# Effect of curing treatments on the material properties of hardened self-compacting concrete

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**Abstract.** This paper presents a study of the properties and behavior of self-compacting concretes (SCC) in the hot climate. The effect of curing environment and the initial water curing period on the properties and behavior of SCC such as compressive strength, ultrasonic pulse velocity (UPV) and sorptivity of the SCC specimens were investigated. Three Water/Binder (W/B) ratios (0.32, 0.38 and 0.44) have been used to obtain three ranges of compressive strength. Five curing methods have been applied on the SCC by varying the duration and the conservation condition of SCC. The results obtained on the compressive strength show that the period of initial water curing methods. The coefficient of sorptivity is influenced by W/B ratio and the curing methods. It is also shown that the sorptivity coefficient of SCC specimens is very sensitive to the curing condition. The SCC specimens cured in water present a low coefficient of sorptivity regardless of the ratio W/B. Furthermore, the results show that there is a good correlation between ultrasonic pulse velocity and the compressive strength.

**Keywords:** self-compacting concretes; initial curing period; compressive strength; sorptivity; ultrasonic pulse velocity

# 1. Introduction

The self-compacting concrete (SCC), one of the recent developments in the technology of the concrete, has shown advantages compared to ordinary concrete. In possessing a great fluidity and sufficient resistance to segregation, the SCC can be poured into place without the need for mechanical compaction, which gives economic benefits, eliminates and maintains or improves concrete durability and appearance. In recent years, there has been immense in the use of SCC (Dehwah 2012, Uysal and Yilmaz 2011, Şahmaran *et al.* 2006, Liu 2010, Leemann *et al.* 2010,

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Kou and Poon 2009).

The first studies on the SCC were mainly aimed to develop formulations that could meet the fluidity requirements. Since then many works that meet the. Many works have been devoted to the study of appropriate formulations to SCC. The compositions from the literature (Sedran 1999, Sonebi and Barto 1999, Bouzoubaa and Lachemi 2001, Bosiljkov 2003, Shen et al. 2009) underline that the SCC contains a volume of fine more important than the ordinary concretes, and incorporate the admixture such as the superplasticizer and sometimes a viscosity agent, the volume of paste in the SCC is higher in the ordinary concrete, the maximum size of the aggregates is limited to 20 mm. Most studies were conducted to investigate the properties of selfcompacting concrete in the fresh state. However, the structures designers' main interest is the properties of SCC in the hardened state, as same as the resistance to compression, the modulus of elasticity, the shrinkage and creep (Domone 2007). One of the differences between the ordinary concrete and self-compacting concrete is the paste volume which is important in the SCC, this requires the use of an important quantity of cement, and it is necessary to use the mineral additions for reducing the cost. (Uysal and yilmaz 2011). Bingöl and Tohumcu (2013) have indicated that the increase in the volume of the silica fume causes an increase of the compressive strength while the increase in the volume of fly ash affects the compressive strength. The tests of concretes in the fresh and hardened state show that it can manufacture SCC by using fly ash and silica fume with acceptable properties. The obtained results on the specimens immersed in water provide higher compressive strength. However, the result on the SCC cured in air shows a decrease in the compressive strength. In the case of a hardening with a temperature of  $70^{\circ}$ C during 16 hours, the SCC, containing a high content of fly ash, can develop importantly compressive strength. Other researchers (Zhao et al. 2012, Bonavetti et al. 2000) have shown that the development of the compressive strength and bending of the SCC depends on the curing methods. Duration of initial cure of 7 days allows to increase compressive strength quickly. Reinhardt and Stegmaier (2006) have stated that the thermal treatment of SCC influences on the size of the pores and the distribution of pore sizes. According to the work of Shirley (1980), during warm periods and particularly during the hardening of cement, thermal variation causes severe constraints in the concrete. The water evaporation rate increases considerably. For example, increasing of temperature from 10°C to 20°C can cause a leads to tow time water evaporation rate in the SCC. A decrease of the relative humidity from 90% to 50%, without change of any other conditions, will increase significantly water evaporation rate of the exposed surfaces (Shirley 1980). The air movement rate is probably the factor that can create more problems during concreting in hot climate.

Le (2014) indicates that it is possible to retain the properties of the SCC at the end of mixing when the initial temperature of the mixture from 20°C to 50°C. Moreover, the elevation of the initial temperature of the concrete from 20°C to 50°C improves its compressive strength.

The maturation of fresh self-compacting concrete is commonly admitted as being the critical parameter responsible for the proper development of the material properties. In high temperature conditions, the cement paste undergoes physical and chemical that can significantly affect the mechanical properties and the sustainability of concrete structures.

Many studies have been conducted to clarify the influence of the period of initial cure by hot condition on the various mechanisms involved during the hydration of the concretes.

Some researchers (Shirley 1980, Rojas *et al.* 2012, Ling and Teo 2011) evaluated the effect of hot weather conditions on the properties of SCC. They have shown that the SCC retained in water develop better mechanical strength compaired to the SCC retained for 3, 7 and 14 days in water

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and then exposed to hot climate. However, Zhao *et al.* (2012) have found that the curing period of seven days in water to follow a ripening in warm climate develop a better mechanical resistance.

In literature, the effects of the curing methods on the evolution of the properties of SCC still a controversial issue. The present study is interested in analyzing the effects of the curing methods on the properties and behavior of the SCC in the fresh and hardened state.

In this study, five different curing regimes were applied to investigate the effect of both the curing environment and initial water curing period on the properties of SCC. The properties of SCC under different initial water-curing periods, the compressive strength, the ultrasonic pulse velocity, the test of sorptivity of SCC, were investigated. Based on these test results, the relationship between compressive strength and curing time was analyzed and also the relationship between compressive strength and sorptivity at 28-days and 90 days of SCC under different initial water-curing periods.

# 2. Materials and method

#### 2.1 Materials

In this study, the SCC was made using the cement compound (CEM II A 42.5). The chemical composition and physical properties of the cement are presented in Table 1. The fine aggregate was of 0-3 mm, its sand equivalent equals to 80. The coarse aggregate was granular class 8/15 mm. The admixture used in this study was a superplasticizer with a density of 1.06, a content of chloride ions less than 0.1% and dry extracts between 28 and 31%. The dosage can vary from 0.2 to 3% according to the fluidity and the desired performance.

## 2.2 Environmental conditions

Hot weather is characterized by high temperatures, low humidity and high solar radiation. The temperature in Chlef a town located in North-West of Algeria often rises to 50°C in inland and even more than the coastal areas during June, July and August being the hottest months of the year (Fig. 1(a)).

Constituent	Weight (%)
SiO <sub>2</sub>	18.25
$Al_2O_3$	4.48
$Fe_2O_3$	3.28
CaO	62.38
MgO	0.94
CaO <sub>free</sub>	0.70
$SO_3$	2.00
Loss on ignition	7.38
$C_2S$	18.68
$C_3S$	58.20
C <sub>3</sub> A	7.55
C <sub>4</sub> AF	11.43

Table 1 Chemical and mineralogical analysis of cement



Fig. 1 Environment of Chlef town (a) Temperature variation and (b) Relative humidity

The often maximum temperature in summer can be as high as 45 °C while the main minimum one ranges from 12 to 20 °C. When this high ambient temperature is combined with about 11 hours of direct sunshine, it is understandable that the surface temperature of concrete and formwork can be much higher. Furthermore, a variation in the ambient temperature (the difference between the Max and Min temperature) of up to 25 °C can occur within 24 hours leading to severe thermal stresses in concrete, especially at early age.

Berhane (1992) retained that there are three groups of warm climates based on the relative humidity (RH) of the regions concerned. In Algeria, two zones are recognized, the North and South (Sahara), However, this study was carried out in Chlef region, which is classified in the second category of the classification according to Berhane (1992).

ACI 305R-10 explains hot weather, hot weather conditions, its negative effects on fresh and hardened concrete properties, testing and required precautions (materials choice, design, pouring and curing applications, etc.) (ACI 305R 2010). It can be said that placing, finishing, and curing concrete require extra care in hot weather. When temperatures rise above 80°F (approximately 27°C degrees), fast setting, lower strengths, and cracking are all more likely. However, these

problems can be avoided by recognizing the causes and minimizing hot weather effects (ACI 305R 2010).

In this manner, the hot weather concreting or the concrete types resistant to hot weather conditions (or less negative affected) will greatly benefit the long-term durability and safety of civil infrastructure for Mediterranean Region (Algeria, Southern France or Southern Turkey, etc.). Therefore, SCC exposed to different curing (wet curing for some period and after then hot climate or only the hot climate) conditions has been investigated in this study.

# 2.3 Method

#### 2.3.1 Mixture proportions

Three self-compacting concrete have been used in this research, with the W/B (water to binder) ratios of 0.32, 0.38 and 0.44. The compositions of the SCC adopted in this study were estimated by using Japanese method (Okamura and Ouchi 2003). The coarse aggregate was limited to 15 mm, the Coarse Aggregates/Fine Aggregates (CA/FA) ratio was approximately 1, the content of the binder was between 527 and 624 kg/m<sup>3</sup> following the W/B ratio. The total quantity of aggregates varies from 1414 to 1427 kg/m<sup>3</sup>.The quantity of superplasticizer was used to improve the workability of the mix. The SCC mix proportions are shown in Table 2.

	Table 2	Comp	osition	of SCC	2
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Materials (kg/m <sup>3</sup> )	SCC32	SCC38	SCC44
W/B	0.32	0.38	0.44
Cement (C)	624.4	572,2	527,8
Fine Aggregates	757.7	722.2	694,5
Coarse Aggregates	770.0	700.0	722.2
Water	199.8	215.7	232.2
Superplasticizer	14.2	7.8	5.0

## 2.3.2 Preparation of specimens

 $10 \times 10 \times 10$  cm<sup>3</sup> cubic molds were used for the determination of compressive strength, ultrasonic pulse velocity (UPV) and the sorptivity. In total, 153 specimens were prepared (Table 3).

After mixing, slump flow test,  $T_{500}$  test, V-funnel test, L-Box, J-Ring test and sieve stability were conducted to characterize the workability of fresh concrete. After having obtained an SCC, the concrete turns into molds, cubic specimen in  $10 \times 10 \times 10$  cm<sup>3</sup> for 24 hours covered with plastic, and then kept in five groups to study the effect of the curing methods on the properties of the SCC. The curing methods were mentioned in Table 3.

Before, the hardened properties have been tested; all series have been exposed to these curing conditions during summer months. In this period, highest atmospheric air temperatures are observed in Algeria. Thus, these conditions can be clearly said as Hot Climate. After the curing periods, the tests on the hardened concrete were as the compressive strength and the ultrasonic pulse velocity at 3, 7, 28 and 90 days, the sorptivity at 28 and 90 days.

## 2.3.3 Tests on fresh SCC

The slump flow test of fresh SCC was conducted according to the (EFNARC 2005). The J-Rin test complies with the (ASTM C1621 2014) standard. It uses again the cone of Abrams but reversed. It allows to characterizing the mobility of the concrete in a confined environment and to

		Ι	Duration of cure (day)			
Specimen Code Th	The Curing Methods		In water	Hot Climate		
specimen code	The Caring Methods	In Mold	24-28°C	35-48°C		
			HR 100%	HR 50-85%		
W3	Completely in water	1	3	0		
W3-7	Partially in the water	1	3	4		
W3-28	Partially in the water	1	3	25		
W3-90	Partially in the water	1	3	87		
W7	Completely in water	1	7	0		
W28	Completely in water	1	28	0		
W90	Completely in water	1	90	0		
W7-28	Partially in the water	1	7	21		
W7-90	Partially in the water	1	7	83		
W14-28	Partially in the water	1	14	14		
W14-90	Partially in the water	1	14	76		
HC3	Completely in the air	1	0	3		
HC7	Completely in the air	1	0	7		
HC28	Completely in the air	1	0	28		
HC90	Completely in the air	1	0	90		

#### Table 3 Curing methods of SCC

Wx: specimen immersed in water during x days;

Wx-y: specimen immersed in water during x days and then in hot climate (y-x) days (example: W7-28: 7 days in water and then 21 days in hotclimate);

HCx: specimen exposed to hotclimate during x days

verify that the establishment of the concrete will not be upset by phenomena of blockages unacceptable. Concerning the L-box test, this test allows characterizing the mobility in a confined environment that is dynamic segregation. For the V-funnel test, this test allows a qualitative assessment of self-compacting concrete (EFNARC 2005). It characterizes the ability of passage of the concrete through an orifice. The test is to observe the flow of concrete through the funnel and to measure the flow time at the moment when the flap is free. The test of stability at the sieve was used to qualify the SSC against the risk of segregation (Fig. 2).

#### 2.3.4 Tests on hardened SCC

After the preparation of SCC specimens with dimension  $10 \times 10 \times 10$  cm<sup>3</sup>, the compressive test has been carried out according to the (EN 206-1 2004).

The capillary absorption test allows measuring the rate of the absorbed water by capillary suctions specimens of concrete, not saturated, put in contact with the water without hydraulic pressure (Skarendahl and Petersson 2000). Specimens were initially oven-dried at  $105\pm5^{\circ}$  for 72 hours to reach constant mass and obtain oven-dry mass. The sorptivity test determines the rate or speed of absorption by the capillary rise of a test piece cubic  $10\times10\times10$  (Fig. 3). Thus, the water does not exceed 5 mm in the specimen. The rest of the specimen was previously water proofed by an epoxy resin on all other sides. Then, the mass of specimen was measured in function of the time from 1, 4, 9, 16, 25, 36, 49 to 64 minutes. If the capillary absorption is high, the material is likely to be rapidly invaded by the fluid in contact.



(a)Performing of concrete



(d) V-funnel test



(b) Slump flow test



(e) L-box test Fig. 2 Tests on fresh SCC



(c) J-Ring test



(f) Milt test



Fig. 3 Schematic of the water absorption test

The coefficient of sorptivity (S) can be estimated using the following Eq. (1)

$$\frac{Q}{A} = S \cdot \sqrt{t} \tag{1}$$

where:

Q: The amount of adsorbed water in cm<sup>3</sup>

A: The surface of the specimen in contact with water in  $cm^2$ ,

t: The time in second,

S: the coefficient of sorptivity of the specimen  $(cm/s^{1/2})$ .

Ultrasonic pulse velocity was also used in this study to determine the homogeneity of the concrete, the presence of cracks or empty, and the changes in properties and physical and dynamic characteristics over time. The pulse velocity through cubical SCC specimens was determined

according to (ASTM C597 2016). The pulse velocity was determined by direct transmission. During the experimental test, the propagation time of an ultrasonic pulse through the concrete was recorded, and the speed can be calculated by Eq. (2) Qasrawi (2000).

$$V = \frac{L}{T}$$
(2)

where: V: speed of the pulse (m/s);

L: length of the course (m);

T: The time taken for the pulse to travel the length (s).

# 3. Results and discussion

# 3.1 Fresh properties of SCC

The measured values of SCC at the fresh state were illustrated in Table 4. As shown in Table 4, It can be seen that the three compositions (SCC32, SCC38 and SCC44) have satisfied the criteria of the SCC. However, diameter values obtained from the slump flow test for all SCC are included in the category SF2 (66-75 cm). According to the indication set by EFNARC (2005), the viscosity can be evaluated by the  $T_{500}$ -time of the slump-flow test or the time of V-funnel test. In addition, the results presented in Table 4 are included in categories (VS2/VF2) for SCC32 and SCC38 but (VS1/VF1) for SCC44.

Fresh st	tate properties	SCC32	SCC38	SCC44	Criteria
Slump flow	Diameter (mm)	750	710	730	EFNARC SF1: 550-650 SF2: 660-750
-	T <sub>500</sub> (s)	3.0	2.4	1.6	EFNARC 2005 : 2-5 s
	Diameter (mm)	725	710	710	ASTM C 1621
J-Ring	D <sub>slump</sub> -D <sub>j-ring</sub> (mm)	25	0	20	0-25 mm : No visible blocking 25-50 mm : Minimal to noticeable blocking > 50 mm: Noticeable to extreme blocking
L-Box	$H_2/H_1$	94.4	91.6	80	EFNARC 2005: ≥ 80%
V-funnel	$T_0(sec)$	11	7	4	EFNARC 2005: 6-12 s
Sieve segregation	(%)	14	11	20	EFNARC2005 : $\leq 20\%$
Density	kg/m <sup>3</sup>	2375	2327	2223	-

Table 4 Properties of SCC at fresh state

It is clearly observed that the viscosity increases with decreasing W/B ratio. In addition, the values of the segregation resistance reflect the low rate of mortar passage through the sieve, corresponding to the SR2 (SCC32 and SCC38) and SR1 (SCC44) categories defined by EFNARC

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(2005). Moreover, the values obtained from L-Box test are greater than 80% satisfied the criteria of the SCC. Concerning density, it is observed that the density increases with decreasing water/binder ratio. In comparison, the mix proportions with a lower W/B ratio (0.32) have a density greater than those with a higher ratio.

#### 3.2 Effects of initial water curing period on the compressive strengths of SCC

The results of the variation in compressive strength of SCC specimens with with different curing methods were presented in Fig. 4. It was found that the curing methods play an important role in the compressive strength development. The compressive strength of SCC retained in the water is higher than those cured in the hot climate regardless of the time and the W/B ratio. In addition, the duration of initial water curing period also contributes in the development of compressive strength. As shown in Fig. 4, it can be seen that the duration of initial water-curing period of 7 days was beneficial for the development of compressive strength as compared to that of the specimens cured in other environments. The same behavior was obtained by Zhao *et al.* (2012).



Fig. 4 Effect of the duration and the curing methods on the compressive strength

The SCC performed with 0.44 of W/B ratio and cured in hot climate developed the lower compressive strength (Fig. 4). However, after initial water curing for 7 days, the SCC specimens with a W/B ratio of 0.32 produced the highest compressive strength. For a longer curing period, a further increase in compressive strength of SCCs mixtures was recorded when the W/B ratio of

0.32 was adopted. It should be noted that in all cases, the compressive strength increased with curing period. In addition, the compressive strength decreased with increasing W/B ratio.

For a W/B ratio of 0.32, the compressive strength values of SCC specimens cured in hot climate (HC) were very low compared to specimens cured in water for any curing period.

For a longer curing period, the significant effect of high initial temperature on the strength can be attributed to the rapid rate of hydration because the cement paste becomes porous and even micro crack occurred between the aggregate and mortar which can negatively affect the long-term strength and pore structure (Nasir *et al.* 2016).

However, the difference in compressive strength values was marginal when the W/B ratio increased. With W/B ratio of 0.32, the increase of compressive strength with time was very pronounced with SCC specimens cured in water and then cured in HC than with those cured initially in water for 3, 7 and 14 days. This behavior was exhibited for all W/B ratios except the case of SCC specimens cured in HC with W/B=0.44.

It is can be clearly seen that the compressive strength of all SCC partially cured in water specimens increased from 3 days up to 7 days but after this curing still to be constant. Furthermore, as shown in Fig. 4, the compressive strength of SSC specimens cured in HC are significantly lower than those completely and partially immersed in water, regardless of water/binder ratio. This can be attributed to the high water evaporation rate due to the semi-arid nature of chlef hot climate (Bushlaibi and Alshamsi 2002).

However, the specimens kept at 7 and 14 days in water and then in the condition of hot climate have higher compressive strength at 90 days in relation to those of the specimens which were completely immersed in water. This can be attributed to the difference in relative humidity. The elimination of the moisture of the intermediate layer of cement freezing would reduce the pressure of disjunction and increased the binding forces between the particles of hydration products (Mindess 1983) and therefore the compressive strength of the SCC.

According to EN 206-1 (2000), the concrete compressive strength grades are defined with respect to the 28-day characteristic compressive strengths of cubic specimens with dimensions of  $150 \times 150 \text{ mm}^3$  and cylindrical specimens with the dimensions of 150 mm diameter and 300 mm lengths. Such cubic and cylindrical specimens are defined as standard cubic specimen and standard cylindrical specimen. Besides, the characteristic compressive strengths of both standard cubic and cylindrical specimens have related to each other. In this manner, compressive strength grades are defined using both characteristic compressive strengths of cubic and cylindrical specimens. For instance, if the characteristic compressive strength of cubic specimens is 37 MPa and characteristic compressive strength of cylindrical specimens is 30 MPa, the concrete strength grade is defined as C30/37 in which C represents concrete grade. In this study,  $10 \times 10 \times 10$  cm<sup>3</sup>  $(100 \times 100 \times 100 \text{ mm}^3)$  cube specimens are used to determine compressive strength of SCC. However, the concrete grade is determined using  $150 \times 150 \times 150$  mm<sup>3</sup> cube specimens regarding NF (EN 206-1 2000). Therefore, the concrete compressive strength of 100 mm cube specimens have to be converted to 150 mm cube specimen strengths. In the study of (Mirza and Lacroix 2002), Eq. (3) has been given to convert the strength of the 100 mm cube to the strength of a 150 mm cube. Thus, this equation has been used to obtain 150 mm cube specimens compressive strengths then the concrete grade (EN 206-1 2000) has been discussed. In Eq. (3) (Mirza and Lacroix 2002),  $f_0$  and  $v_0$  are the concrete strength and volume of a 100 mm cube, respectively; and f and v represent the concrete strength and volume of the cube of a given size, respectively.

$$f = f_0 \cdot \left[ 0.58 + 0.42 \left(\frac{v_0}{v}\right)^{1/3} \right]$$
(3)

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Fig. 5 Sorptivity of the three SCCs at 28 and 90 days curing

It is obvious in Fig. 4 that the minimum compressive strength values for the series with the W/B ratio of 0.44. This situation is valid for all concrete types including SCC. While W/B or W/C is increasing, the volume of capillary pores increase due to evaporation of mixing water. This increases porosity and thus, the compressive strength decreases. Besides, as mentioned before, hot weather has some negative effects on concrete compressive strength (ACI 305R 2010). In general, a hot weather decreases the setting time of fresh concrete and increases the concrete temperature, and hence increase the hydration rate at early ages. Early setting of concrete makes it difficult to settling and compacting concrete. Therefore, the compressive strength may decrease. In addition, the mixing water may evaporate and causes the slowdown of the rate of hydration. This means that concrete cannot gain desired or expected compressive strength. Finally, it can be said that the desired and designed characteristic compressive strength cannot be obtained. Thus, the concrete strength grade or concrete quality may not be as designed. In this manner, the cross sections of structural elements such as columns or beams designed by the planned concrete strength grade may not bear to the design loads or may not behave as designed against dynamic loads during earthquakes.

In concrete series with W/B ratio of 0.44 and curing conditions of HC (which no wet curing is applied) are expected to be obtained as in Fig. 4. However, in Fig. 4, the minimum mean concrete

		1			1							
Pulse velocity (UPV) in km/s												
W/B		0.32				0.38				0.44		
	3d	7d	28d	90d	3d	7d	28d	90d	3d	7d	28d	90d
W	4.440	4.450	4.500	4.510	4.380	4.400	4.400	4.420	4.050	4.140	4.160	4.230
W3		4.470	4.480	4.490		4.380	4.400	4.420		4.190	4.190	4.190
W7			4.530	4.590			4.470	4.490			4.190	4.200
W14			4.520	4.550			4.520	4.550			4.140	4.150
HC	4.170	4.240	4.270	4.390	4.240	4.270	4.270	4.390	4.030	4.080	4.100	4.110
		- 07 - 06 Coefficient of sorptivity (×10-3) - 07 - 07 - 08 - 0 - 08 - 0 - 08 - 0 - 08 - 08 -	0	40		50		//B=0.32 //B=0.44 //B=0.32 //B=0.34 Eq. (5) Eq. (6)	2 (28 da 3 (28 da 4 (28 da 2 (90 da 3 (90 da 4 (90 da	ays) ays) ays) ays) ays) ays) ays)	)	
					Compr	essive st	trength (	(MPa)				

Table 5 Ultrasonic pulse velocity of SCC specimens

Fig. 6 Correlation between compressive strength and sorptivity at 28 and 90 days

compressive strength is 36.5 MPa ( $100 \times 100 \times 100 \text{ mm}^3$ ) at the end of 28 days for the cube specimens with the edge of 100 mm. If it is converted to the mean compressive strength of standard cube specimens ( $150 \times 150 \times 150 \text{ mm}^3$ ) to determine the concrete compressive strength grade with respect to (EN 206-1 2000), it will be calculated as 30.62 MPa using Eq. (3) (Mirza and Lacroix 2002). As indicated,  $fc_{mean} \ge f_{ck} + 4$  MPa criteria must be provided (EN 206-1 2000). In this manner, if  $fc_{mean}$  is as 30.62 MPa, the characteristic concrete compressive strength of 150 mm cube specimens is calculated as 26.62 MPa (EN 206-1 2000). This means that the strength grade for series with W/B ratio of 0.44 and HC curing conditions can be considered as C20/25 (28-day 150 × 300 mm<sup>3</sup> characteristic cylindrical concrete compressive strength/28-day 150 mm cube characteristic cube concrete compressive strength) according to (EN 206-1 2000).

# 3.3 Effect initial water curing period on the sorptivity of SCC

The experimental results of sorptivity coefficient (S) of SCC specimens for both 28 and 90 days of curing periods and curing methods were presented in Fig. 5. It was clearly found that the sorptivity coefficient (S) decreases with time (Nagaratnam *et al.* 2015). The sorptivity coefficient of SCC specimens retained in hot climate was significantly higher than those cured in water regardless of the time and the W/B ratio. The (S) values of all SCC specimens cured for 28 days

were much higher than those of the SCC specimens cured for 90 days. Compared to the sorptivity coefficient of SCC specimens between hot climate and other initial periods of curing at 28 days, it was found that regardless of W/B ratios, the hot climate curing is significantly increased than those curing in other regime. This was probably related to the little degree of cement hydration caused by a shorter period of water curing and also linked to the micro-cracks formed on the surface of concrete resulting from the early dissipation of moisture from the concrete (Chan and Ji 1998).

According to Nagaratnam *et al.* (2015), the low amount of hydration produced and the poor microstructure within the concrete matrix were responsible for the high sorptivity values at 28 days. The high sorptivity values at 28 days are due to the low amount of hydration produced, thus leading to poor microstructure within the concrete matrix. It can be seen that sorptivity values of SCC specimens cured in HC with W/B ration for 0.44 were very higher compared with those cured in water at 28 days. In addition, the sorptivity strongly reduces with age, while the effect of W/B ratio was pronounced. With W/B ratio of 0.32, the sorptivity of SCC specimens partially cured in water are similar to those completely cured in water for both 28 and 90 days. For comparison, the largest decrease was achieved for the SCC specimens performed with W/B ratio of 0.44.

# 3.4 Ultrasonic pulse velocity (UPV)

Table 5 presents the values of ultrasonic pulse velocity (UPV) with curing period (3-90 days) of SCC specimens and W/B ratios under five types of curing methods. For comparison, the increase in the UPV with age was observed in all SCC specimens. Furthermore, the UPV values of SCC specimens cured in hot climate were lower than those cured in other curing methods. The decrease in UPV of SCC specimens cured in HC can be explained by the formation of microcracks (presumably due to increased shrinkage strain and the differential thermal movements of the SCC constituents) and the reduction in the moisture content of the specimen (Almusallam 2001).

The UPV of SCC specimens (W/B=0.32) cured completely or partially in water (W, W3, W7, W14) for 3, 7, 28 and 90 days varied between 4.440 and 4.510 km/s. However, the UPV values of SCC specimens (W/B=0.32) cured in HC during the same periods varied between 4.170 and 4.390 km/s. In addition, highest UPV value reached in the SCC was (W7-90) with a W/B ratio 0.32. In contrast, the lowest UPV was obtained by SCC44 cured in HC. The pulse velocity increased at the early ages of drying since the rate of strength gain was higher than the rate of loss of moisture content (Al-Sugair 1995).

## 3.5 Correlation between compressive strength and sorptivity

Fig. 6 shows the relationship between the compressive strength at 28 and 90 days of all SCC specimens and the coefficients of sorptivity. In order to analyze the relationship between the compressive strength and the sorptivity, an exponential equation shown as Eq. (4) was proposed

$$S = a.e^{b.Rc}$$
(4)

Where: Rc: compressive strength (MPa), a and b: model parameters, S: coefficient of sorptivity  $(cm/s^{1/2})$ .

However, it can be seen from Fig. 6 that the sorptivity coefficient decreased with increasing compressive strength. For all SCC specimens, the exponential relationships between sorptivity and compressive strength at 28 and 90 days of curing can be adopted Eqs. (5) and (6). According to Siad *et al.* (2014), the decrease is more important for the SCC specimens at 90 days. Based on the



Fig. 7 Correlation between compressive strength and UPV in function of different curing

results obtained, the relationship between the compressive strength (Rc) and the sorptivity (S) at 28 and 90 days are respectively

$$S = 77.20 e^{-0.03.Rc} (R^2 = 0.886)$$
, for the SCC at 28 days (5)

S=31.19 
$$e^{-0.02.Rc}$$
 (R<sup>2</sup>=0.719), for the SCC at 90 days (6)

The determination coefficient between the sorptivity coefficient and compressive strength for SCC with all W/B ratios at 28 days was  $R^2$  of 0.886, this explains a good correlation between S and compressive strength. Furthermore, at 90 days of curing the determination coefficient value was decreased slightly to 0.719. This decrease becomes minimal at 90 days.

On the other hand, Leung *et al.* (2016) have reported that any obvious correlation could not be obtained between sorptivity and 28-day cube strength of SCC containing fly ash and silica fume. They indicated that the sorptivity of SCC and its compressive strength depend on the proportion of mineral admixtures and other environmental factors. Furthermore, they concluded that concrete strength at a longer time period may be a durability indicator (Leung *et al.* 2016). It seems that sorptivity of SCC incorporating different pozzolans or mineral admixtures still need further investigations.

# 3.6 Correlation between compressive strength and ultrasonic pulse velocity

The relationship between the compressive strength and the ultrasonic pulse velocity (UPV) of SCC specimens was given in Fig. 7. The values of UPV increased with increasing compressive strength for all SCC specimens. Similar results have been obtained in previous studies (Rojas-Henao *et al.* 2012, Ulucan *et al.* 2008). Breysse (2012) reported that many types of empirical relation-ships can be used, the most common being the exponential model.

There is a good correlation between the compressive strength and pulse velocity for all SCC specimens performed with different W/B ratios ( $R^2$ =0.938) regarding Eq. (7).

$$Rc = 0.118e^{1.406..Pv}$$
 (R<sup>2</sup>=0.938) (7)

where: Rc: Compressive strength (MPa) and Pv: Ultrasonic pulse velocity (km/s)

Similar results were also reported by other researchers. In comparison, Rojas-Henao *et al.* (2012) proposed an exponential relation of type in Eq. (8)

$$Rc = 0.35e^{1.12.Pv}$$
 (R<sup>2</sup>=0.756) (8)

The type of cement used is CEMI-52.5, this curve is close to our curve, and the difference is probably due to the type of cement used. However, Ulucan *et al.* (2008) found the same curve of exponential type in Eq. (9)

$$Rc = 0.0031e^{2.0714.Pv} \quad (R^2 = 0.740) \tag{9}$$

The difference is significant, this is probably due to the different proportion of silica fume used In this study, However, the UPV values decreased with increased silica fume (SF) at all curing ages, indicating the sensitivity of SF to water during the hydration stage, due to the higher specific surface area of SF.

# 4. Conclusions

Based on the above discussion, the following conclusions can be drawn:

The compressive strength is strongly influenced by the curing method, seven days of initial curing in water followed by a ripening in a hot climate was the optimal duration for a better development of compressive strength. It was found that the specimen immersed in water presents the lower sorptivity (capillary absorption) coefficient, regardless the W/B ratio.

Moreover, it was observed that the compressive strength could be estimated by using nondestructive technique UPV. However, there is a good exponential correlation between UPV and compressive strength.

In addition, the sorptivity coefficient of SCC decreases with age regardless the W/B ratio. However, there is an exponential relationship between compressive strength and coefficient of sorptivity with the regression coefficient of 0.886 and 0.719 at 28 and 90 days, respectively.

On the other hand, the hot climate worsened the properties of fresh and hardened concrete. Moreover, it usually decreases its compressive strength. Some precautions have to be taken into account during concrete curing. However, SCC series even exposed to hot climate, show high compressive strengths which can meet the requirement specified by some standards.

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