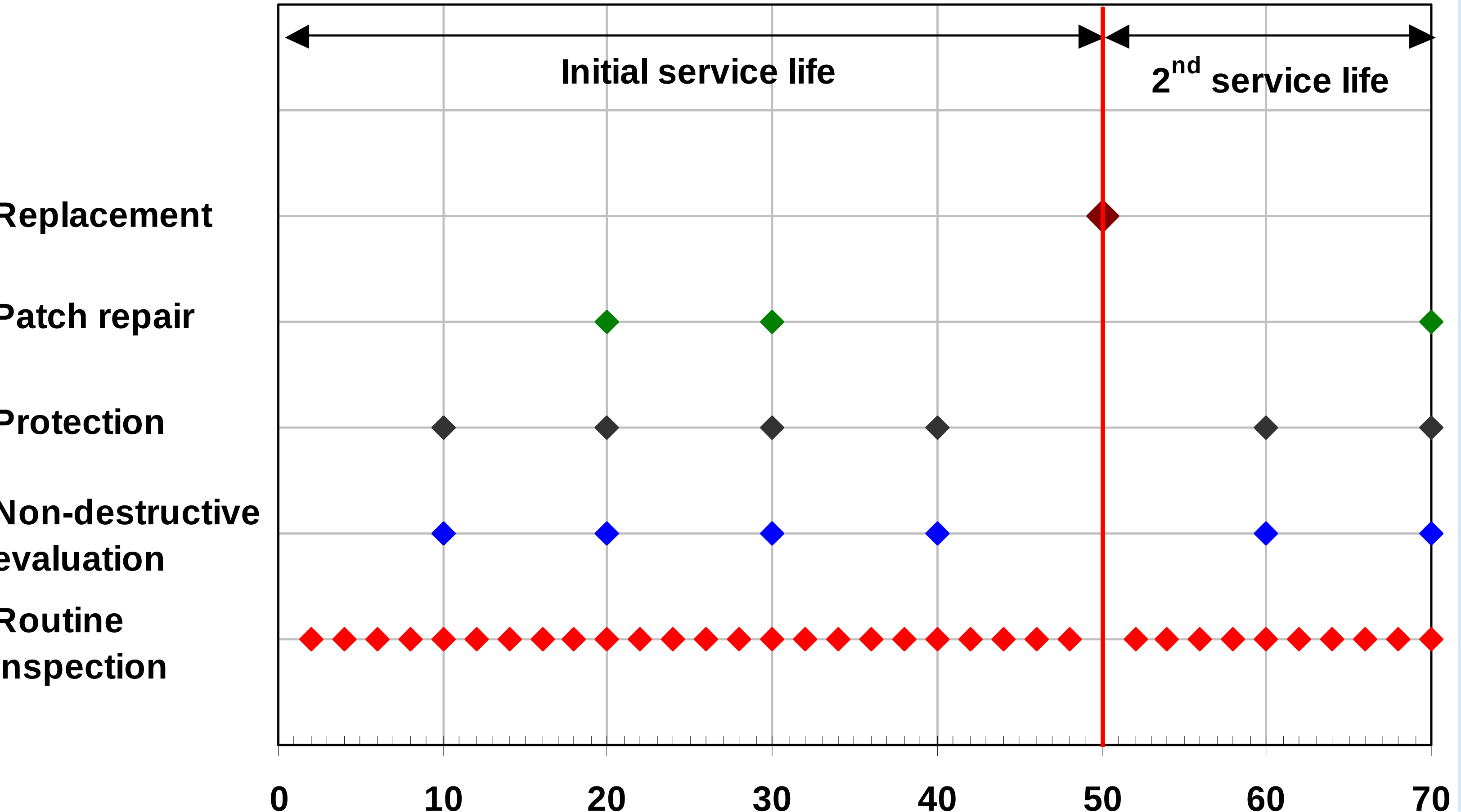
Life cycle cost modelling

→ Maintenance of HPC deck



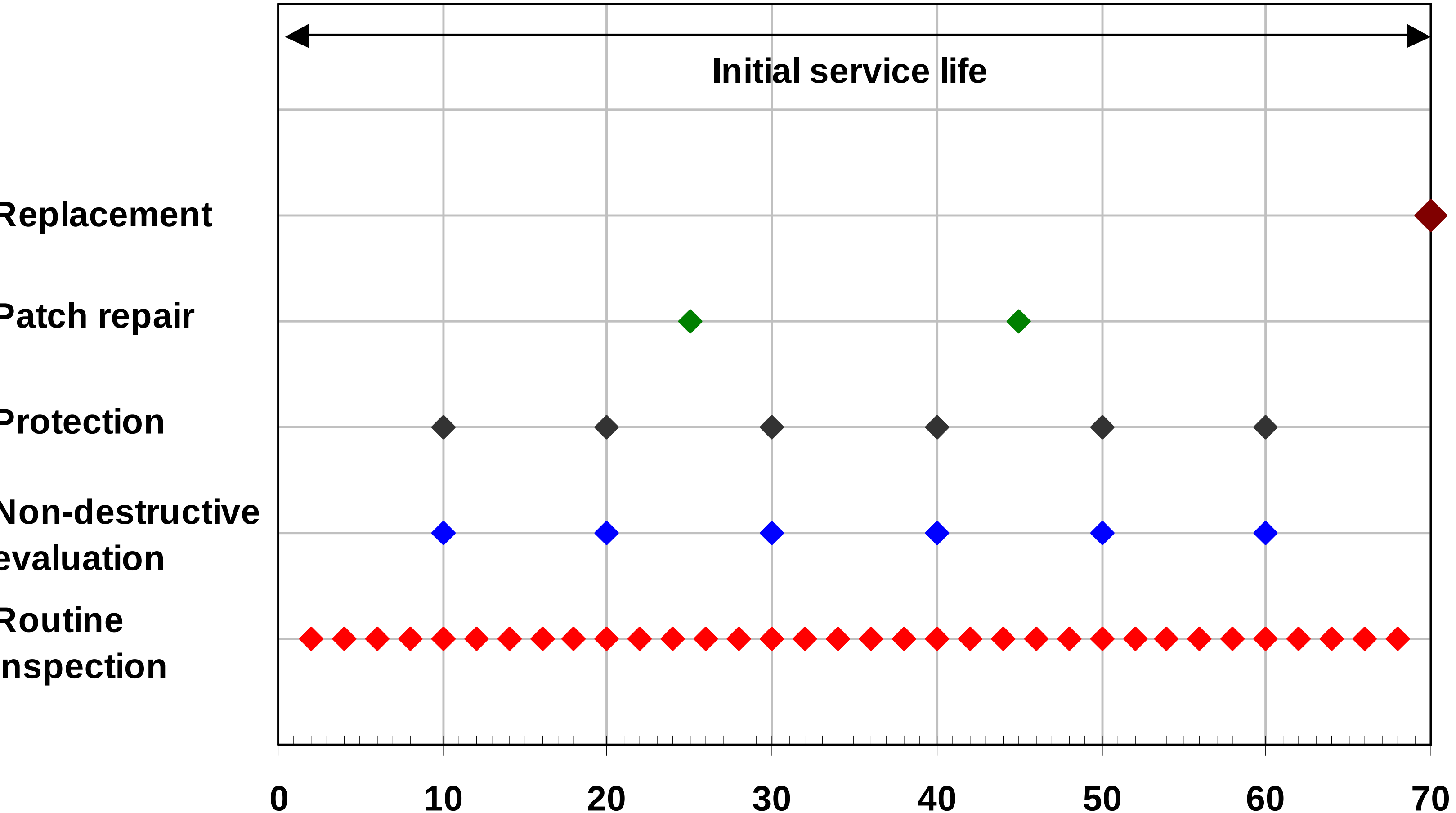
Life cycle cost modelling

→ Maintenance of HPC-IC deck



Life cycle cost modelling

→ Maintenance of VHPC-IC deck



Life cycle cost modelling

→ Maintenance costs to agency

Activity	Agency Cost	Duration	Road length affected	Reduced traffic speed
Routine inspection	2 $/m^2$	0.25 d	0.25 km	70 km/h
Non-destructive evaluation	20 $/m^2$	1 d	0.5 km	50 km/h
Protection	20 $/m^2$	1 d	0.5 km	50 km/h
Patch repair	200 $/m^2$	2 d	1 km	50 km/h
Replacement (disposal & reconstruction)	C.C. + 350 $/m^2$	15 d	1 km	50 km/h

Life cycle cost modelling

→ Maintenance costs to users

Costs to users:

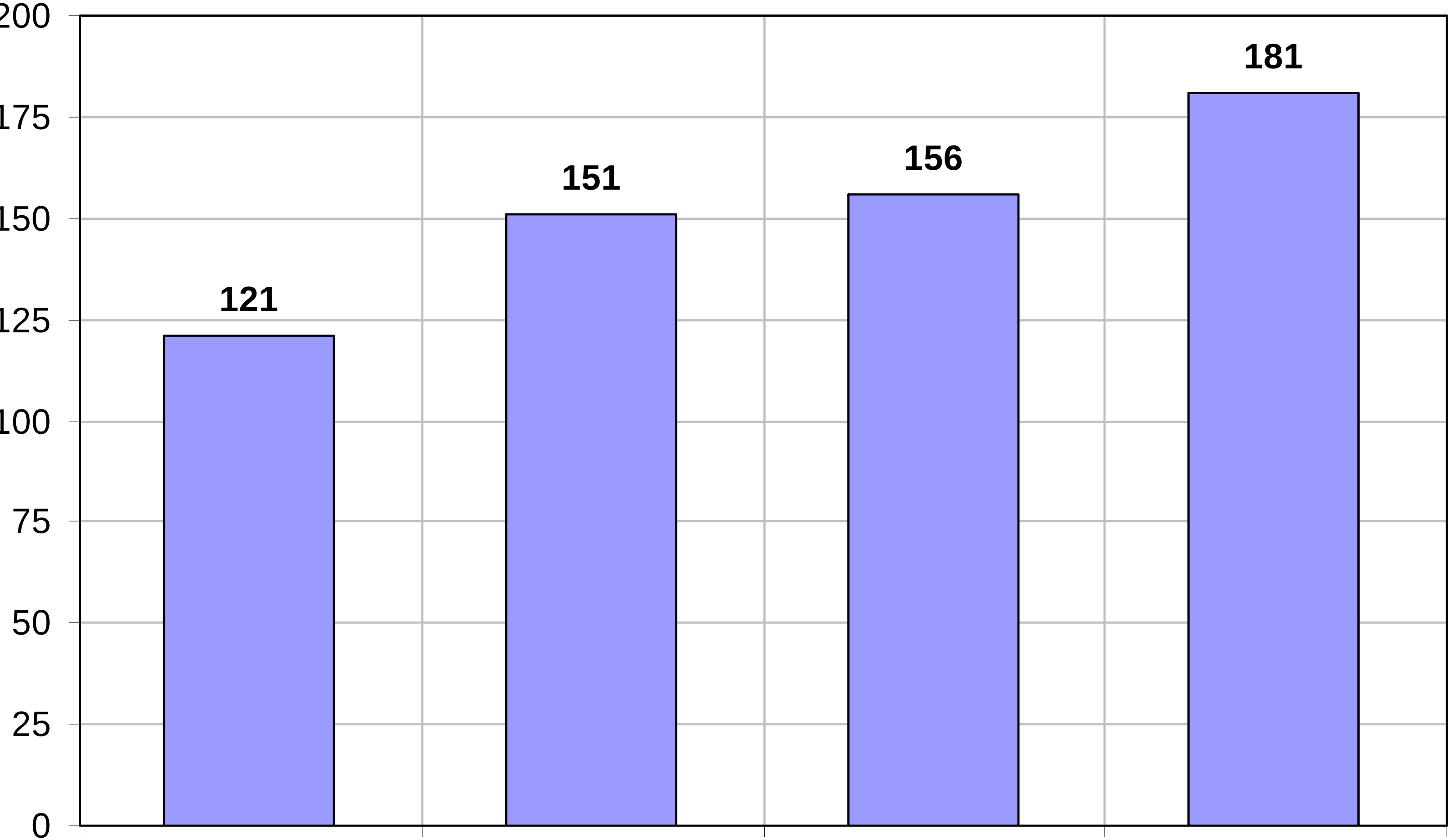
Value of car driver's time	$12/h
Value of truck driver's time	$20/h
Vehicle operating cost	$9/h
Accident rate during activity	6 accidents per million vehicle-km
Cost per accident	$40,000

Traffic information:

Annual average daily traffic (AADT)	4000
Percent of truck in AADT	25%
Normal traffic speed	100 km/h
	2 accidents per

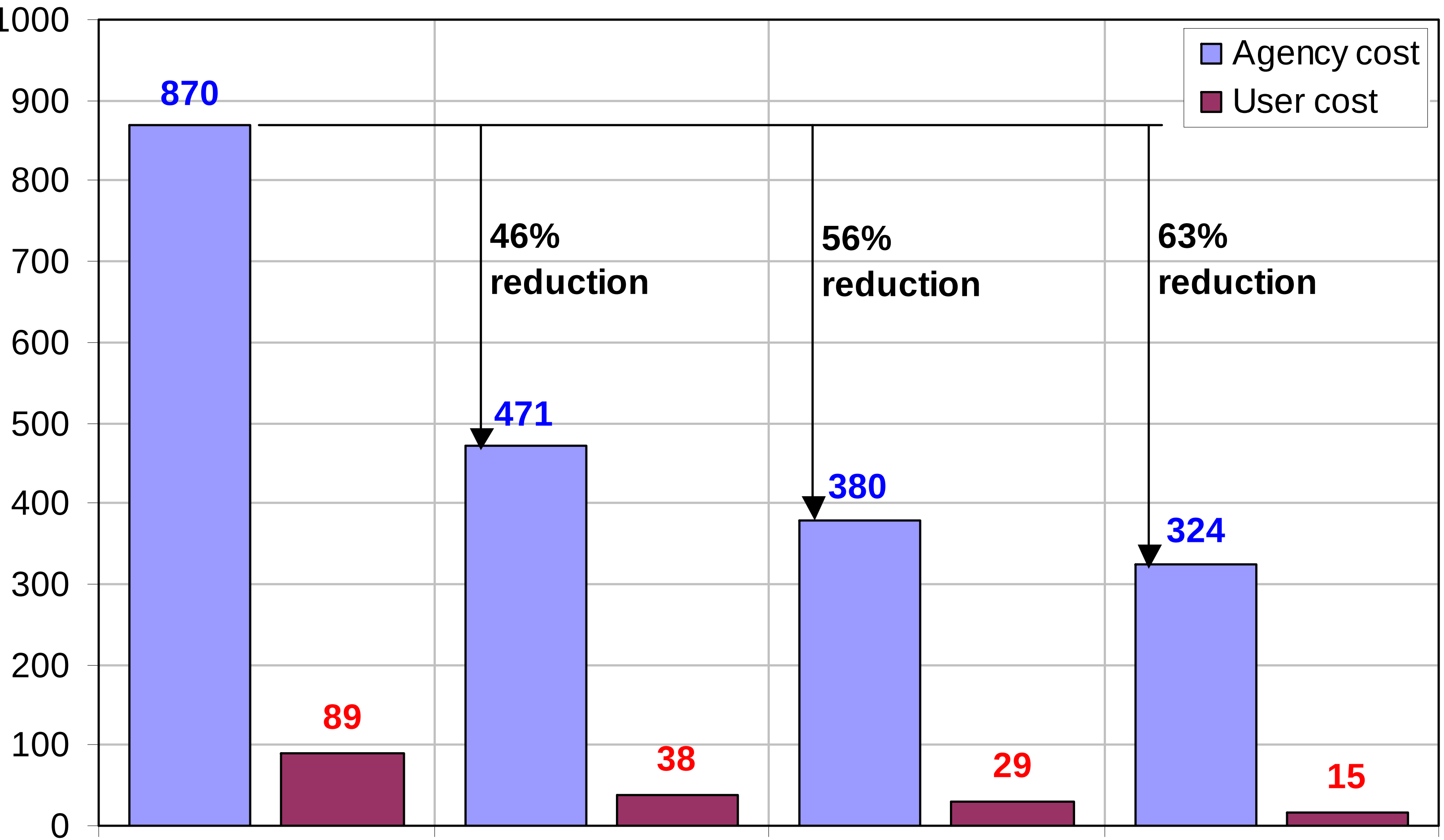
Life cycle cost modelling

→ Initial construction cost



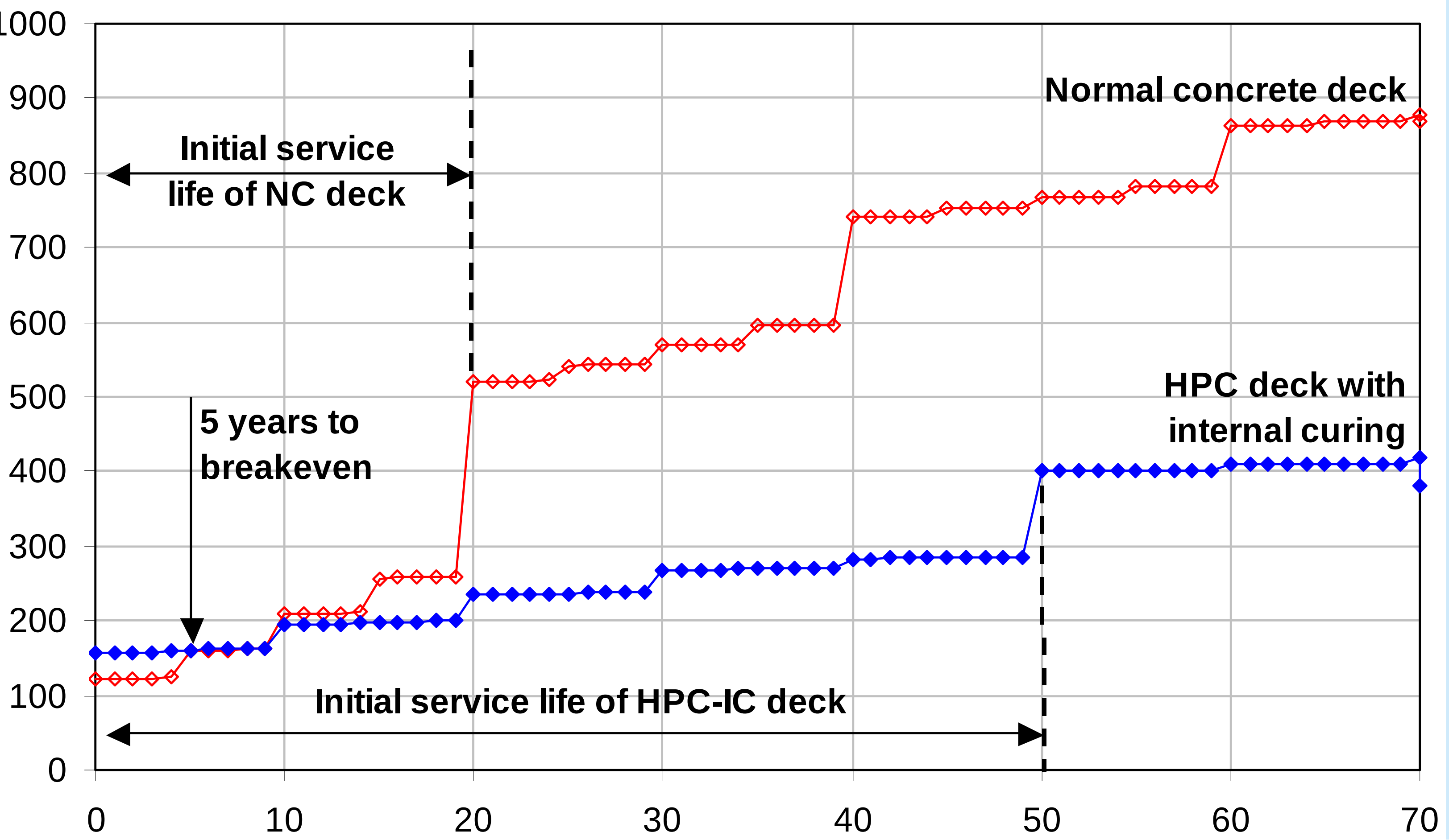
Life cycle cost modelling

→ Present value of life cycle cost



Life cycle cost modelling

→ PV cumulative expenditure



– Part 6 –

Environmental Impact

Environmental impact

→ CO_2 emissions

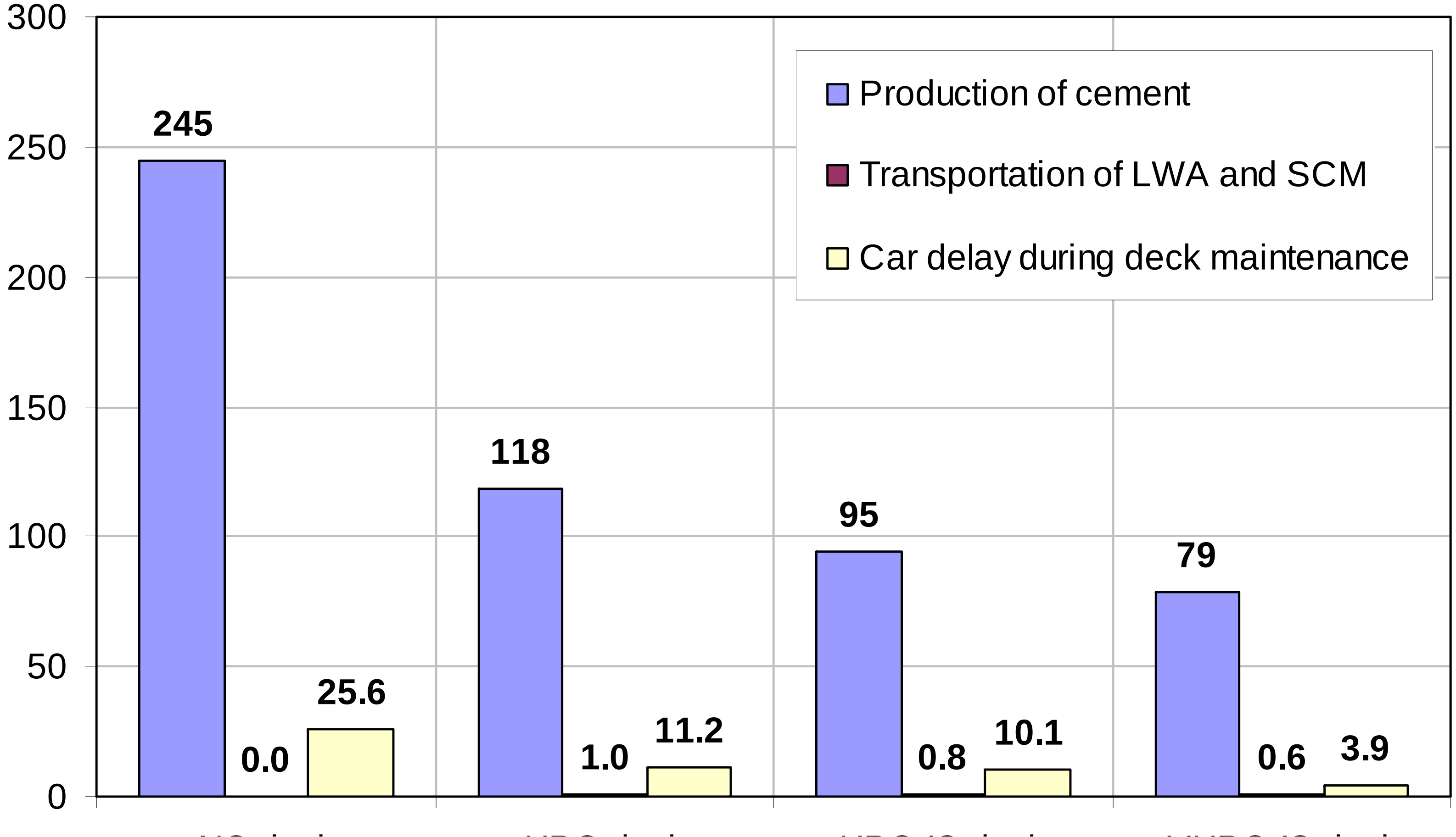
ng service life and low maintenance of concrete structures can nimize impact on environment by reducing CO_2 emissions.

nission of carbon dioxide can be reduced by:

- Using SCM to reduce cement content in concrete; 25% SCM (1 ton of cement produced = 1 ton of CO_2),
- Reducing transportation of non-locally available LWA and SCM (1 ton of material transported over 1000 km = 0.022 ton of CO_2),
- Reducing car delays due to deck maintenance activities (1 hour car delay = 4 kg of CO_2).

Environmental impact

→ CO_2 emissions over life cycle



Conclusions

- C structures can be designed to include new shrinkage prevention hnologies without significantly increasing initial construction cost.
- service performance of bridge decks can be improved due to luced shrinkage cracking and reduced reinforcement corrosion.
- rvice life of bridge decks can be extended by at least 10 years due to ernal curing alone, and by up to 50 years due to use of VHPC and IC.
- fe cycle costs of bridge decks can be substantially reduced due to:
  - Fewer maintenance activities (inspection, protection and repair),
  - Lower user costs (delays and accidents),
  - Longer service life (over 70 years).
- gher initial construction cost of HPC-IC deck vs. NC deck can be set in only 5 years.
- vironmental impact can be reduced due to fewer maintenance activities d longer service life.