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Consistent set of random variables for characterizing properties of 3 concrete types in chloride and carbonation environment

MRGenCi reports and Publications. Ref: MRGenCi-Rep-2016/1

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Since 2003, actions of MRGenCi, the non-profit french scientific network for Risk Management in Civil Engineering were motivated and devoted to respond to:

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Chloride ingress and carbonation are the most frequent phenomena that lead to Reinforced Concrete corrosion. The prediction of the evolution of these phenomena is hence of utter importance for inspection planning or structural health monitoring and maintenance planning. The use of predictive models is recommended for such an approach. However, the physical input parameters of these models are affected by uncertainties. These parameters depend on the simplified models themselves and the type of test used for their calibration (fitting ? estimation ?). This report aims at providing a unified definition and relationships between parameters and defining ***realistic range of variability*** both for models of chloride ingress and carbonation (a nomenclature of these parameters is available at the end of this report). In order to represent various existing concrete structures, three typical concrete mixes have been accounted for: they are referred as C25, C35 and C45. We consider here only CEM I cement type, because this is the most widely adopted for structural design in concrete. These concretes were studied within the ANR-EVADEOS project[1]. The information provided may help for benchmarking models, improving probabilistic approach (sensitivity analysis, reliability, meta-models setting, etc.) and for optimization of inspection and maintenance strategy.

[1] http://www-lmdc.insa-toulouse.fr/evadeos/accueilevadeos.htm

1. Description of the studied materials

The compositions of CEM I cement and mixes of these concretes are reported in Table 1 and Table 2 respectively. Useful contents of hydrates in cement paste and concrete properties are reported in Table 3, where it can be noted that average resistances comply with European standard [1]. As it can be seen in Table 4, cement compositions are similar for all concretes and mix proportions mainly cause the variation of material parameters. For instance, incorporating three classes of aggregate size with an efficient balance between the respective amounts, led to a good compactness of the C45 concrete, with a favorable effect on strength. But simultaneously the low water to cement ratio, w/c, prevented the content of hydrates to be high and the porosity remained rather elevated for C45, despite the use of a superplasticizer. An almost opposite situation prevails for the C35 concrete, where both porosity and strength are rather low. Finally the C25 concrete is an ordinary quality concrete.

Table 1 Cement composition (%)

Concrete	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
C45	20.1	5	3	64.1	1	3.2	0.72
C35	20.43	4.9	1.83	65.4	1.06	3.5	0.25
C25	20.29	5.56	2.32	64.22	2	3.17	0.57

Table 2 Concrete mixes (kg/m^3)

Concrete	Cement	Fly ash	Sand 0/4	Aggregates 4/12	Aggregates 12/20	Water	Superplasticizer	w/c
C45	350	80	900	320	630	177	3	0.51
C35	350	0	815	998	0	195	1.4	0.56
C25	295	0	989	792	0	200	0	0.68

Table 3 Main hydrated compounds contents (mol/l) and properties of concrete

Concrete	[AFm]	[AFt]	[CSH]	[CH]	SiO_2	Porosity (%)	Rc (MPa)
C45	0.41	0.25	3.16	3.11	0	11.8	58
C35	0.41	0.15	3.185	3.585	0	12.7	46.2
C25	0.34	0.25	2.879	2.9	0	14	40.2

2. Mean values and variability of input model parameters

Mean values and variability (coefficient of variation or/and min and max values) were obtained thanks to statistical treatment from samples when available, as well as on the basis of expertise, calculations and literature review.

Mean values and corresponding variability for the 3 concretes studied are reported in Table 4 and Table 5. More details are given in the next section for some parameters.

Table 4 Mean values and variability of each input parameter of simplified chloride ingress models

Parameter	Units	Mean	Coef. of var.	Min	Max	References
Cs-C45	% mass of cement	6,24	-	5,29	7,19	[2]
Cs -C35		8,76	-	8,37	9,17	
Cs -C25		10,01	-	9,52	10,49	
D_a -C45	10^{-12}m^2/s	2,99	0,136	1,95	2,57	Statistical treatment of data
D_a -C35		4,57	0,136	2,99	3,92	See next section
D_a-C25		4,79	0,133	6,15	8,04	
W_{gel}-C45	kg/m^3	205,19	-	198,62	211,76	See next section
W_{gel} -C35		208,56	-	201,88	215,23	
W_{gel} -C25		174,58	-	168,99	180,17	
w -C45	kg/m^3	118	0,05	112,1	123,9	See next section
w -C35		127	0,012	125,47	128,52	
w-C25		140	0,06	131,6	148,4	
k_c	-	0,656	0,26	0,48	0,82	[2]
k_t	-	0,832	0,029	0,80	0,85	[2]
k_e-C45,C35	-	1,325	0,17	1,09	1,55	[2]
k_e-C25	-	0,676	0,18	0,55	0,79	
n-C45	-	0,69	0,07	0,6417	0,7383	[2]
n-C35,C25	-	0,3	0,17	0,249	0,351	
D_{rcm}-C45	10^{-12}m^2/s	4,14	0,136	3,57	4,70	[2]
D_{rcm}-C35		6,33	0,136	5,47	7,19	
D_{rcm}-C25		13	0,133	11,27	14,73	
Parameter	**Units**	**Mean**	**Coef. of var.**	**Min**	**Max**	**References**
γ_{cl}	-	1,05	-	0,9	1,2	[3]
α_s	-	0,15	0,02	0,147	0,15	[4]
w/c-C45	-	0,51	0,027	0,50	0,52	[5]
w/c-C35		0,56	0,027	0,54	0,57	
w/c-C25		0,68	0,027	0,66	0,70	

Table 5 Mean values and variability of each input parameter of simplified concrete carbonation models

Parameter	Unit	Mean	Coef. of var.	Min	Max	Reference
γ	-	-	-	0,9	1,2	[6]
R_c-C45	MPa	58	0,06	54,52	61,48	Statistical treatment of data
R_c-C35		46,2	0,04	44,35	48,04	[7]
R_c-C25		40,2	0,03	38,99	41,40	
k_c	-	0,63	0,26	0,46	0,79	[2]
k_t	-	0,98	0,023	0,96	1,005	[2]
n	-	0,4	0,08	0,32	0,48	[2]
R_{carb}-C45	10^{10}kgCO2/m3/(m2/s)	2	0.075	1.9	2.1	[2]
R_{carb}-C35		0.4	0.089	0.36	0.43	
R_{carb}-C25		0.28	0.05	0.271	0.3	
ϕ -C45	-	0,118	5	0,112	0,124	Statistical treatment of data
ϕ -C35	-	0,127	1,6	0,124	0,129	[7]
ϕ –C25	-	0,14	8	0,129	0,151	
Parameter	**Unit**	**Mean**	**Coef. of var.**	**Min**	**Max**	**Reference**
c-C45	kg/m3	350	14	345	355	[5]
c-C35		350	13,6	345	355	
c-C25		295	16	290	300	
α-C45	-	0,81	3,9	0,778	0,842	[5]
α-C35	-	0,84	3,8	0,808	0,872	
α-C25	-	0,89	3,6	0,858	0,922	

3. Detail for some parameters

a) Apparent diffusion coefficient D_a

$$D_a = k_c k_t D_{rcm}$$

b) CSH gel content (W_{gel})

During hydration process, silicium oxide contained in calcium silicates of the cement contribute to form CSH[2]gel. Thus, the number of moles of silicium oxide that have participated to the reaction is equal to the number of moles of CSH.

$$CSH(t) = SiO_2(t) = \alpha(t) SiO_2$$

where $CSH(t)$ is the number of moles of CSH at the time t, $SiO_2(t)$ is the number of moles of silicium oxide that have reacted at the time t, $\alpha(t)$ the hydration degree at the time t and SiO_2 is the initialnumber of moles of silicium oxide in the cement. Knowing $CSH(t)$, the density of CSH could be assessed, given that its chemical formula for one mole of silicium oxide is: $CC/S-S-HH/S$. According to [8]: $H/S = C/S+0.8$. We choose the ratio C/S equal to 1.81 which is the mean observed by [9] in a CEMI based concrete, in a 20-year old structure. The variability is introduced through the hydration degree at the time *t*, the standard deviation of which was assessed thank to experimental data of hydration degree for various concretes [7].

c) Water content w

The water content is expressed as $w = \phi S_r \rho_w$ where ϕ is porosity, S_r the saturation degree and ρ_w the water density. *F*or simplified model of chloride ingress. tailored for saturated porous media S_r=1 and the variability of w is introduced through the porosity.

[2] In the field of cement based material C indicates CaO, S means SiO_2, and H the H_2O

4. Nomenclature

Cs – Chloride content at the exposed surface of the structure

D_a – Apparent diffusion coefficient of chloride into concrete

W_{gel} – Gel content into the concrete (CSH)

w - Water content into the concrete

k_c – Parameter taking into account the cure condition [2]

k_t – Parameter taking into account the transfer from accelerated test of diffusion to natural condition [2]

k_e – Parameter taking into account environmental conditions [2]

n - Ageing parameter [2]

D_{rcm} – Migration coefficient of chloride obtained from Rapid Migration Test [10].

γ_{cl} – Safety factor of the JSCE model [3]

α_s – ageing factor of the EuroLightCon model [4]

w/c –Water to cement ratio

γ- Safety factor of the Oxand carbonation model

R_c – Compressive strength of the concrete

R_{carb} – Resistance against carbonation of the concrete [2]

ϕ – Concrete porosity

c – Cement content

α – Hydration degree

5. References

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