WATER PERMEABILITY OF SELF COMPACTING CONCRETE

Konstantinos G. Trezos, Assistant Professor, School of Civil Eng., N.T.U.A., Greece
Ioannis P. Sfikas, MSc, PhD Candidate, School of Civil Eng. N.T.U.A., Greece
Dimosthenis I. Pavlou, Postgraduate Student, School of Civil Eng. N.T.U.A, Greece

ABSTRACT

Self Compacting Concrete (SCC) is considered as one of the most revolutionary innovations in the worldwide construction industry. Along with the studies that have been conducted concerning the fresh rheological properties of SCC (filling ability, passing ability, segregation resistance) and their benefits, there is a substantial need for exploring the behavior of SCC during curing time and in the early hardened state, and for examining how the durability of the material is affected compared to Normal Concrete (NC).

The proposed paper examines water permeability of SCC as an important step towards the definition of concrete durability. Three SCC mixtures and two NC mixtures have been produced and concrete specimens have been cured in two different ways (air curing, underwater curing). Water permeability has been evaluated by conducting permeability tests at various ages (7, 14, 28 and 56 days), evaluating the water flux into the concrete surface.

Flux decay as a function of time has been compared between different SCC mixtures in terms of the curve type and slope, as well as of the values at the beginning of the measurement and of final (asymptotic) values. The effects of different curing conditions and testing ages have been evaluated. Flux in SCC specimens of different mixtures has been compared to NC types.

Keywords: Self Compacting Concrete, Water Permeability, Durability

INTRODUCTION

SELF COMPACTING CONCRETE

Self-compacting concrete (SCC) is defined as a highly flowable, nonsegregating type of concrete that can spread into place, fill highly congested formwork and consolidate under its own weight without the need of any additional mechanical compaction, while maintaining homogeneity and stability[1,2]. Self-compacting concrete has been initially developed in Japan in the late 1980s, although other concrete types that required little mechanical consolidation were already being used over Europe since the early 1970s. During the 1990s, the use of the new type of concrete has been expanded over Europe and America, and in the last ten years SCC is also being used in construction retrofit.

Self-compacting concrete can be produced using constituent materials of the same origin but in different proportions compared to those in normal concrete[*]. Fillers (limestone, fly ash, silica fume, etc.) are often used to achieve smaller particle size distribution, together with admixtures that provide higher flowability (polycarboxylic ether superplasticizers) and better cohesion of the mixture (high-performance viscosity modifying agents). The increased productivity, achieved by the ease of flow in formwork with dense reinforcement and the rapid placement and construction rates, meets an improved working environment, in terms of fewer health and safety risks for the technical personnel. Those benefits, along with the stable and homogeneous nature of the mixture, the minimal concrete inner deficiencies and high quality final surfaces offer a highly enhanced total construction quality.

DURABILITY

A concrete structure can be considered as durable, when it can adequately perform above a minimum intended level of functionality and serviceability for a minimum predicted life cycle and for an expected level of potential deteriorative environmental conditions (mechanical, physical or chemical)[3]. Concrete durability is mainly related to the properties of the transport zone of the surface layer, in terms of its resistance to the penetration of aggressive agents (water, chloride, carbon dioxide, various acids) into the capillary pore microstructure that could initiate injurious attacking procedures both for the concrete and the reinforcement bars (corrosion, carbonation, frost, etc.).

Proper placing and curing of fresh concrete, diminished defects of the inner concrete structure and better surface quality are critical to ensure durable structures. Mechanical consolidation methods used in normal concrete placement are thought of as a discontinuous process, due to the lack of uniformity of the compaction energy and often result in low and uneven surface quality throughout the structure and thus to poor overall durability performance. On the other hand, the finer porosity and better microstructure of SCC is expected to lead to a more homogeneous surface layer (fewer weak points) that would provide higher protection against attack of aggressive agents and low permeability.

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[*] In the current study, Normal Concrete (NC) is referred to as concrete that does not meet the definition of SCC.

WATER PERMEABILITY

Permeability is defined as the ability of the transition zone of the surface layer to transport fluids or gases to the inner microstructure of concrete. The heterogeneous nature of concrete results in a porous network that allows movement of the aggressive agents by flow, diffusion or sorption. The combination of all three ways of ingress is referred to as permeability.

Considering the fact that water, which is the most important fluid in nature, has the ability to dissolve a great amount of substances and to easily penetrate into small pores or cracks, water permeability of concrete is thought to be essential for the preservation of inner quality of the structure[4]. While the presence of water during the cement hydration in fresh concrete is highly important for the proper hardening and compressive strength development, at later ages and after the cease of hydration reactions it may cause critical deterioration of the concrete and reinforcements. Likewise, the above stated ability of transporting aggressive agents into the inner concrete microstructure can propagate a series of harmful chemical reactions that could lead to serious degradation of the structure quality.

PAPER PURPOSE

In this paper, three SCC mixtures have been cured under two different environmental conditions (air curing, underwater curing) and have been tested at various ages (7, 14, 28 and 56 days) to derive useful conclusions concerning the water permeability behavior of SCC.

EXPERIMENTAL PROPERTIES

MATERIALS AND SCC MIXTURES

Three different mixtures of SCC (SCC-1, SCC-2, SCC-3) and two mixtures of normal concrete (NC-1, NC-2) have been produced in the laboratory. The constituent materials and compressive strengths are shown on **Table 1** and the results of fresh SCC rheology tests are presented on **Table 2**.

Table 1. SCC and NC Mixtures Proportions, Critical Ratios and Compressive Strenghts

	Cem. Mat.(cm)		Aggregates				Water	Admixtures		Mixture critical ratios				Comp. Strength
	C	F	S	G1	G2	G3	W	SP	VMA	W/ cm	G/ Btot	P/ Btot	M/ Btot	fcc
	kg	kg	kg	kg	kg	kg	kg	%	%	%	%	%	%	MPa
SCC-1	333	48	1043	284	380	0	193	1.01	0.39	38	29	31	77	44.4
SCC-2	345	0	1202	320	295	0	194	1.29	0.34	39	26	30	80	38.9
SCC-3	390	0	1140	316	292	0	211	1.17	0.51	40	25	32	80	42.1
NC-1	230	0	575	---570---		855	180	0.00	0.00	78	24	17	41	18.9
NC-2	265	0	580	---555---		830	180	0.00	0.00	68	23	18	43	32.8

C: cement CEM II A/L 42.5, F: limestone filler, S: sand 0/4, G1: gravel 4/8, G2: gravel 8/16, G3: gravel 16/32, SP: polycarboxylic ether superplasticizer, VMA: high-performance viscosity modifying agent, Btot: Total mixture weight per m^3, G: total gravel, P: paste (cm+admixtures+water), M: mortar (paste+sand)

Table 2. SCC Rheology Tests Results

	Slump-Flow					J-Ring		V-Funnel		L-Box		U-Box	
	S mm	SF mm	T_{50} s	TF s	VSI -	SF_J mm	Δh_J mm	$T_{V,A}$ s	$T_{V,B}$ s	$T_{L,20}$ s	$T_{L,40}$ s	$\lambda_{H,L}$ %	ΔH_U mm
SCC-1	275	700	2.70	19.2	0	670	11	8.19	14.59	0.49	1.06	95	18
SCC-2	265	650	1.68	17.7	0	600	15	6.94	9.09	0.80	1.28	95	20
SCC-3	270	645	3.02	26.0	0	655	10	4.78	5.15	0.97	1.69	94	5

TESTING EQUIPMENT

The experimental part of the study has been conducted with GWT-4000 of Germann Instruments A/S. The testing equipment, which can be easily used both in the laboratory and on site, is designed and used for testing of microcracking and porosity of the concrete surface layer ("skin-concrete").

Figure 1 shows the parts of the testing equipment. A pressure chamber containing a watertight gasket is secured tightly to the surface of the standard concrete cube of 150mm by two anchored clamping pliers. The chamber is filled with deionized water and the filling valve is closed. The top cap of the chamber is turned until the desired initial water pressure of 120kPa is displayed on the gauge and the pressure drop is recorded over time.

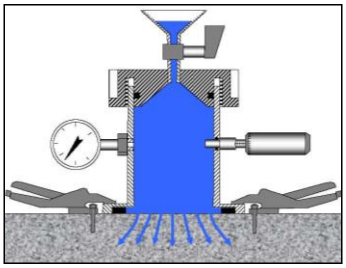


Figure 1. GWT-4000 Testing Equipment

The testing equipment can be used to maintain the selected pressure by means of the lateral micrometer gauge pushing a piston into the chamber. Piston movement compensates for the volume of water penetrating into the material. A relation between piston movement Δg [mm] and the pressure drop ΔP [kPa] has been estimated as follows:

$$\Delta g = 0.1135 \Delta P \tag{1}$$

Given the pressure drop we can estimate the proportional piston movement and thus calculate the flux of penetrating water. According to the Instructions Manual[5], the flux q [mm/s] of water penetrating the concrete surface (no water visible on the surface during testing) for given water pressure may be calculated as the difference in micrometer readings Δg [mm] for a given testing time Δt [s]:

$$q = \frac{B}{A} \cdot \frac{\Delta g}{\Delta t} = \frac{78.6}{3018} \cdot \frac{\Delta g}{\Delta t} = 0.026 \frac{\Delta g}{\Delta t} \tag{2}$$

where A: the water pressure surface area (gasket inner diameter 62mm)
B: the area of the micrometer pin being pressed into the chamber (diameter 10mm)

The results obtained represent a combination of the influence of three factors, i) surface porosity, ii) water permeability and iii) absorption. Thus, we assume that the estimated flux is a reliable indication for the permeability of concrete surface. The non-constant flux does not allow the use of Darcy's law for the exact estimation of the permeability coefficient. Still we consider that the flux is proportional to the permeability coefficient.

THEORETICAL STUDY

The pressure drop was recorded as a function of time. The flux q_i has been calculated using the above equations (1) and (2). Using the method of least squares, we identified the relationship between q_i and t_i as a power-law distribution:

$$q = a \cdot t^{-b} \tag{3}$$

where a and b constant values that affect the scale and the slope of the curve.

We assume that the flux is stabilized at the point where the derivative of the power curve equals -10^{-8} mm/s (negative sign represents the negative value of slope decay). The area below the curve can be calculated as the integral of the power-law distribution (see Eq.3) using the above stabilization time point t_{st} [s] as the upper limit of integration:

$$E = \int_{t_0=1\sec}^{t_{st}} \left(at^{-b}\right) dt = \frac{a}{1-b} \int_{t_0=1\sec}^{t_{st}} t^{1-b} dt = \frac{a}{1-b} \cdot \left(t_{st}^{1-b} - 1^{1-b}\right), \text{ where } \; t_{st} = \left[\frac{-10^{-8}}{-ab}\right]^{\frac{1}{-b-1}} \tag{4}$$

The mean value of flux can be calculated as:

$$q_m = E/t_{st} \tag{5}$$

Using non-linear regression analysis, the mean values of flux for each different mixture (SCC-1, SCC-2, SCC-3, NC-1 and NC-2) have been correlated with the age of testing T (7, 14, 28 and 56 days) separately for the different curing conditions (AC: air curing, UW: underwater curing). The used model function is:

$$q_m = c_1 + c_2 e^{-c_3 T} \tag{6}$$

where c_1: asymptotic mean flux value (constant value)
c_2: constant which designates the initial mean flux value, as well as the upward (positive) or downward (negative) direction of the fitted curve slope
c_3: constant which designates the slope of the fitted curve

The assumptions that were taken into account concerned the boundary conditions:

- T=0, q_m=0: fresh concrete, no capillary pore structure, zero flux
- T=∞, q_m=c_1: hardened concrete, capillary pore final structure, constant flux

EXPERIMENTAL RESULTS

FLUX DECAY OVER TIME

For each different mixture (SCC-1, SCC-2, SCC-3) under different curing conditions (AC: air curing, UW: underwater curing) and for every different testing age T (7, 14, 28 and 28 days) a discrete power curve has been estimated (see Eq.3). Most of the resultant curves have rather high R-squared values ($R_m^2 \approx 0.86$). The estimated values of power curve constants a and b are shown on **Table 3** and the resultant power curves are presented and compared on the charts that follow.

Table 3. Estimated values of power curve constants a and b for each mixture (SCC-1, SCC-2, SCC-3) at various testing ages T (7, 14, 28, 56 days) for different curing conditions (AC, UW)

Curing Method	Testing Age T	SCC-1			SCC-2			SCC-3		
		a	b	R^2	a	b	R^2	a	b	R^2
Air Curing	7	0.0028	0.6340	0.7222	0.0087	0.7962	0.9294	0.0071	0.8530	0.8890
	14	0.0085	0.7300	0.9163	0.0118	0.8064	0.9401	0.0080	0.7400	0.9473
	28	0.0175	0.8224	0.9712	0.0097	0.7154	0.9760	0.0184	0.8607	0.9459
	56	0.0317	0.9162	0.9814	0.0192	0.8081	0.9747	0.0281	0.8780	0.9685
Underwater Curing	7	0.0035	0.6477	0.5881	0.0293	0.9585	0.9225	0.0037	0.6316	0.9387
	14	0.0007	0.7786	0.8672	0.0048	0.7699	0.8696	0.0025	0.9057	0.8269
	28	0.0007	0.3317	0.4330	0.0038	0.8106	0.8667	0.0012	0.5831	0.8696
	56	0.0010	0.6606	0.7136	0.0086	0.9260	0.8909	0.0009	0.8615	0.6832

In the following **Charts 1a, b** flux decay for the mean curves of all three SCC mixtures is compared by testing age T separately for the different curing conditions (AC, UW)

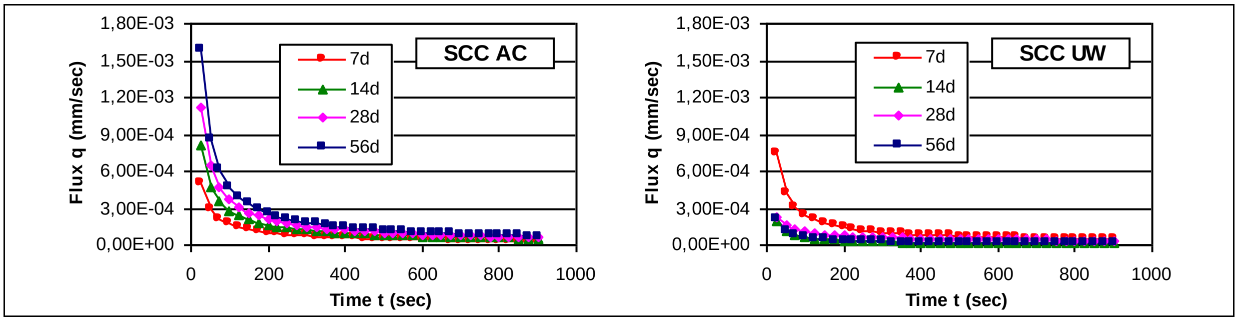


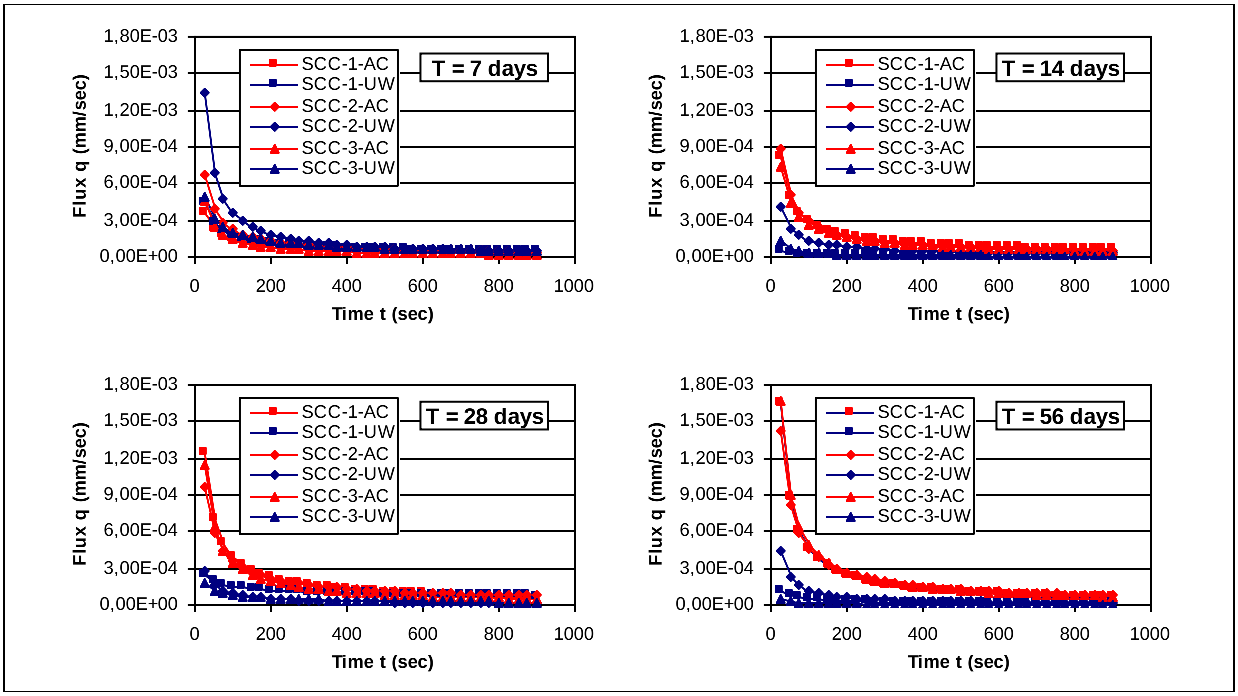
Chart 1a, 1b. Flux decay for the mean curves of all SCC mixtures under different curing conditions (AC, UW).

Studying the above charts, we observe the following:

- Flux at the beginning of the measurement (t=1s): For AC specimens the flux at the beginning of the measurement is higher for later testing ages T. These values vary between 5×10^{-4} mm/s (lower values at T=7 days) and 16×10^{-4} mm/s (higher values at T=56 days). On the other hand, UW curing results in higher flux at the beginning of the measurement at the testing age T=7 days. These values vary between 2×10^{-4} mm/s (lower values at T>14 days) and 8×10^{-4} mm/s (higher values at T=7 days). Compared to respective results for AC specimens, the flux at the beginning of the measurement is about 70-75% less (SCC-2, T=7 days value excluded).

- Asymptotic flux values: The asymptotic value of flux is about 1×10^{-4} mm/s independently of curing conditions, testing age or mixture.
- Flux decay as a function of time: for a given time t the corresponding flux value is lower for a higher testing age T.
- Generally, flux of underwater cured specimens is higher at the age of T=7 days and it is reduced and stabilized at later testing ages (T≥14 days)
- Mean flux values: Mean values of flux for air cured specimens are higher than for specimens cured underwater.

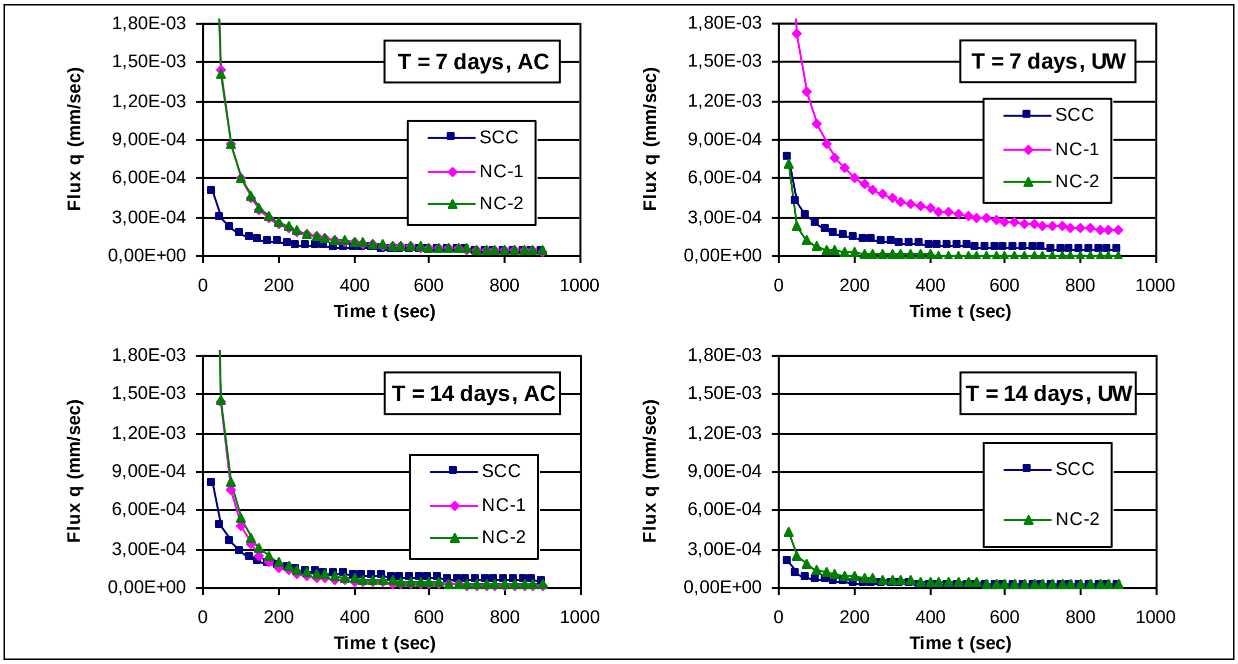
In the following **Charts 2a-2d** flux decays for all three mixtures of SCC (SCC-1, SCC-2, SCC-3) are compared as a function of curing conditions (AC, UW) separately at each different testing age T (7, 14, 28 and 56 days).



Charts 2a-2d. Flux decay for all three mixtures of SCC (SCC-1, SCC-2, SCC-3) as a function of curing conditions (AC, UW) at different testing ages T (7, 14, 28, 56 days).

As commented on previous charts, flux is lower for underwater cured specimens compared to air cured specimens. This conclusion is more clear as testing age increases and it does not apply for T=7 days, where a confused situation is confronted. This confusion is due to the development of the inner structure of concrete, which is more intense at early ages.

Finally, in the following **Charts 3a-3d** flux decay is compared by concrete type (SCC, NC-1, NC-2), for two different testing ages T (7 or 14 days) and different curing conditions (AC, UW).



Charts 3a-3b. Flux decay by concrete type (SCC, NC-1, NC-2), at different testing ages T (7 or 14 days) and for different curing conditions (AC, UW).

Studying the previous charts, the following observations can be made:

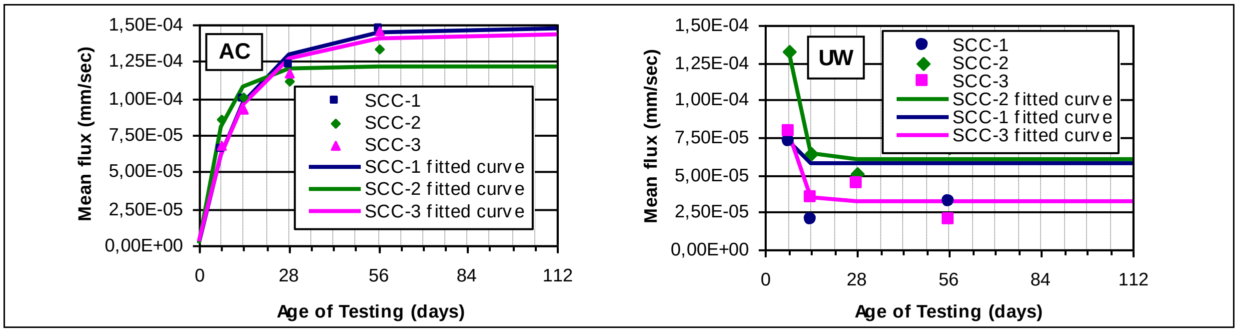
- The flux at the beginning of the measurement of air cured SCC specimens is significantly lower than the flux of NC specimens, regardless of compressive strength at both testing ages (7 or 14 days). As far as underwater cured SCC specimens are concerned, the starting flux is same with NC-2, but significantly lower than NC-1 for T=7 days, while the flux at the beginning of the measurement at T=14 days is bare lower for SCC than NC-2.
- Despite the difference of the flux at the beginning of the measurement, flux values for both SCC and NC mixes seem to converge quickly at the testing age of 14 days for both curing methods. The same conclusion applies at testing age T=7 days for air cured concrete, while on the other hand underwater cured NC-1 follows a slightly higher flux curve.

FLUX DECAY OVER AGE

The values of the parameters c_1, c_2 and c_3 calculated with non-linear regression analysis for the assumed model curve of mean flux q_m as a function of testing age T (see Eq.6) are shown on **Table 4** and presented on **Charts 4a, 4b**.

Table 4. Parameters of non-linear equation of mean flux as a function of the testing age T

	Air Curing Method (AC)				Underwater Curing Method (UW)			
	$c_1 \times 10^{-4}$ mm/s	$c_2 \times 10^{-4}$ mm/s	$c_3 \times 10^{-1}$ s^{-1}	R^2 -	$c_1 \times 10^{-4}$ mm/s	$c_2 \times 10^{-4}$ mm/s	$c_3 \times 10^{-1}$ s^{-1}	R^2 -
SCC-1	1.47	-1.45	0.76	0.989	0.58	20.0	15.3	0.702
SCC-2	1.22	-1.21	1.51	0.973	0.60	13.8	4.20	0.962
SCC-3	1.43	-1.40	0.77	0.986	0.32	9.86	4.37	0.837
NC-1	15.0	-1.52	0.95	0.395	0.49	6.37	1.36	0.985
NC-2	8.80	-9.07	2.20	0.519	0.48	9.21	2.91	0.840

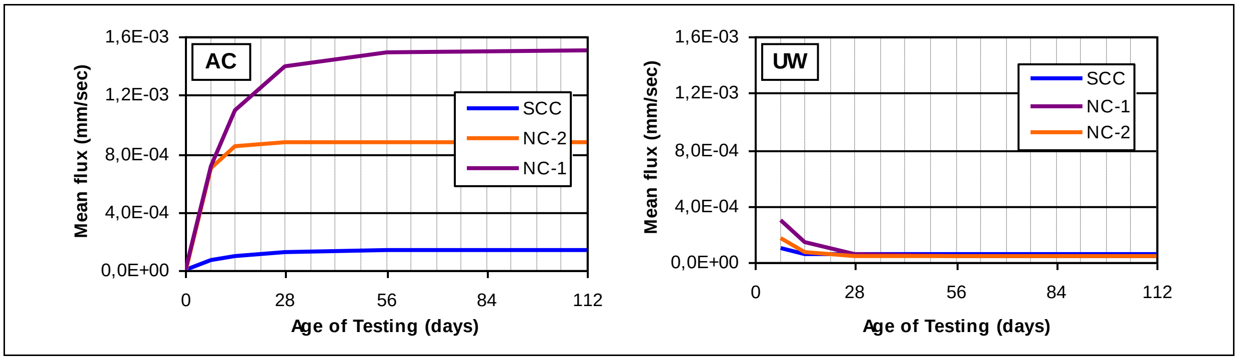


Charts 4a, 4b. Non-linear regression model curves for mean flux as a function of testing age T of SCC mixtures (SCC-1, SCC-2, SCC-3) under different curing conditions (AC, UW)

Studying the previous charts, the following observations can be made:

- The mean flux for air cured specimens increases with testing age and it seems to reach a higher asymptotic value at later ages. This phenomenon depends on the curing conditions (temperature, humidity, etc) and on the evaporation velocity of surface bound water (and the contemporary capillary pore structure development). The asymptotic value is less than 1.50×10^{-4} mm/s for SCC-1 and SCC-3, and about 1.25×10^{-4} mm/s for SCC-2. Most R-squared values are exceptionally high.
- The mean flux for underwater cured specimens is decreasing with testing age and it seems to reach a lower asymptotic value at an earlier age compared to air cured specimens. This value is about 0.3 to 0.6×10^{-4} mm/s for the various mixtures.

In the following **Charts 5a, 5b**, the mean flux for all SCC specimens as a function of testing age T (7, 14, 28, 56 days) is being compared with the corresponding curves for NC specimens under different curing conditions (AC, UW).



Charts 5a, 5b. Non-linear regression model curves for mean flux as a function at testing age T of all mixtures (SCC, NC-1, NC-2) under different curing conditions (AC, UW)

Studying the above charts, we observe that:

- The asymptotic value of mean flux is ten times lower than NC-1 and less than 50% of mean flux for NC-2 for air cured specimens. For underwater curing conditions the asymptotic value of flux is being reached earlier in SCC than NC-1 or NC-2.

CONCLUSIONS

- The flux at the beginning of the measurement of SCC air cured specimens is higher for later testing ages, while the corresponding flux for underwater cured specimens is higher for earlier testing ages. The above flux value of UW cured specimens is about 70-75% lower than AC cured specimens. The flux at the beginning of the measurement of air cured SCC specimens is significantly lower than normal concrete, regardless of the compressive strength for both testing ages (7 or 14 days). As far as underwater cured SCC specimens are concerned, the flux at the beginning of the measurement is same as for NC-2, but significantly lower than NC-1 for T=7 days, while the corresponding flux value at T=14 days is bare lower for SCC than NC-2.
- The asymptotic value of flux is about 1×10^{-4} mm/s independently of curing conditions (AC, UW), testing age (7, 14, 28, 56 days) or SCC mixture.
- Flux decay as a function of time for air cured specimens reduces for later testing ages, while in the case of underwater curing the relation between flux decay and testing age is not explicit. Generally, flux of underwater cured specimens is higher at the age of T=7 days and it is reduced and stabilized at later testing ages (T≥14 days). A confused situation is usually confronted at T=7 days due to the development of the inner structure of concrete, which is more intense at earlier ages. The same conclusion applies for the testing age T=7 days for air cured concrete, while on the other hand underwater cured NC-1follows a slightly higher flux curve.
- Mean values of flux for air cured specimens are higher than the mean flux values for underwater curing. The flux in underwater cured specimens is faster fixed on its final value. The mean flux for air cured specimens is increasing with testing age and it seems to reach a higher asymptotic value at later ages, while the mean flux for underwater cured specimens decreases with testing age and seems to reach a lower asymptotic value at an earlier age compared to air cured specimens. The flux is sensitive to curing conditions (temperature, humidity, etc) and the evaporation velocity of surface bound water (and the parallel capillary pore structure development). In underwater curing, the uninterrupted hydration procedure enhances the stability of the corresponding specimens.

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