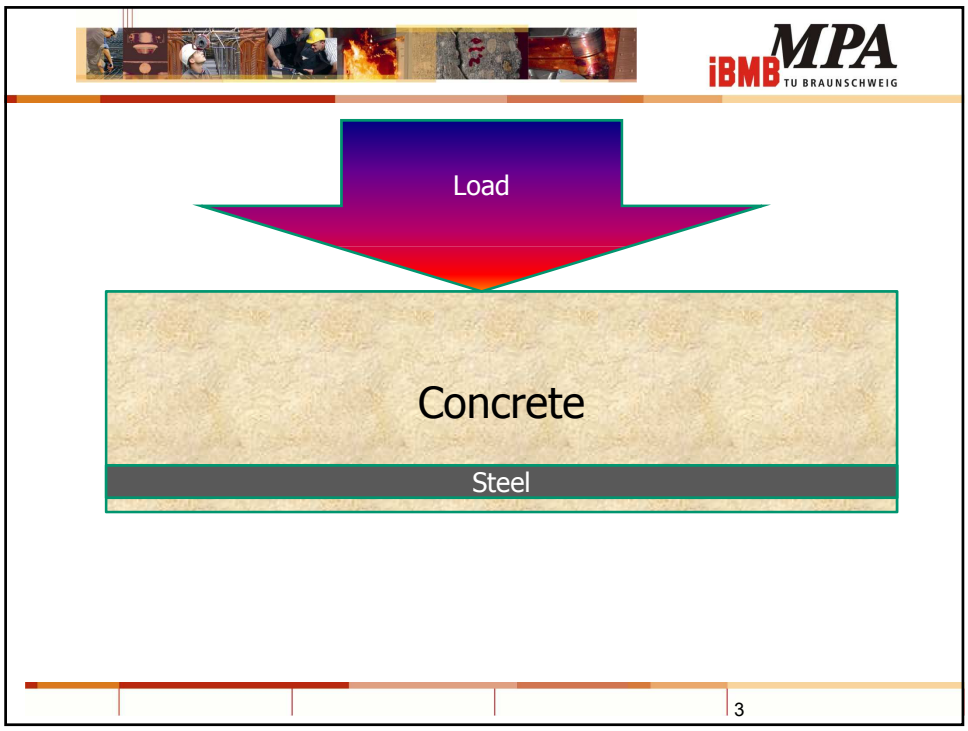
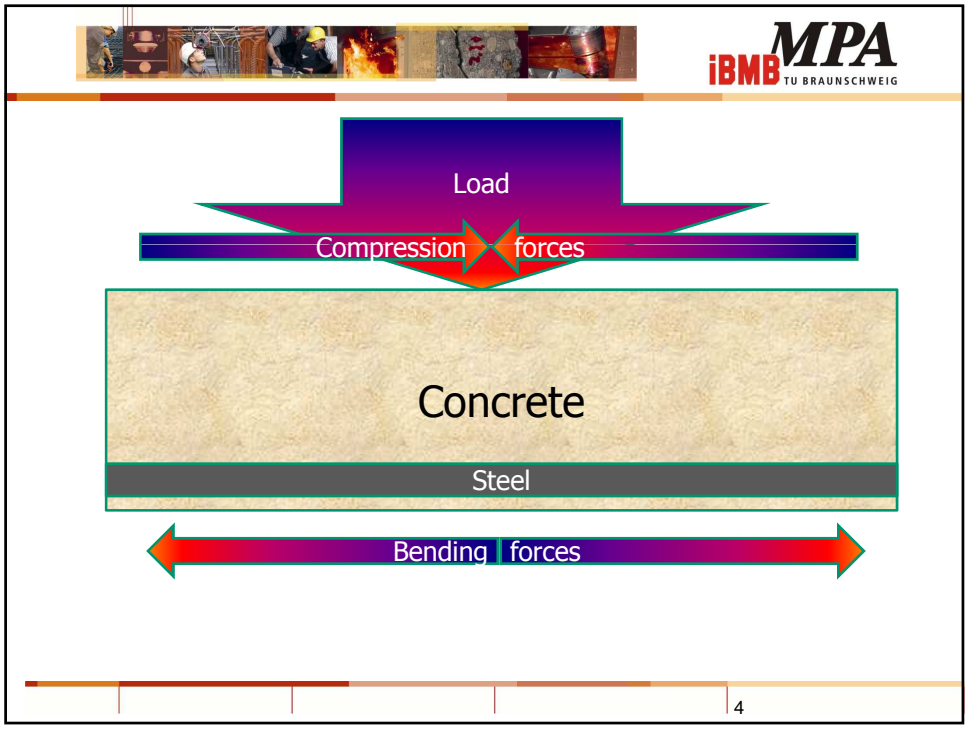
A probabilistic approach to assessing the compliance of concrete regarding the content of dissolved chloride in its components

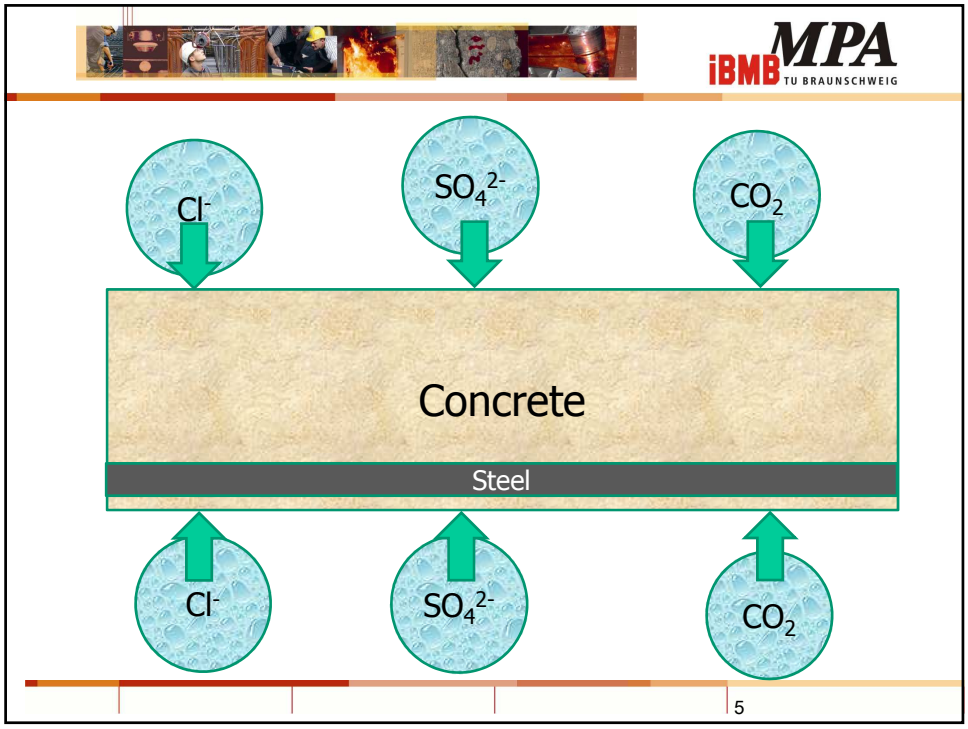
Dr.-Ing. Wilfried Hinrichs

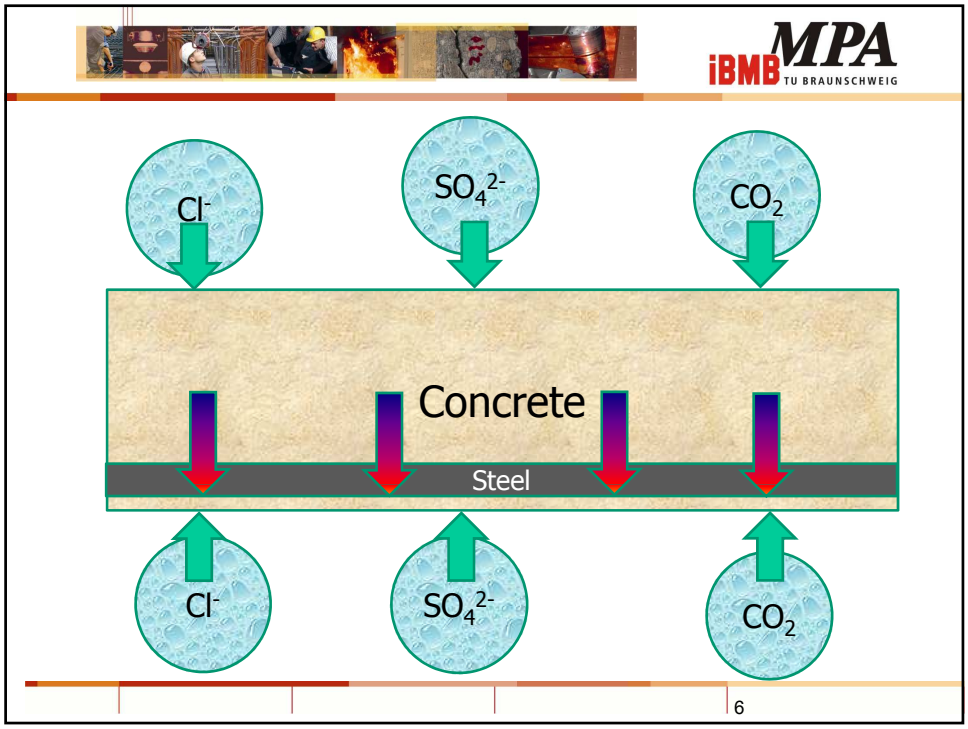
Concrete

Steel


Load
Concrete
Steel
3


Load
Compression forces
Concrete
Steel
Bending forces
4


iBMB MPA TU BRAUNSCHWEIG
Cl-
SO4 2-
CO2
Concrete
Steel
Cl-
SO4 2-
CO2
5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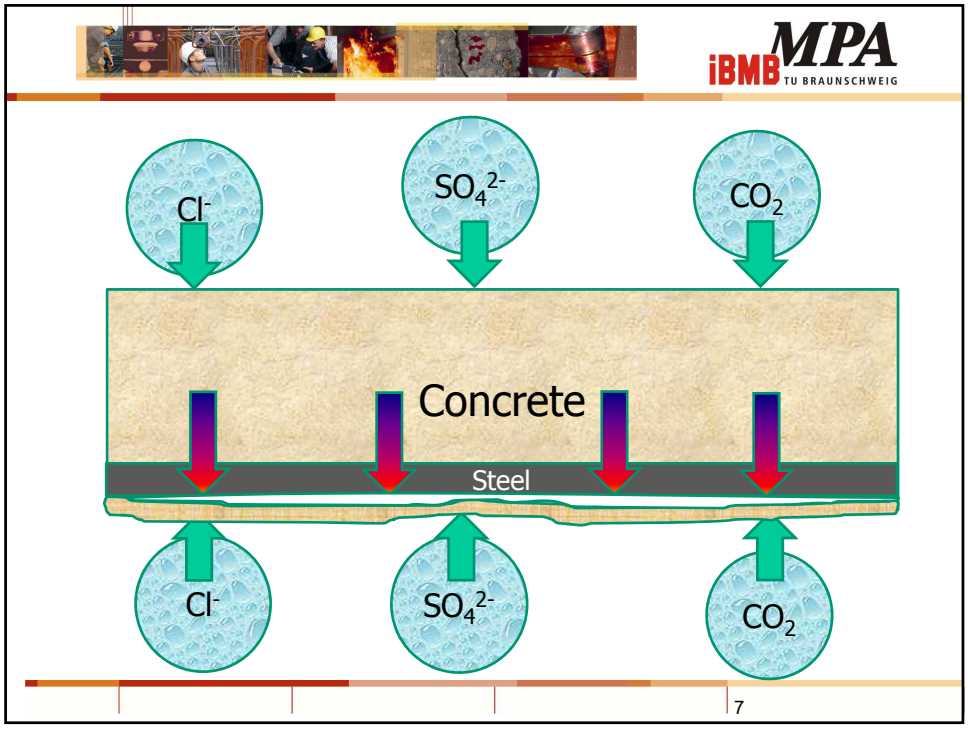
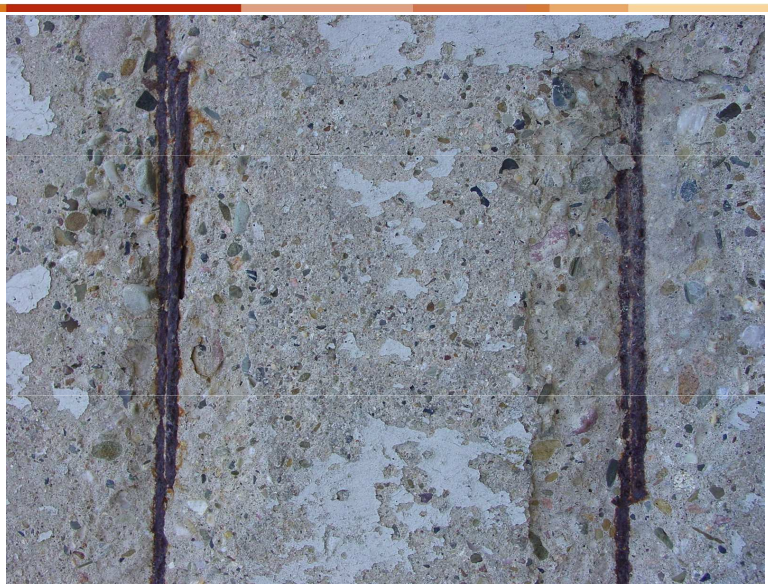
Cl-
SO4 2-
CO2
Concrete
Steel
Cl-
SO4 2-
CO2
6


iBMB MPA TU BRAUNSCHWEIG
Cl-
SO4 2-
CO2
Concrete
Steel
Cl-
SO4 2-
CO2
7


iBMB MPA TU BRAUNSCHWEIG
8



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Corrosion of steel in concrete

- A corrosion process starts when both humidity and oxygen are present.
- In good concrete the steel is well embedded and thus protected against the access of oxygen.
- The durability is jeopardized by the destruction of the embedment, i.e. through the access of oxygen and of other harmful substances, including chlorides.

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Steel corrosion by chlorides

- There is no minimal level under which the chloride concentration is known to be harmless.
- The low level of chloride concentration for the design of concrete is clearly prophylactic.
- The durability is additionally jeopardized by migrating chlorides from the environment.

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Limit values for chlorides in concrete

Concrete	Limit values (EN 206-1)
without embedded steel	1.0 M-%
with embedded steel	0.2 M-% / 0.4 M-%
with pre-stressed steel	0.1 M-% / 0.2 M-%

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Concrete 1 (worked example)

Component	Nominal fraction	Average content of water-soluble chlorides in M-%	Average content with reference to the cement fraction in M-%
Aggregates	0.800	0.010	0.059
Cement	0.137	0.080	0.080
Water	0.062	0.001	0.000
Sealant	0.001	0.010	0.000
Sum	1.000	-	**0.139**

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Concrete 2 (worked example)

Component	Nominal fraction	Content of water-soluble chlorides in M-%	Content with reference to the cement fraction in M-%
Aggregates	0.515	0.010	0.040
Recycled concrete	0.286	0.110	0.244
Cement	0.129	0.250	0.250
Water	0.070	0.003	0.002
Sum	1.000	-	**0.536**

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Component	Concrete 1: Standard deviation of water-soluble chlorides in M-%	Concrete 2: Standard deviation of water-soluble chlorides in M-%
Aggregates	0.017	0.012
Recycled concrete	-	0.133
Cement	0.011	0.090
Water	0.000	0.000
Sealant	0.000	-
Sum	**0.028**	**0.235**

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- Concrete 1 $c_{Cl,1} = (0.139 \pm 0.028)$ M-%
- Concrete 2 $c_{Cl,2} = (0.536 \pm 0.235)$ M-%
- Gamma distribution of the chloride concentrations

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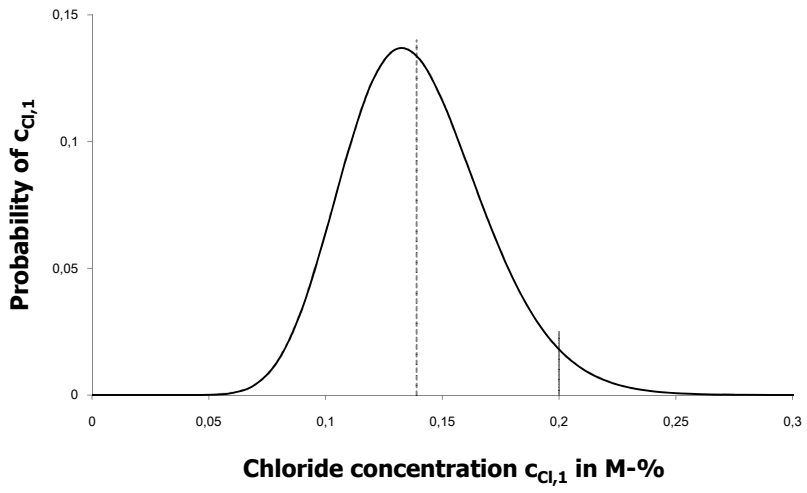

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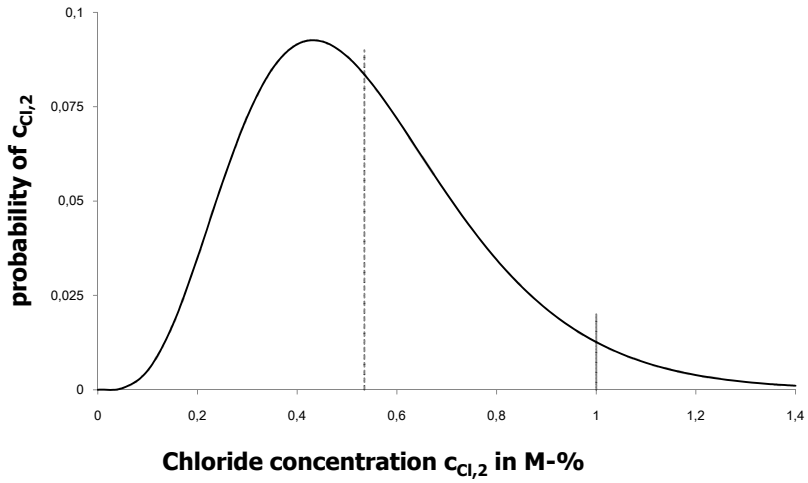

Factors contributing significantly to the dispersion of test results

- Technical realization of the fractioning (u_P)
- Heterogeneity of the material (u_H)
- **Uncertainty of the product**
- Sampling ($u_{Sampling}$)
- Preparation of samples ($u_{Preparation}$)
- Testing of samples ($u_{Testing}$)
- **Uncertainty of testing**

Uncertainty of the product

- The product standard EN 206-1 quantifies a requirement for the realization of the concrete mixture.
- Raw materials for concrete show considerable long-term dispersions of the water-soluble chloride concentrations. Their long-term means are taken as estimates for the materials' heterogeneities.

Uncertainty of testing

- The test standards quantify a specific form of precision data by numbering a repeatability limit r_1 and a reproducibility limit R_1. It encompasses both testing and preparation, thus excluding sampling effects.
- As in the long run testing conditions vary it seems more appropriate to use the given reproducibility data.
- The literature reports that the uncertainty of testing depends on the chloride content, i.e. it strongly increases with lower values.

Uncertainty of sampling

- No precision data available
- Estimation based on long-term experiences
  - the uncertainty of sampling is about the size of the uncertainty of testing for materials with low concentrations of water-soluble chlorides
  - the sampling of recycled materials is significantly more uncertain with concentrations varying between low and high concentrations of water-soluble chlorides
- Rough estimates for sampling:
  - low content of water-soluble chloride: $u_{sampling} = 1.0u_{testing}$
  - recycled products: $u_{sampling} = 2.5u_{testing}$

Two model (sub)functions

$$u_M = \sqrt{u_P^2 + u_H^2}$$

$$u_{T'} = \sqrt{u_{Sampling}^2 + u_{Testing}^2}$$

Process / inherent property	Uncertainty estimates in M-% for	
	concrete 1	concrete 2
realization of the concrete mixture	0.010	0.010
heterogeneity	0.028	0.232
uncertainty of the product	**0.030**	**0.232**
sampling	0.009	0.015
preparation and testing	0.009	0.006
uncertainty of testing	**0.013**	**0.016**

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Remark

EN 206-1 does not provide rules for the rounding of the sum before compared with the specification. This has a significant impact on the statement of compliance.

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Probabilities of conformity for concrete 1

This probabilistic approach:	The semi-probabilistic approach of EN 206-1:
p = 0.950	p = 0.950
$c_{Cl,1}$ = **0.148 M-%**	$c_{Cl,1}$ = **0.155 M-%**

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Probabilities of conformity for concrete 2

This probabilistic approach:	The semi-probabilistic approach of EN 206-1:
p = 0.950	p = 0.950
$c_{Cl,2}$ = **0.566 M-%**	$c_{Cl,2}$ = **0.614 M-%**

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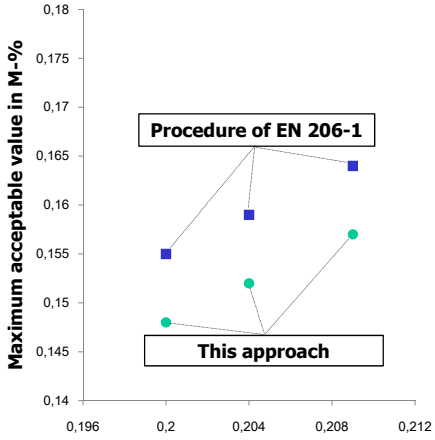
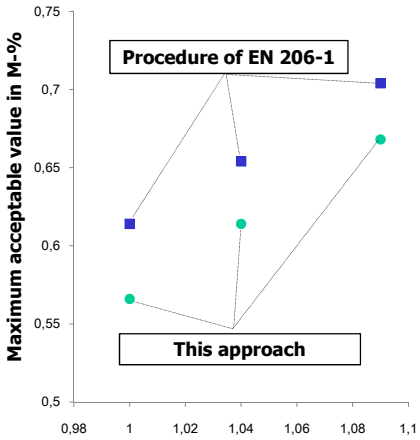
Interpretation of EN 206-1



Concrete 1: Sum of chloride concentration in M-%



Concrete 2: Sum of chloride concentrations in M-%

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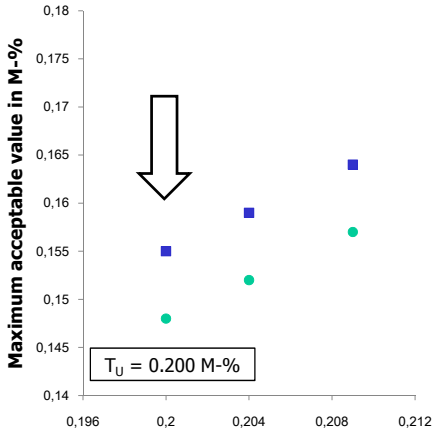
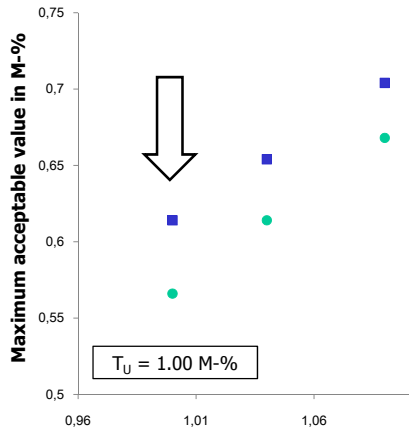
Interpretation of EN 206-1



Concrete 1: Sum of chloride concentration in M-%



Concrete 2: Sum of chloride concentrations in M-%

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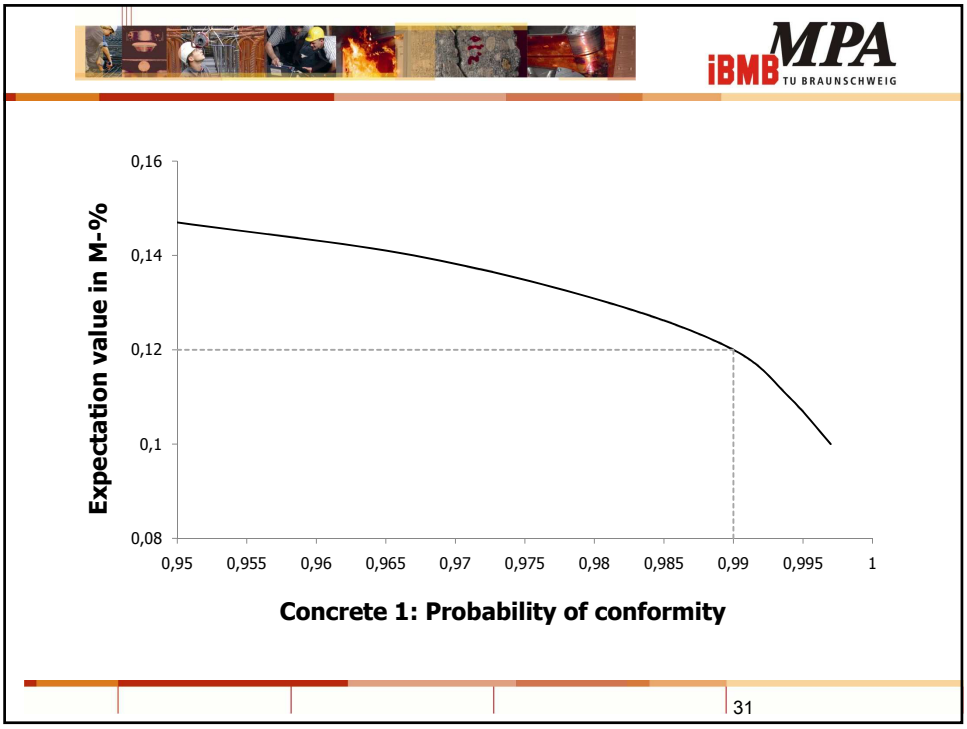
0,16
0,14
0,12
0,1
0,08
Expectation value in M-%
0,95
0,955
0,96
0,965
0,97
0,975
0,98
0,985
0,99
0,995
1
Concrete 1: Probability of conformity
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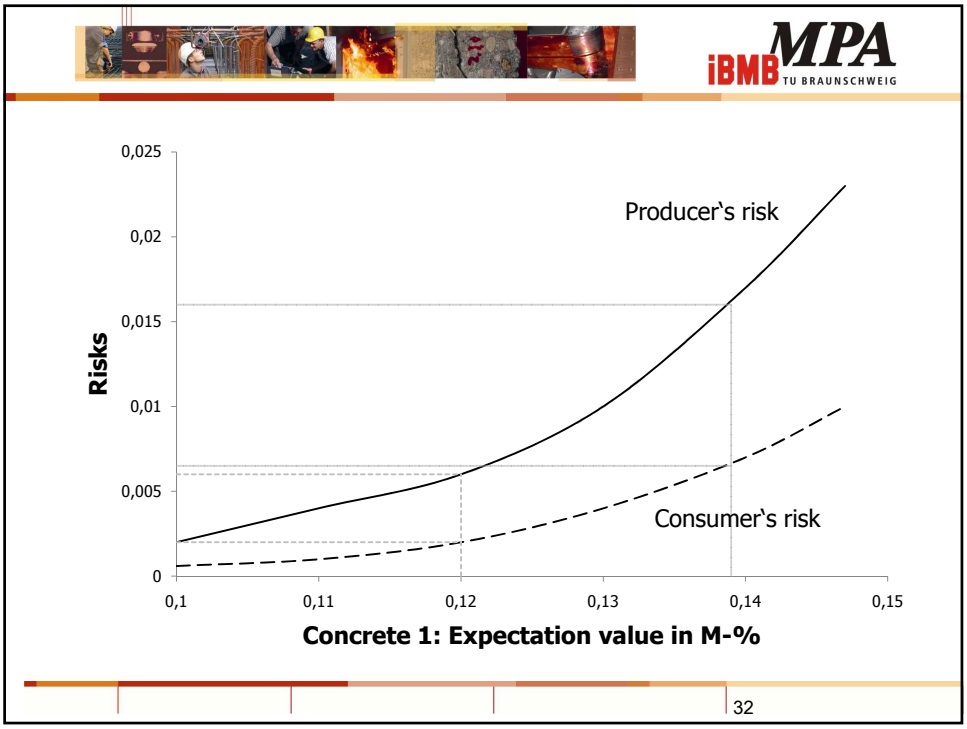
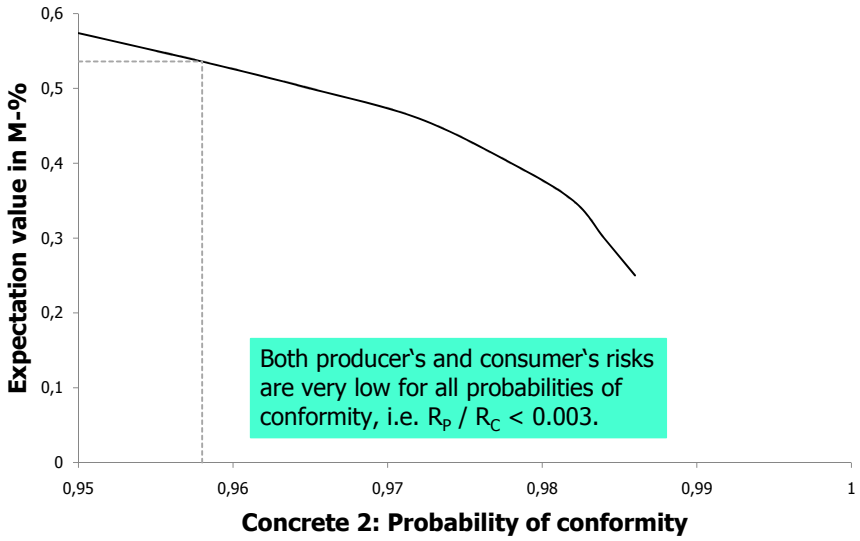

0,025
0,02
0,015
0,01
0,005
0
Risks
Producer's risk
Consumer's risk
0,1
0,11
0,12
0,13
0,14
0,15
Concrete 1: Expectation value in M-%
32



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Decision rule (1st level)

- Reject the design of a concrete, if the figure calculated on the basis of EN 206-1 exceeds the maximum limits of table 10, i.e.
  - concrete 1: T_U= 0.155 M-%
  - concrete 2: T_U= 0.614 M-%
- Make sure that the decision is based on a rounding rule accepted by the parties involved.
- Check on the basis of the contract with the client, i.e. either on the basis of the probability of conformity or according to a risk-based concept, if the provisions of the 2nd level of this decision rule are met.

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Decision rule (2nd level)

Concept based on the probability of conformity	Risk-based concept
T_U = 0.148 M-% for p = 0.950 T_U = 0.131 M-% for p = 0.980	T_U = 0.130 M-% for R_P = 0.010 T_U = 0.100 M-% for R_P = 0.002
T_U = 0.566 M-% for p = 0.950 T_U = 0.370 M-% for p = 0.980	T_U = 0.536 M-% for R_P = 0.002 T_U = 0.400 M-% for R_P = 0.001
If the requirements are not met, reject the design.	If the requirements are met, check the 3rd level.

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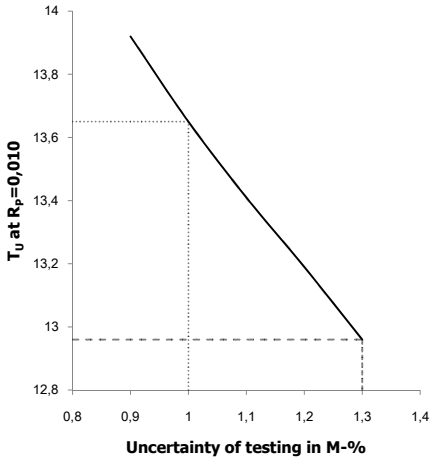
Risk-based decision rule (3rd level)

Check the possibilities for reducing the uncertainty of both sampling and testing at the given risk-level.

Reject the design, if the sum of chlorides is above T_U.



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EN 206-1 vs. this probabilistic approach

▪ deterministic / semi-probabilistic and easily applicable	▪ probabilistic and not easily applicable
▪ at least one additional decision necessary	▪ some additional decisions necessary
▪ independent of the individual performance of the laboratory	▪ the individual performance of the laboratory is taken into account
▪ no room left for interpretations as regards the decision on compliance	▪ some possibilities to ground the decision on compliance on alternative requirements

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Conclusions

- Results produced on the basis of this probabilistic approach are comparable to those of EN 206-1 but they tend to be more 'on the safe side'.
- The application of the probabilistic approach allows to introduce additional risk-based decision rules.
- The compliance assessing body may take into account the individual data on measurement uncertainty.
- The producer can define guard bands using this probabilistic approach.

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