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SHRINKAGE BEHAVIOR OF A SELF-COMPACTING CONCRETE

VEDENJE SAMOZGOŠČEVALNEGA BETONA PRI KRČENJU

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This paper presents the influence of the mixing constituents on the behavior of self-compacting concretes (SCCs), especially, the effect of the paste volume in their fresh and hardened state. It explains the roles of the pore network and the microstructure of the hydrates in drying and autogenous shrinkage of SCCs. Several tests such as slump flow, L-box, sieve stability, bleeding, mechanical strength, free shrinkage (drying and autogenous shrinkage) and microstructural tests (mineralogical characterization, porosimetric distributions) were carried out in order to understand the roles played by various components likely to influence the formulation of an SCC. The results obtained offer interesting prospects to optimize a SCC using local materials in Algeria. This study has allowed the development of various SCC formulations that fulfill the rheological criteria such as good deformability, low bleeding, low segregation and a better mechanical performance.

Keywords: self-compacting concrete, limestone fillers, porosimeter, drying shrinkage, autogenous shrinkage, mechanical strength

Članek opisuje vpliv primešanih dodatkov na vedenje samozgoščevalnega betona (SCC) na volumen v svežem in v strjenem stanju. Razložena je vloga mreže por in mikrostrukture hidratov pri sušenju in avtogenem krčenju SCC. Da bi razumeli vlogo posameznih delov in sestavin, ki opredeljujejo SCC, je bilo izvršenih več preizkusov, kot pojemanje toka, L-Box, stabilnost pri sejanju, izcejanje, mehanska trdnost, prosto krčenje (sušenje in avtogeno krčenje), mikrostrukturni preizkusi (mineraloška karakterizacija, razporeditev por). Dobljeni rezultati dajejo zanimive možnosti za optimiranje SCC z uporabo lokalnih mineralov v Alžiriji. Ta študija je omogočila različne formulacije SCC, ki izpolnjujejo reološka merila, kot je dobra deformabilnost, manj izcejanja, manj segregacij in boljše mehanske zmogljivosti.

Ključne besede: samozgoščevalni beton, polnila iz apnenca, porozimeter, krčenje pri sušenju, avtogeno krčenje, mehanska trdnost

1 INTRODUCTION

Self-compacting concrete is a fluid mixture suitable for being placed in the structures with a congested reinforcement without any vibration. Such concrete should have a low viscosity during the pouring to ensure the high-flow ability, and moderate viscosity to resist segregation and bleeding. Moreover, it must maintain its homogeneity during the transportation, placing and curing to ensure an adequate structural performance and long-term durability.

However, despite the interesting features that they offer, in particular, in their fresh state, some drawbacks of their long-term behavior can hinder their use. Indeed, the physicochemical phenomena inherent to the free shrinkage of SCCs have not yet been clearly specified. If it seems, from the formulation point of view, that one controls the proportioning of various components, to obtain a suitable fluidity, by preserving a good homogeneity and even a high mechanical strength,[1,2] it should also be noted that the problem of the strains remains to be treated.

This research was undertaken in this context and must give answers to several questions, some of them concerning the progression of mechanical and physical properties of concrete with time. The objective of the current work, using the local materials, is to acquire some knowledge explaining the shrinkage behavior of SCCs with variations in the relevant constituents, in particular, the volume of paste. The results obtained in this study will help us to have a more precise idea about the values of shrinkage and to determine the difference between the SCC and the ordinary concrete (OC), adopting an optimum formulation.

2 MATERIALS AND METHODS

2.1 Materials used

2.1.1 Cement

The cement used is CPJ CEM II/A 32.5, obtained from the Zahana factory (in the west of Algeria). Its physical and chemical properties in weight percent are given in **Table 1**.

2.1.2 Limestone fillers

The limestone used is from the Kristel quarry (in the west of Algeria). The sample analyzed is essentially constituted of limestone ($w(CaCO_3)$ = 85.45 %) containing also a considerable quantity of silica ($w(SiO_2)$ = 10.81 %). Its physical and chemical properties in mass fractions are given in **Table 1**.

Table 1: Physical properties and chemical analysis of the cement and limestone fillers
Tabela 1: Fizikalne lastnosti in kemijska analiza cementa ter polnil iz apnenca

Properties	Cement	Limestone fillers
Physical properties		
Bulk density (g/cm^3)	1.09	0.87
Specific gravity (g/cm^3)	3.00	2.66
Fineness (Blaine) (cm^2/g)	3100	2880
Chemical analysis (mass fractions, *w*/%)		
SiO_2	21.93	10.81
CaO	63.87	47.51
MgO	0.21	0.21
Fe_2O_3	4.26	0.76
Al_2O_3	6.81	0.31
SO_3	1.31	–
Loss on ignition	1.83	40.69
Free CaO	0.13	–
Carbonates	–	85.45
CO_2	–	37.60
H_2O	–	3.09

2.1.3 Aggregates

Table 2 gives the aggregate properties for all the mixes used in this study.

Table 2: Physical properties of the aggregates
Tabela 2: Fizikalne lastnosti agregatov

	Marine sand (Sm)	Quarry sand (Sc)	Gravel (G)	
Grade	0/2	0/3	3/8	8/15
Composition	siliceous	limestone	limestone	limestone
Specific gravity (g/cm^3)	2.64	2.66	2.67	2.67
Absorption (%)	–	–	1.28	0.93

2.1.4 Admixture

A Viscocrete 20 HE superplasticizer, non-colored, containing acrylic copolymer, developed by the company of Sika, France, and complying with NF EN 934-2, was used for all the SCC mixes. This high-range water-reducing admixture has a dry extract content of 40 % and a unit mass of 1.085.

For the ordinary concrete (OC), the water-reducing superplasticizer used was a Plastiment BV 40. This admixture has a dry extract content of 36.6–40.4 % and a unit mass of 1.185.

2.2 Concrete mixtures

Three self-compacting concretes and one ordinary vibrated concrete were designed to study the effect of the paste volume on the SCC behavior in its fresh and hardened states.

The superplasticizer proportioning and the water/cement and filler/cement ratios were maintained constant for all the SCC mixes, i.e., *Sp* = 1 %, *W/C* = 0.5 and *F/C* = 0.25.

For the ordinary vibrated concrete, the mix was obtained using the Dreux-Gorisse method and the same *W/C* ratio as for the SCC was used for comparison. The compositions of different mixes are given in **Table 3**.

2.3 Tests on the fresh concrete

The fresh-state characterization of the SCC was limited to the tests recommended by the French Association of Civil Engineering (AFGC),[3] i.e, the mini slump flow, L-box, sieve stability and bleeding.

2.4 Tests on the hardened concrete

2.4.1 Mechanical strengths

The samples used to determine the compressive mechanical strength for different concretes studied, are cylindrical test tubes with an diameter 11 cm and height 22 cm. Once removed from the mold, they were preserved in water for (1, 7, 28 and 90) d.

2.4.2 Free shrinkage

The shrinkage strains were measured using a contractometer on the prismatic test tube with the dimensions of 7 cm × 7 cm × 28 cm, fulfilling two requirements:

- to obtain the total shrinkage with hydrous exchange of the material with the environment;
- to measure the autogenous shrinkage, without hydrous exchange with the environment, by wrapping the test tubes in one or two aluminum sticker sheets.

After the removal from the mold (after 24 h), the total- and autogenous-shrinkage measurements are, at the beginning, worked out at very short times, followed by a periodic increase.

Table 3: Mix proportioning
Tabela 3: Mešalna razmerja

Description	V_{paste} (%)	Mix proportioning (kg/m^3)								
		Cement	Limestone fillers	Efficient water	Viscocrete 20 HE	Plastiment BV 40	Sm	Sc	G (3/8)	G (8/15)
SCC1	35	375.5	94	188	3.76	–	601	259	346	519
SCC2	37.5	400	100	200	4	–	578	249	333	499
SCC3	40	429	107	215	4.29	–	554	239	319	479
OC	34	350	–	175	–	5.25	129	576	204	947

2.4.3 Measure of porosity

With the mercury intrusion porosimetry (MIP), the samples are introduced into a chamber, the chamber is evacuated, the samples are surrounded by mercury and the pressure on mercury is gradually increased. As the pressure increases, mercury is forced into the pores on the surface of the sample. By tracking the pressure and intrusion volumes during the experiment, it is possible to measure the connecting pore necks of a continuous system or the breakthrough pressure in a discontinuous system. The pore width corresponding to the highest rate of the mercury intrusion per change in the pressure is known as the "threshold", "critical" or "percolation" pore width. Using this technique, one also measures the total porosity of a sample as that corresponding to the volume of the mercury intruding at the maximum experimental pressure, divided by the bulk volume of the unintruded sample.

The humidity exchanges of the concrete with the external media are then linked to the porous structure. The knowledge of the concrete porosity can thus prove to be useful when estimating the relative differences between the microstructural formulations of the SCCs that are likely to explain the results obtained for the shrinkage with respect to its composition. In this context, the porosities of different SCC formulations were characterized (after about 300 d, i.e., the last period of the shrinkage measurement). The measurements were realized in the civil engineering laboratory of La Rochelle (France) by means of a mercury porosimeter Autopore III from Micrometrics (ASTM D4404-10). The range of the measurement was from 3 nm to 200 μm.

3 RESULTS AND ANALYSIS

3.1 Fresh state

The response of the characterization tests performed on the prepared concrete is given in **Table 4**.[4]

Table 4: Influence of the *W/C* and *F/C* ratios on the behavior of SCC in the fresh state

Tabela 4: Vpliv razmerij *W/C* in *F/C* na vedenje SCC v svežem stanju

Tests	SCC1	SCC2	SCC3
	V_{paste} = 35 %	V_{paste} = 37.5 %	V_{paste} = 40 %
Slump flow (mm)	570	700	750
L-box H2/H1	0.73	0.87	0.91
Sieve stability π (%)	5.66	7.68	15.01
Bleeding (‰)	0.93	1.15	3.15

The volume of paste is supposed to play two roles in SCC. Initially, it fluxes the material by limiting the contacts between the aggregates. Then, it splits off the gravels sufficiently to avoid a formation of clusters against the reinforcements, responsible for the flow blocking. It is supposed that a minimum volume of paste is needed to fulfill the two functions.

Table 4 shows that among the tested concretes, only one presents a slump shorter than 60 cm. It is clear that an increase in the volume of paste contributes to a significant improvement in workability. This improvement is principally due to the reduction of the coarse aggregate content and, moreover, an increase in the volume, in particular, in the crushed aggregates, induces an important friction.[5] This is the case of the SCC with a volume of paste of 35 %.

The results obtained from the L-box test given in **Table 4** show a good proportioning between the volume of paste and the h_2/h_1 ratio of the concretes. The SCC with a volume of paste of 35 % showed a poor flow in the L-box test with the blocking h_2/h_1 ratio not exceeding 0.80.

For this purpose, it is noted that a paste content of approximately 35 % does not allow an SCC to fulfill the requirements of the AFGC.

Contrary to the slump and L-box tests, the concrete with the 40 % volume of paste was at the extreme limit to the domain of self-compactness since the percentage of its latency is slightly higher than 15 %.

This concrete also developed a poor stability with respect to bleeding, as its percentage exceeded 3 ‰. This segregation is principally due to the increase in the volume of paste compared to that of the aggregates.

3.2 Hardened state

3.2.1 Evolution of the compressive mechanical strength

An SCC presenting a good workability must contain enough volume of paste to cover the aggregate surface in order to minimize the frictions between the particles, on the one hand, and, on the other hand, an additional quantity of paste is necessary to obtain a better workability.[6] When injected into the pores of the aggregates, this paste is called the matrix and its apparent properties are affected by the geometric arrangement of the skeleton.

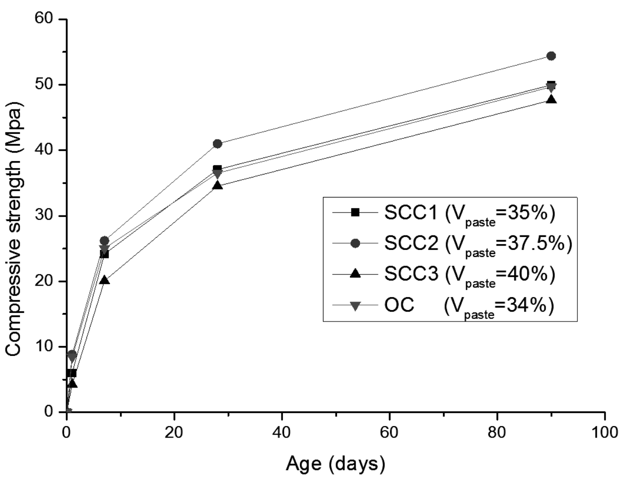

Figure 1: Influence of the volume of paste on the compressive strengths of SCCs

Slika 1: Vpliv količine paste na tlačno trdnost SCC

More precisely, it is the average distance between two coarse adjacent aggregates, called the maximum thickness of the paste, which reflects the topology influence of the skeleton: the shorter the distance, the higher is the concrete strength. It is supposed that there is a minimum volume of paste supporting this condition.

Figure 1 shows the effect of the volume of paste on the compressive strength after (1, 7, 28 and 90) d. At the first approximation, it is the density of the paste that varies with respect to its volume percentage. It is noted that the volume of paste within the interval (37.5–40 %) contributes to the increase in the strengths for two aging periods before causing their decrease when its rate exceeds the critical value of about 37.5 %.

There is only one explanation for that: within the volume-of-paste interval (37.5–40 %), the quantity of paste is important and the distance between the aggregates is larger, causing the frictions between them and, consequently, engendering the weaker strengths.

The compressive strength deviation for SCC/OC observed in **Figure 1** can be explained with a higher proportion of the paste used for SCC (376 l/m^3 against 341 l/m^3 for OC) and the absence of the limestone fillers in OC which may have had a negative effect upon the density.[7]

3.2.2 Free shrinkage

The concrete starts to undergo geometric strains as soon as its installation in the framework has been completed. These dimensional changes develop in different directions and are governed by various physical and chemical phenomena. They take place in the material free from stresses, creating a need for a loaded material.

3.2.2.1 Autogenous shrinkage

The development of autogenous shrinkage begins as soon as the concrete begins to settle and it will stabilize after a few months. This is linked to the auto-drying, i.e., the internal-humidity decrease due to the water consumption by the hydrates.[5]

The volume of paste in the concrete is generally much lower than in the mortar. And yet, it is the paste which retracts and not the aggregate skeleton, which, on the contrary, obstructs the shrinkage. Therefore, it can be concluded that it is the volume-of-paste proportioning that mainly governs the shrinkage values.

It is observed in **Figure 2** that the autogenous shrinkage increases with the volume of paste. The shrinkage progress, with respect to the volume of paste, does not seem to be linear. This is perhaps due to the skeleton-structure variation.

The autogenous shrinkage after 300 d is about 317 μm/m for the SCC with the V_{paste} of 40 % and 275 μm/m for the SCC with the V_{paste} of 37.5 %, showing a difference of 42 μm/m. The SCC with the V_{paste} of 35 % presents a shrinkage of 248 μm/m, i.e., a reduction of 69 μm/m compared to the first formula. These results reveal that the recorded autogenous strains on the SCC with the V_{paste} of 40 % are much higher than those measured on the two other SCCs. This highlights the importance of the aggregate content. In fact, the strains measured on the concrete are the effective strains of this heterogeneous material, consisting of the aggregates and the paste (cement + fillers + superplasticizer + water). And yet, the aggregates restrict the straining of the paste due to the physical/chemical process linked to hydration. Therefore, an aggregate-content reduction and an increase in the volume of paste allow much higher effective strains.

Indeed, the effective strains are determined with the respective parameters (especially the elastic properties, but also the dry density of the granular mixture).

At last, it can be said that the autogenous shrinkage of an SCC increases with an increase in the volume of paste. The reason is that only the paste creeps. The volume of paste is also a parameter that influences the shrinkage. The same result was reported in the literature.[8,9]

The results show that, on the whole, the autogenous shrinkage of an SCC is greater than that of the ordinary concrete (OC). After the first three months, the observed difference between the two types of concrete varied from 10 % to 40 %, i.e., having a strain range of 1.1 to 1.4 (**Figure 2**).

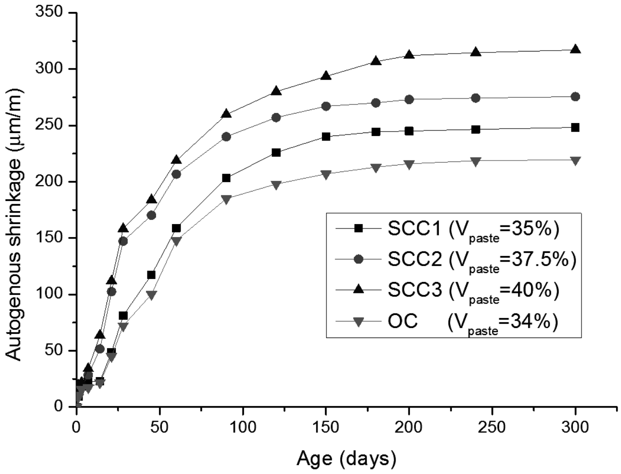

Figure 2: Influence of the volume of paste on the autogenous shrinkage of SCC
Slika 2: Vpliv količine paste na avtogeno krčenje SCC

3.2.2.2 Shrinkage due to drying and weight loss

Figure 3 shows a variation in the shrinkage time due to drying, for an SCC with respect to the volume of paste. This shrinkage can be considered to be due only to the evaporation of the water contained in the hydrated cement paste that develops from the surfaces when exposed to external ambiance.

The drying shrinkage increases with an increase in the volume of paste. Two distinct phases appear in the strains developed: during the first phase of six months

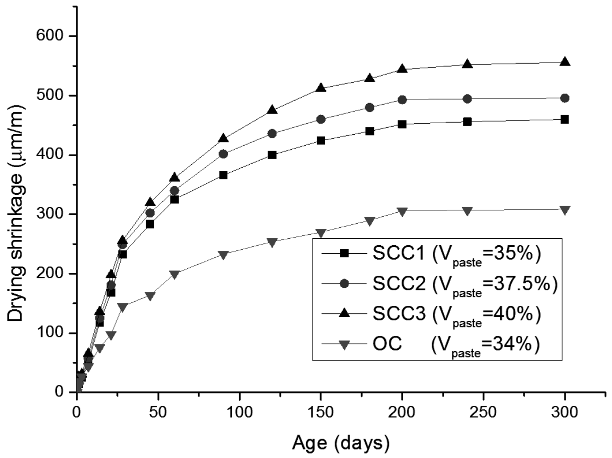

Figure 3: Influence of the volume of paste on the drying shrinkage of SCC
Slika 3: Vpliv količine paste na krčenje pri sušenju SCC

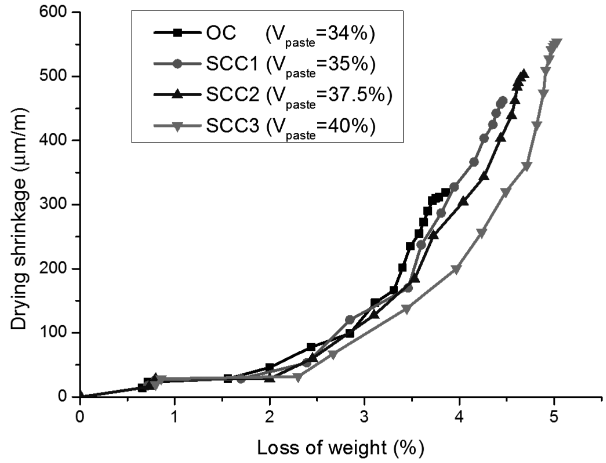

Figure 5: Drying shrinkage versus the loss of mass
Slika 5: Krčenje pri sušenju v primerjavi z zmanjšanjem mase

the evolution speed is high and in the second phase it slows down significantly to become constant. These results are very compatible with those obtained from reference.[9]

The strain analysis of the SCCs shows that the formulation with the V_{paste} of 40 % is characterized with a higher drying shrinkage than that of the two other formulations (V_{paste} = 37.5 % and V_{paste} = 35 %) after 300 d; the differences are 60 μm/m when compared to the SCC with the V_{paste} of 37.5 % and 96 μm/m compared to the SCC with the V_{paste} of 35 %, corresponding to the increase range of 12 % and 21 %, respectively.

The differences in drying shrinkage between the SCC and the OC shown in **Figure 4** are explained with the paste proportioning that is very important for the SCCs (the minimum proportioning for the SCCs is higher by 35 l/m^3), leading to a much higher volume of hydrates in the SCCs than in the OC and, therefore, creating a very important volumetric strain.

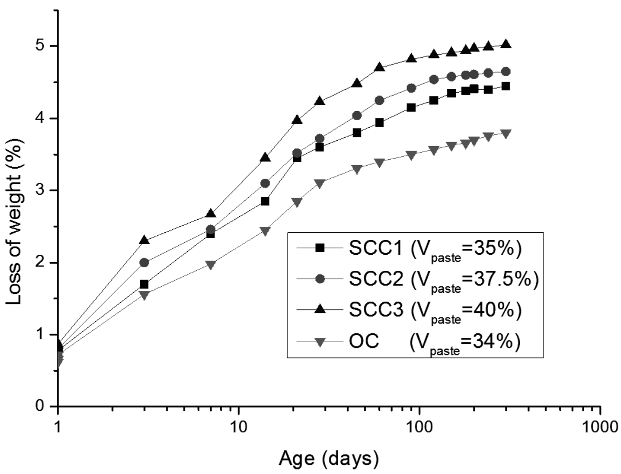

Figure 4: Loss of weight with respect to the volume of paste – a logarithmic scale
Slika 4: Zmanjšanje mase glede na količino paste – logaritemsko merilo

On the other hand, **Figure 4** shows that the water-quantity variation for all the concretes is approximately linear as long as the water evaporation continues with a logarithmic time scale. All the concretes continue to hydrate and the evaporated quantity of water is then the function of the volume of paste.

Figure 5 brings an additional proof of the influence of the volume of paste on the shrinkage due to drying. In fact, different evolution curves of the shrinkage due to drying, with respect to weight loss, show that after the first evaporation of water with no consequences on the shrinkage, there is the second stage, where the shrinkage progresses with the water consumption.

It is observed that the weight losses for the SCC and OC are different, but also that the drying-shrinkage evolution with respect to the weight loss can be considered as linear.

3.2.2.3 Total shrinkage

The relative results for the SCC total shrinkage during 300 d are presented in **Figure 6**. From the quantitative point of view, the experimental value for the total shrinkage of the SCC containing a higher quantity of paste (40 %), after 300 d, is 873 μm/m. The values, for the same time, for the two other formulations are as follows: 771 μm/m for the SCC containing 37.5 % of paste and 708 μm/m for the SCC containing 35 % of paste.

The shrinkage of the SCC with the V_{paste} of 35 % is slightly lower than that of the SCC with the V_{paste} of 37.5 %, but it shows a defect in the stability, observed during the L-box test, causing a problem according to the AFGC recommendations.

The observed experimental data reveal significant differences between the total shrinkages of the SCCs. This deviation can be seen as a consequence of the volume-of-paste increase.

The SCCs are more susceptible to deformability than the OC (**Figure 6**) because of a higher quantity of paste.

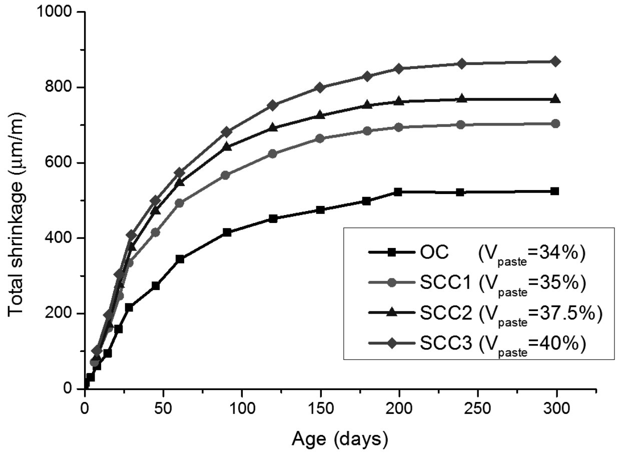

Figure 6: Influence of the volume of paste on the total shrinkage
Slika 6: Vpliv količine paste na celotno krčenje

While making this conclusion, we neglect, however, the fact that the SCC paste does not have the same composition as the OC paste (additions, superplasticizer, water quantity). Besides, E. Proust[8] has found an opposed tendency of the other concretes. B. Persson[10] has shown that, with the same strength, there will be no behavioral difference between SCC and OC, in spite of the volume-of-paste deviation.

On the other hand, Y. Klug and K. Holschemacher[11] found repeatedly in a large database that the total SCC shrinkage was higher, by 10 % to 50 %, than that of the OC. The SCC shrinkage was also found to be higher than that of the OC by other researchers.[12–14]

3.3 Study of porosity

The results obtained from the porosimetry test for the SCCs with respect to different values of paste proportioning (V_{paste} = 35 %, V_{paste} = 37.5 % and V_{paste} = 40 %) are shown in **Figures 7** and **8**.

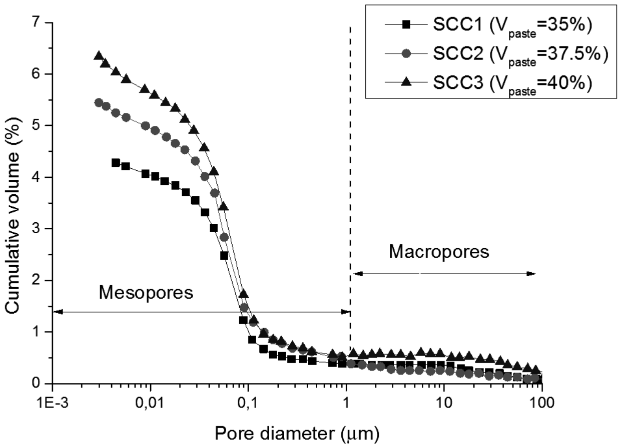

Figure 7: Cumulative volume of the mercury intrusion into the sample versus the pore diameter
Slika 7: Kumulativni volumen vdora živega srebra v vzorec v primerjavi s premerom por

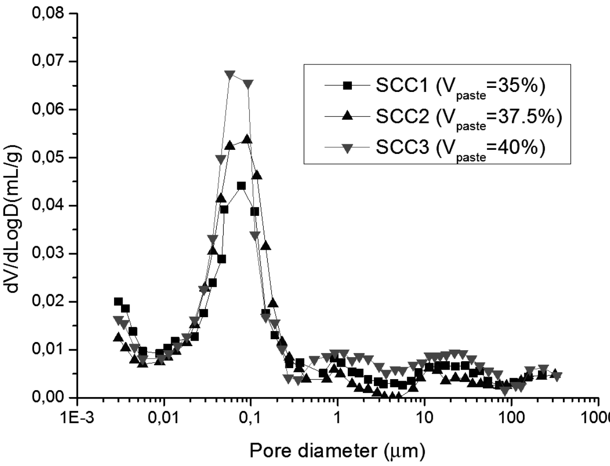

Figure 8: Differential volume of the mercury intrusion into the sample versus the pore diameter
Slika 8: Diferenčni volumen vdora živega srebra v vzorec v primerjavi s porami

In **Figure 7**, it is observed that the cumulative volume of the SCC pores containing a higher paste proportioning (40 %) becomes more important than those of the two other SCCs (the V_{paste} of 35 % and the V_{paste} of 37. 5 %) as the pore size decreases. This seems to be in accordance with the autogenous shrinkage obtained for these concretes.

As far as the shrinkage due to drying is concerned, the smallest pores (<0.01 µm) in the SCC with the V_{paste} of 40 % have a greater proportioning than those of the SCC with the V_{paste} of 37.5 % and the SCC with the V_{paste} of 35 %. The experimental results given in section 3.2.2 reveal, effectively, that the drying shrinkage of the SCC with a high quantity of paste (V_{paste} = 40 %) is greater than in the case of the two other formulations (V_{paste} = 37.5 % and V_{paste} = 35 %).

On the other hand, it is noted on the graph of **Figure 8**, for all the SCCs, that the porosities are closer in a very marked peak zone, between 0.02 µm and 0.2 µm, and, leaving aside the presence of the remainder of the peak in the zone (10–100 µm) for the SCC with the V_{paste} of 40 % and the SCC with the V_{paste} of 35 %, the other formulation shows a low porosity for higher pore sizes. The paste corresponding to this SCC (V_{paste} = 37.5 %) must appear on this scale as a homogenous and, consequently, tougher material.

Figure 8 shows, in fact, that a lower macroporosity difference (0.1 %) seems to explain a much higher mechanical strength of the corresponding SCCs (section 3.2.1).

4 CONCLUSION

In this study, it is confirmed that it is possible to produce SCCs with the Algerian local materials having the same properties as those known internationally. Therefore, it is advisable to pay attention to the importance of the mix proportioning, which is of great influence, in particular, the *W/C* and *F/C* ratios, to achieve the best required properties of an SCC.

Based on the obtained results, it has been shown that, in the tested range (35–37.5 %), the volume of paste contributes to an increase in the SCC strength. In the range of 37.5–40 %, the paste proportioning has a significant influence on the concrete behavior resulting in a remarkable fall in the strength.

The SCC shrinkage is directly proportional to the paste proportioning. The presence of a net difference between the values for the tested SCC shrinkage seems to indicate that the volume of paste is also a principal parameter affecting the shrinkage.

The results obtained from the mercury-intrusion porosimetry test support certain assumptions put forward and allow us to explain, in a pertinent manner, the behavior of the SCCs in their hardened state. In fact, the microstructural study of the samples has confirmed that the hydration process is not the same for different SCCs, depending on the paste quantity. The volumetric porosity also shows relative differences in the SCC microstructure formulations, confirming the results obtained experimentally.

Finally, taking into account the relative measurement uncertainties, it is believed that the stabilization of the SCC strains will be faster than that for the OC, for which the tendency to stabilization seems to differ with time. Therefore, certain reduced deviations can be observed over a long term. More tests made over several years will be necessary for a better quantification of this phenomenon.

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