OPEN ACCESS
The Journal of Engineering and Exact Sciences – jCEC, Vol. 09 N. 04 (2023)
journal homepage: https://periodicos.ufv.br/jcec
eISSN: 2527-1075
ISSN: 2446-9416

Study of the durability of self-compacting concrete made from recycled gravel

Estudo da durabilidade do concreto autoadensável de brita reciclada

Article Info:
Article history: Received 2023-05-04 / Accepted 2023-06-01 / Available online 2023-06-06
doi: 10.18540/jcecvl9iss4pp15927-01e

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Abstract
Research has been carried out in Japan recently with the aim of creating concrete formulations characterized by high workability while being stable in order to adapt concrete to structures with more complex and heavily reinforced sections. (Low segregation, compaction, and bleeding) with strong mechanical properties. The result of this research is self-compacting concrete (SCC), a new type of concrete that can fulfill the aforementioned properties. SCC is distinguished by a high paste volume, a high fines volume, the use of superplasticizers, and a low gravel volume. Due to the increasing demand for aggregates, crushed gravel may be replaced with recycled gravel in the interests of environmental conservation and sustainable development goals. Steel fibers are added to recycled concrete and gravel SCCs to improve their properties. The objective of this research is to examine the durability in the hardened state as well as the physico-mechanical characteristics of self-compacting concrete (SCC) made from recycled concrete gravel. According to the results, the best recycled concrete gravel contains 50%, and the addition of 0.5% fibers improves the properties of these SCCs.
Keywords: Self-compacting concrete, Durability. Steel fiber. physico-mechanical properties, Recycled gravel. Limestone gravel. Open porosity.

Resumo
Recentemente, pesquisas foram realizadas no Japão com o objetivo de criar formulações de concreto caracterizadas por alta trabalhabilidade e estabilidade, a fim de adaptar o concreto a estruturas com seções mais complexas e fortemente armadas. (Baixa segregação, compactação e sangramento) com fortes propriedades mecânicas. O resultado desta pesquisa é o concreto autoadensável (CAA), um novo tipo de concreto que pode cumprir as propriedades acima mencionadas. O SCC se distingue por um alto volume de pasta, alto volume de finos, uso de superplastificantes e baixo volume de cascalho. Devido à crescente demanda por agregados, o cascalho triturado pode ser substituído por cascalho reciclado no interesse da conservação ambiental e dos objetivos de desenvolvimento sustentável. Fibras de aço são adicionadas ao concreto reciclado e SCCs de cascalho para melhorar suas propriedades. O objetivo desta pesquisa é examinar a durabilidade no estado endurecido, bem

como as características físico-mecânicas do concreto autoadensável (CAA) feito de cascalho de concreto reciclado. De acordo com os resultados, o melhor cascalho de concreto reciclado contém 50%, e a adição de 0,5% de fibras melhora as propriedades desses CAA.
Palavras-chave: Concreto autoadensável, Durabilidade. Fibra de aço. propriedades físico-mecânicas, cascalho reciclado. Cascalho de calcário. Porosidade aberta.

1. Introduction

Concrete is now used for a wider range of projects due to its versatility in production, use, and placement, as well as its affordability, mechanical performance, and durability. Among the concretes used, self-compacting concrete (SCC) was a step further after the search for durability and increased strength of concrete with high workability at the end of the 1980s in Japan (Okamura *et al*., 1999; Okamura *et al*., 2000; Okamura *et al*., 2003). Self-Compacting Concretes (SCCs) are concrete mixes that can flow and set into place without the need for external vibration. They offer better compactness and reduced noise emissions during installation compared to traditional vibrated concretes.

The widespread growth of urbanization has greatly accelerated the development of the construction industry. About 30 billion tons of concrete are made each year, making it the second-most consumed material in the world, second only to water. Due to its durability and lack of degradation, the dumping of this material causes a crucial environmental problem during the demolition of old buildings or in the event of natural disasters. Recycling this material would avoid both waste and useful materials. The construction industry is now very interested in making new concrete from demolition waste. Protecting the environment, preserving natural aggregate resources, eliminating public landfills, reducing waste treatment costs, and reducing the carbon footprint, especially if recycled concrete is used on site, are the main reasons for this growing interest. Recycling is currently underway on a global scale, involving many construction and scientific specialists to determine the standards for the use of this innovative material.

The study of the durability of self-compacting concretes based on recycled gravel is an interesting and relevant subject in the current context of sustainable development and waste reduction.

2. Materials and methods

2.1 Raw materials

We used regional materials readily available on the Algerian market to achieve our goals. The materials used to create all self-compacting concrete are the same. The materials used are listed in Table 1, and a summary of the physical-mechanical characteristics of the steel fiber and the aggregates is given in Tables 2 and 3, respectively.

Table 1 – Materials used.

Materials used	Type	Nature
Cement	CPA CEM II / 42,5	Portland
Gravel	(3/8) and (8/16)	Limestone
		Recycled
Sand	(0/5)	Alluvial
Fiber	Steel	Viscochape
Water	-	Potable
Superplasticizer	MEDAPLAST SP40	Water reducer

Table 2 – Steel fiber's mechanical and physical properties.

Characteristics	Figure 1 – Steel fiber used

Absolute density	78 kg/m^3	
Tensile strength	1120 MPa	
Geometry of Steel fibers (mm)	L_f = 30	
	$Ø_f$ = 0,55	
Slenderness (L_f/$Ø_f$)	54,54	

Table 3 – Aggregates' physical-mechanical characteristics.

Physical property	Sand	gravel			
		Limestone		Recycled	
	(0/5)	$(3/8)_L$	$(8/16)_L$	$(3/8)_R$	$(8/16)_R$
Absolute density (g/cm^3)	2,59	2,66	2,67	2,52	2,57
Apparent volumetric mass (g/cm^3)	1,54	1,36	1,38	1,20	1,26
Absorption (%)	1,36	2,31	2,31	6,71	6,21
Sand equivalent (%)	90	-	-	-	-
Fineness modulus	2,28	-	-	-	-
Los Angeles coefficient (%)	-	-	21,6	-	23,1

2.2 Formulation of self-compacting concrete with steel fiber

The Dreux-Gorisse method is used to create regular concrete, but self-compacting concrete (SCC) cannot be created using this method (Su et al., 2003). Currently, the majority of SCC formulas are created empirically. Thus, the formulation is based on knowledge gained in recent years.

If necessary, the ratios, particularly W/C and Sp/C, will be adjusted to achieve results sufficient for a good spread without segregation or bleeding when determining the dosage of superplasticizer and fiber required based on the results of tests on mortar.

We have met the requirements to ensure self-placing while basing our compositions on those suggested in specialized literature by formulating the reference SCC_L with 100% crushed limestone gravel (0% recycled gravel).

The ratios of the components in 1 m^3 of concrete must be chosen, using the following parameters as data (Brouwers et al., 2007):

Cement (C) + Sand (S) + Gravel (GL) + Water (E) + Air (A) = 1000 liters.

♦ ratio G/S ≃1 ♦ percentage of 2.45% Sp

♦ ratio W/C = 0.42 ♦ cement C= 450 kg /m^3.

After obtaining the reference SCC_L, we use the same reference compositions as the control, with the exception of the sand, to create the fiber-reinforced SCC_L. We adjust the replacement by 0.5, 1, 1.5, and 2% of the fiber volume and measure the self-compacting concrete.

We discover that the characteristics of the self-compacting concrete in its fresh state are satisfactory at 0.5 % of fiber, so we use this percentage as a guide. With regard to the second SCC, we begin by replacing 50% of the gravel with recycled gravel before moving forward with all of the tests on brand-new concrete. Table 4 gives the notations used in our work for the different SCCs tested.

Five (05) mixtures were created; Table 5 provides a summary of the various concrete compositions. According to the most recent recommendations of the French Association of Civil Engineering (AFGC) (French association of Civil engineering, 2000), self-compacting concrete was created.

Table 4 – The symbols for the various SCCs.

Notations	Designations

SCC_L	SCC with 100% limestone gravel (G_L)
SCC_{fL}	SCC with fiber, reference SCC with 100% limestone gravel (G_L)
SCC_{fR50}	SCC with fiber and 50% recycled concrete gravel (G_R) + 50% (G_L)
SCC_{fR75}	SCC with fiber and 75% recycled concrete gravel (G_R) + 25% (G_L)
SCC_{fR100}	SCC with fiber and 100 % recycled concrete gravel (G_R) + 0% (G_L)

Table 5 – Composition of the different SCC in kg for 1m^3.

Composition	Concrete				
	SCC_L	**SCC_{fL}**	**SCC_{fR50}**	**SCC_{fR75}**	**SCC_{fR100}**
Cement	450				
Sand 0/5	849.4	844.4	844.4	844.4	844.4
Gravel $(8/16)_L$	583.84	583.84	291.92	145.96	-
Gravel $(3/8)_L$	290,82	290,82	145.47	72.71	-
Gravel $(8/16)_R$	-		280.95	421.43	561.88
Gravel $(3/8)_R$	-		173.74	206.58	275.46
Steel fiber	-	39			
Water	191	191	211.9	222.4	232.9
S_p (%)	2,45				
W/C	0,42				

3. Test results and discussion

3.1 Characteristics of the (SCC) in a fresh state

Just after the mixing, the characteristic tests on freshly mixed concrete were conducted. They are as follows: spreading out with the slump test, flow with the box in L, and stability with the sieve, which are those suggested by the French Association of Civil Engineering. They want to gauge the fluidity, static segregation, and dynamic segregation of the (SCC). The characteristics obtained for the various (SCC) tested in the fresh state are summarized in Table 6.

Table 6 – Table of test results summary in a fresh state (SCC).

Test	Mixture descriptions				
	SCC_L	**SCC_{fL}**	**SCC_{fR50}**	**SCC_{fR75}**	**SCC_{fR100}**
Slump test (cm)	74.1	70.2	71.3	72.5	74.2
	1,63	1,62	1,51	1,71	1,33
L-Box test (%) "Filling capacity"	88,6	85.2	89.2	80,6	86.2
	3,45	3,3	2,9	5,35	5
	1,41	1,21	1.1	2,4	2,5
V-funnel flow, T_V (s)	7,6	7.1	6,6	18	21,5
Sieve stability test Π (%) "Stability in the sieve"	8,94	7,8	7,2	8,3	9,4

It should be noted that all of the self-compacting concrete's fresh state characteristics are satisfactory, with the exception of the V-funnel flow test for the two concretes SCC_{fR75} and SCC_{fR100} due to the quantity of large fines, and that the visual evaluation is positive for all self-compacting concrete.

<u>Characteristics of the (SCC) in a hardened state:</u> Test tubes (10 10 10 cm3) in the shape of cubes were used to create the formulations for the studied concretes. We perform the subsequent actions:

Under laboratory conditions (T=20 ± 1°C and HR= 45±5%), the test tubes were left in the open for 28, 60, and 90 days, and a cure in water for 28 days.

Test of absorption of water (initial absorption by capillarity): The term "absorption of water" refers to the movement of liquid through a porous material as a result of surface stresses in the capillaries. The open porosity and porous networks of the concrete are what determine how much water will be absorbed by capillary increase inside the no-slump concrete. This test is designed to determine how quickly concrete test tubes absorb water through capillary suctions after being exposed to water without pressure for 28, 60, and 90 days. The samples will be packaged in the drying oven at roughly 105 °C until they reach a constant mass prior to sorptivity measurements. The elaborate concrete test tubes are weighed on the day of the test to determine their masses before and after absorbing water for an hour, that is:

$$A_{bi} = [(M_{P2}-M_{P1}) / S_u \, (t)^{0.5}] \quad (1)$$

M_{P2}: mass (test piece) after absorption of water;
M_{P1}: mass before absorption of water;
S_u: surface of the base of the test piece (10^2 cm^2);
t: time (1 hour).

The amount of water absorptive per unit of area at the end of an hour's absorption, it expresses the size of the largest pores within the concrete sample concerned (Balayssac *et al*., 1993; Rabehi *et al*., 2012), with these capillaries being the most efficient.

Water is prevented from evaporating by the side faces by using a plastic film (an adhesive ribbon plastic) to waterproof them. This film forces water to move in a uniaxial direction. Succeeding test-tube weighings yield the absorptive water mass (see Figure 2).

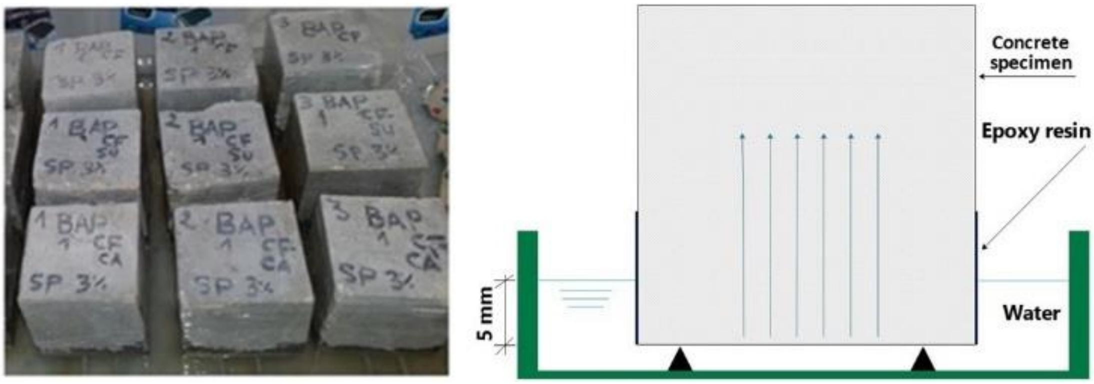

Figure 2 – Test of the absorption of water by capillaries.

After one hour of sucking water, the absorption coefficients of the initial water will be noted as A_{bi} ($kg.m^{-2}.h^{-1/2}$). In Table 7 and Figure 3, the rate of gain is used to represent the totality of the SCCs.
Rate of gain:

$$A_{bi} = \left| \frac{A_{bi_{j\,(without\ cure)}} - A_{bi_{j\,(cure)}}}{A_{bi_{j\,(without\ cure)}}} \right| \quad (2)$$

Table 7 – SCC's initial water absorption coefficients (A_{bi}) and their rate in A_{bi}.

		Differents SCC				
Age (days)	**Mode of curing**	**SCC_L**	**SCC_{fL}**	**SCC_{fR50}**	**SCC_{fR75}**	**SCC_{fR100}**

	Water	1,64	1,54	1,61	1,63	1,81
28	Air	2,61	2,46	2,51	2,63	2,76
	R_{Abi}	36,55	36,74	36,01	37,41	34,56
	Water	1,59	1,52	1,54	1,66	1,79
60	Air	2,54	2,42	2,43	2,57	2,66
	R_{Abi}	37,26	36,52	36,49	35,67	32,46
	Water	1,56	1,49	1,50	1,63	1,67
90	Air	2,51	2,38	2,42	2,57	2,62
	R_{Abi}	37,21	37,25	37,87	36,06	35,64

R_{Abi} = Rate in A_{bi} (%)

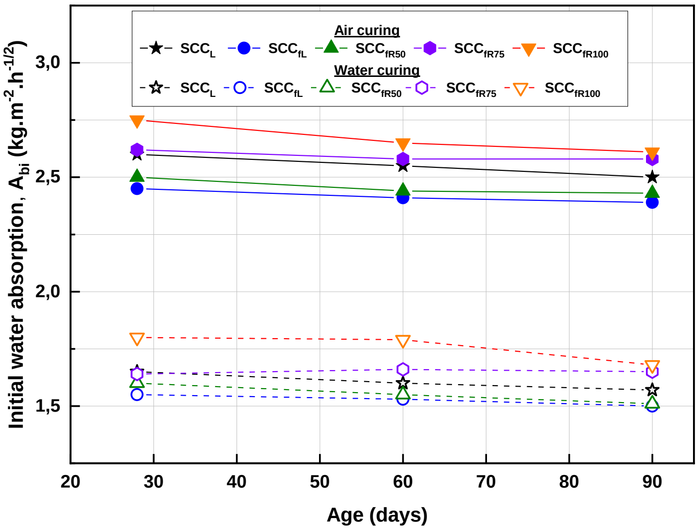

Figure 3 – Absorption of initial water (A_{bi}) of the all.

Figure 3 presents the results of the initial water absorption (A_{bi}) of the prepared self-compacting concrete (SCC). We note that the absorption decreases with age (28, 60, and 90 days) and according to the percentage of gravel additions recycled. The results shown in Figure 3 show a decrease over time of (A_{bi}) for all of the SCC. We notice that the substitution of 50% of limestone gravel by recycled gravel in the presence of steel fibers gives an absorption similar to that of the control concrete SCC_{fL}.

This means that SCC_{fL}, SCC_{L}, and SCC_{fR50} are less porous and have better transport properties than other concretes. This can be explained, on the one hand, by a decrease in the porous network, by the fines of recycled concrete, and by the presence of metal fibers (Youness *et al*., 2021). On the other hand, the improvement is due to the reduction in cracking by the fibers (Lee *et al*., 2021).

Test of unaxal pressng: Compression testing is done in accordance with the requirements of standard (NF P 18-406). It entails applying axial compression to crush the concrete test tube. Until the test tube ruptures, loading must be done continuously (see Figure 4).

Fig. 4 – Test-tubes before and after crushing.

Table 8 and Figure 5 show the averages of the direct compression crush (C_{Sj}) test results at 28, 60, and 90 days of age. On the one hand, the findings in Figure 5 demonstrate a definite shift and increase in the compressive strength of various SCCs produced as a function of age. We were able to determine that the compressive strengths of SCC_{fL}, SCC_{L}, and SCC_{fR50} are superior to those of SCC_{fR75} and SCC_{fR100}. These findings can be attributed to the type of gravel used, its percentages, the use of steel fiber, and the effects these factors had on the increased compressive strength.

Table 8 – Compressive strength C_{Sj} of SCC (MPa).

		Differents SCC				
Age (days)	**Mode of curing**	**SCC_{L}**	**SCC_{fL}**	**SCC_{fR50}**	**SCC_{fR75}**	**SCC_{fR100}**
28	Water	41,65	42,85	42,20	41,48	39,92
	Air	40,52	41,73	40,54	40,10	39,47
	R_{Abi}	2,65	2,58	4,05	3,62	1,27
60	Water	43,72	43,76	42,92	42,83	40,54
	Air	42,10	42,22	42,07	42,13	39,91
	R_{Abi}	3,67	3,55	2,11	1,65	1,49
90	Water	44,93	45,34	44,92	44,42	41,31
	Air	44,21	44,32	44,05	43,61	40,31
	R_{Abi}	1,57	2,22	2,01	1,81	2,43

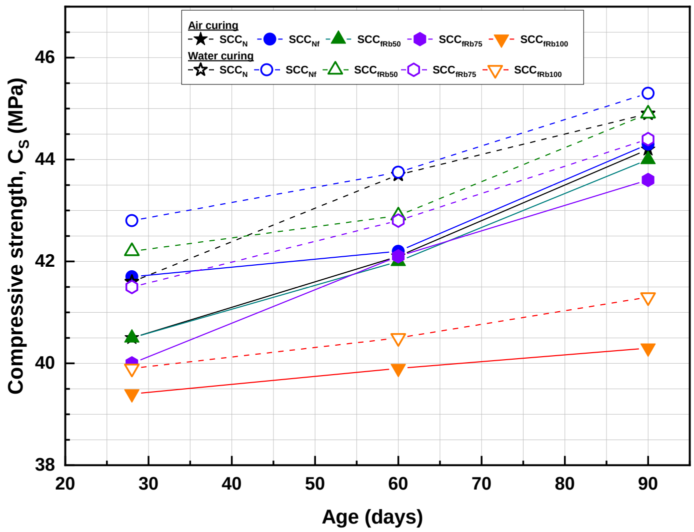

Fig. 5 – Evolution of the compressive strength C_S of the concretes according to their age.

Test of tensle strength (by three-pont bendng): In the tensile strength test, prismatic specimens (7x7x28 cm^3) supported by two supports are subjected to an increasing load until they fail. A digital reading press that is connected to an acquisition system (PC) and through which the loading speed (50 N/s) is entered is used to apply the load. The same system also provides the breaking force. By performing a straightforward calculation of the materials' strengths, the tensile strength is determined.

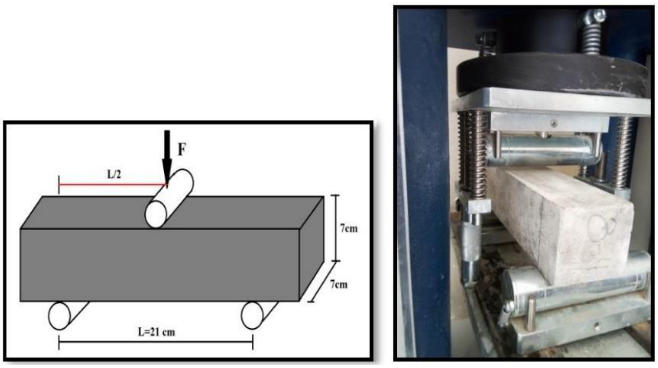

Fig. 6 – Device and static diagram for the bending tensile test.

Figure 7 displays the outcomes of the three-point flexural tensile test at the ages of 28, 60, and 90 days.

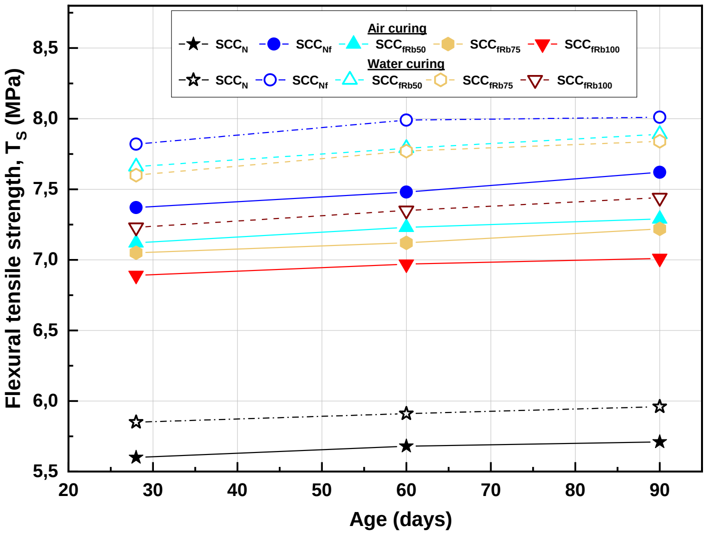

Fig. 7 –The bending tensile strength T_{Sj}

As a function of age, the results shown in Fig. 7 demonstrate, on the one hand, a noticeably increased tensile strength of the various concretes produced. On the other hand, the presence of water treatment led to improvements in all of the studied mixtures. SCC_L, SCC_{fR75}, and SCC_{fR100} scored lower resistance than SCC_{fL} and SCC_{fR50}. Thus, the steel fiber is attributed to the improved flexural strength of SCC in the presence of limestone and recycled gravel.

4. Durability

The test of resistance to attack of SCCs by acids is done for the purpose of evaluating the capacities of these SCCs to resist degradation when it is vulnerable to an acidic environment which is aggressive. In this study, five SCC compositions were tested for aggressiveness, the SCC without steel fiber, the control SCC (SCC_{fL}) and the control SCC containing percentages (50%, 75, and 100 %) of recycled gravel in place of limestone gravel. We observe the evolution of the mass of the samples while they are in solutions with a concentration of 5% acid by volume, they are placed in a medium of ambient temperatures of 22°. It is noted that in the literature, this concentration (5%) at instead of 3% is frequently chosen (Samimi *et al.*, 2016; Omrane *et al.*, 2017; BENOSMAN *et al.*, 2010; Omrane kenai *et al*., 2017; DOUARA *et al*., 2019), since a low concentration would require more testing time. The acids used are hydrochloric acid (HCl) and sulfuric acid (H_2SO_4).

The samples of five SCCs tested are cubically (10x10x10) cm^3. Three specimens are used for the different SCCs produced. These samples were kept for 28 days in water before testing. Concentrations of 3.8% HCl acid and 9.8% H_2SO_4 acid were used to prepare very aggressive solutions with a 5% concentration. The samples were dried at 20°C and 50% relative humidity for 24 hours before immersion in order to determine their initial mass. Each of the 5 types of SCC is placed in the same containers for each acid solution. The test images are shown in Figure 8.

Figure 8 – Preservation of SCC specimens in acid media.

After 28 days, 90 days and 180 days of immersion, acid degradation was evaluated. Samples were taken from the solution at each measurement, rinsed gently with water to get rid of bulk reaction products, then left to dry at 20°C and 50% RH for half an hour before analysis. The resistances to degradation by the acids mentioned before were physically evaluated (variations (loss) of mass). Formula (4) is used to determine by how much the masses of each sample change at each measurement age:

$$\Delta M_{SCC\,(d)}\,(\%) = [(M_{(0)} - M_{(d)}) / M_{(0)}] \times 100 \quad (4)$$

Where: $\Delta M_{SCC\,(d)}$: Loss of mass at (d) days of the targeted SCC sample (%) $M_{(0)}$: The mass of a SCC specimen before immersion in acid (g), $M_{(d)}$: The mass of a SCC specimen after the attack at (d) days (d, 28,56, 90 and 180) (g).

4.1 Loss of mass

Attack by HCl: For various self-compacting concrete stored in the 5% concentrated HCl solution, Figure 9 represents the change in mass (%) measured at the end of each period (days) of immersion.

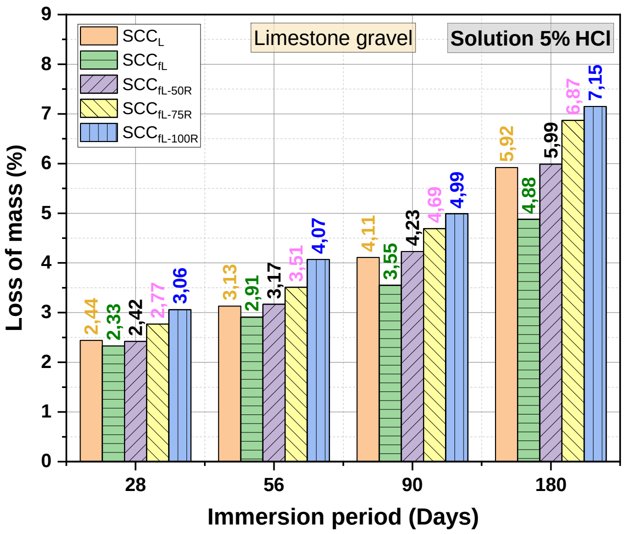

Figure 9 – Variation in the mass of SCC according to the age of immersion in HCl

The graphs show that the results have the same trend and that there is a progressive mass loss with age for all types of SCC exposed to the HCl solution regardless of the type of gravel used, i.e. say that all the SCCs suffered mass losses. The degradation kinetics gradually increase with time up to 180 days.

The comparison between SCC with fiber and without fiber confirms that the use of fiber decreases the loss of mass by 21.3% compared to the SCC at 180 days. This shows that the use of fiber has a positive and beneficial effect.

It is noted that the use of recycled gravel increased the mass loss, and this increase is magnified by the increase in the percentage of recycled gravel. The mass loss of SCC_{fL} with (25%, 50%, and 75%) recycled gravel is higher than that of control SCC_{fL} and was respectively 22.75%, 40.78%, and 46.52% after 180 days of immersion. It can be seen that the loss in mass reaches 7.15% at 180 days of SCC_{fL-75R}, with SCC_f containing 25% limestone gravel and 75% recycled gravel; this means that it is the most likely SCC to degrade in all immersion ages and is followed by SCC_{fL-50R}, which has losses in mass after 180 days of immersion of 6.87%. The control SCC_{fL} has good resistance to HCl attack after all periods of immersion.

Hydrochloric acid HCl reacts with portlandite ($Ca(OH)_2$) released during hydration of portland cement to form the highly water-soluble calcium chloride salt $CaCl_2$. On the other hand, hydrochloric acid is a strong acid that can react with the mineral components of concrete, such as cement and aggregates, to cause chemical dissolution of the material. Specifically, when in contact with concrete, hydrochloric acid can react with the carbonate ($CaCO_3$) components present in concrete, such as limestone, to produce water and carbon dioxide. This chemical reaction equation (1) can cause the concrete to lose mass and deteriorate its structure.

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O \quad (1)$$

Additionally, hydrochloric acid can also react with the alkaline components of concrete, such as silica and alumina, to form chlorides. Chlorides can penetrate the concrete and cause corrosion of the metal reinforcements, which in turn can weaken the structure of the concrete.

Attack by H_2SO_4: For various self-compacting concrete preserved in the 5% concentrated H_2SO_4 solution, Figure 10 represents the variation in mass (%) measured at the end of each period (days) of immersion.

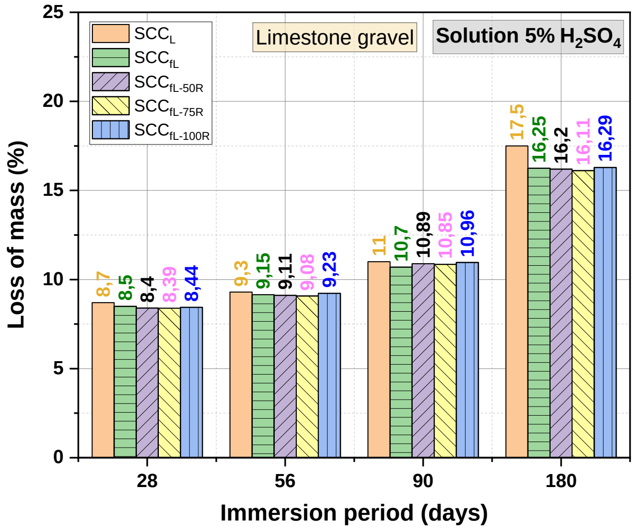

Figure 10 – Variation in SCC mass as a function of H_2SO_4 immersion age.

The graphs show that the results show the same tendency for SCC deterioration and that there is a progressive mass loss with age for all types of SCC exposed to the H_2SO_4 solution, regardless of the type of gravel used.

The degradation kinetics increase progressively with time until day 180. The comparison between SCC_{fL} control SCCs and the SCCs with recycled gravel confirms that the mass loss of the SCCs containing 25% recycled gravel is slightly lower between 0.24% and 1.74% than SCC_f without recycled gravel, and the mass loss of SCC_f containing 50% recycled gravel is slightly lower between 0.24% and 1.31% than SCC_f without recycled gravel. This shows the advantage of using recycled aggregates because it stops further degradation.

Note that the effect of sulfuric acid, H_2SO_4, is very aggressive compared to HCl acid. The mechanism of sulfuric attack on concrete begins with the interaction of sulfuric acid with the alkaline components of concrete, such as Portland cement and calcium hydrates. When sulfuric acid reacts with these alkaline components, it forms calcium sulfate ($CaSO_4$), which can crystallize inside the pores of the concrete.

Calcium sulfate crystals are larger in size than cement hydrates and therefore can cause an increase in internal pressure, which can ultimately cause cracking of concrete [221]. Calcium sulfate crystals can also dissolve and settle in concrete pores, which can cause a reduction in concrete strength and durability.

5. Conclusions

Results for SCC with both limestone gravel and recycled concrete gravel in the presence of steel fiber are presented in the article. The following are the key findings:

- The self-compacting concrete under study possesses qualities that meet AFGC (the French Association of Civil Engineering) specifications.
- The steel fiber used for our study's development can help the SCC in particular by enhancing its tensile and compressive strength.
- All of the tested self-compacting concrete's compressive strength C_S and flexural tensile strength T_S increase with age without decreasing.
- In comparison to SCC_{fR75} and SCC_{fR100}, this resistance is higher for SCC_{fL}, SCC_L, and SCC_{fR50}.
- The SCC's behavior changed as a result of the fiber addition, and the SCC reinforced with metal fiber experienced an increase in compressive and flexural strength.
- When compared to other concretes, the substitution of crushed gravel with 50% recycled concrete gravel has produced the best results in terms of physico-mechanical properties.
- The results show the fragility of all SCC formulations with respect to the aggressiveness of sulfuric acid and HCl. All studied SCCs show progressive degradation with immersion time. This degradation kinetics increase with the percentage of recycled gravel.

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