The use of corrosion resistant reinforcement – the chance for durable concrete reinforced structures

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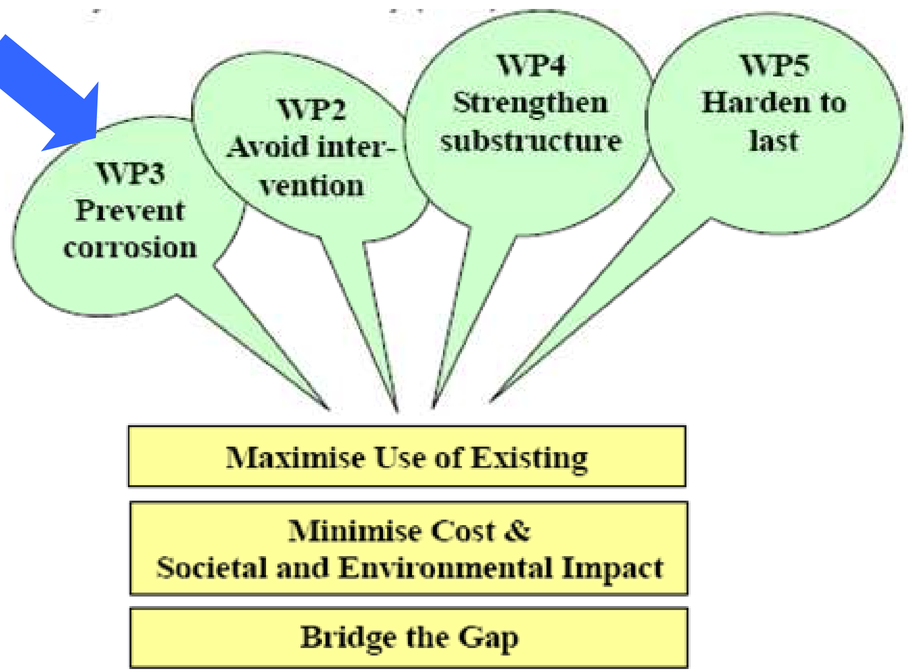
3.1 Corrosion resistant steel reinforcement
3.2 Cathodic protection/prevention
3.3 ER monitoring probes



Outline

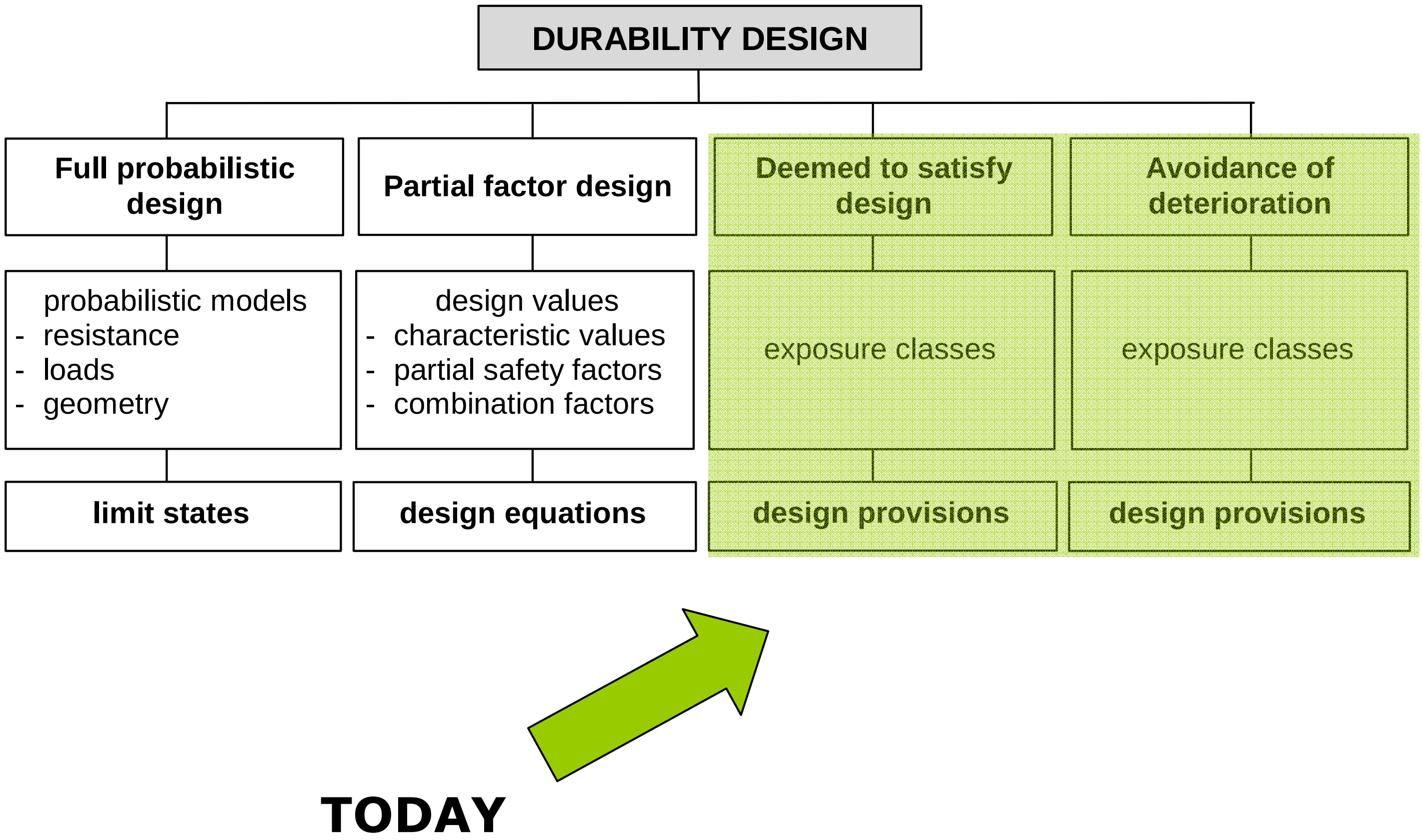
1. Background on durability problems
2. Corrosion of steel in concrete
3. Idea and aim of the research
4. Experimental program
5. Conclusions

Requirements in civil engineering

- Concrete structures have to be designed and constructed with the ability to preserve **functionality, stability and aesthetic** properties under expected environmental influences **without larger maintenance and repair costs** during **designed service life**.

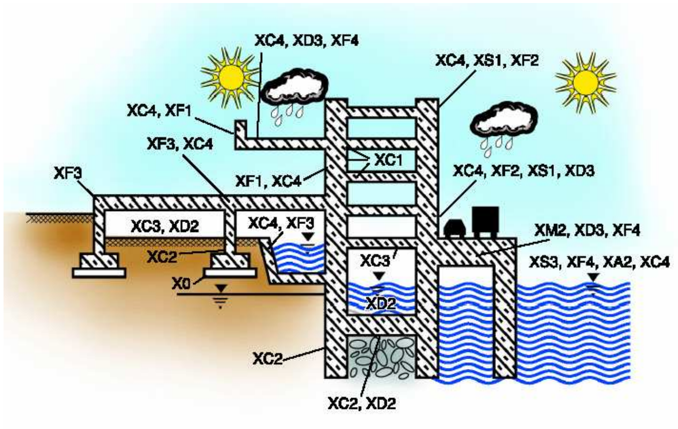
Service life (years)	Example
1-5	Temporary structures
25	Replaceable structural elements
50	Residental structures
100	Monumental structures (bridges)

Approaches to durability design



Deem-to-satisfy design

- European standard EN 206-1 defines six major classes of different environmental conditions



Class	Description	Subclasses
X0	*No risk of corrosion*	-
XC	*Corrosion induced by carbonation*	*XC1, XC2, XC3, XC4*
XD	*Corrosion induced by chlorides of other than marine origin*	*XD1, XD2, XD3*
XS	*Corrosion induced by chlorides present in seawater*	*XS1, XS2, XS3*
XF	*Freeze-thaw cycles with or without de-icing salts*	*XF1, XF2, XF3, XF4*
XA	*Chemical attack*	*XA1, XA2, XA3*

Torpedo, Rijeka

- Built in 1920’s

Krk Bridge

- Built from 1976 - 1980
- Total span 1430 m; concrete arch span 390 m

Maslenica Bridge

- Built from 1995 - 1996
- Concrete arch span 200 m

Corrosion of steel in concrete

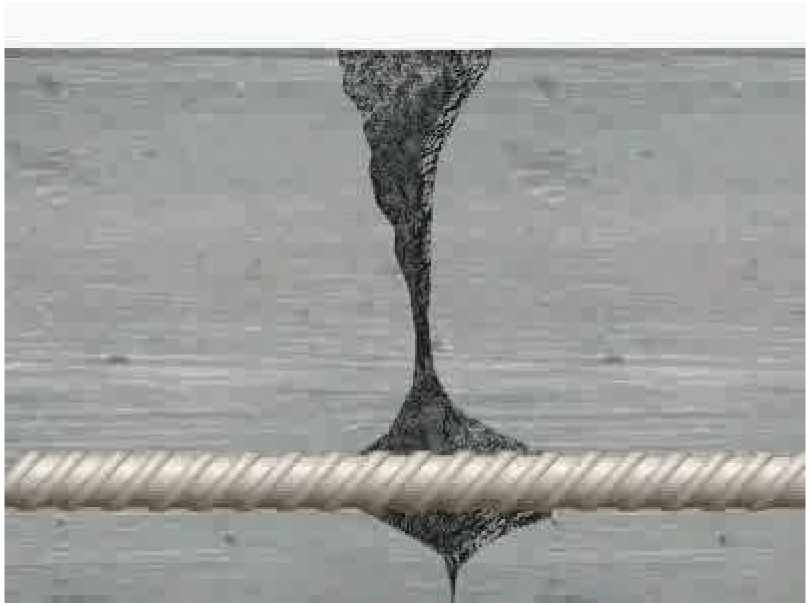
- Carbonation
- Chloride attack

Carbonation

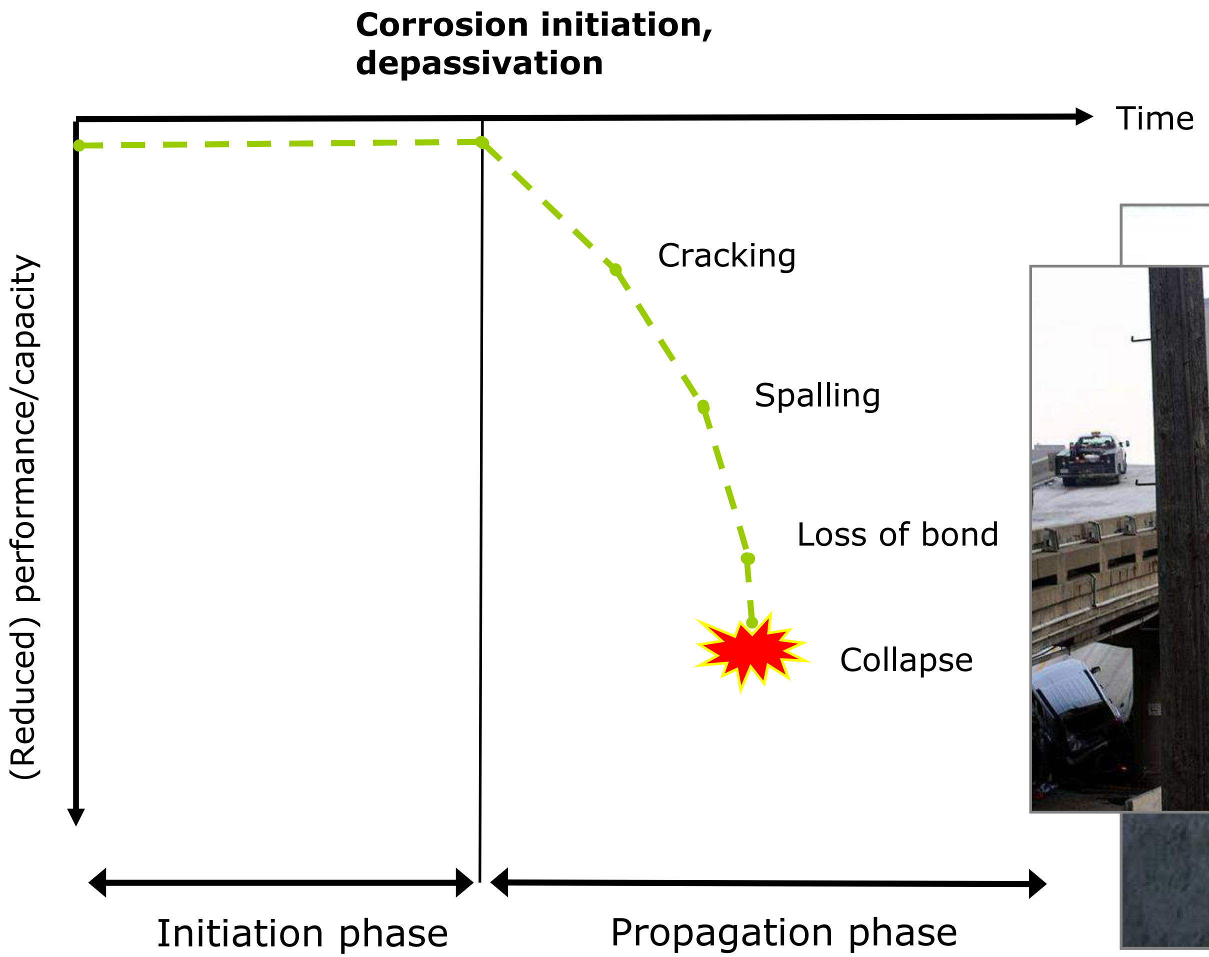
- Carbon dioxide, CO_2 from the atmosphere, penetrates into the concrete and reacts with calcium hydroxide, $Ca(OH)_2$ from the cement
- pH of the concrete decreases causing dissolution of the passive layer formed on steel surface

Chlorides

- When present in pore solution, chloride ions react with ferrous ions, water and oxygen, which leads to destruction of passive oxide layer formed on steel surface



Corrosion consequences



Idea of the research

- Stainless steel - resistant to corrosion in concrete environment with high chloride contamination
- The use of stainless steel reinforcement limited by concerns over the increase in initial construction costs
- Recent results:
  - some low alloy steels behave significantly better than ordinarily used black steel reinforcement
  - the price of low alloy steel reinforcement is lower than the price of stainless steel reinforcement - economically justified

Aim of the research

1. To research presently available corrosion resistant reinforcement
2. To evaluate their efficiency in normal, carbonated and concrete contaminated with chlorides
3. To define service life of corrosion resistant reinforcement and their limit state application

Chosen steel grades

Grade	Chemical composition									
	C	Si	Mn	P	S	N	Cr	Cu	Mo	Ni
Black steel										
B500B	0.19	0.10	0.62	0.020	0.022	0.005	0.07	0.04	<0.02	0.02
Feritic steel										
TOP12	0.018	0.80	0.56	0.013	<0.001	0.0139	12.37	0.02	0.024	0.46
Austenitic steel (lower Ni content)										
204Cu	0.038	0.42	7.94	0.021	0.005	0.1486	16.23	2.14	0.322	2.11
Austenitic steel										
AISI 304	0.058	0.42	1.46	0.019	<0.001	0.0506	18.24	0.11	0.036	7.93
AISI 304L	0.016	0.38	1.50	0.025	0.008	0.0278	18.19	0.44	0.107	9.22
Duplex steel										
SAE/UNS S3 2205	0.030	0.36	1.78	0.030	0.02	0.1412	22.50	0.04	3.221	4.51
UGIGRIP 4362	0.020	0.58	1.09	0.022	<0.001	0.072	22.22	0.28	0.282	3.57

Mechanical properties

Grade	$R_{p0,2}$ [MPa]	R_m [MPa]	$R_m/R_{p0,2}$	A_{gt} [%]
TOP 12	566	748	1,32	8,2
204Cu	688	872	1,27	18,0
AISI 304	882	992	1,12	10,3
AISI 304L	697	825	1,18	5,7
1.4462	1005	1138	1,13	2,1
1.4362	1005	1138	1,13	2,1
Black steel	631	737	1,17	6,9

Experimental program

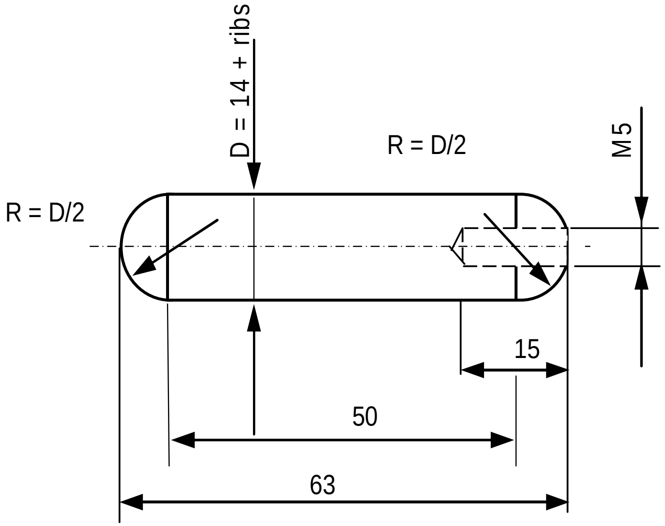
Accelerated corrosion testing of steel electrodes in alkaline media with different pH values and concentrations of chloride ions

Testing in pore solution

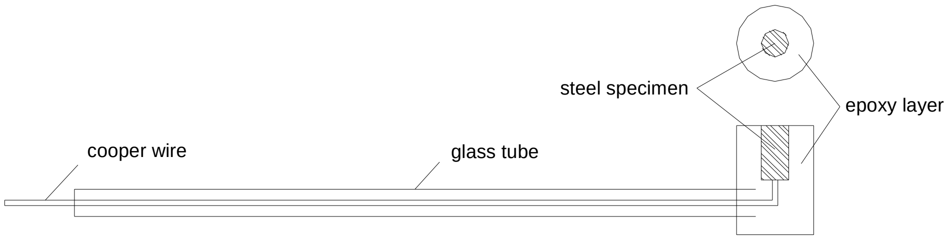
- Electrochemical testing on steel specimens in:
  - pH value 12,4
  - pH 10,1
  - with different concentration of NaCl
- Methods:
  - linear polarization,
  - potentiodynamic measurements,
  - electrochemical impedance spectroscopy.

Specimens

Type A

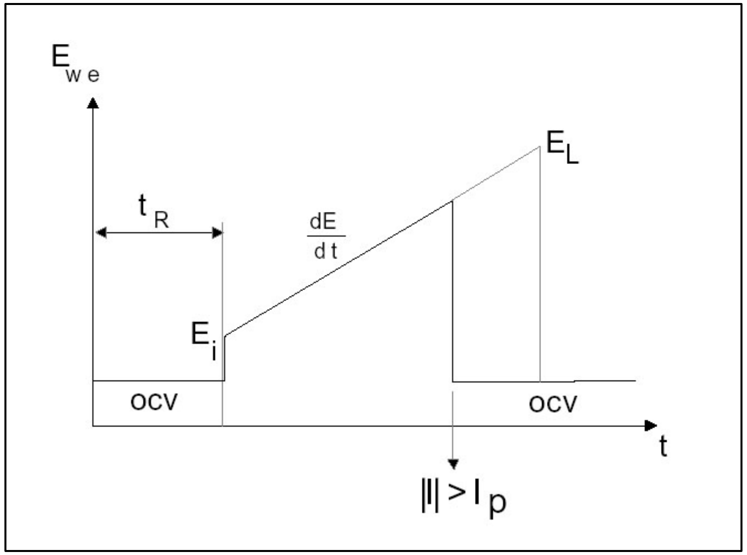


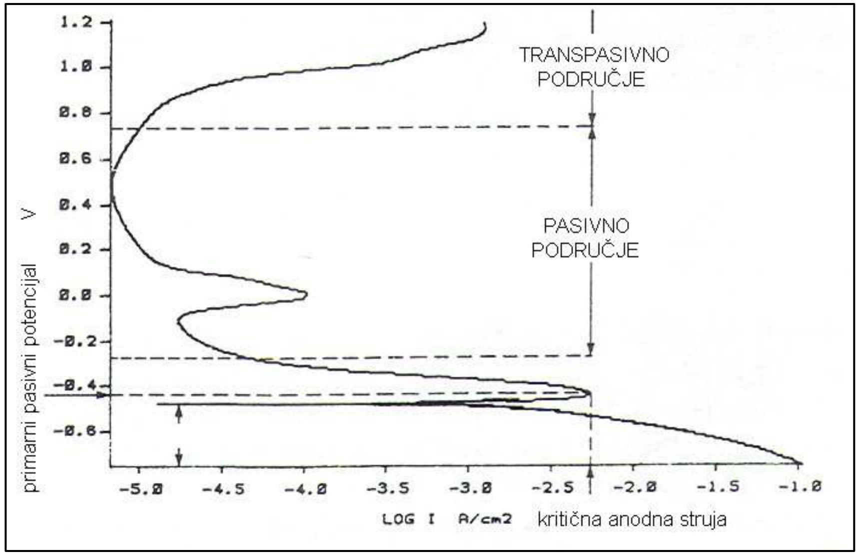
Type B



Anodic polarisation (LP)

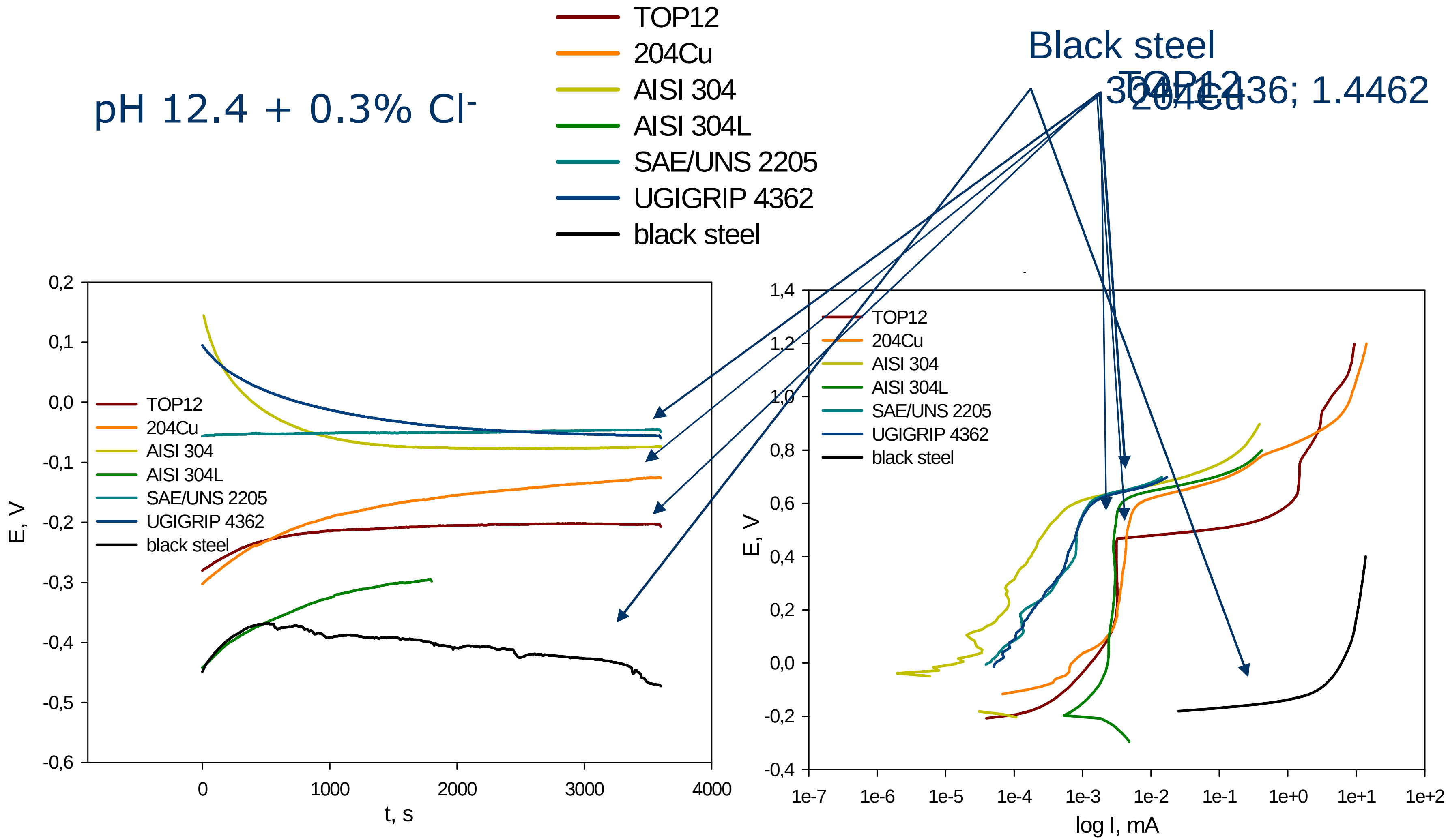
- Open circuit voltage monitoring for 60 minutes
- Anodic polarisation, 1.0 mV/s - scanning pitting potential





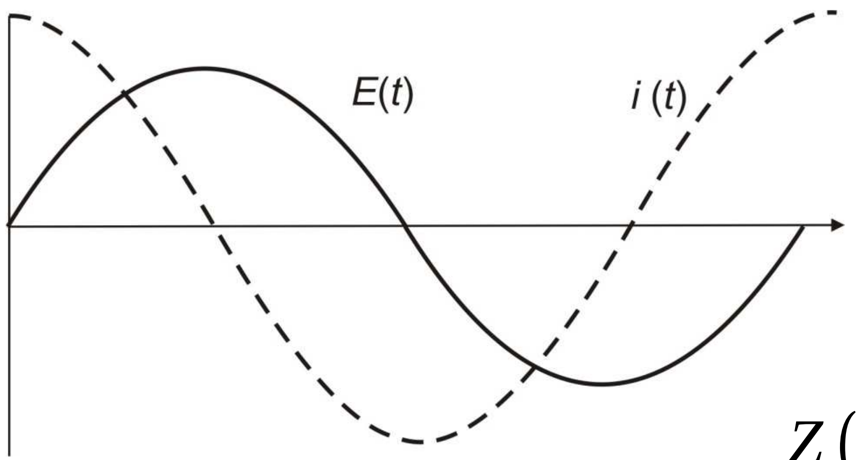
Results LP - pH 12.4

pH 12.4 + 0.3% Cl^-

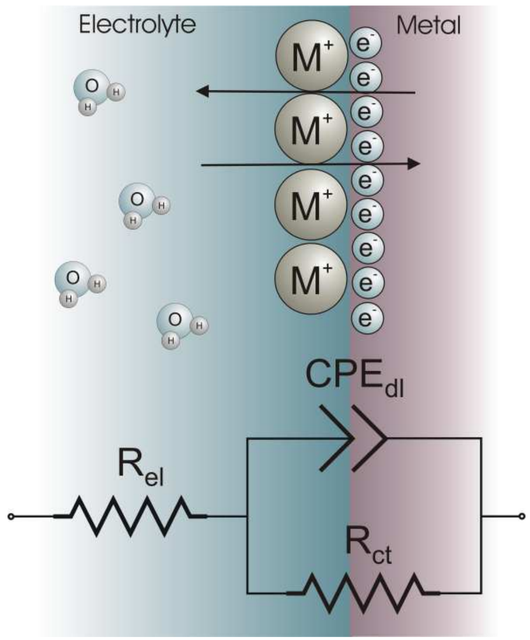


Electrochemical impedance spectroscopy

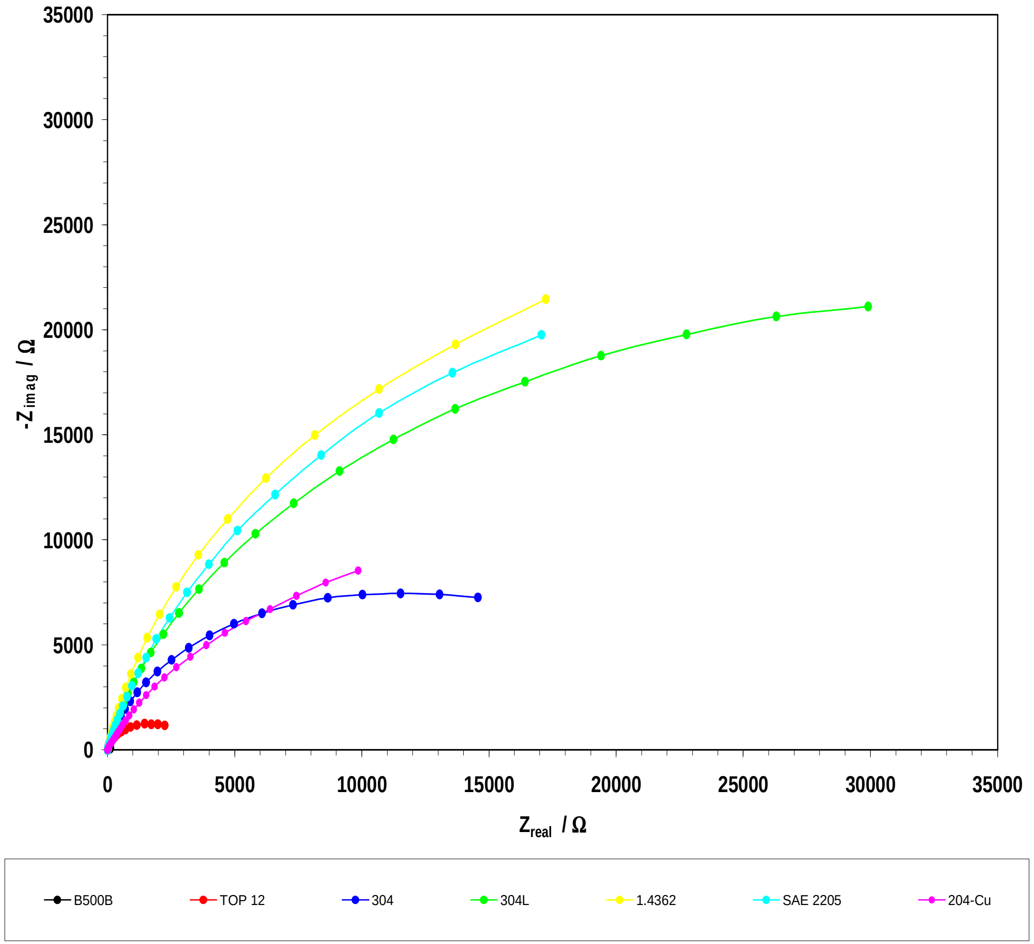
- the response of the corroding electrode to periodic voltage in the frequency domain
- (10 mHz – 100 kHz; ±10 mV).



$$Z(\omega) = \frac{E(t)}{I(t)}$$



Results EIS - pH 12.4



pH 12.4 + 0.2% Cl^-

Grade	|Z| [Ohm]
B500B	123
TOP 12	2532
204Cu	13039
AISI 304	16274
AISI 304L	36614
SAE/UNS S3 2205	26111
UGIGRIP 4362	27520

SPENS ARCHES CERTAIN

Experimental program

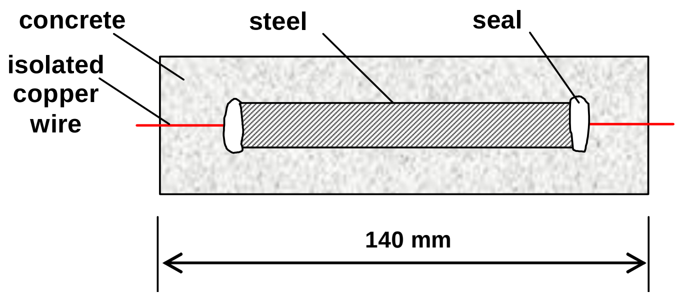
Accelerated corrosion testing of steel electrodes in alkaline media with different pH values and concentrations of chloride ions

↓

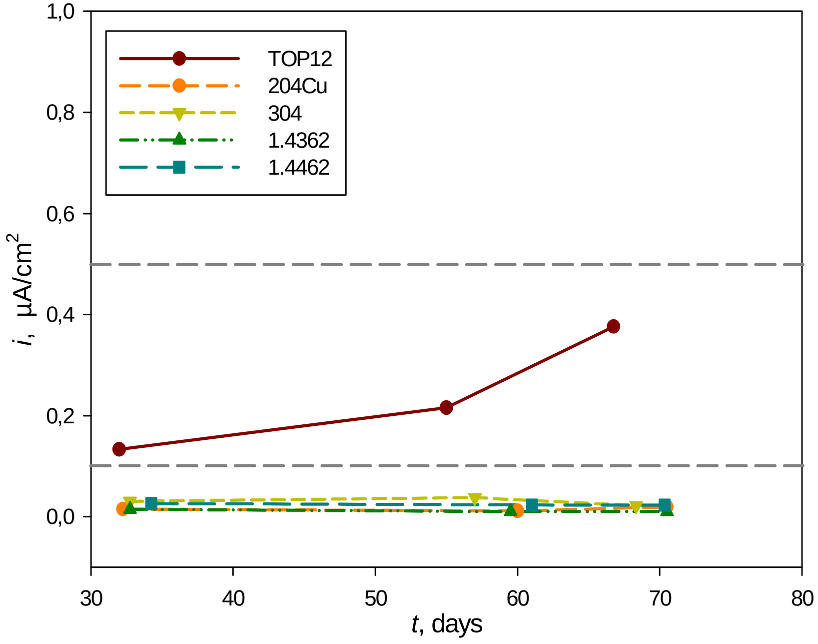
Accelerated corrosion testing of steel specimens embedded in concrete "lollipops"

Testing in concrete - type A

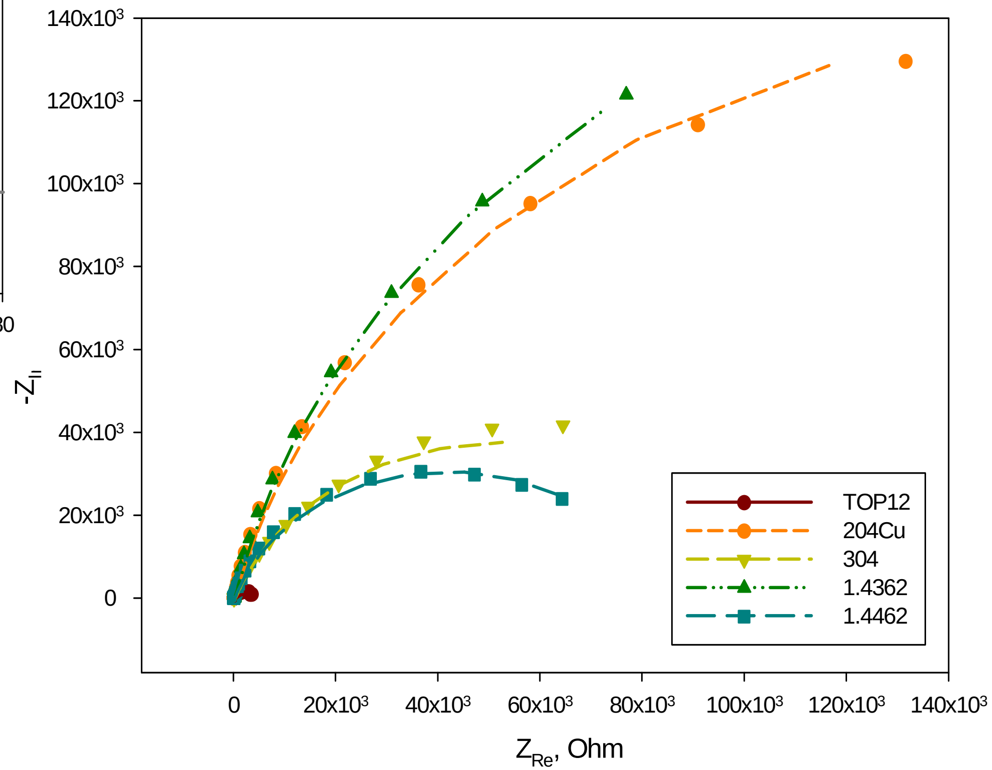
- Electrochemical testing on steel specimens in:
  - smaller concrete specimens (“lollipops”)
- Methods:
  - polarization resistance,
  - potentiostatic polarization,
  - electrochemical impedance spectroscopy.



Results



After 2 months



Experimental program

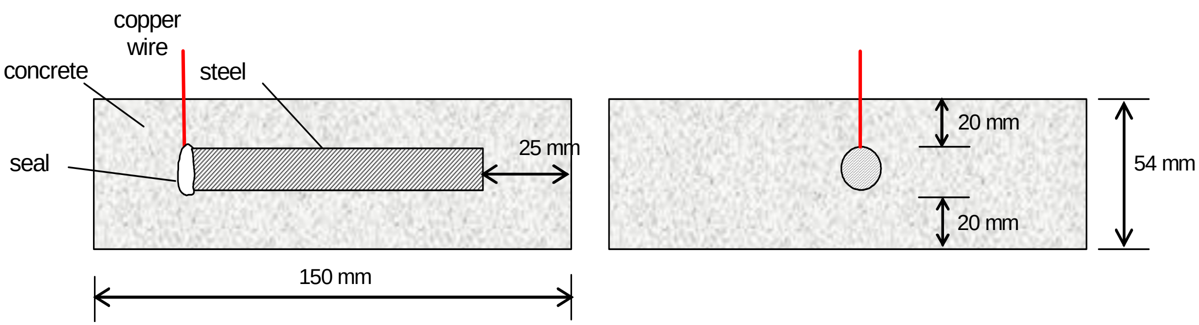
Accelerated corrosion testing of steel electrodes in alkaline media with different pH values and concentrations of chloride ions

Accelerated corrosion testing of steel specimens embedded in concrete "lollipops"

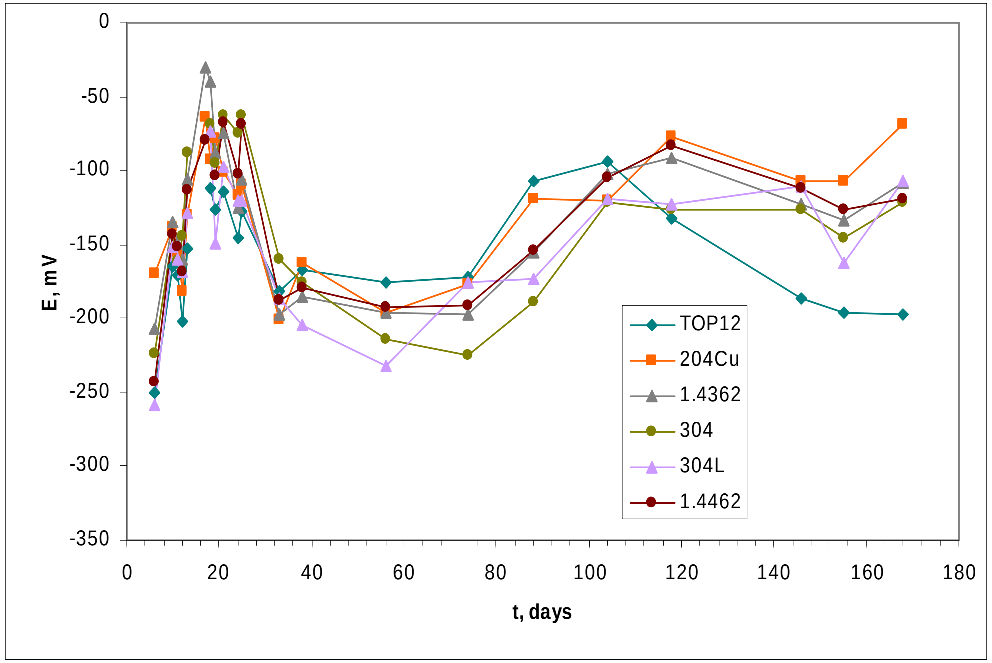
Testing of steel specimens embedded in concrete beams exposed to simulated aggressive marine environment (salt spray chamber or ponding)

Testing in concrete - type B

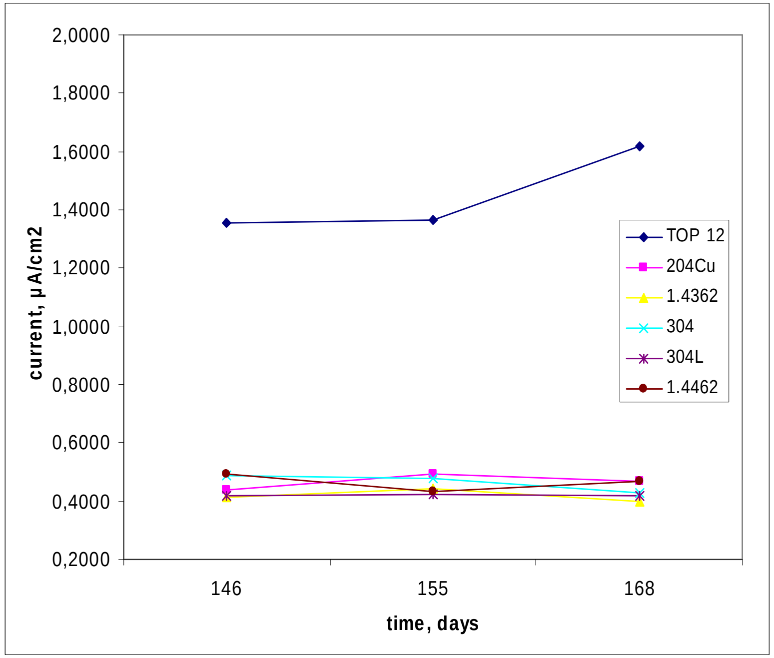
- Simulating aggressive marine environments in salt spray chamber
- Methods:
  - potential,
  - current.



Results



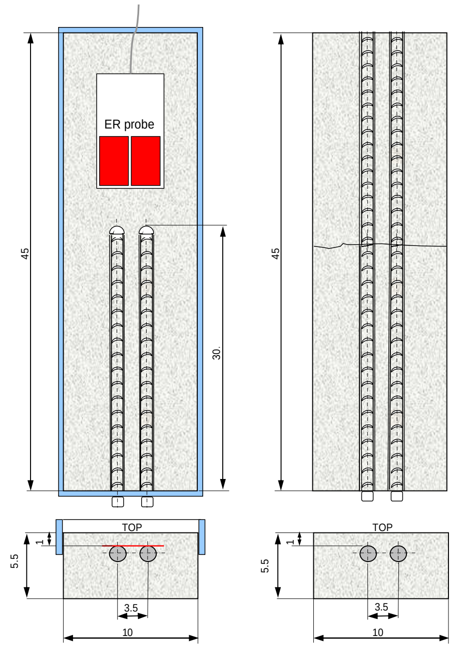
E, mV
0
-50
-100
-150
-200
-250
-300
-350
0
20
40
60
80
100
120
140
160
180
t, days
TOP12
204Cu
1.4362
304
304L
1.4462



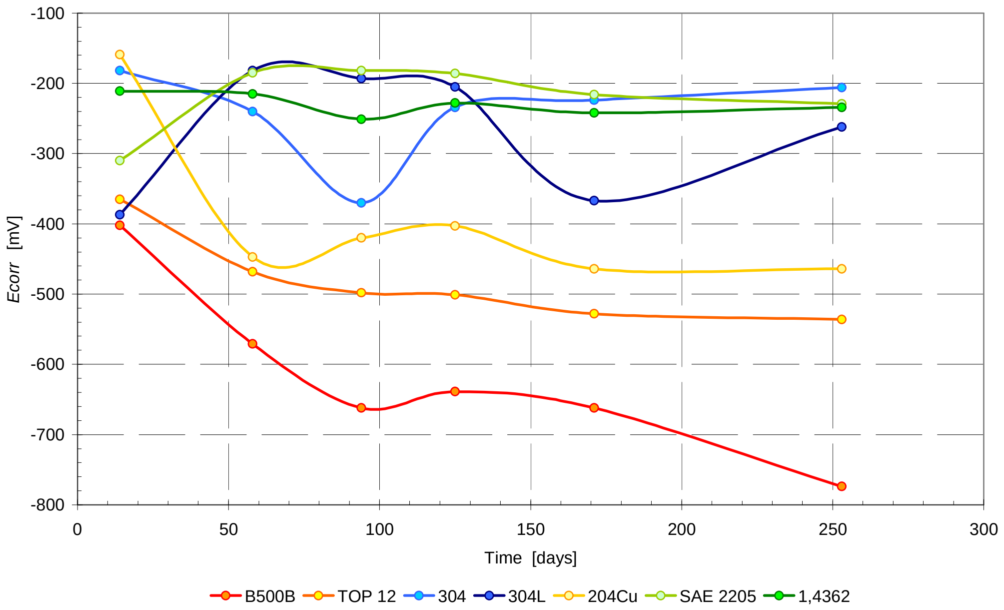
current, µA/cm2
2,0000
1,8000
1,6000
1,4000
1,2000
1,0000
0,8000
0,6000
0,4000
0,2000
146
155
168
time, days
TOP 12
204Cu
1.4362
304
304L
1.4462

Testing in concrete - type B

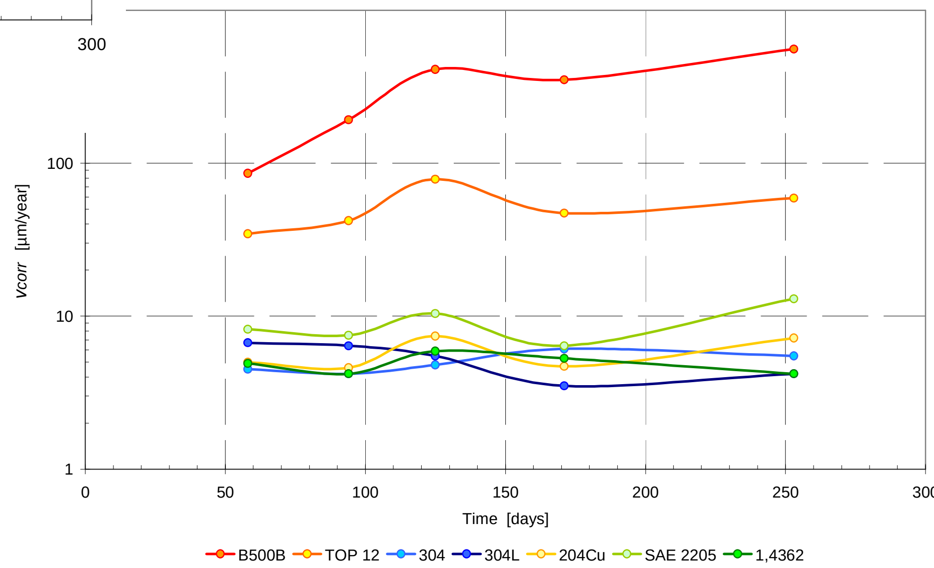
- Simulating aggressive marine environment by ponding with NaCl solution
- Measuring potential, current and resistivity



Results



Ecorr [mV]
-100
-200
-300
-400
-500
-600
-700
-800
0
50
100
150
200
250
300
Time [days]
B500B
TOP 12
304
304L
204Cu
SAE 2205
1,4362



Vcorr [µm/year]
100
10
1
0
50
100
150
200
250
300
Time [days]
B500B
TOP 12
304
304L
204Cu
SAE 2205
1,4362

Experimental program

Accelerated corrosion testing of steel electrodes in alkaline media with different pH values and concentrations of chloride ions

Accelerated corrosion testing of steel specimens embedded in concrete "lollipops"

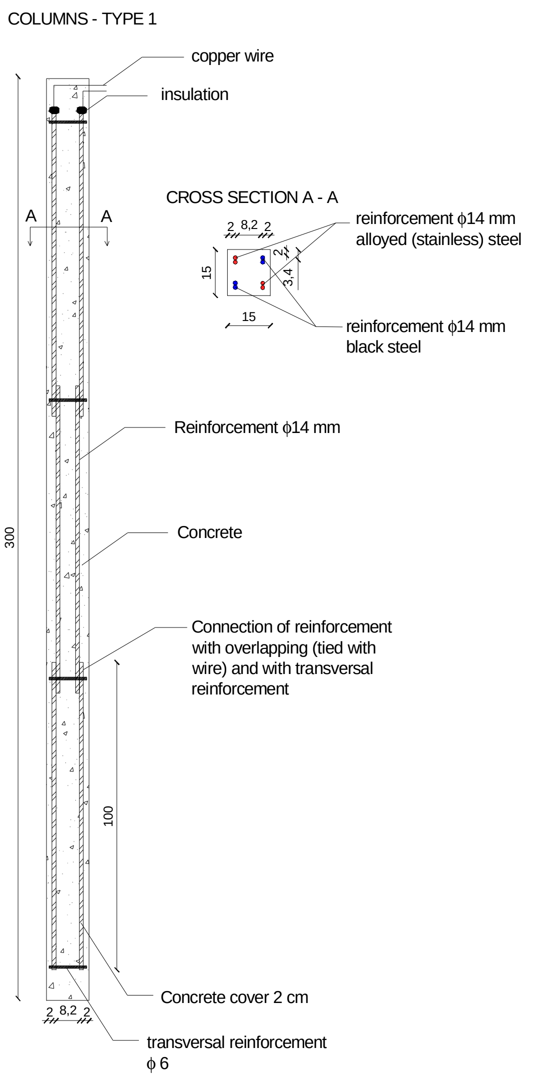
Testing of steel specimens embedded in concrete beams exposed to simulated aggressive marine environment (salt spray chamber or ponding)

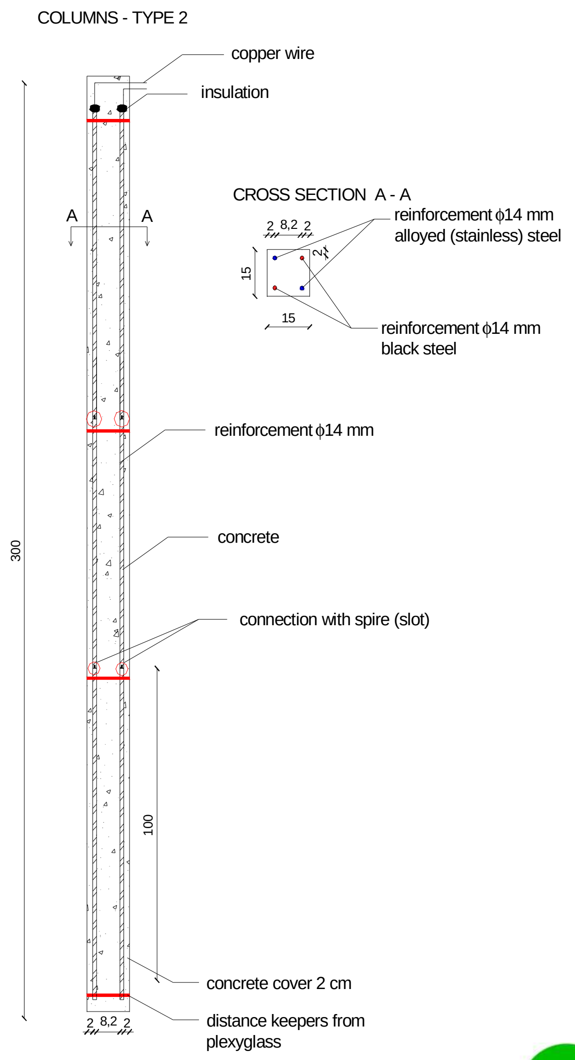
Testing of steel specimens embedded in concrete columns exposed to natural aggressive marine environment (field test)

Field testing

- Testing zone near Krk Bridge on Adriatic coast

Reinforced concrete columns





Testing zone

Project outcome

- Tailored application of corrosion resistant steel

Chlorides	***Carbonation***	***TOP12***	***204Cu***	***AISI 304***	***AISI 304L***	***SAE/UNS S3 2205***	***UGIGRIP 4362***
Low	***No*** ***Yes***	✓✓ ✗	✓✓ ✓✓	✓ ✓	✓ ✓	#	#
Moderate	***No*** ***Yes***	✗ ✗	✓ ✓	✓✓ ✓✓	✓✓ ✓✓	#	#
High	***No*** ***Yes***	✗ ✗	✗ ✗	✓ ✓	✓ ✓	✓✓ ✓✓	✓✓ ✓✓
Extreme	***No*** ***Yes***	✗ ✗	✗ ✗	✗ ✗	✗ ✗	✓✓ ✓✓	✓✓ ✓✓

✗ – not recommendable, ✓– recommendable, ✓✓ - very recommendable, # - unnecessary

Conclusion

- With smart and tailored application of corrosion resistant reinforcement service life of structures can be prolonged under acceptable price!

- Guidelines for choice of and designing with corrosion resistant steel are given in »Recommendations for the use of corrosion resistant steel reinforcement«

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Thank you for your attention!