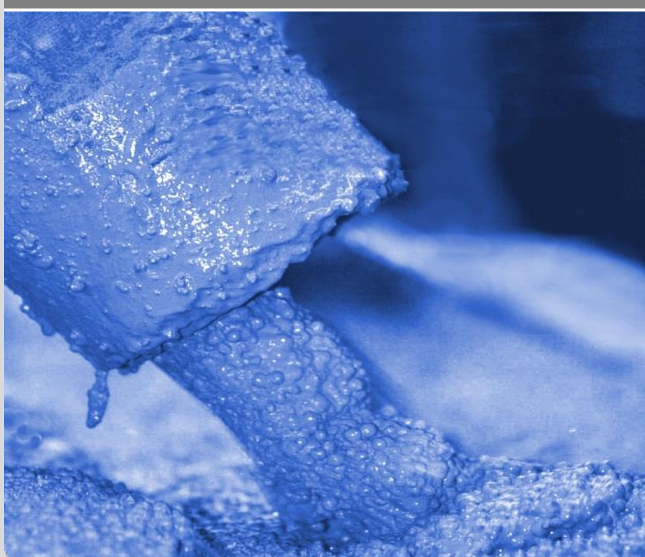
Conventional, new and upcoming concrete materials – a challenge for the fib Model Code

Harald S. Müller, Immediate Past President of the fib

Institute of Concrete Structures and Building Materials – Department Building Materials

IMB KARLSRUHE



Workshop by
ABECE, Abcic and *fib*
fib Model Code 2020

Sao Paulo, Brazil
29 September 2017

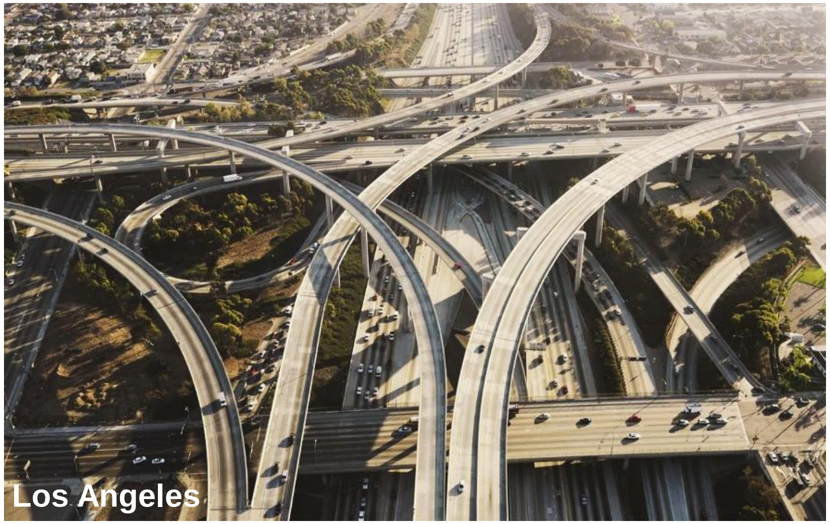
Outline

Presentation of concrete models – Challenge for the fib Model Code 2020

- Boundary conditions for concrete worldwide
- Types and design of structural concretes in the future
- Classification of structural concrete in Model Code 2020
- Modelling of structural concrete and associated problems
- Models for strength, deformation and durability
- Conclusions and outlook

Construction sector worldwide – some facts

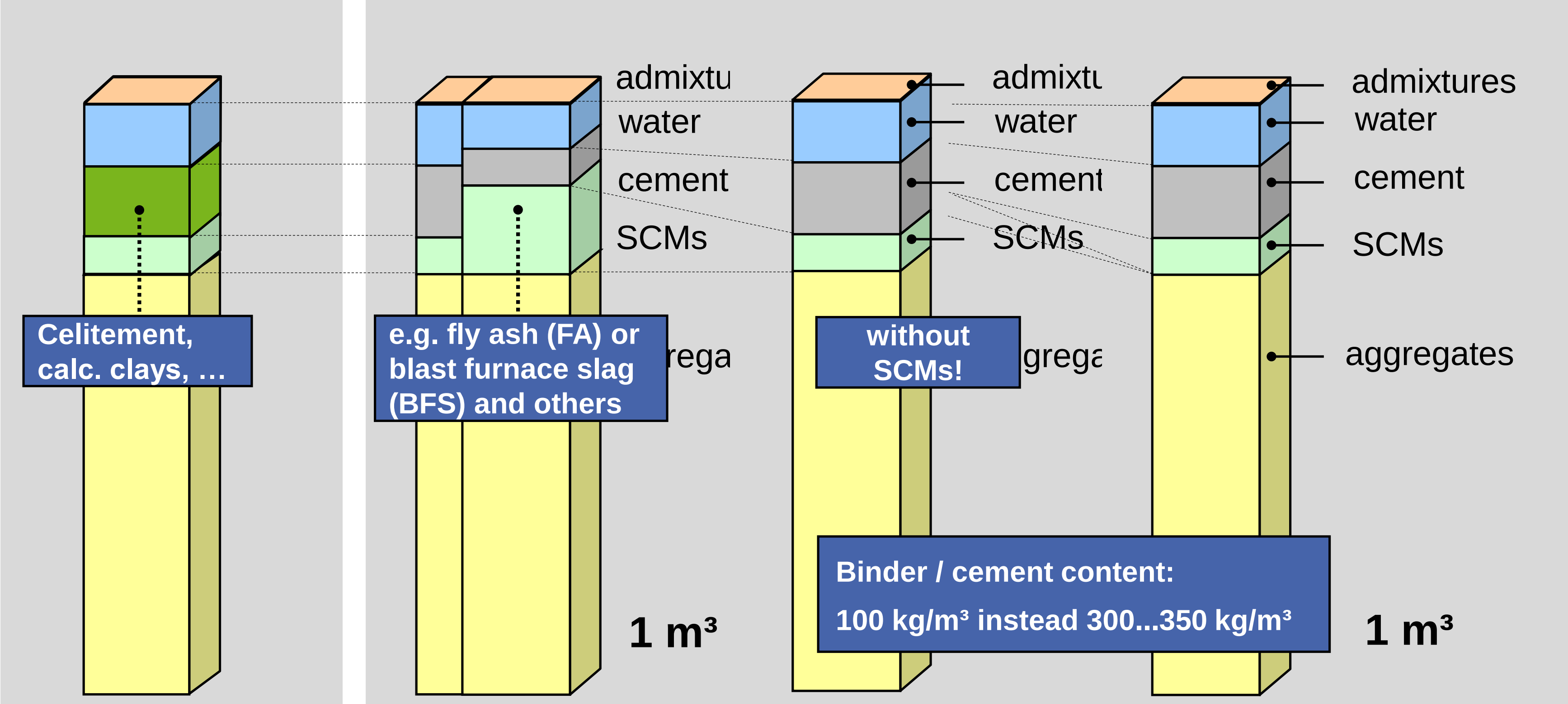
- Concrete use correlates strongly with the economical growth and the development of the civil infrastructure
- Concrete is indispensible as building material; annual production: 7 billion m³/year; **strong increase expected**
- Concrete production is associated with 6 - 8 % of the global CO_2 emissions today; ⇨ **sustainable concretes will enter the market**
- In developed countries rehabilitation exceeds construction of new structures



Paths toward sustainable concrete

Aim: **Minimal use of materials with significant influence on environmental impact**

1. New binder materials	2. Substitution by SCMs	3. Increase agg. content	Standard concrete



Concrete development until today

Portland cement ca. 300 – 400 kg/m³

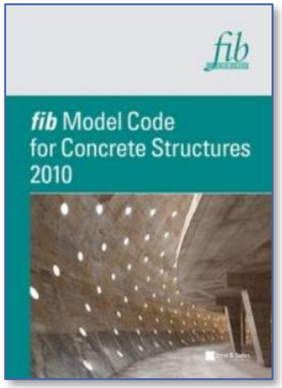
empirical mix design formulas

Concrete

empirical knowledge on reaction mechanisms

Concrete strength

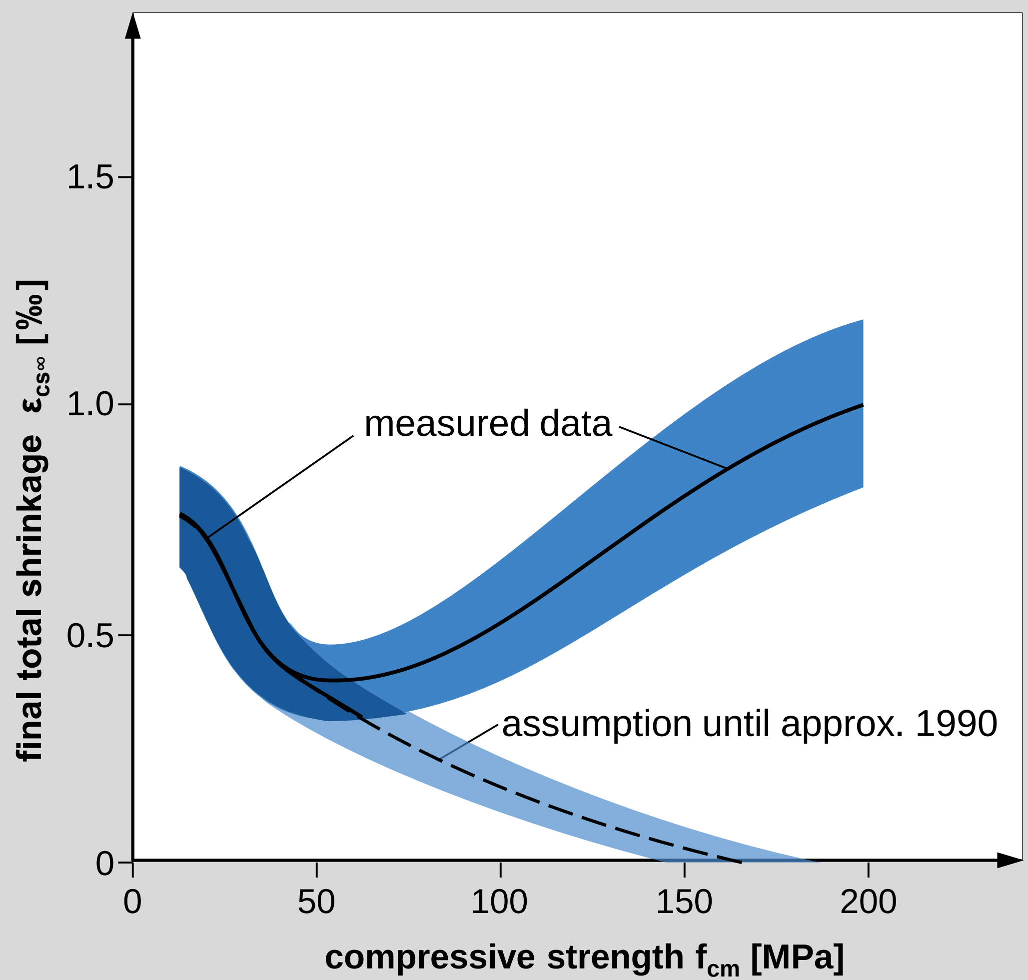
empirical knowledge on microstructure

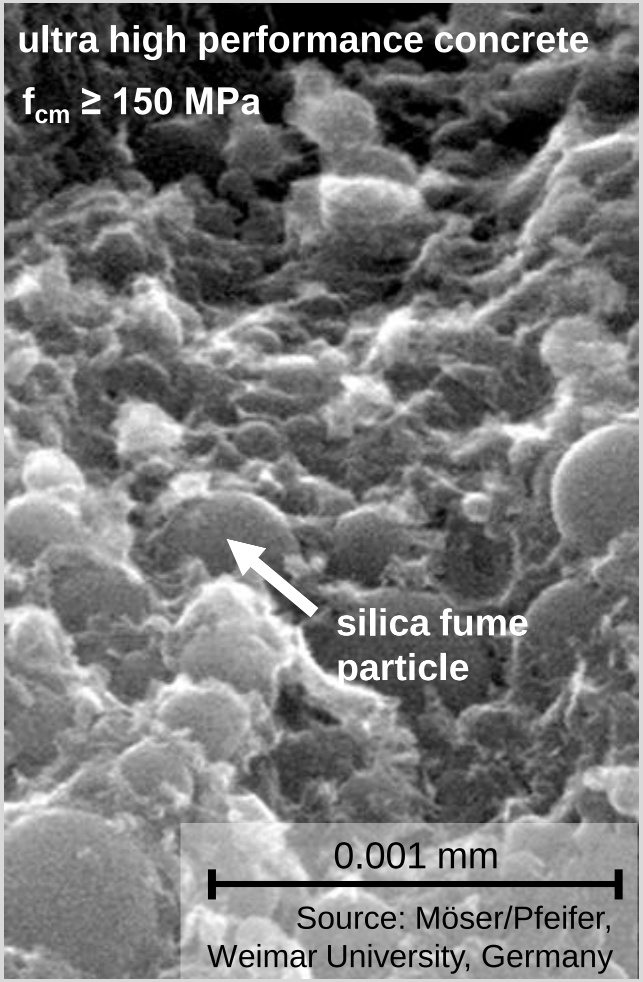


compendium for concrete modelling

Deformation behaviour	**Physical properties**	**Durability**

Final shrinkage of concrete – dependence on concrete strength





Constitutive strength-based modelling of shrinkage

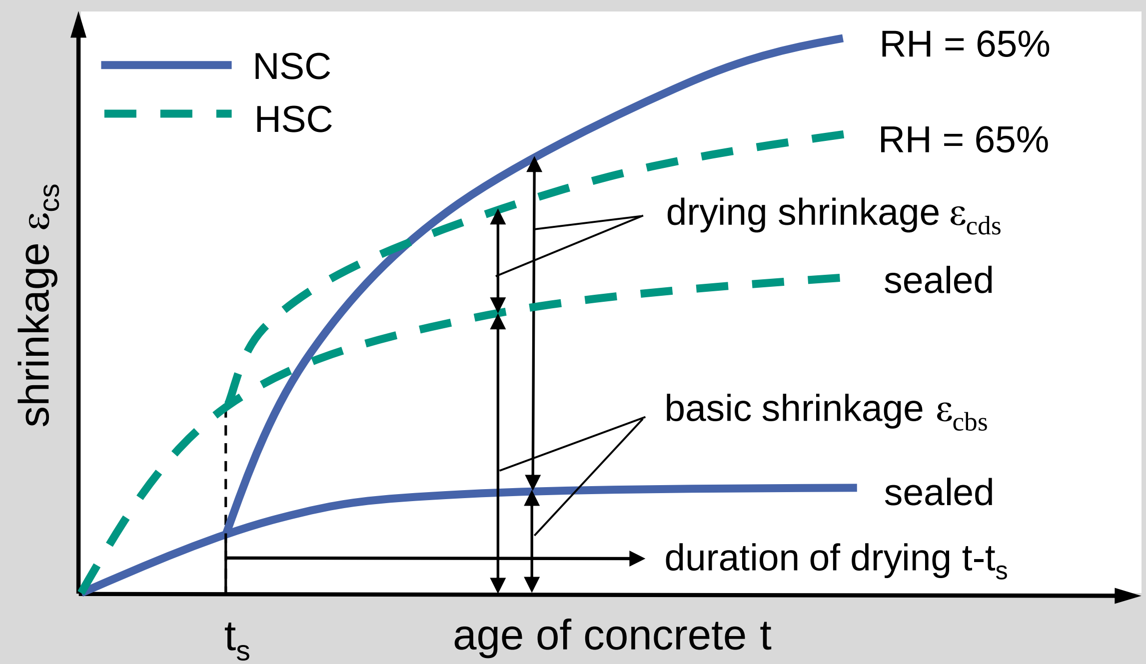
MC 1990: valid for NPC	MC 2010: valid for NPC and HPC
$\varepsilon_{cs}(t,t_s) = \underbrace{\varepsilon_s(f_{cm}) \cdot \beta_{RH} \cdot \beta_s(t-t_s)}_{\text{total shrinkage } \varepsilon_{cs}}$	$\varepsilon_{cs}(t,t_s) = \underbrace{\varepsilon_{cbs0}(f_{cm}) \cdot \beta_{bs}(t)}_{\text{basic shrinkage } \varepsilon_{cbs}} + \underbrace{\varepsilon_{cds0}(f_{cm}) \cdot \beta_{RH}(t) \cdot \beta_{ds}(t-t_s)}_{\text{drying shrinkage } \varepsilon_{cds}}$

MC 2020: new concretes

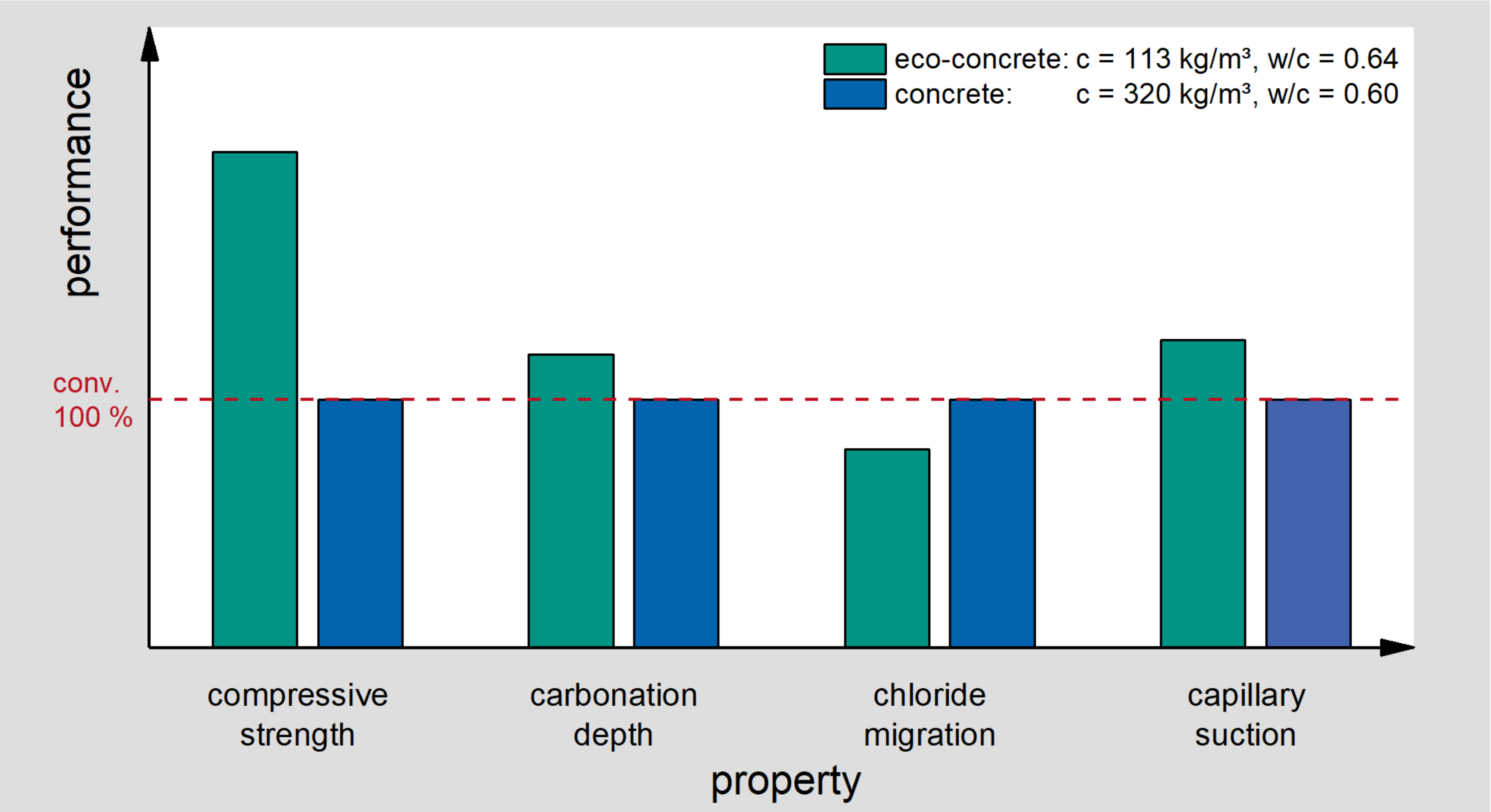
strength-based modelling:

- to be kept for UHPC
- not to be kept for eco-concrete and old concrete

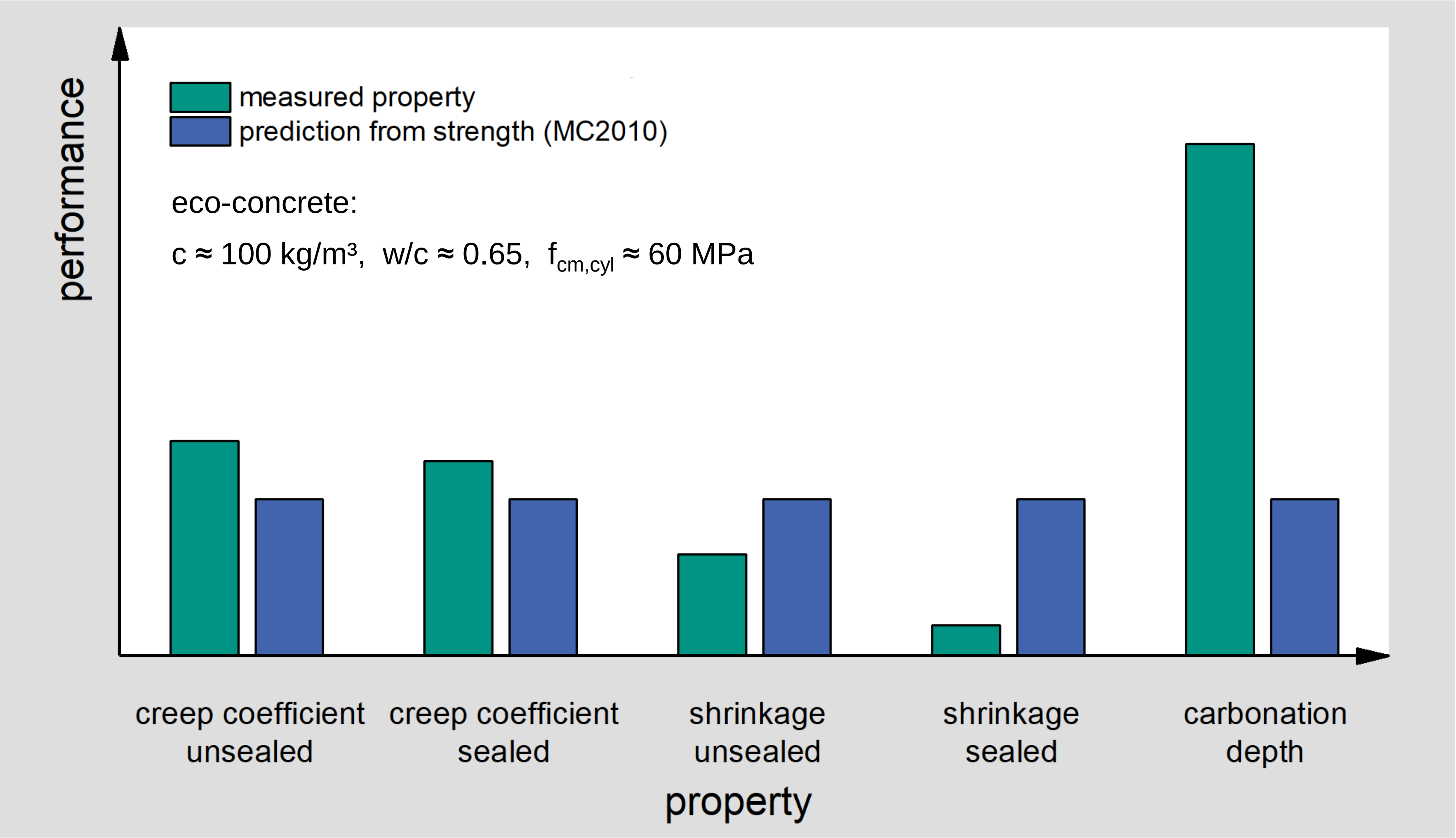
➡ different approach



Comparison of eco-concrete and conventional concrete



Performance of eco-concrete – Strength based prediction and measurement



Concrete development in the future

new binders

- **Composite CEM**
- **Calcined Clay**
- **Isochemical Cements**
- **Others**

ca. 100 kg/m³

new design concept and testing tools

Concrete: computational designed

performance based approach (lab testing)

Properties: strength, durability, sustainability, functionality

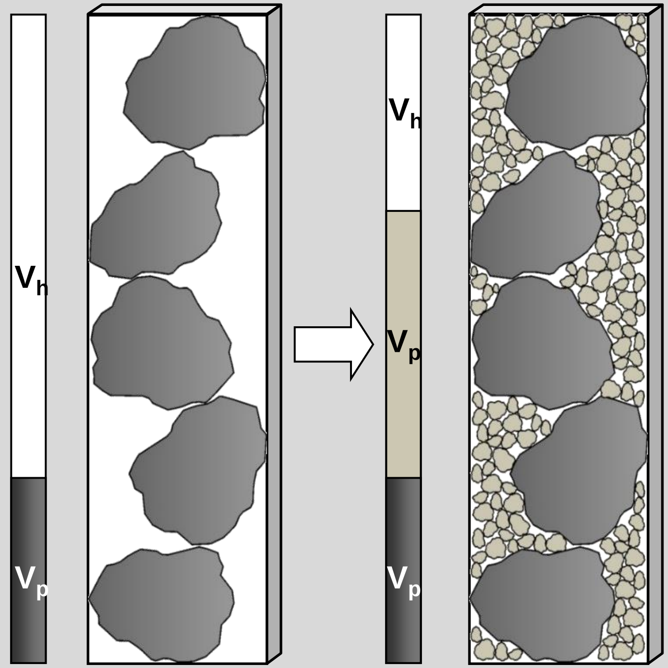
advanced material modelling (virtual lab)

new research

Microstructural understanding of strength formation, deformation properties and durability behaviour required

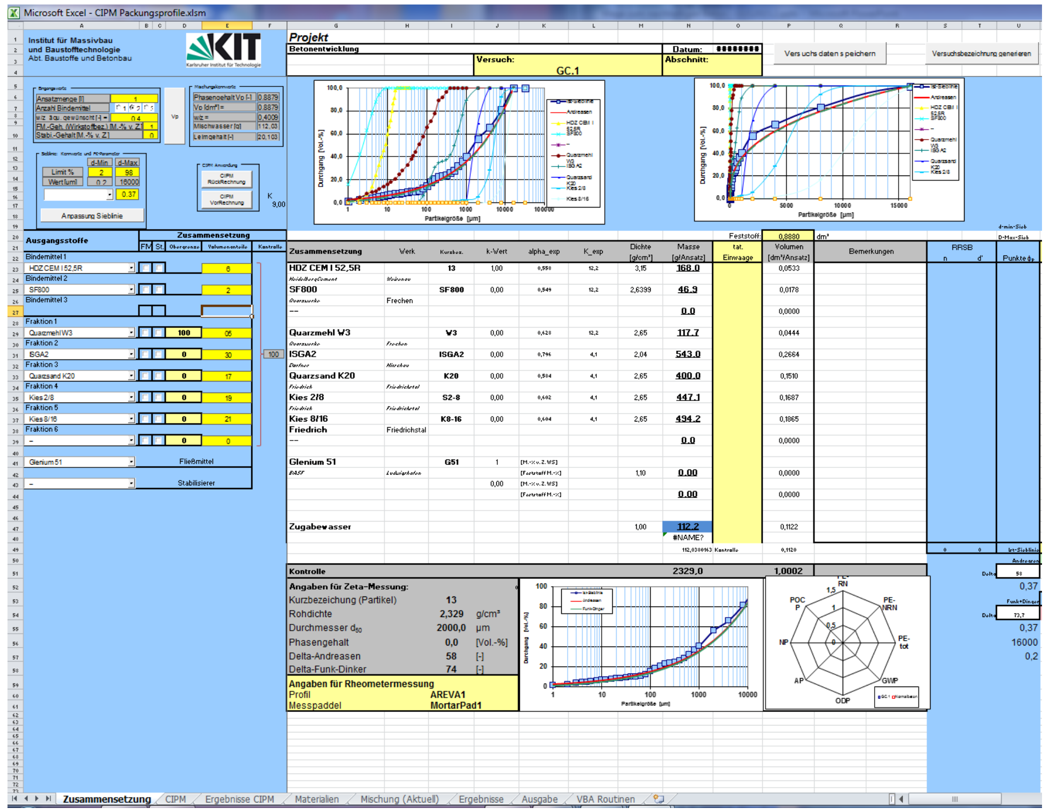
Development of cement-reduced concrete

Packing optimization



$$\phi_{p,\max} = V_p / (V_p + V_h)$$

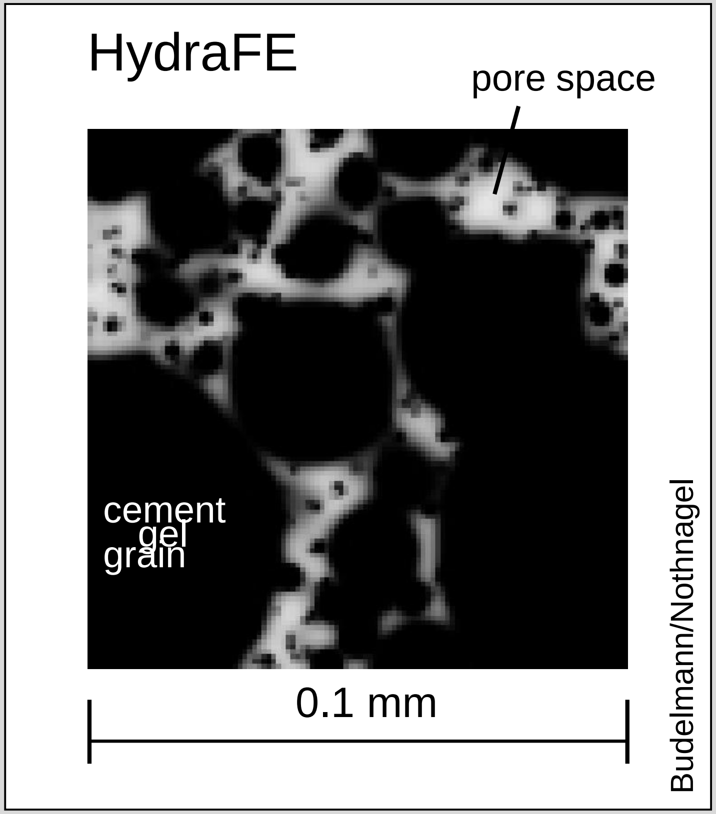
KIT-virtual concrete mixture calculation

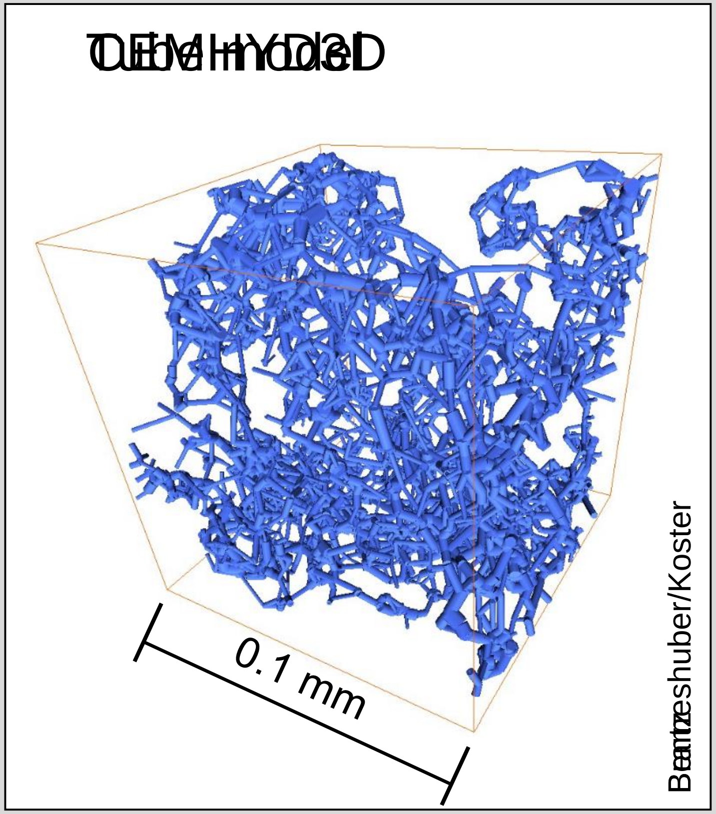


Excel based software calculates optimal packing density based on the models of Andreasen, de Larrard, Fennis and own works

Virtual concrete design

Simulation of microstructure



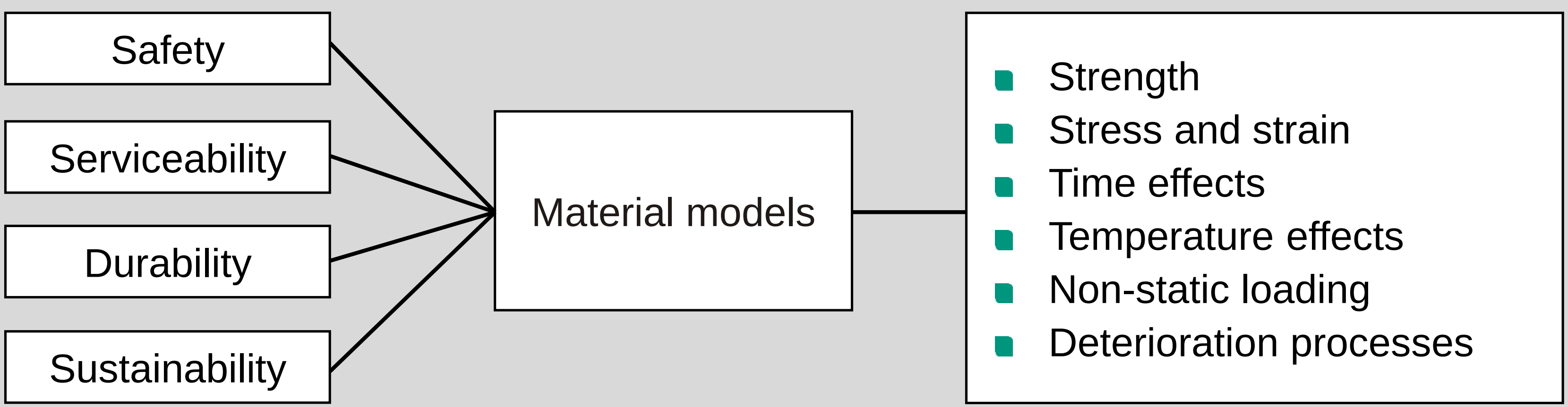


Numerical tools to predict: porosity, transport coefficients, strength, …

Main objective of the chapter „Concrete“ in the MC 2020

- Provide the designer with input data on material properties
  - for crude estimates
  - for more sophisticated methods of design
  - for FE applications
- Improvement of the models in chapter 5.1 of MC 2010 where necessary
- All types of structural concrete should be covered

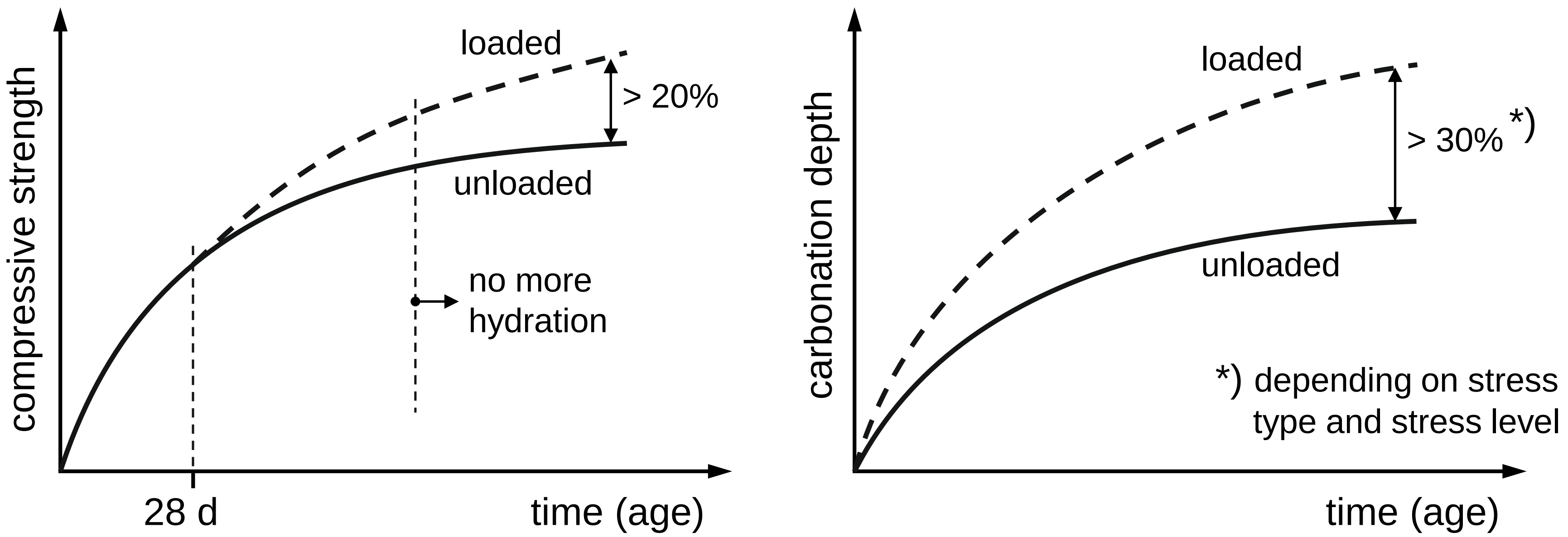
Holistic approach of construction‘s life cycle:



Range of applicability

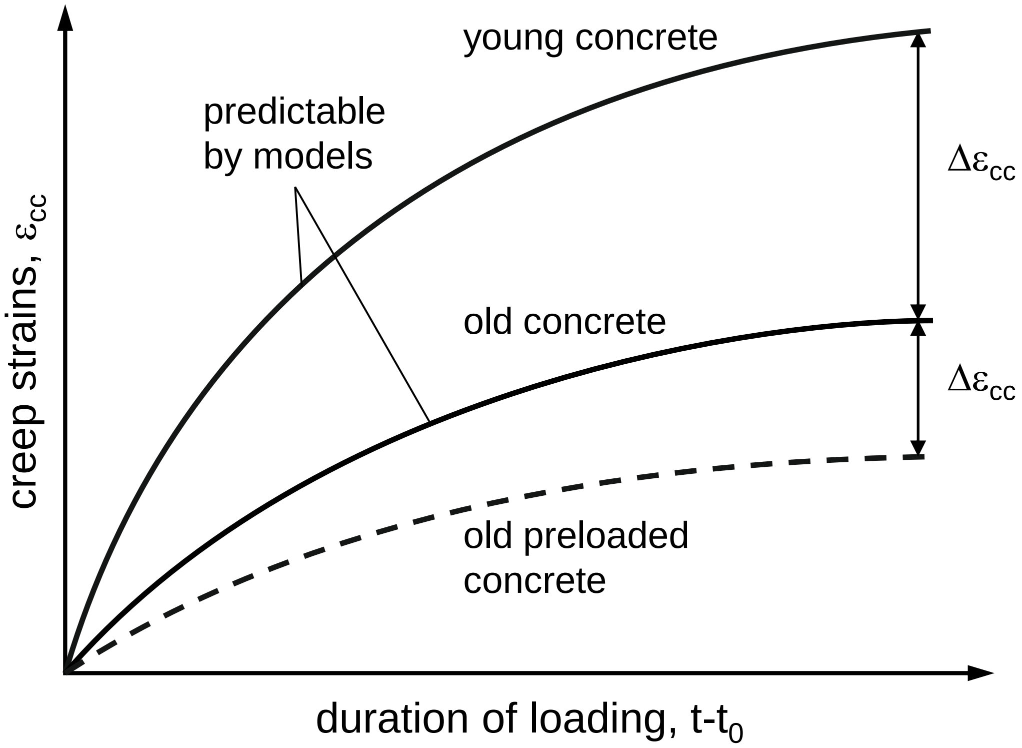
Criterion	MC 1990	MC 2010	MC 2020
concrete strength	20 … 60 (90) MPa	20 … 130 MPa	20 … 130 MPa
concrete type	normal strength	▪ normal strength ▪ high strength ▪ lightweight (10 … 90 MPa) ▪ self-compacting ▪ green (eco-concrete)	▪ normal strength ▪ high strength ▪ lightweight (10 … 90 MPa) ▪ self-compacting ▪ green (eco-concrete) ▪ ultra-high strength (… 250 MPa) ▪ old concrete
concrete loads	different ranges of applicability, depending on the related load (static, impact etc.); temperature range: mainly 0 °C < T < 80 °C		
tailor-made concrete		reference to test standards or recommendations	

Old concrete – the aging problem



- Aging can‘t be sufficiently described by hydration
- Interrelation of actions (load, environment) plays a decisive role

Old concrete – creep characteristics

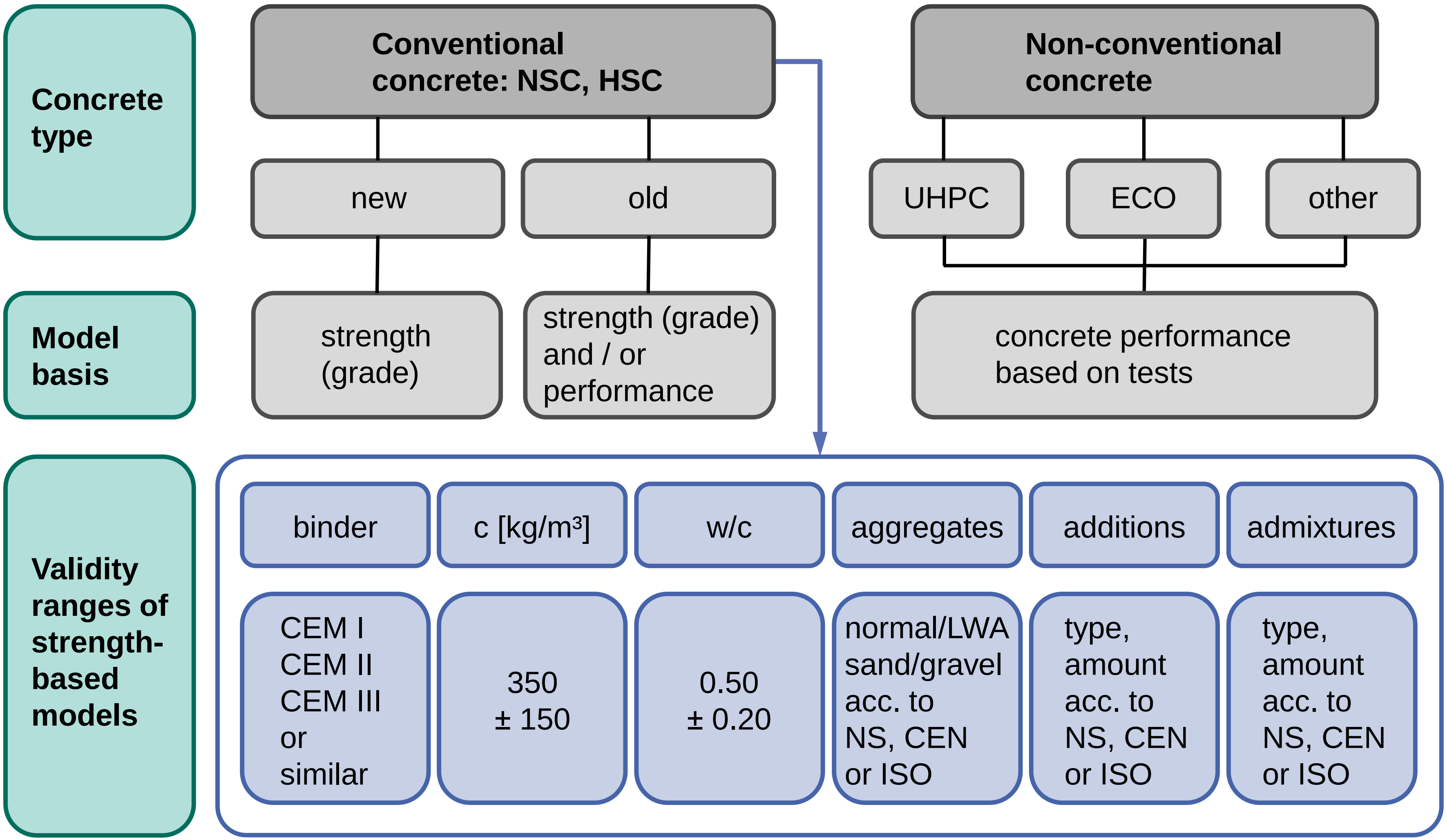


dependent on age of concrete and moisture content (size and environment)

dependent on stress level, age of concrete and moisture content (size and environment)

For creep sensitive old structures tests are required.
However, creep of old concrete is very low.

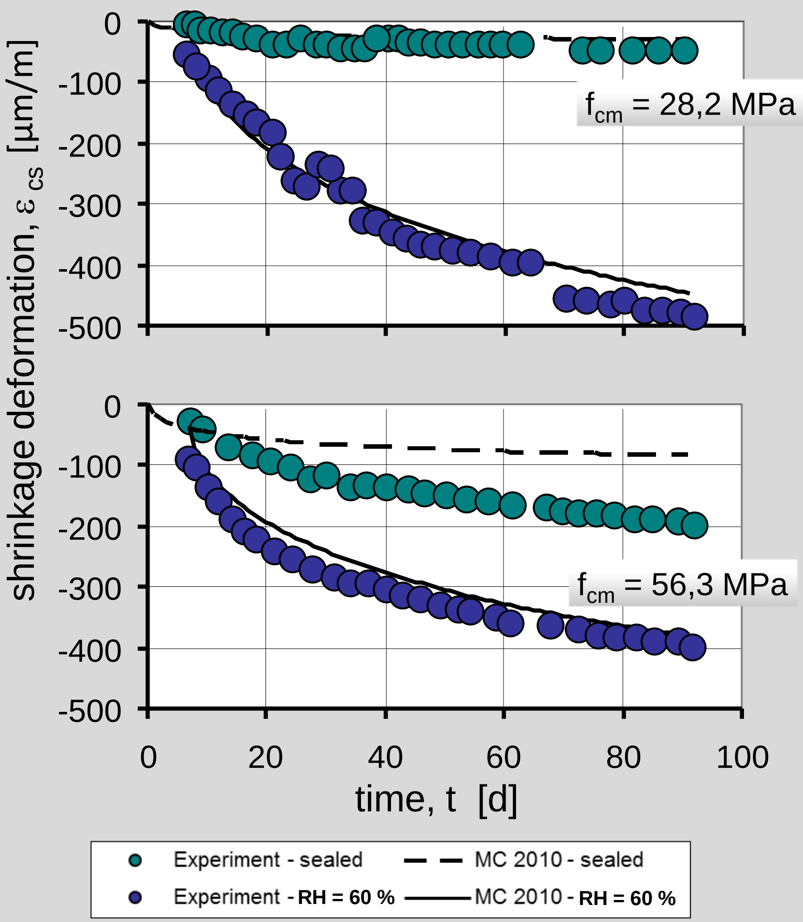
Classification of concrete with respect to modelling its performance



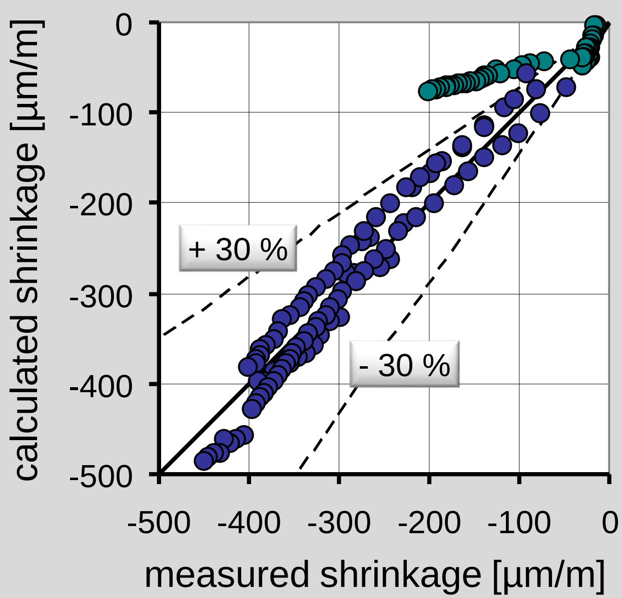
Deformation

Shrinkage prediction for Brazilian concretes

Test data and MC 2010 prediction



Statistical assessment



Source: Kataoka, Luciana T.. Análise da deformabilidade por fluência e retração e sua utilização na monitoração de pilares de concreto

The model predicts the total shrinkage deformations for NSC and HSC very well. For HSC a poor prediction of basic shrinkage was seen. However, this is just one test!

Constitutive modelling of shrinkage

MC 2010 and MC 2020

$$\varepsilon_{cs}(t,t_s) = \underbrace{\varepsilon_{cbs0}(f_{cm}) \cdot \beta_{bs}(t)}_{\text{basic shrinkage } \varepsilon_{cbs}} + \underbrace{\varepsilon_{cds0}(f_{cm}) \cdot \beta_{RH}(t) \cdot \beta_{ds}(t-t_s)}_{\text{drying shrinkage } \varepsilon_{cds}}$$

Extension in MC 2020 – final shrinkage

$$\varepsilon_{cs}(t,t_s) = \xi_{cbs1} \cdot \varepsilon_{cbs}(t) + \xi_{cds1} \cdot \varepsilon_{cds}(t,t_s)$$

adaption factors for final shrinkage

Extension in MC 2020 – time-development

Basic shrinkage:

$$\beta_{bs}(t) = 1 - \exp\left(-0{,}2 \cdot \xi_{cbs2} \cdot \sqrt{t}\right)$$

Drying shrinkage:

$$\beta_{ds}(t,t_s) = \left(\frac{(t-t_s)}{0{,}035 \cdot \xi_{cds2} \cdot h^2 + (t-t_s)}\right)^{0{,}5}$$

adaption factors for time-development

Adaption factors to be determined from a few well-defined shrinkage tests

Improvement of shrinkage prediction by short-term tests

Shrinkage model in MC 2020

$$\varepsilon_{cs}(t,t_s) = \xi_{cbs1} \cdot \varepsilon_{cbs}(t) + \xi_{cds1} \cdot \varepsilon_{cds}(t,t_s)$$

adaption factors

Time-development functions in MC 2020

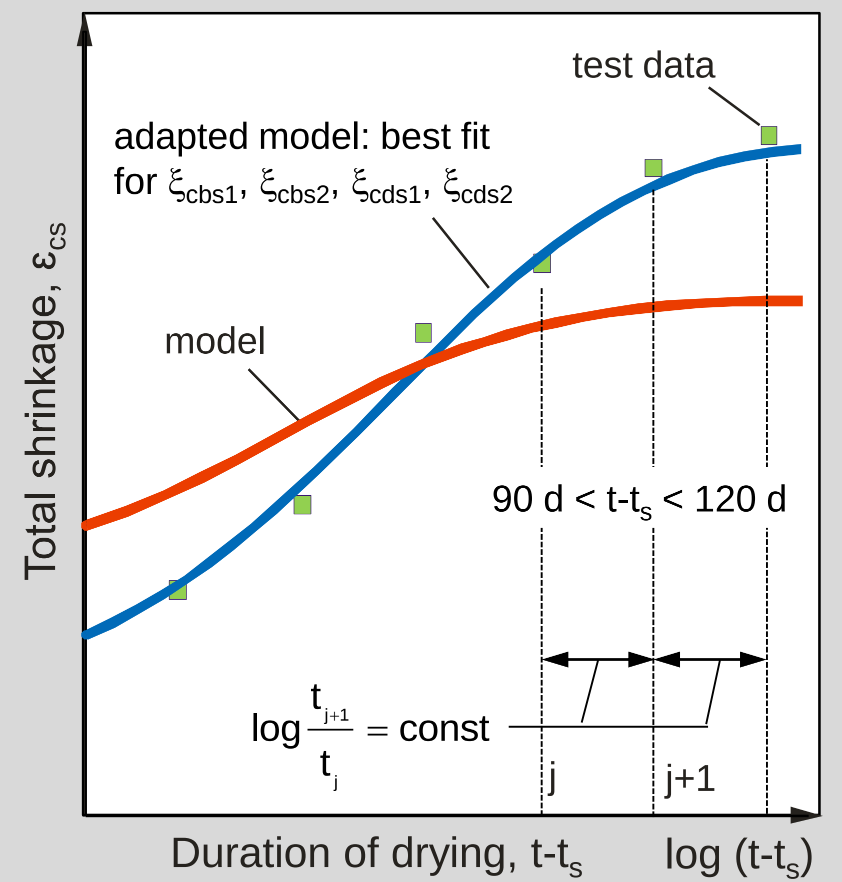
Basic shrinkage:

$$\beta_{bs}(t) = 1 - \exp\left(-0{,}2 \cdot \xi_{cbs2} \cdot \sqrt{t}\right)$$

adaption factors

Drying shrinkage:

$$\beta_{ds}(t,t_s) = \left(\frac{(t - t_s)}{0{,}035 \cdot \xi_{cds2} \cdot h^2 + (t - t_s)} \right)^{0,5}$$



Accuracy gain through tests: Coefficient of variation drops from V ≈ 30 % to V ≈ 10 %

Constitutive modelling of stress-linear creep

Variable stresses and strain

$$\varepsilon_{c\sigma}(t) = J(t,t_0)\cdot\sigma_c(t_o) + \int_{t_o}^{t} J(t,\tau)\cdot\frac{\partial\sigma_c(\tau)}{\partial\tau}\cdot d\tau$$

with: $$J(t,t_0) = \frac{1}{E_c(t_0)} + \frac{\varphi(t,t_0)}{E_{ci}}$$

$$\varphi(t,t_0) = \varepsilon_{cc}(t,t_0)\cdot\frac{E_{ci}}{\sigma_c(t_0)}$$

Approximation:

$$\varepsilon_{c\sigma}(t) = \frac{\sigma_c(t_o)}{E_{ci}}\cdot\left[1+\rho(t,t_0)\cdot\varphi(t,t_0)\right]$$

with: $\rho(t,t_0)\approx 0.80$

Constant stress

Product type model:

$$\varphi(t,t_0) = \beta_1(t_0)\cdot\ldots\cdot\beta_i\cdot\ldots\cdot\beta_n(t-t_0)$$

Summation type model:

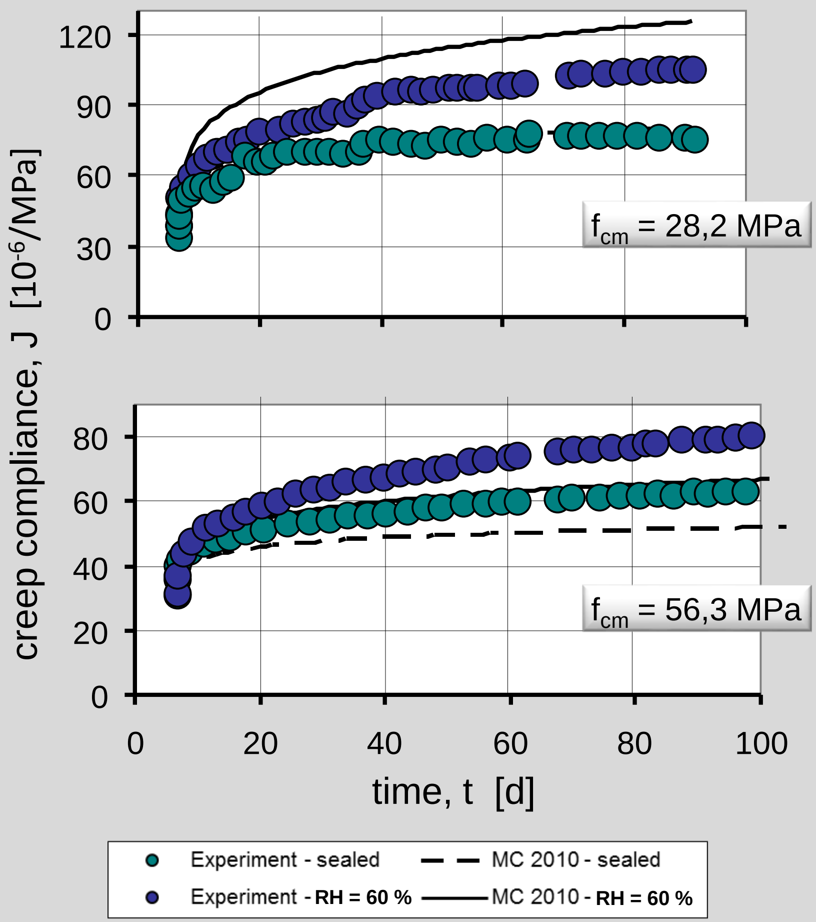
$$\varphi(t,t_0) = \underbrace{\varphi_r(t,t_0)}_{\text{delayed elasticity}} + \underbrace{\varphi_f(t)-\varphi_f(t_0)}_{\text{flow}}$$

Both types of model may be expressed as:

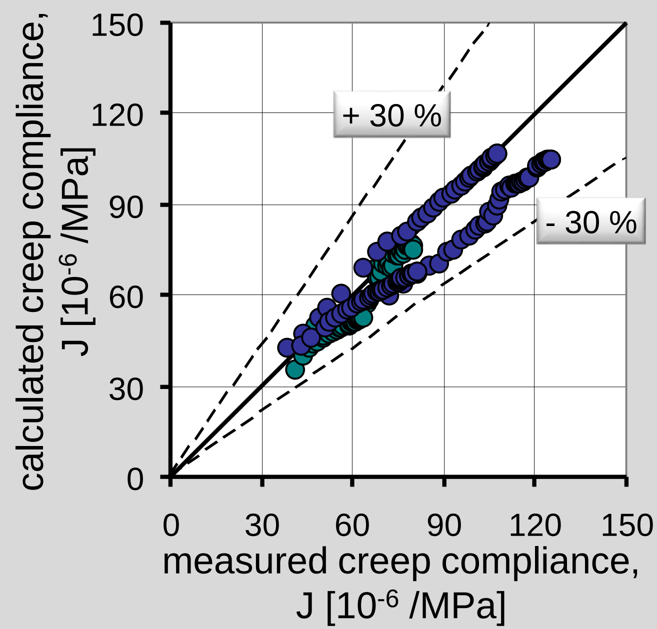
total creep = basic creep + drying creep

Creep prediction for Brazilian concretes

Test data and MC 2010 prediction



Statistical assessment



Source: *Kataoka, Luciana T.. Análise da deformabilidade por fluência e retração e sua utilização na monitoração de pilares de concreto*

The model predicts the creep deformations in both cases within the expected scatter range

Constitutive modelling of creep

MC 2010 and MC 2020

$$\varphi(t,t_0) = \underbrace{\beta_{bc}(f_{cm})\cdot\beta_{bc}(t,t_0)}_{\text{basic creep}} + \underbrace{\beta_{dc}(f_{cm})\cdot\beta(RH)\cdot\beta_{dc}(t_0)\cdot\beta_{dc}(t,t_0)}_{\text{drying creep}}$$

Extension in MC 2020 – Total creep

$$\varphi(t,t_0) = \xi_{bc1}\cdot\varphi_{bc}(t,t_0) + \xi_{dc1}\cdot\varphi_{dc}(t,t_0)$$

adaption factors
for creep magnitude

Extension in MC 2020 – Time-development

Basic creep:

$$\beta_{bc}(t,t_0) = \ln\left(\left(\frac{30}{t_{0,adj}} + 0{,}035\right)^2 \cdot \frac{(t-t_0)}{\xi_{bc2}} + 1\right)$$

Drying creep:

$$\beta_{dc}(t,t_0) = \left(\frac{(t-t_0)}{\beta_h\cdot\xi_{dc2} + (t-t_0)}\right)^{\gamma(t_0)}$$

adaption factors
for time-
development

Adaption factors to be determined from a few well-defined creep tests

Improvement of creep prediction by short-term tests

Adapted creep model

$$\varphi(t,t_0)=\xi_{bc1}\cdot\varphi_{bc}(t,t_0)+\xi_{dc1}\cdot\varphi_{dc}(t,t_0)$$

adaption factors

Adapted time-development functions

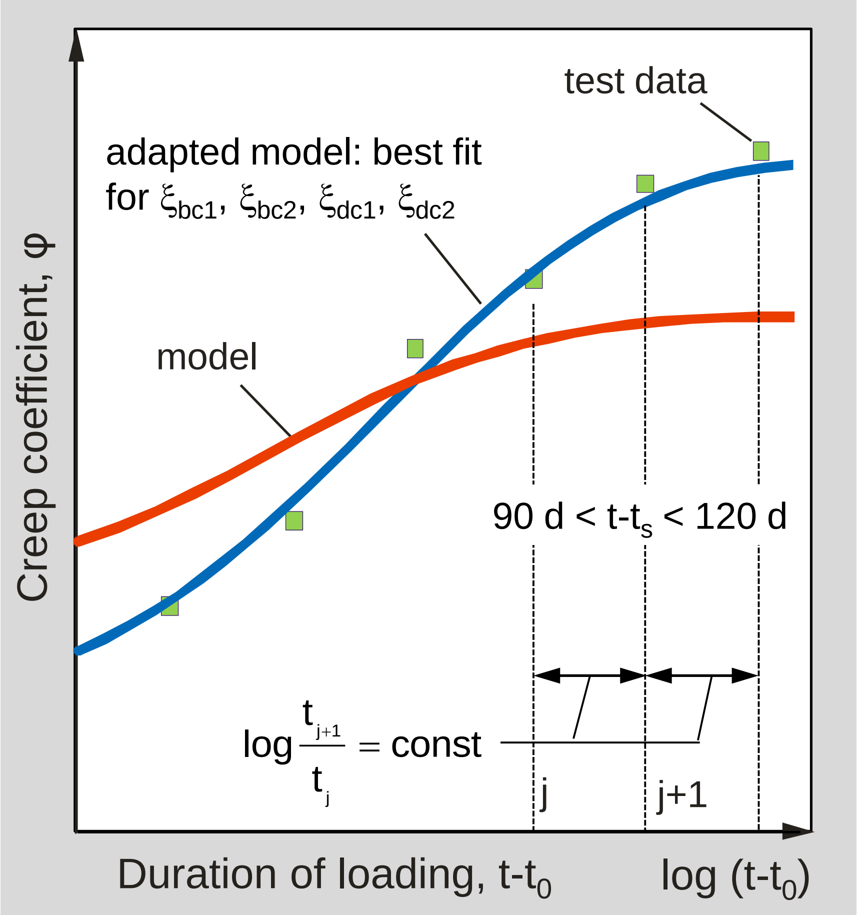
Basic creep:

$$\beta_{bc}(t,t_0)=\ln\left(\left(\frac{30}{t_{0,adj}}+0{,}035\right)^2\cdot\frac{(t-t_0)}{\xi_{bc2}}+1\right)$$

Drying creep:

$$\beta_{dc}(t,t_0)=\left(\frac{(t-t_0)}{\beta_h\cdot\xi_{dc2}+(t-t_0)}\right)^{\gamma(t_0)}$$

adaption factors



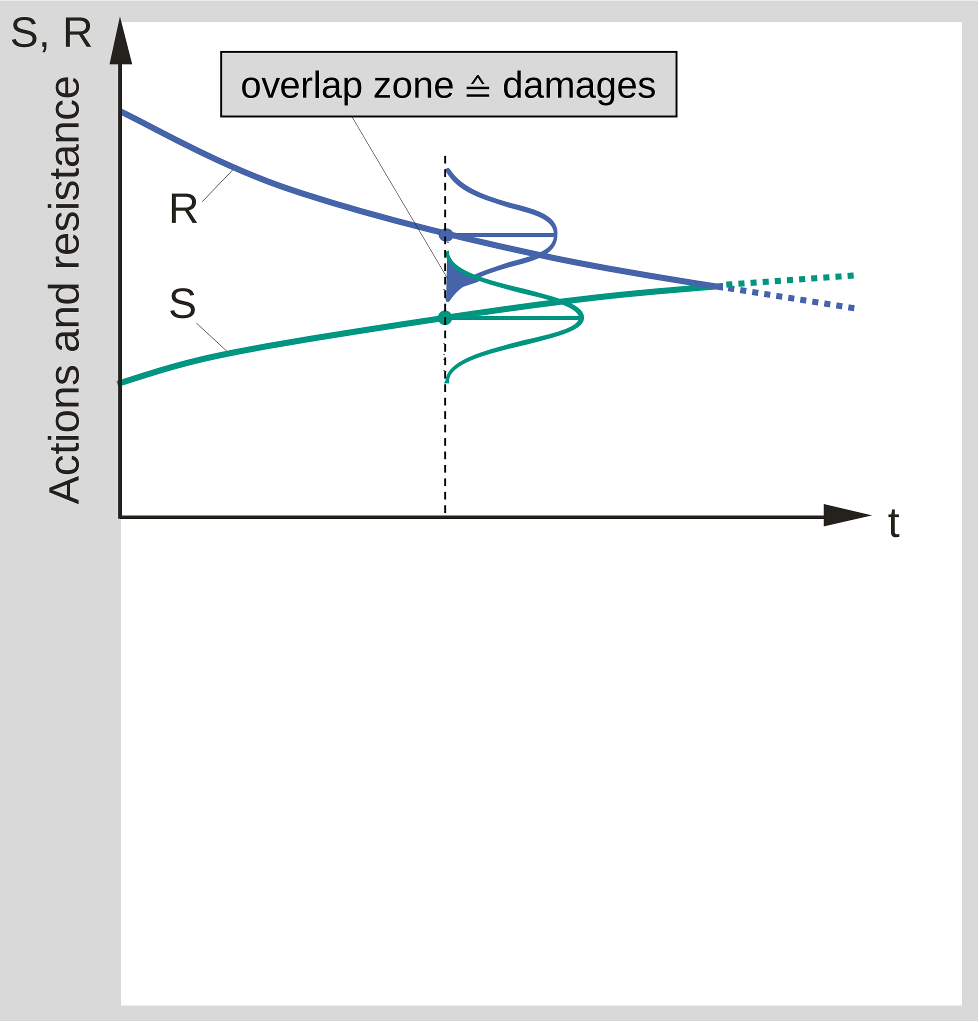
Accuracy gain through tests: Coefficient of variation drops from V ≈ 30 % to V ≈ 10 %

Durability

Deterioration processes and limit states

Reinforcement corrosion

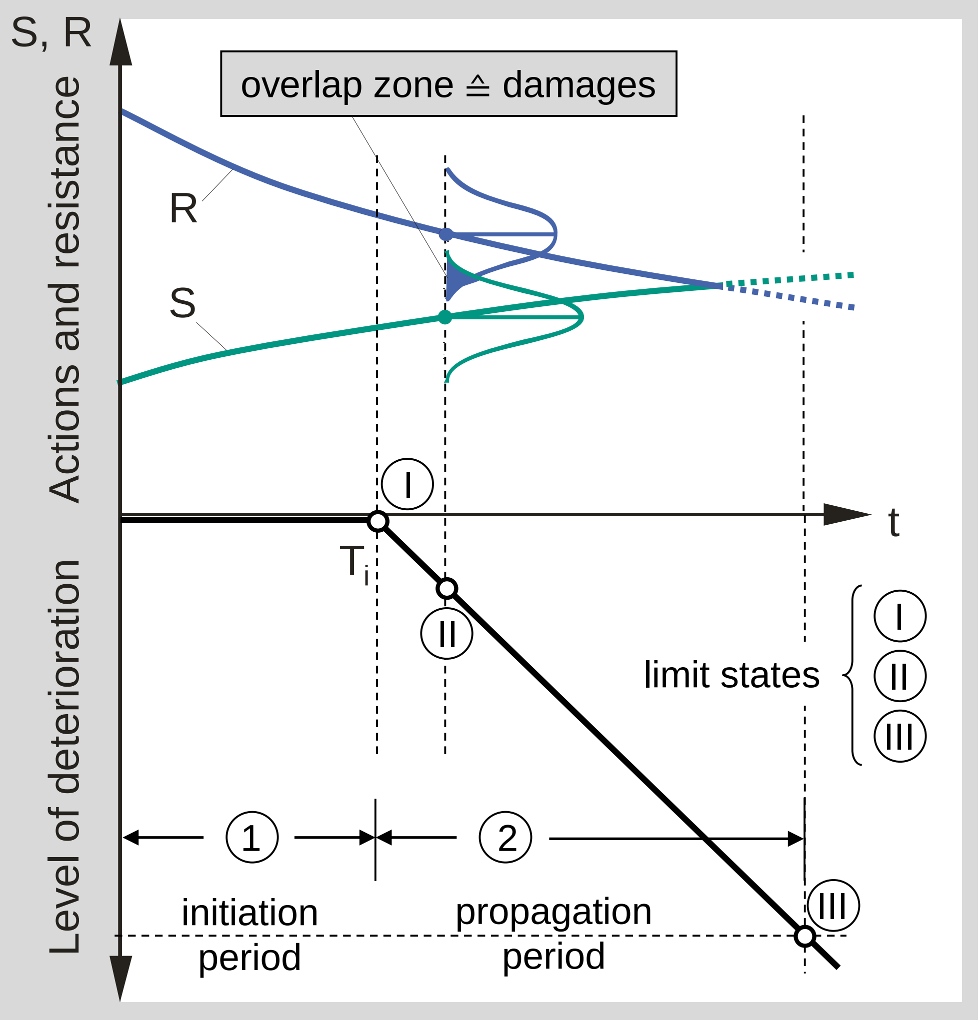
Frost or chemical attack



Deterioration processes and limit states

Reinforcement corrosion

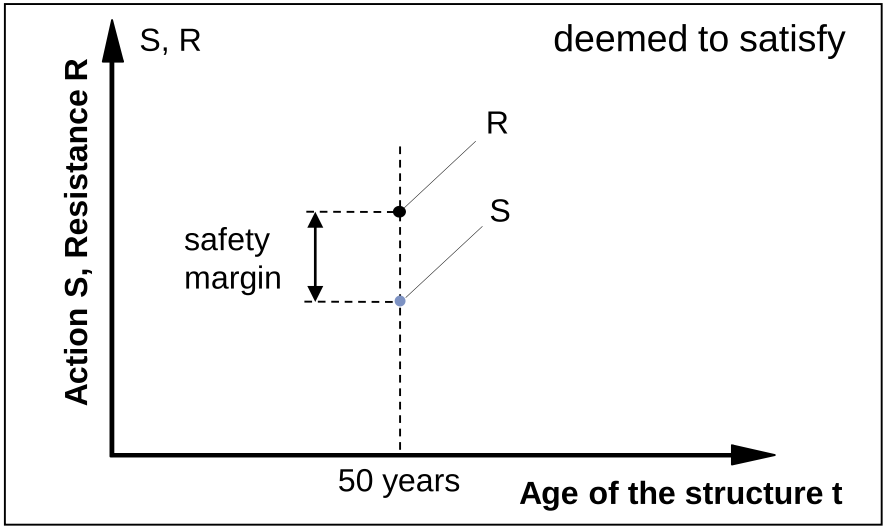
Frost or chemical attack



Service life design – Basic approaches

Descriptive Concept

approach: R – S > 0

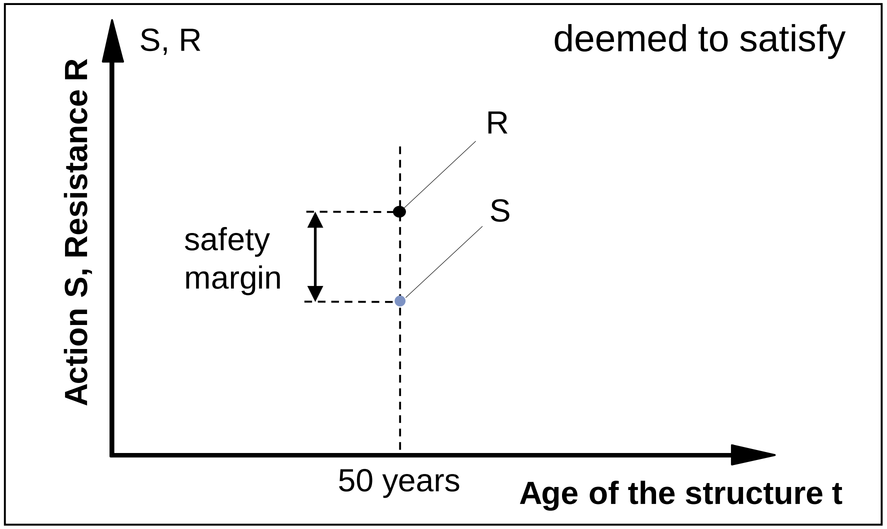


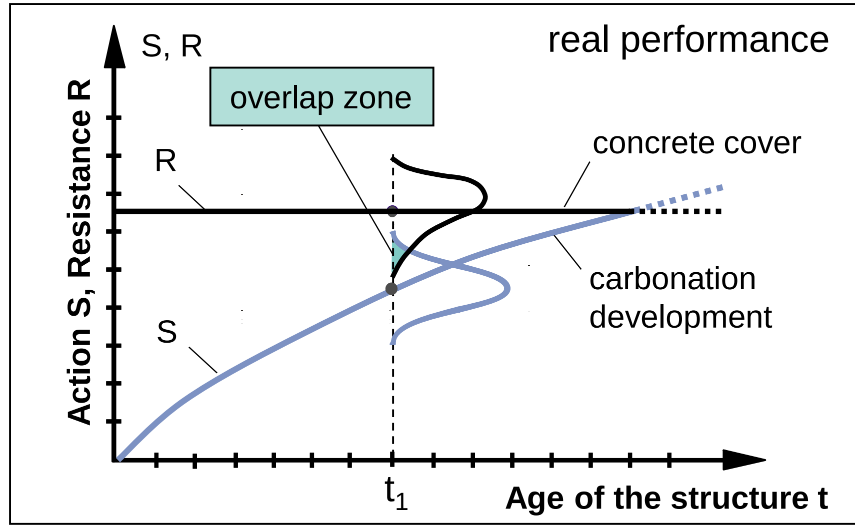
Descriptive Concept of Eurocode 2, national standards

empirical data (carbon. induced corrosion)	action S	resistance R			
	ambient conditions	max w/c [-]	min β [N/mm²]	min c [kg/m³]	concrete cover [mm]
	XC 4: reinf. corrosion alternate wet/dry	0.50	C30/37	300	40

Service life design – Basic approaches

Descriptive Concept	Probabilistic Concept
approach: R – S > 0	approach: $p_f(t) = p_f\,[R(t) - S(t) \leq 0] \leq p_{target}$





Descriptive Concept of Eurocode 2, national standards

empirical data (carbon. induced corrosion)	action S	resistance R			
	ambient conditions	max w/c [-]	min β [N/mm²]	min c [kg/m³]	concrete cover [mm]
	XC 4: reinf. corrosion alternate wet/dry	0.50	C30/37	300	40

Probabilistic Concept of *fib* Model Code 2010

physical models (carbon. induced corrosion)	
	$S = x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot C_S} \cdot \sqrt{t} \cdot W(t)$
	R = c = const; c = concrete cover

Service life design – Basic approaches

Descriptive Concept	Probabilistic Concept
approach: $R - S > 0$	approach: $p_f(t) = p_f\,[R(t) - S(t) \leq 0] \leq p_{target}$

Descriptive Concept:
- very simple but also very crude: „deemed to satisfy“
- service life is fixed, e.g. 50 years; no information on other ages, e.g. 20 or 100 years
- no information on the failure probability (risk of failure, damage development)

Probabilistic Concept:
- overcomes all weeknesses of the Decriptive Concept
- needs damage models (not yet available for some deteroriation processes)
- needs statistical software and tests on concrete

⇨ Target for MC 2020: Find compromise for everyday practice

Descriptive Concept of Eurocode 2, national standards

empirical data (carbon. induced corrosion)	action S	resistance R			
	ambient conditions	max w/c [-]	min β [N/mm²]	min c [kg/m³]	concrete cover [mm]
	XC 4: reinf. corrosion alternate wet/dry	0.60	C25/30	280	40

Probabilistic Concept of *fib* Model Code 2010

physical models (carbon. induced corrosion)	
	$S = x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot C_S} \cdot \sqrt{t} \cdot W(t)$
	R = c = const; c = concrete cover

Carbonation induced corrosion – Simplified design aid

Performance testing (ACC-Test, 28 days of curing and 28 days of testing)

$$R_{ACC,0}^{-1} = \left(\frac{x_c}{\tau}\right)^2$$

$R_{ACC,0}^{-1}$	inverse effective carbonation resistance of concrete [(m²/s)/(kg/m³)]
τ	time constant for described test conditions (τ = 420) [(s/kg/m³)$^{0.5}$]
x_c	measured carbonation depth [m]

Design parameters			
$R_{ACC,0}^{-1}$ [(m²/s)/(kg/m³)]	Service life [years]	β [-]	p_f [%]
high values (> $1{,}7\cdot10^{-10}$)	50	1.7	5
		1.3	10
	100	1.7	5
		1.3	10
medium values ($1{,}7\cdot10^{-10}$ – $1{,}9\cdot10^{-11}$)	50	1.7	5
		1.3	10
	100	1.7	5
		1.3	10
low values (< $1{,}9\cdot10^{-11}$)	50	1.7	5
		1.3	10
	100	1.7	5
		1.3	10

Carbonation induced corrosion – Simplified design aid

Performance testing (ACC-Test, 28 days of curing and 28 days of testing)

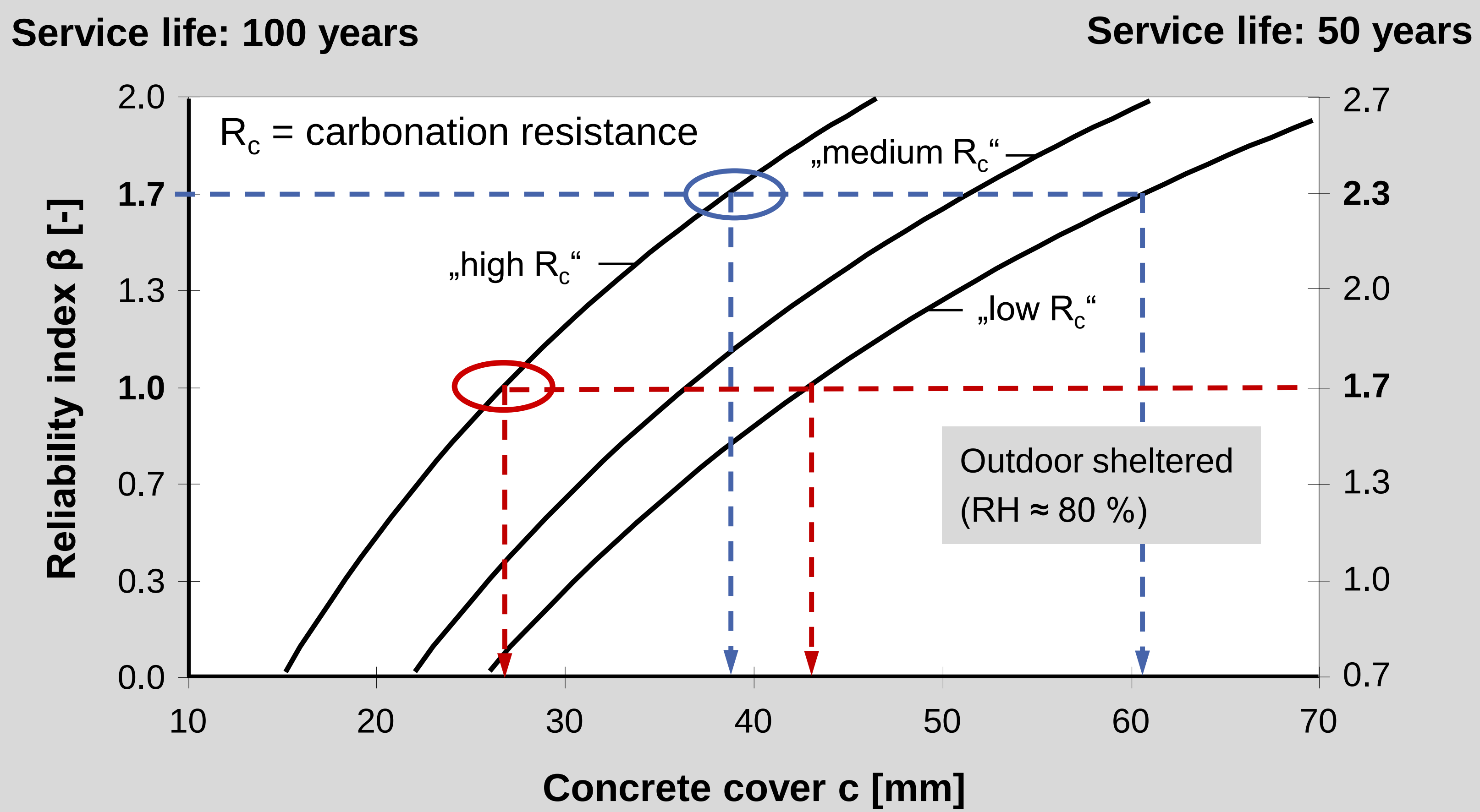
$$R^{-1}_{ACC,0} = \left(\frac{x_c}{\tau}\right)^2$$

$R^{-1}_{ACC,0}$	inverse effective carbonation resistance of concrete [$(m^2/s)/(kg/m^3)$]
τ	time constant for described test conditions (τ = 420) [$(s/kg/m^3)^{0.5}$]
x_c	measured carbonation depth [m]

Design parameters				Design results	
$R^{-1}_{ACC,0}$ [$(m^2/s)/(kg/m^3)$]	Service life [years]	β [-]	p_f [%]	Carbonation depth / Concrete cover c [mm] Indoors [50 %]	Carbonation depth / Concrete cover c [mm] Outdoors [80 %]
high values (> $1,7\cdot10^{-10}$)	50	1.7	5	95	75
		1.3	10	90	65
	100	1.7	5	135	110
		1.3	10	125	95
medium values ($1,7\cdot10^{-10}$ – $1,9\cdot10^{-11}$)	50	1.7	5	35	30
		1.3	10	30	25
	100	1.7	5	50	40
		1.3	10	45	35
low values (< $1,9\cdot10^{-11}$)	50	1.7	5	20	15
		1.3	10	15	10
	100	1.7	5	30	20
		1.3	10	20	15

Carbonation induced corrosion – Simplified design aid (2)

Limit state: Depassivation due to carbonation



Conclusions and outlook

- With respect to the variety of different concrete types to be addressed in MC 2020 the classical strength based approach for modelling concrete behaviour has to be partially shifted towards a performance based modelling.

- Models for strength and deformation characteristics in MC 2020 will be presented such that test results obtained on the respective concrete may be introduced to improve the accuracy considerably.

- For the performance based concept for durability and service life prediction suitable simplified design tools will be made available. These tools will be as simple as the deemed-to-satisfy approaches of today but much more accurate.

Thank you for your attention!