INFLUENCE OF NATURAL POZZOLANA AND RECYCLED QUARRY SAND WASTE ON THE DIFFUSION OF CHLORIDE IONS IN SELF-COMPACTING SAND CONCRETE

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This study aims at evaluating the durability of* self-compacting sand concrete *(SCSC) based on pozzolan, brought from the north-western town of Beni-Saf (Algeria), with respect to the diffusion of chloride ions. The influence of the addition of a large amount of natural pozzolana on the diffusion of chloride ions in SCSC samples was studied in the first part of this paper. The compressive strengths of several SCSC samples, which were formulated with different percentages of natural pozzolana, were then compared with those of standard self-compacting concrete (SCC) and vibrated concrete (VC) in the second part. The experimental tests carried out on these formulations indicated that self-compacting sand concrete (SCSC) exhibits better mechanical behavior and also only a small number of chloride ions can penetrate in it as compared to other types of concrete. This study also showed that the partial substitution of cement in the SCSC by natural pozzolana from Beni-Saf improves its resistance to the diffusion of chloride ions.

Keywords: *Self-compacting sand concrete; Natural pozzolana; Mechanical strength; Durability; Diffusion of chloride ions; Porosity; Capillarity*

1. Introduction

One of the major concerns in the formulation of concrete is sustainability. It is conditioned by the transport of aggressive chemical species within the porous network of the cementitious material. Corrosion of reinforcements is the main cause of degradation of reinforced concrete structures, and repair costs are generally high [1]. In this respect, the degradation of concrete due to chloride ion infiltration remains a subject of major importance. It is therefore necessary to be well acquainted with all the mechanisms involved in the penetration of these ions into concrete.

Several works have been carried out namely, Shanmuga Priya et al. and [2] studied the effect of fly ash and silica fume which are very appreciable at 180 days. The SCC with 30% fly ash had higher strength at 180 days. This indicates a strong correlation between chloride strength and compressive strength of concrete. Ali Sadrmomtazi et al. [3] studied the durability of slag-based geopolymer in corrosive environments, they found silica fume and fly ash have positive impacts up to 20% replacement rate and an improvement of the durability against chloride permeability can be obtained in the case of mineral additions such as slag and pozzolan.

Gao et al. [4] have shown that the penetration and diffusion of chloride ions influence in the transition zone of the recycled concrete waste interface. The strengthening effect is mainly at the old aggregate - old mortar interface.

Steel depassivation may take place through two main processes, namely the carbonation of concrete by carbon dioxide (CO_2) from the atmosphere, or by chloride ion infiltration in concrete. Chloride ions can come from the concrete itself (aggregates, mixing water) or from the external environment (seawater, marine spray, or de-icing salts) [5].

Comparatively, corrosion due to chlorides is more dangerous than carbonation as it develops more rapidly and there is a higher risk for a sudden rupture in the case of severe environments [6].

The degradation of structures depends on their exposure conditions, the type of exposure, and also on the different transport mechanisms of chloride ions [7].

The study of ion transport in porous media provides an interpretation and characterization of ion displacement within cementitious materials. The transport of ions inside these materials is particularly affected by the diffusion coefficients of these ions. The measurement of the diffusion coefficient of chloride ions is very important as it allows predicting the lifetime of reinforced concrete structures [8].

The influence of mineral additions such as natural pozzolan on the durability of self-placing sand concrete becomes a more than necessary study and in particular the diffusion of chloride ions to protect the reinforcement against corrosion and especially in the case of repair and rehabilitation of old structures [1]

The purpose of the present study is to investigate the influence of pozzolan additions on the mechanical and physico-chemical characteristics of self-compacting sand concrete (SCSC) versus standard self-compacting concrete (SCC) and vibrated concrete (VC). In this context, some essential tests, such as the fresh state tests of SCSC and SCC, were carried out according to the.

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Fig.1 - Cutting a spherical specimen into slices, and samples immersed in lime

Fig. 2- Mounting system for the cell migration assay

SCSC FC SCSC PN

Fig. 3 - Diffusion profile of chloride ions

European Federation of National Associations Representing producers and applicators of specialist building products for Concrete [6-9]. Regarding the cured state, some mechanical tests were performed in order to determine the compressive strengths of the concrete. To determine the durability, some chloride ion migration tests were performed to measure the diffusion coefficient. In the end, some other tests were carried out to find the porosity accessible to water and capillary absorption.

2.Experimental procedure

2.1. Sample preparation

Sixty days after casting concrete into cylindrical specimens (110 x 220) mm for durability testing, they were stored in a humid chamber with controlled temperature and humidity. The specimens used in the chloride ion diffusion tests were prepared according to the recommendations of the standard NT BUILD 492 [10], The testing methodology of NT Build 492 is primarily based on the chloride ions migration into previously vacuum saturated concrete specimens in analyte solution (0.3 M NaOH) by applying an external electrical voltage (30 V DC) that is adjusted between 10 and 60 V according to the electrical current in the scheme. Each cylindrical specimen was sawn into slices with a thickness of (50 ± 2) mm (see Figure1). Two of them were used to perform the diffusion tests and the other two were used to determine the physical properties (porosity and capillarity).

A solution of lime at 3 g/L (Ca (OH) 2) was prepared by dissolving lime into distilled water. The concrete samples were saturated with lime using the previously prepared solution and then stored in the same solution until the start of the migration test (see figure 1). The first solution was prepared with 100 g of sodium chloride (NaCl) diluted in 900 g of distilled water to obtain about 2 moles of NaCl; it is a cathodic solution. The second solution was obtained by diluting 12 g of sodium hydroxide (NaOH) into 1 liter of water to have about 0.3 M of NaOH; it is an anodic solution (see Figure 2).

To measure the depth of penetration (X_d) of the chloride ions, the following procedure was followed:

• The samples were removed from the cells, then rinsed with tap water. Excess water was then removed from all sample surfaces.
• The samples were sawn along the axis into two pieces, as shown in Fig. 3. •
• A solution of silver nitrate (0.1 Mol / L) was vaporized on the part which was exposed to the cathodic solution (NaCl). After 15 minutes, the penetration depth of chloride ions could be seen.
• The penetration depth of the chlorine ions (X_d) was measured using a scale with 10 mm graduations, as recommended by the standard NT BUILD 492 [10].

2.1.1. Calculation of the diffusion coefficient of chloride ions

The diffusion coefficient D_{nssm} of chloride ions was calculated using the following relationship:

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(X_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right)\left(10^{-12} m^2/s\right) \quad (1)$$

Dnssm is the non-steady-state migration coefficient, x10-12 m^2/s
U: absolute value of applied voltage (V).
T: mean value of the initial and final temperatures in the anolyte solution (°C).
L: thickness of the sample (mm).
X_d: mean value of penetration depths (mm).
t: duration of test (hours).

2.2. Materials used

The aggregates used in this work are sand (quartz sand 0/2, and quarry sand 0/5) and three types of gravel (gravel 3/5, gravel 3/8, and gravel 8/15). The quartz sand was brought from the quarry of Kristel, in the northwestern city of Oran, in

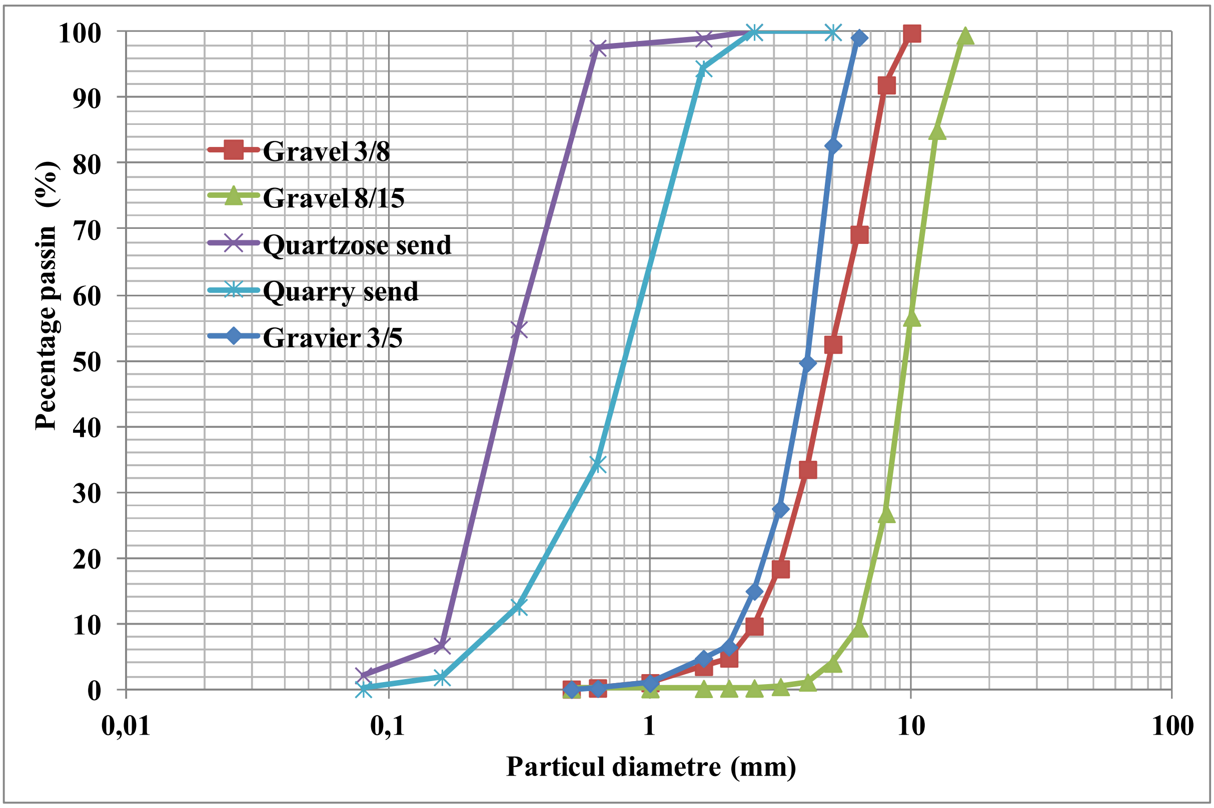


Fig.4 - Granulometric analysis of aggregates

Table 1

Chemical characteristics of the cement used

Chemical composition	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	SO3	Na2O	K2O	P. A. F	Total
%	23.19	64.22	0.21	4.87	3.32	2.5	0.006	0.1	1.6	99,98

Algeria; the quarry sand and gravel were from the quarry of Sidi-Belabbes, a town in western Algeria. The results of the analysis of these aggregates are given in Fig. 4.

The cement used is of type CEM II / A 42.5, from Zahana Cement Company, in the Province (Wilaya) of Mascara in western Algeria. Its specific density is 3200 Kg/m^3 and its specific surface area (*Blaine*) is 309 m^2/Kg. Its chemical characteristics are given in Table 1. The granulometric analysis is illustrated in figure 5.

The mineral addition used is natural Pozzolana, which is a volcanic rock composed of silica, alumina, and iron oxide. This rock has pozzolanic properties and its chemical composition is given in Table 2 and Fig. 6.

Natural pozzolana (Beni-Saf) was used in the formulation of self-compacting sand concrete (SCSC) and self-compacting concrete (SCC) [11], [12]. All the pozzolan used as a substitute for cement was appropriately prepared; it was first selected, then homogenized, dried, crushed and powdered with a grinder, for a period of about 1 hour (d_{max} = 80 µm), to finally have a specific surface area (*Blaine*) of 440 m^2/Kg and a specific density of 2700 Kg/m^3. The granulometric analysis is given in Fig. 5.

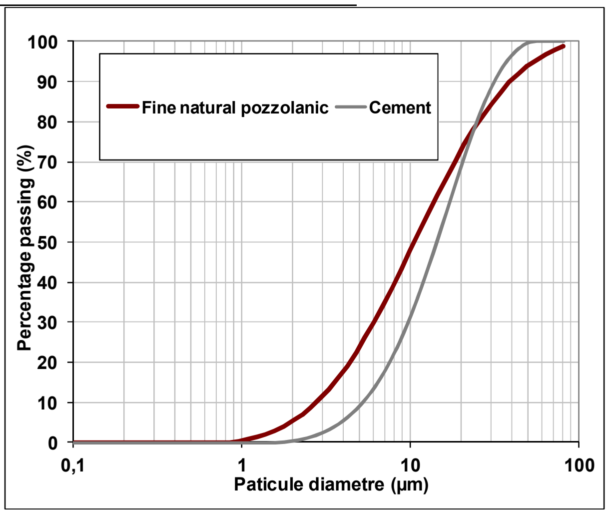


Fig. 5 - Granulometric analysis of cement and pozzolana

X-ray diffraction spectrum of natural pozzolana (Beni-Saf) in Fig. 6

Scanning electron microscopic view of pozzolanic fillers after grinding in Fig.7

The adjuvant used in our study is a super-reducer "MEDAFLOW 30" Granitex. It is based on polycarboxylates and allows obtaining concretes and mortars with very high quality. In addition to its

Table 2

Chemical analysis of natural pozzolana from Beni-Saf

Chemical composition	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	P. A. F	Total
%	56.25	9.83	1.81	16.98	8.57	6.54	99.98

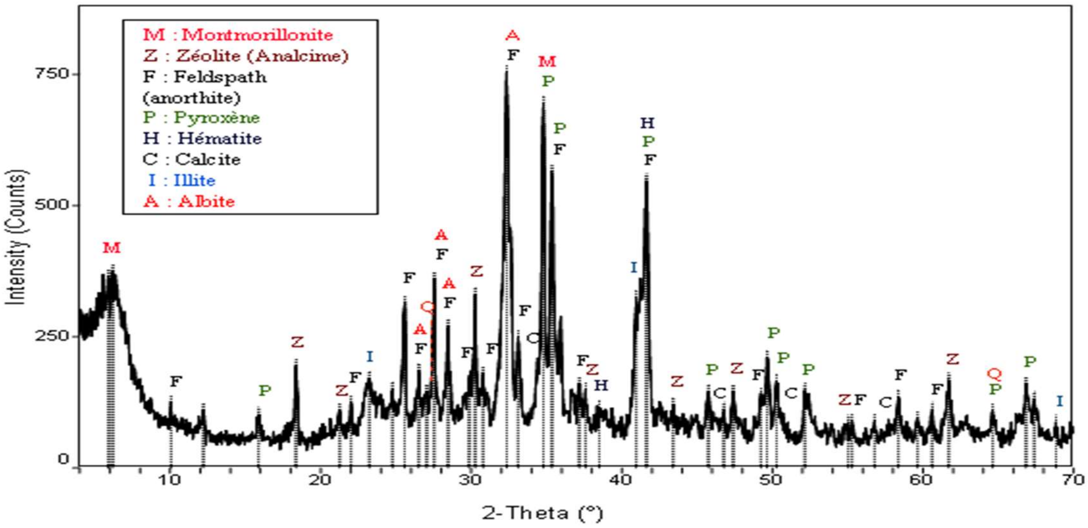


Fig. 6. X-ray diffraction spectrum of natural pozzolana (Beni-Saf)

main function as a superplasticizer, it also significantly reduces the water content of concrete. It is mainly used in self-compacting concretes (SCCs).

3. Formulation of concrete

The experimental procedure consisted of five types of concrete: three formulations for self-compacting sand concrete (SCSC1, SCSC2 and SCSC3), another one for self-compacting concrete (SCC), as a control sample, and the last one for vibrated concrete (VC) for comparison. The percentage of pozzolana addition was varied in the first three formulations, and large amounts of sand with small gravel fractions of class (3/5) were used. The fourth formulation was used as a reference. The four previous formulations were compared to the fifth one (vibrated concrete). All five formulations are shown in Table 3. The five concrete formulations are shown in the following Table 4.

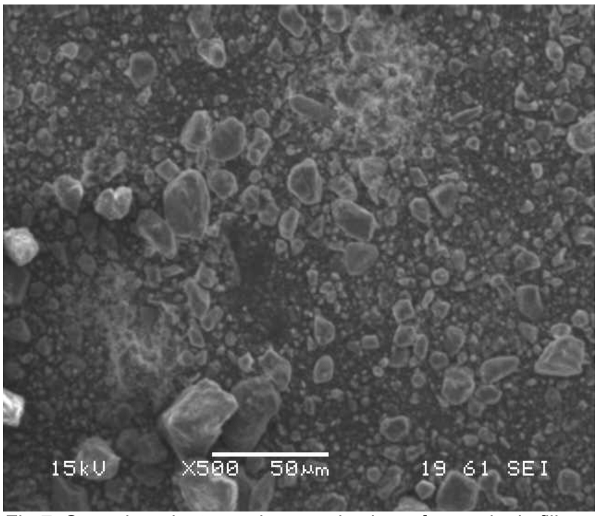


Fig.7. Scanning electron microscopic view of pozzolanic fillers after grinding

Table 3

The formulations used

N°	REF	Formulations SCSCs
1	SCSC1	SCSC with W/C =0.35
2	SCSC2	SCSC with + 20% natural pozzolan fine de SCC1 avec W/C =0.35
3	SCSC3	SCSC with + 30% natural pozzolan fine SCC1 avec W/C =0.35
4	SCC	SCC with W/ C=0.57
5	VC	VC with W/C=0.57

Table 4

Composition of mixtures (kg/m^3)

Quantity (kg/m^3)	SCSC1	SCSC 2	SCSC 3	SCC	VC
Cement	420	336	294	350	350
Natural pozzolan fine	200	284	326	130	0
Water (l/m3)	220	220	220	200	190
Quartzose sand	443	443.3	440	486	480
Quarry sand	731,6	717	717	400	482
Gravel (3/5)	295	299.88	296.39	/	/
Gravel (3/8)	/	/	/	389	221
Gravel (8/15)	/	/	/	400	636
Medaflow30	12.44	12.44	13.28	8.11	0
paste Volume (l/m^3)	429.6	433.6	435.6	442.5	312.9

Table 5

Test results of concrete in the fresh state, according to the standard

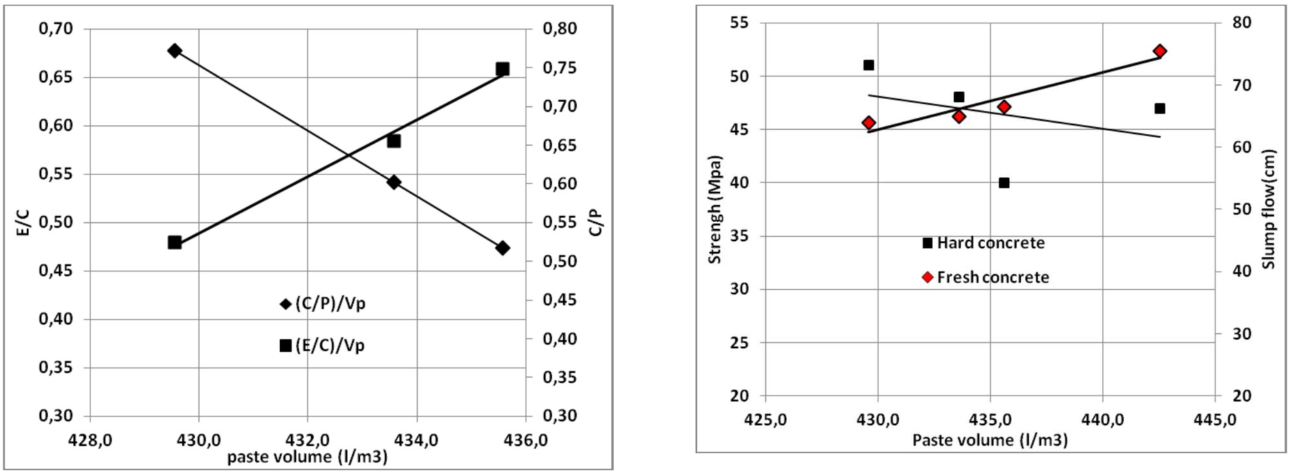
	ref	SCSC1	SCSC 2	SCSC 3	SCC	VC	Vérification
slump flow (cm)	D (cm)	64	65	66.5	75.5	h=6cm	60<D<80
T_{50} (s)	t_{50} (s)	7.34	15	9	4		/
L Box	H2/H1	1	1.1	1.6	1	/	H2/H1≥0.8
L Box= 30 cm	t_1(s)	9	8	12	5	/	/
L Box= 60 cm	t_2(s)	23	27	35	12	/	
segrégation (%)	SR(%)	1.40	1.02	2.04	2.5	/	0<SR<15

4.Results and discussions

4.1. Characterization of mixtures in the fresh state

After unmolding, the specimens were stored in plastic tanks, filled with water, in a room with an ambient atmosphere at a temperature of (20 ± 2) °C until the test was carried out at the scheduled time. Characterization of the self-compacting concrete in the fresh state was limited to the EN 12350-10 [10] recommended tests, such as Abrams cone slump test, L-box test, and Sieve stability test. In addition, the flow time was measured at 30 and at 60 cm in the L-box test in order to examine the mobility of SCSC and SCC in confined media. The flow time was also measured in a slump cone with a diameter of 50 cm (T50) for unconfined media. The properties of each composition in the fresh state are given in Table 5.

Recommendations. The SCSC and SCC spreads were between 64 and 76 cm. The results obtained for concrete spread show that this requirement of the contract documents has been correctly satisfied by the various self-compacting sand concretes (SCSC) and self-compacting. concrete (SCC). For all self-compacting sand concrete and self-compacting concrete compositions, the aureole on the periphery of the round concrete slabs was very low. Moreover, the large aggregates were always correctly driven by the cementitious matrix and did not remain piled up in the middle of the concrete slabs. The slump class obtained for vibrated concrete (VC) was class S2 (from 5 to 9 cm of plastic concrete, according to the European standard [13]. The increase in spread, which was found equal to 64, 65 and 66.5cm for the first formulations, i.e., SCSC1, SCSC2, and SCSC3, respectively, was probably due to the increase in fines content [14]. The filling percentage and static segregation of self-compacting sand concrete (SCSC) and self-compacting concrete (SCC), which underwent L-box testing and sieve stability testing, are shown in Table 5. The results obtained were found to be in good agreement with those expected from the self-compacting concrete. Nevertheless, it is important to note and indicate that the tested concrete flowed through the frames properly. In addition, no problem could be reported



A B

Fig. 8 - **A.** Influence of W/C and C/P ratios on paste volume, **B.** Influence of paste volume on fresh and hardened states of SCSC and SCC.

with all self-compacting sand concretes (SCSC) and self-compacting concrete (SCC) which presented fill rates above 80% (Table 5). Regarding the static segregation, it was found that all self-compacting sand concretes and self-compacting concrete have a segregation rate smaller than 15%, which corresponds to the correct stability. The following figure 8 A. illustrates the influence of the W/C and C/P ratios, with different volumes of paste, and figure 8 B. Influence of paste volume on fresh and hardened states of SCSC and SCC.

In the fresh state, it can be seen that as the volume of paste increases, the W/C ratio as well as the spread increase too, but the C/P ratio decreases. In the hardened state, the strength decreases as the volume of paste rises. From the two previous figures A and B, it can be observed that there is an optimum paste volume, which is of the order of (430-435) l/m^3 in the case of SCSCs. It is found at the intersection of the two curves in both Figures 8 A and B, with the four parameters (W/C, C/P, spread and mechanical strength). Also, it can be said that the value 0.6 of the C/P ratio is a good choice for an optimal formulation in both fresh and hardened states. This hypothesis is approved in the studies of [15]and [16]. All these observations show that the typical couple cement/superplasticizer (viscosity agent) and the dosage in fines have a direct impact on the rheological behavior of self-compacting sand concretes (SCSCs) and self-compacting concretes (SCCs).

4.2. Characterization of mixtures in the hardened state

After a cure of 3, 7, 28, 60, 90 and 356 days in the wet room, the cubic concrete samples of dimensions (7×7×7) cm^3 were tested in order to determine the compressive strength. The mechanical compressive strength is an essential characteristic of concrete; it is one of the fundamental parameters considered in our study. The determination and evolution of this mechanical

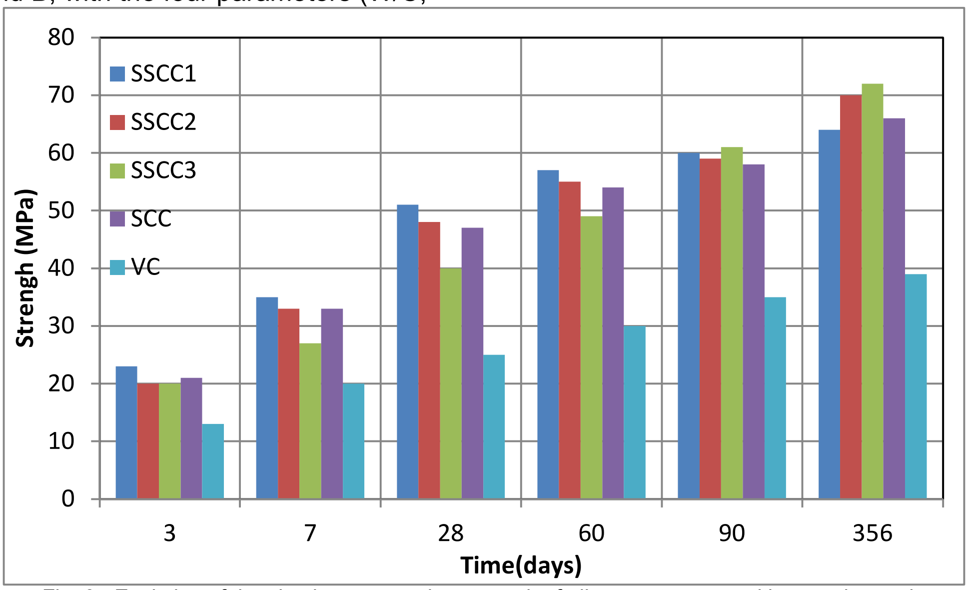


Fig. 9 - Evolution of the simple compressive strength of all concrete compositions under study
Pozzolana cement-based concrete offers higher mechanical performance than concrete

Table 6

Simple compressive strength of different concrete compositions

Time (days) / **composition**	3 days (MPa)	7 days (MPa)	**28 days (MPa)**	60 days (MPa)	90 days (MPa)	356 days (MPa)
SCSC1	23	35	**51**	57	60	64
SCSC2	20	33	**48**	55	59	70
SCSC3	20	27	**40**	49	61	72
SCC	21	33	**47**	54	58	66
VC	13	20	**25**	30	35	39

characteristic was achieved for all concrete compositions studied in this work. For all compositions, the simple compressive strength was measured at different dates. It was obtained by calculating the arithmetic mean of the strengths obtained on three cubic concrete samples whose dimensions are (7x7x7) cm^3. The values of the average compressive strengths of the different types of concrete are given in Table 6.

These same compressive strength values are represented as a function of time in Fig. 9 where the curves represent the evolution of the compressive strength of concretes as a function of time. This strength of self-compacting sand concrete was found to be more important than that of vibrated concrete. Figure 9 clearly shows that beyond 7 days, the mechanical strength of self-compacting sand concrete (SCSC) and self-compacting concrete (SCC) becomes larger than that of vibrated concrete. These differences are of the order of 40 and 50%, respectively.

The compressive strength of self-compacting concrete (SCC) is identical to that of self-compacting sand concrete SCSC2. The maximum strength was obtained for self-compacting sand concrete SCSC3; it reached the value of 72 MPa.

Fig. 9: Evolution of the simple compressive strength of all concrete compositions under study

Pozzolana cement-based concrete offers higher mechanical performance than concrete without pozzolana, and especially in the long term. This can be explained by the greater pozzolanic activity in these concretes. Thus, pozzolana can be considered as an essential element that is responsible for the increase of resistance. The results obtained were found to be in good agreement with those reported by [11], [12] and [17]. Self-compacting sand concrete SCSC3 contains more than 60% of pozzolanic fines, as compared to self-compacting concrete (SCC), and presents a 10% increase in strength for a 356-day curing. This increase is due to long-term pozzolanic activation which is associated with cement and water. As a result, more calcium silicate hydrates (CSH) are produced in the long term. The differences in compressive strength between self-compacting sand concrete (SCSC) and vibrated concrete (VC) may also be due to the significant presence of mineral additions, such as natural pozzolana, in the self-compacting concrete. Thus, the cementitious matrix becomes denser due to the production of calcium silicate hydrates [18]. The compressive strength of self-compacting sand concrete (SCSC2) is basically similar to that of SCC, while the mechanical strength of self-compacting sand concrete (SCSC3) is lower than that of SCC, at an early age. This is probably due to the use of large amounts of sand mixed with a significant quantity of fines. It is well known that the replacement of part of cement by natural pozzolana leads to low strength, at an early age; this is because the largest part of pozzolana only manifests itself in the long term. At 28 days of hardening, and even after, strength becomes more significant and this means that the use of a large amount of pozzolan gives, in the long term, a higher mechanical performance [19]. Figure 10 illustrates the evolution of the compressive strength, for all concrete compositions, over time with respect to the compressive strength at 28 days.

It can easily be seen from Figure 10 that the mechanical performance of vibrated concrete (VC) develops faster than that of self-compacting sand concrete (SCSC) and self-compacting concrete (SCC) in the short term.

At 28 days and beyond, the compressive strength of self-compacting sand concrete (SCSC) and self-compacting concrete (SCC) increases faster than that of vibrated concrete (VC), especially for the third formulation (SCSC3), which contains 60% pozzolan. Therefore, one can say that pozzolanicity was the determining factor in this improvement, because it gave rise to significant increases in the strength of these pozzolanic concretes.

4.3. Sustainability indicators

One of the main issues of this research project concerns the sustainability of self-placing sand concrete (SCSC). In this section, the porosity,

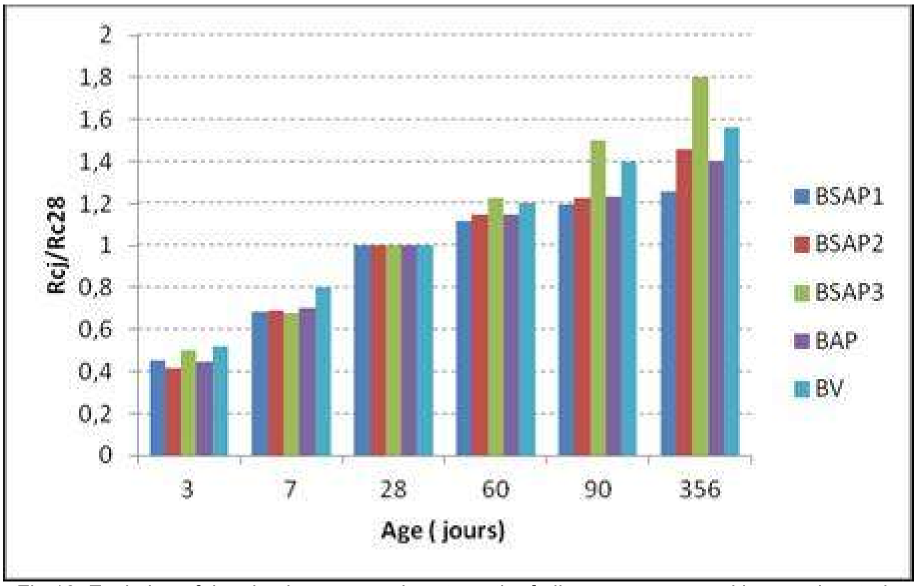


Fig.10. Evolution of the simple compressive strength of all concrete compositions under study

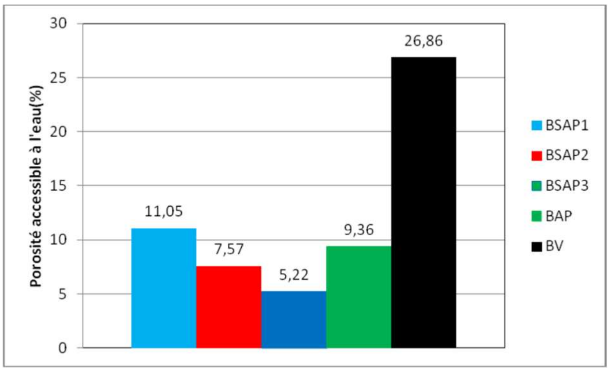


Fig. 11- Evolution of the simple compressive strength of all concrete compositions under study

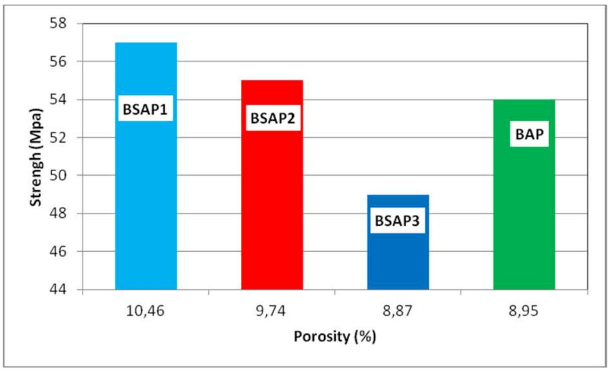


Fig 12 - The compressive strength at 28 days of the different types of concrete as a function of the open porosity.

capillary absorption, and diffusion of chloride ions in the SCSCs are studied and the results obtained are compared with those of the SCC and vibrated concrete (VC). The compressive strength is therefore taken as a point of comparison between these different types of concrete.

4.3.1. The porosity accessible to water

To study the durability of cementitious materials, it is necessary to know the structure of pores because it allows to define the microstructure and the performance of the material. Furthermore, the porosity structure inside concrete has a great influence on its mechanical properties, such as the strength, permeability, diffusion of chloride ions, etc. Three samples were considered for each one of the different formulations of concrete. The porosity was measured according to the procedure recommended by AFREM [20]. The mean values of porosity are shown in Figure 11.

From Figure 11, it is easy to see that vibrated concrete (VC) has an open porosity of 12.06%, which is greater than those of SCSC1, SCSC2, SCSC3 and SCC, which are equal to 10.46, 9.74, 8.87 and 8.95%, respectively. This slight difference is mainly due to the addition of mineral additions to SCSCs and SCC.

It is noted that the open porosity decreases (10.46%, 9.74%, 8.87%) when cement is replaced by known percentages of pozzolana in the case of SCSC1, SCSC2, SCSC3, respectively. The addition of fines has a filling function (filler effect).

The values of the mechanical resistance to compression as a function of the porosity accessible to water, of the different types of concrete, are shown in Figure 12.

The porosity accessible to water of vibrated concrete (VC) is higher than that of self-compacting sand concrete (SCSCs) and self-compacting concrete (SCC). For example, percentages equal to 13.27, 19.24, 26.45, and 25.79% were calculated for SCSC1, SCSC2, SCSC3, and SCC, respectively, at 28 days. High porosity values give lower compressive strengths, and this is the case of VC. It is confirmed that the mechanical resistance to compression of self-compacting sand concretes is inversely proportional to their porosity accessible to water. This means that if the porosity decreases, the mechanical resistance to compression increases; this is the case of SCSCs and SCCs. This is due to the filler effect of natural pozzolana. The behavior of self-compacting concrete is like that

Table 7

Results of capillary water absorption

Caractéristiques	SCSC1	SCSC2	SCSC3	SCC	VC
Sample thickness L (mm)	50	50	50	50	50
Average penetration depth X_d (mm)	21.56	19.88	12.18	26.57	33.52
Migration coefficient Dnssm $(m^2/s)x10^{-12}$	11.05	7.57	5.22	9.36	26.86

of self-compacting sand concrete regarding the porosity for all the durations considered.

4.3.2. Capillary water absorption

This physical phenomenon can make aggressive substances penetrate from the outside into concrete, which is indeed a material that has capillary pores whose size varies according to the characteristics of the composition (W/C ratio, mineral additions, etc.). When a liquid is in contact with this type of pores, superficial tensions cause this liquid to rise inside the capillaries. During the absorption test, only the total amount of water entering the sample is measured, and not the maximum height reached by the liquid, although water rises higher inside concretes with finer capillaries. The amount of water absorbed during this test decreases with the W/C ratio. The number and volume of pores in these types of concrete are smaller than in those which have a lower W/C ratio.

After an ordinary curing period, the capillary water absorption tests were carried out for a period of 24 hours, according to the recommendations of AFREM [20]. This made it possible to calculate the kinetics of this physical phenomenon in the case of self-compacting sand concrete (SCSC). The capillary absorption results obtained for these types of concrete are presented in Table 7.

From this table, it was possible to obtain the capillary absorption coefficients, and also the results of the kinetics of this absorption which were calculated in order to facilitate the comparison between the self-compacting sand concretes (SCSCs), self-compacting concrete (SCC) and vibrated concrete (VC).

First of all, it can be seen that the concretes with the highest W/C ratio (SCC and VC, W/C ratio equal to 0.57) have significant capillary absorption and absorption kinetics after a period of 24 hours. When self-compacting sand concrete (SCSCs) is directly compared with vibrated concrete (VC), one can easily note that self-compacting sand concretes have a capillary absorption and an absorption kinetics slightly lower than those of vibrated concrete. Therefore, it is possible that there may be some differences in the evolution of the microstructure between the two families of concrete. These results are found to be in good agreement with those of [21]. During the test, it was noted that in the case of vibrated concrete, the specimen is totally saturated after a test period equal to 24 hours. Table 7 shows that vibrated concrete (VC) has a larger capillary absorption coefficient than those of self-compacting sand concretes SCSC1, SCSC2, SCSC3, and self-compacting concrete SCC by 42.84, 44.54, 56.03, and 40.42%, respectively. Self-compacting sand concretes (SCSCs) behave similarly to self-compacting concrete (SCC) with respect to their capillary absorption.

4.3.3. **Chloride ion migration tests**

Diffusivity is a major indicator of sustainability. Measurement of the diffusion coefficient of chloride ions is very important for the prediction of the lifetime of reinforced concrete structures. Indeed, the attack of concrete by chloride ions leads to the destruction of the passivation layer on the steel surface and therefore causes their corrosion in the presence of water and oxygen. These chloride ions can come from concrete itself (aggregates, mixing water), but the existence of limiting norms in this respect push us to focus on chloride ions coming from the external environment (sea water, melting salts) [22]. It is therefore important to know the resistance of concrete to the aggressive chloride ions penetration. The determination of chloride ion diffusion in the different concrete samples under study was carried out by means of a migration test, as required by standard NT BUILD 492 [10].

The experimental results, of the apparent diffusion coefficient obtained for the various concretes tested, are shown in Table 8 and Figure 13.

One can see from Table 8 and Figure 13 that vibrated concrete (VC), which has a high W/C ratio (0.57) and a water porosity (12.06 %) that is higher than those of the other concretes (SCSCs and SCC), has a significant diffusion coefficient. These findings explain why the diffusion coefficient in vibrated concrete is of the order of 26.86 x 10^{-12} m^2/s; this value is quite high compared to that of other concretes which have values within the range extending from 9.36 to 11.05 x 10^{-12} m^2/s. If the different SCSC formulations are compared with that of SCC, one can easily notice that the chloride ion diffusion coefficient in SCSC1, SCSC2, SCSC3 is smaller, with the values 11.05, 7.57, 5.22 x10^{-12} m^2/s, respectively, knowing that the amount of pozzolana in SCSC2 is 20% greater than that in

Table 8

Values of the diffusion coefficients

Caractéristiques	SCSC1	SCSC2	SCSC3	SCC	VC
Capillary absorption coefficient for 24h (kg/m^2)	4.03	3.91	3.10	4.20	7.05
Capillary absorption kinetics (10^{-2}kg/(m².s$^{1/2}$))	1.37	1.33	1.05	1.43	2.40
Water porosity (%)	10.46	9.74	8.87	8.95	12.06

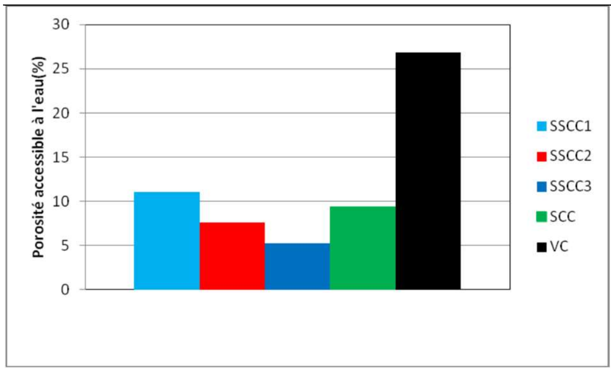


Fig. 13 - Representation of the diffusion coefficients of chloride ions

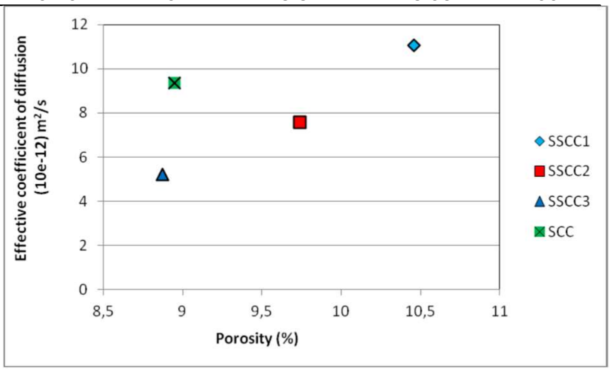


Fig. 14 - Diffusion coefficient as a function of porosity in our concretes

SCSC1 and in SCSC3 it is 30% greater than that in SCSC1. Thus, it can be said that the main factor responsible for the decrease in the diffusion coefficient of chloride ions is the increase in the amount of natural pozzolana. These results are consistent with those of Page C. L et al. [23-25].

Using large amounts of sand in the three formulations results in a more compact concrete with lower porosity (the porosity accessible to water decreases after each substitution of part of cement by the pozzolanic addition of 10.46, 9.7, 48.87%, for SCSC1, SCSC2, SCSC3, respectively. It may be noted that there is a direct relationship between the coefficient of chloride ion diffusion and open porosity. If the porosity decreases, then the diffusion coefficient decreases, as shown in Fig. 14 [26].

This figure shows that the combination of all these results indicates that vibrated concrete (VC) has a higher diffusion coefficient, i.e., 58.84%, 71.79%, 80.55%, 65.14% higher than those of SCSC1, SCSC2, SCSC3 and SCC. Similarly, vibrated concrete (VC) has higher values of porosity, i.e., 13.26%, 19.24% 26.45%, 25.79% higher than those of SCSC1, SCSC2, SCSC3, and SCC, respectively. The diffusion coefficients of self-compacting sand concretes have a proportional relation with the porosity accessible to water. Self-compacting sand concretes (SCSCs) have characteristics similar to that of self-compacting concrete (SCC). The variation of chloride ion diffusion coefficients as a function of porosity occurs in a similar way for self-compacting sand concrete (SCSC) and self-compacting concrete (SCC). For an easy experimental comparison of the durability values of SCSCs with those of VC, based on the results of chloride ion diffusion tests, it is worth representing these results as a function of the compressive strength of the different concretes, at 28 days, as shown in Figure 15.

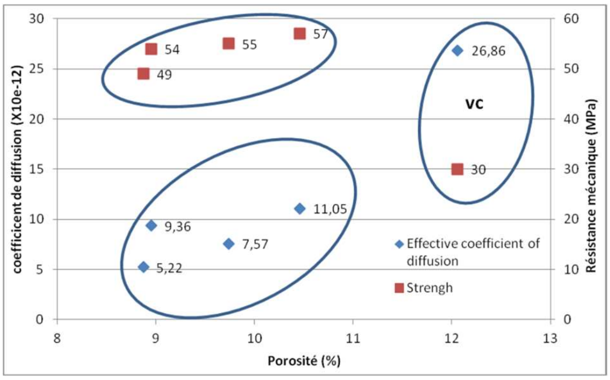


Fig. 15- Coefficient of *chloride ion diffusion* as a function of the compressive strength of the different concretes

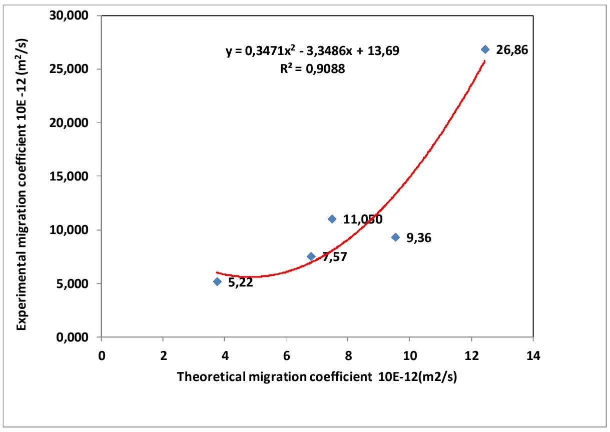


Fig. 16 - Theoretical and experimental chloride ion diffusion coefficients

This figure (Fig.16) shows that the results obtained in this research tend to indicate that vibrated concrete (VC) has a diffusion coefficient higher than that of self-compacting sand concrete (SCSC) and self-compacting concrete (SCC). This difference may be due to the formulation of concrete. Tang et al. reported that the presence of fines in concrete can lead to a decrease in the diffusion coefficient [27]. The diffusion coefficient of chloride ions in SCSCs and SCC increases with porosity. Similarly, the compressive strength varies with the diffusion coefficient. However, some researchers have reported that the compressive strength values of the concretes they considered were slightly larger than those of the SCSCs studied in this work. This difference is probably due to the cement dose, to the quantities of the different mineral additions, type and quantity of superplasticizer used, and to the presence or absence of a viscosity agent. The diffusion coefficients of chloride ions in SCSCs and SCC are different from that of vibrated concrete (VC). Thus, the remarkable differences between the microstructures of SCSCs and VC must result from the nature of the cementitious matrices of these concretes. Moreover, this difference between the diffusion coefficients in the two types of concrete tends to show that the differences in the composition of concretes (in particular the volume of paste and the quantities of adjuvants which are more important in the SCSC and SCC) play a preponderant role in the transfer properties of fluids inside concrete. Figure 16 shows the diffusion coefficients, which were calculated using the mathematical model developed by Tang and Lars-Olof Nilsson [28] using formula (1), as well as the experimental diffusion coefficients. It should be noted that the experimental values were found to be in good agreement with the theoretical ones. It was also observed that when the amount of pozzolan increases, the coefficient D increases as well.

$$D = 1.189 * 10^{-11} (X_d - 1.061X_d^{0.589}) / t \quad (m^2/s) \quad (2).$$

D: the diffusion coefficient (m^2/s).
X: means value of penetration depths (mm)

To better compare these sustainability indicators, one can observe the ratios of the experimental values of SCSC and SCC to those of vibrated concrete (VC), presented in Table 9. Regarding the formulation of vibrated concrete (VC), it was found that the values of porosity accessible to water were greater than those of self-compacting sand concretes (+27%) and superior to that of self-compacting concrete (+26%). The porosity accessible to water decreased from 0.87 for the SCSC1 to 0.81 for the SCSC2 and reached 0.73 for the SCSC3, for each substitution of cement by the pozzolanic fines. The diffusion coefficient decreased with 0.41, 0.28, 0.19, for the self-compacting sand concrete formulations, SCSC1, SCSC2, SCSC3, respectively, for each substitution of part of cement by the pozzolanic fines. On the other hand, the same coefficient was found to be higher in vibrated concrete than in self-compacting sand concrete (+ 81%) and self-compacting concrete (+ 65%). Capillary absorption was found to be greater in vibrated concrete than that in self-compacting sand concrete (SCSC) by +43, +45, +56% for SCSC1, SCSC2, SCSC3, respectively, and +51% for self-compacting concrete (SCC). The durability characteristics of the vibrated concrete are slightly different from those calculated for the SCSCs and SCC. The differences observed in these characteristics between the two types of concrete can therefore be explained by the significant differences between the porous network of SCC and that of vibrated concrete.

A parametric study of the ratios W/C and C/P as well as the different durability parameters are presented in Figure 17.

Table 9

Comparison of the physicochemical properties of all concretes studied.

Caractéristiques	**SCSC1**	**SCSC2**	**SCSC3**	**SCC**	**VC**
Compressive strength for 28 days (MPa)	51	48	40	47	25
Water porosity(%)	10.46	9.74	8.87	8.95	12.06
Potential durability (AFGC 2004)	Low	Low	Low	Low	Very low
Migration coeffcient (10-12m2/s)	11.05	7.57	5.22	9.36	26.86
Potential durability	Moderate	High	High	High	Low
Ratio	**SCSC1/VC**	**SCSC2/VC**	**SCSC3/VC**	**SCC/VC**	**VC/VC**
Water porosity (%)	0,87	0,81	0,73	0,74	1
Capillary absorption coefficient for 24h (kg/m^2)	0.57	0.55	0.44	0.59	1
Migration coeffcient Dnssm (m^2/s)x10^{-12}	0.41	0,28	0,19	0.35	1

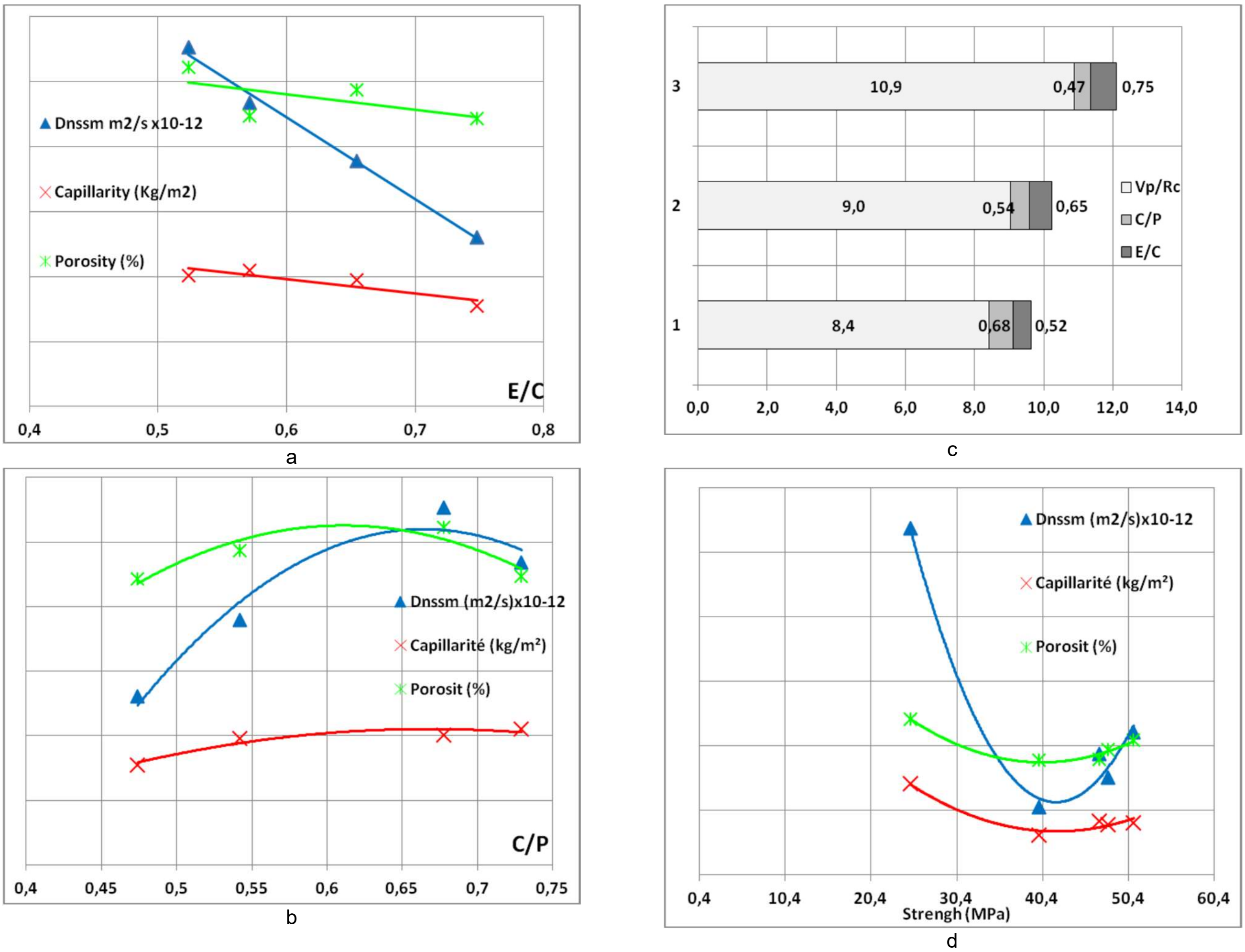


Fig. 17- Influence of the ratios W/C and C/P on the sustainability of SCSCs

Figures 17A and 17B show the evolution of porosity, capillarity, and diffusion of chloride ions in self-compacting sand concrete (SCSCs) as a function of the W/C and C/P ratios. It is noted that, unlike the diffusion coefficient, the porosity and capillarity decrease slightly with the variation of the W/C ratio. One can also notice that the maximum value of the C/P ratio is around 0.6.

Figure 17.C shows the ratios of paste volume to the mechanical strength as it changes with the ratios W/C and C/P. It can clearly be noted that the ratio W/C is inversely proportional to C/P; when the volume of paste increases, the W/C ratio decreases and the C/P ratio increases.

5.Conclusions

First, it should be recalled that the paste volumes of the SCSC and SCC compositions were larger than the volume of vibrated concrete. In addition, the granular skeletons were different for self-compacting sand concretes.

The main conclusions to be drawn from this work are:

• The compositions of self-compacting sand concretes (SCSCs) and self-compacting concrete (SCC) perfectly meet the required specifications in the fresh state (spreading, dynamic and static segregation, and stability).

• The compressive strengths of self-compacting sand concretes (SCSCs) and self-compacting concrete (SCC) are larger than that of vibrated concrete. This is certainly due to the use of natural pozzolana which leads to the formation of HSCs in the long run. This helps obtaining a more resistant concrete.

The capillary absorption coefficients, determined during the tests, show that the behavior of self-compacting sand concretes is similar to that of vibrated concrete.

• The porosities of self-compacting concrete (SCC) and self-compacting sand concrete (SCSC) are smaller than that of vibrated concrete. Porosity decreases when part of cement is replaced with 20% and 30% pozzolanic fines. Thus, pozzolan plays a filler effect role, in addition to its pozzolanic reaction.

• The use of materials containing pozzolanic additions allows better resistance to chloride aggression due to a lower diffusion coefficient for each substitution of part of cement with pozzolan.

• The coefficient of chloride ion diffusion is proportional to the porosity accessible to water. If the porosity decreases, the diffusion coefficient decreases and strength increases. On the other hand, if the porosity increases, the diffusion coefficient also increases but the strength decreases.

The overall results provide a clear answer regarding the sustainability of self-compacting sand concrete compared to vibrated concrete.

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