



**HAL**  
open science

## **Durability and transport properties of SCC incorporating dredged sediments**

Amine El Mahdi Safhi, Patrice Rivard, Ammar Yahia, Kamal Henri Khayat,  
Nor-Edine Abriak

### ► **To cite this version:**

Amine El Mahdi Safhi, Patrice Rivard, Ammar Yahia, Kamal Henri Khayat, Nor-Edine Abriak. Durability and transport properties of SCC incorporating dredged sediments. *Construction and Building Materials*, 2021, 288, pp.123116. <10.1016/j.conbuildmat.2021.123116>. <hal-03772404>

**HAL Id: hal-03772404**

**<https://hal.science/hal-03772404v1>**

Submitted on 24 Apr 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

# Durability and transport properties of SCC incorporating dredged sediments

**Amine el Mahdi Safhi<sup>1,2,3\*</sup>, Patrice Rivard<sup>3</sup>, Ammar Yahia<sup>3</sup>, Kamal Henri Khayat<sup>4</sup>,  
Nor-Edine Abriak<sup>2</sup>**

<sup>1</sup> Mohammed VI Polytechnic University, EMEC Program, Ben Guerir, Morocco

<sup>2</sup> Université de Lille, Institut Mines-Télécom Lille Douai, ULR 4515 - LGCgE, Douai, France

<sup>3</sup> Université de Sherbrooke, Civil and Building Engineering Department, Sherbrooke, Canada

<sup>4</sup> Missouri S&T, Center for Infrastructure Engineering Studies, Rolla, MO, USA

## ABSTRACT

The use of sediments as supplementary cementitious material is increasing, but very limited information on their effect on durability are available. The aim of this study is to evaluate the durability and transport properties of self-consolidating concrete (SCC) incorporating treated marine sediments (TMS) dredged from Dunkirk harbor. Three SCC mixtures made with 0% (SCC-R), 10% (SCC-1), and 20% (SCC-2) sediments as partial substitution of cement weight were investigated. The mixture proportions were optimized to provide adequate self-consolidating characteristics, including high filling and passing abilities, as well as adequate stability. The optimized SCC mixtures exhibited comparable hardened and microstructural properties at 91 days of age, including compressive strength of  $66 \pm 1$  MPa, splitting tensile strength of  $6 \pm 0.3$  MPa, and total porosity of  $9 \pm 0.4$  %. The obtained test results revealed that the incorporation of TMS reduced the critical pore volume ( $< 20$  nm) due to their pozzolanic reaction and filling ability. Despite this reduction, increasing TMS content increased permeability and diffusion (e.g., carbonation). Indeed, SCC-1 and SCC-2 showed higher sorptivity of 7.5% and 19.8%, respectively, than that of SCC-R

\* Corresponding author: Amine el Mahdi Safhi

Email: [amineelmahdi.safhi@um6p.ma](mailto:amineelmahdi.safhi@um6p.ma)

Current address: Mohammed VI Polytechnic University, EMEC Program, Ben Guerir, Maroc

23 (2.81 E<sup>-3</sup> mm<sup>3</sup>/mm<sup>2</sup>.s<sup>1/2</sup>). However, SCC-1 showed comparable durability performance to the  
24 reference mixture, including chloride penetrability, electrical resistivity, drying shrinkage, external  
25 sulfate attack, and alkali-silica. Meanwhile, the use of 20% TMS negatively influenced the chloride  
26 penetrability, external sulfate attack, and carbonation velocity. This substitution rate can be  
27 considered without mitigating durability of reinforced concrete in moderate exposure conditions.

28 **Keywords:** Blended cement; Dredged sediment; Durability; Self-consolidating concrete;  
29 Supplementary cementitious materials; Transport properties.

## 30 1. INTRODUCTION

31 In compliance with the EN 206-1 specifications [1], concrete performance encompasses  
32 mechanical properties and durability. The reported “Performance-based Approach” is based on  
33 testing relevant durability indicators given predefined exposure classes, such as corrosion, chemical  
34 attacks, and/or physical degradation [2]. Concrete durability is greatly related to its transport  
35 properties, including permeability, sorptivity, and diffusion. These properties are governed by the  
36 pore structure of the matrix and their connectivity. Durable concrete requires lower porosity and  
37 permeability to limit penetration of aggressive ions due to diffusion and capillary absorption [3]  
38 depending on the targeted exposure conditions. Durability improvement can be achieved by using  
39 supplementary cementitious materials (SCMs). Indeed, the pozzolanic activity of SCMs consume  
40 calcium-hydroxide (CH) produced during cement hydration to form additional calcium-silicate-  
41 hydrate (C-S-H). This can lead to a dense microstructure, reduces the permeability of the hydrated  
42 cement, thus lowering ingress of chlorides (reinforcement corrosion) [4] and carbon dioxide  
43 (concrete carbonation) [5].

44 Partial replacement of cement with SCMs is an efficient way to reduce the demand for natural  
45 resources and decrease the CO<sub>2</sub> footprint. SCMs contain a large amount of amorphous silica and  
46 alumina, which can react with calcium hydroxide in hydrating cement to form additional hydration  
47 products. Industrial by-products, including fly ash, ground blast furnace slag, and silica fume have

48 been used as SCMs for many decades. In addition, various sub-products such as ceramic waste  
49 powder [6], waste perlite powder [7], raw diatomite [8], natural zeolite [9], as well as  
50 nanomaterials, i.e. silicon dioxide ( $\text{SiO}_2$ ), titanium oxide ( $\text{TiO}_2$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), calcium  
51 carbonate ( $\text{CaCO}_3$ ), zirconium oxide ( $\text{ZrO}_2$ ), ferric oxide ( $\text{Fe}_2\text{O}_3$ ), clay, and carbon nanotube  
52 [10,11] have been used as SCMs. The use of SCMs is essential to increase the volume of paste and  
53 enhance workability of self-consolidating concrete (SCC). However, the limited availability of  
54 natural resources opens the way for searching viable source for SCM. Dredged sediments appeared  
55 to be good alternative SCMs as they are available in huge quantities exceeding one-billion-meter  
56 cube per year all over the world [12–14].

57 The pozzolanic potential of dredged sediments has been reported in literature [14–16]. However,  
58 very limited studies have been carried out to evaluate their effect as SCMs on properties and  
59 durability performances of SCC [17–19]. Rozas et al. [17] provided a guideline to assess the  
60 performance of recycled dredged sediments from Spanish Mediterranean Harbor, which were used  
61 as filler. Only one mixture was tested using  $450 \text{ kg/m}^3$  of cement,  $100 \text{ kg/m}^3$  of dredged sediments,  
62 and a w/c ratio of 0.45. The investigated concrete exhibited compressive strength of 44 MPa, total  
63 porosity average of 9.2%, electrical resistivity of  $49 \text{ k}\Omega\cdot\text{cm}$ , chloride diffusion coefficient ( $D_s$ ) of  
64  $1.12 \text{ E}^{-8} \text{ cm}^2/\text{s}$ , and capillary absorption of  $1.44 \text{ E}^{-3} \text{ kg/m}^2\cdot\text{min}^{1/2}$  after 28 days of age. In accordance  
65 with the durability indicators described in “Concrete design for a given structure service life” in the  
66 Spanish Code on Structural Concrete (EHE-08), the authors claimed that sediments can be used as  
67 fillers in SCC, although tests have been conducted on only one mixture. Rozière et al. [18] used  
68 dredged sediments as total replacement of limestone filler for SCC production. Sediments were  
69 collected from the Dampremy - Charleroi region in Belgium and treated using the Novosol<sup>®</sup> process  
70 (phosphatation and calcination). In the case of a constant w/c ratio of 0.57, the sediments-based  
71 SCC showed approximately 8% drop in slump flow, higher yield stress and plastic viscosity, as well  
72 as workability loss. However, comparable compressive strength and density were found at different  
73 ages. Nanoindentation measurements showed that the elastic modulus of hydrated cement pastes in

74 the sediment-based SCC was 27 GPa (16% higher than the reference mixture). Bouhamou et al.  
75 [19] investigated the influence of 10%, 15%, and 20% replacements of cement by calcined dam  
76 mud sediments on the shrinkage of SCC. The sediments were dredged from the dam of Fergoug in  
77 Algeria and treated at a temperature of 750 °C. The authors reported that the use of calcined mud  
78 resulted in viscous and less workable SCC mixtures. Also, the sediments showed a negative effect  
79 on strength, but the use of 10% sediments did not significantly affect the compressive strength (less  
80 than 10% variation) compared to the control mixture. Moreover, lower autogenous and drying  
81 shrinkage values were observed. Indeed, SCC containing 20% of sediments developed a total  
82 drying shrinkage of 150  $\mu\text{m}/\text{m}$  after 90 days of exposure, which is 23% less than the control  
83 mixture. This paper is part of a wide investigation on valorizing sediments from Dunkirk Port as  
84 SCM in SCC mixtures.

## 85 **2. RESEARCH SIGNIFICANCE**

86 Previous investigations on pastes and mortars [20,21] revealed that dredged marine sediments  
87 did not show negative effect on fresh properties when the water demand of sediment is taken into  
88 account. Using a multi-objective optimization for workability properties and compressive strength  
89 development at different ages, an optimal substitution content of 7% to 35% were reported in the  
90 case of binder content ranging between 380 and 600  $\text{kg}/\text{m}^3$  and water-to-cementitious materials  
91 ( $w/cm$ ) of 0.32 and 0.34. Based on these findings, a scale-up study of these sediments has been  
92 conducted to evaluate their effect of durability of SCC [22]. The investigated SCC mixtures were  
93 proportioned with total binder content of 450  $\text{kg}/\text{m}^3$ , two different sediment's contents of 10% and  
94 20%.

95 The investigated SCC mixtures exhibited adequate self-consolidation characteristics with high  
96 filling ability, high passing ability, and high stability resistance. Furthermore, the investigated SCC  
97 mixtures showed similar compressive strength of  $66 \pm 1$  MPa and a total porosity of 9% at 91 days  
98 of age. This was attributed to the pozzolanic reaction of the sediments that contributed to refining  
99 microstructure of the interfacial transition zone (ITZ). Nevertheless, durability study of those SCC

100 mixtures was not established. This paper investigated the durability indicators and transport  
101 properties, including capillary absorption, sorptivity, chloride penetrability, electrical resistivity,  
102 drying shrinkage, external sulfate attack, alkali silica reaction, and accelerated carbonation of the  
103 investigated SCC mixture containing dredged marine sediments provides useful information on the  
104 use of TMS in SCC production, which goes along with the 3R concept, Reduce, Recycle, and  
105 Reuse.

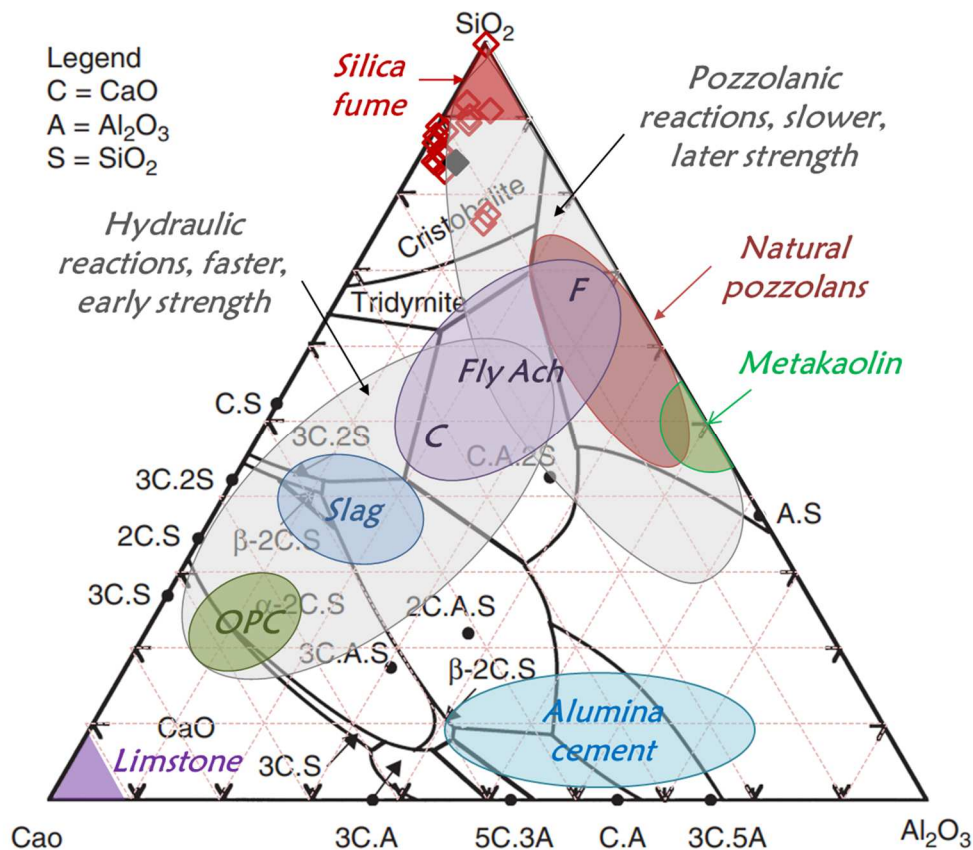
### 106 **3. MATERIALS, MIXTURE PROPORTIONS, AND METHODOLOGY**

#### 107 **3.1. Constituent materials**

108 The investigated mixtures were proportioned using a ternary binder complying with the  
109 ASTM C150 specifications [23]. The binder is composed of 70% General Use (GU) cement, 25%  
110 Class F fly ash, and 5% of silica fume. It has a specific density of 2890 kg/m<sup>3</sup> and a BET surface  
111 area of 2535 m<sup>2</sup>/kg. Two crushed coarse aggregates CA<sub>1</sub> (10/20 mm) and CA<sub>2</sub> (5/10 mm) were  
112 used. The CA<sub>1</sub> and CA<sub>2</sub> have specific densities of 2.76 and 2.72 g/cm<sup>3</sup>, absorption rates of 0.48%  
113 and 0.41%, and bulk densities of 1465 and 1444 kg/m<sup>3</sup>, respectively. A siliceous river sand with a  
114 specific density of 2.66 g/cm<sup>3</sup>, an absorption rate of 1.09%, and a bulk density of 1785 kg/m<sup>3</sup> was  
115 used.

116 The sediments were collected from the Dunkirk Harbor in France, dried in an oven at 60 °C,  
117 and subsequently ground and sieved on 2-mm sieve. The sediments were heated at 800 °C for one  
118 hour to eliminate water-content, organic matter, and chemically activate the raw sediments. After  
119 the calcination process, the obtained product was sieved to meet a d<sub>50</sub> less than 45 μm comparable  
120 to that of cement. The density of the sediments increased from 2467 to 2704 kg/m<sup>3</sup> after one hour of  
121 thermal treatment. The treated marine sediment (TMS) has a BET surface area of 3143 m<sup>2</sup>/kg,  
122 which is 24% higher than that of cement. Its chemical composition determined using XRF  
123 spectrometry analysis revealed that it can be considered as pozzolan according to the ASTM C618  
124 specifications [24]. It is composed of 72% silica, 9.7% calcium oxide, 5.3% ferrite oxide, and 3.8%

125 aluminum oxide. In addition, its  $\text{SO}_3$  content is below 0.1%, which is considerably below the  
 126 maximum limit of 4%. The chemical composition of the sediments is similar to that of ground glass  
 127 powder reported in different studies [25–34], as shown in Fig. 1.



128  
 129 *Fig. 1: Composition of TMS (black), composition of ground glass powder cf. [25–34],*  
 130 *superimposed on mainly used SCMs, adapted from [35,36]*

131 The particle-size distribution was determined using a laser diffraction Coulter complied with  
 132 ISO 13320 specifications. The median particle-size of the sediment is 17  $\mu\text{m}$  compared to 13  $\mu\text{m}$   
 133 for cement. Shao et al. [28] reported that 30% cement replacement by glass particles (73% silica) of  
 134 30  $\mu\text{m}$  size resulted in 14% and 33% higher compressive strength than concrete made with powder  
 135 of 75  $\mu\text{m}$  and 150  $\mu\text{m}$ , respectively. The detailed characterization of the raw and treated sediments  
 136 were reported by Safhi et al. [22].

### 137 3.2. Mixtures proportioning and mixing sequence

138 In addition to the control SCC mixture (SCC-R), two SCC mixtures incorporating 10% (SCC-  
 139 1) and 20% (SCC-2) of TMS were prepared (Table 1). All of the investigated mixtures were  
 140 proportioned with a  $w/c$  of 0.40 plus an additional water corresponding to 0.35 of the mass of TMS  
 141 was added to secure adequate workability; this water content was determined using the method  
 142 proposed by Sedran et al. [37] for water demand. The sand,  $CA_1$ , and  $CA_2$  contents were 893, 147,  
 143 and 578  $kg/m^3$ , respectively. These proportions were optimized in a previous study to achieve well-  
 144 graded skeleton and maximum packing density [22]. A commercial high-range water-reducer  
 145 (HRWRA) was incorporated at a dosage of 1200 ml/100 kg of cementitious materials to achieve a  
 146 targeted slump flow ( $S_{flow}$ ) of  $680 \pm 20$  mm. All the investigated mixtures were prepared in batches  
 147 of 60 l using a rotating drum mixer. The mixing sequence consists of homogenizing sand for 30 s,  
 148 followed by adding coarse aggregate and mixing for 60 s. One third of the water was then added,  
 149 and the material was mixed for 30 s. The cementitious materials were added and mixed for 30 s  
 150 before introducing HRWRA diluted with one third of mixing water. The concrete was then mixed  
 151 for an additional 120 s before introducing the last portion of mixing water. The concrete was mixed  
 152 for 60 s and left to rest for 2 min, after which the mixing was resumed for another 3 min.

153 *Table 1: Mixture proportions of the investigated SCC mixtures, content in  $kg/m^3$*

<i>Mixture</i>	<i>Cement</i>	<i>TMS</i>	<i>CA<sub>1</sub></i>	<i>CA<sub>2</sub></i>	<i>Sand</i>	<i>Water</i>		
						<i>Base w/c = 0.4</i>	<i>Additional water for TMS (w/TMS) = 0.35</i>	<i>Total</i>
<i>SCC-R</i>	450	0	147	578	893	180	0	180
<i>SCC-1</i>	405	45				162	15.8	178
<i>SCC-2</i>	360	90				144	21.5	176

### 154 3.3. Tests methods

155 After the mixing process, fresh properties were measured, and various samples were prepared  
 156 to determine the hardened properties. Each sample was cast in one layer without any vibration.

157 Immediately after casting, specimens were properly covered to avoid water evaporation and left  
 158 undisturbed at room temperature of  $23 \pm 2^\circ\text{C}$ . After  $24 \pm 4$  h, the specimens were demolded and  
 159 transferred to a curing chamber at 95% relative humidity (RH) and controlled temperature of  $23 \pm$   
 160  $2^\circ\text{C}$  until the age of testing. Table 2 summarizes the tests conducted on the mixtures. For each test,  
 161 measurements were made on three different samples.

162

*Table 2: Test methods of the investigated mixtures*

<b>Properties</b>		<b>Test method</b>	<b>Samples</b>	<b>Testing periods</b>
<b>Fresh properties</b>				
<i>Filling ability</i>	$S_{flow}$ (mm)	ASTM C 1611 [38]	-	Fresh
	$T_{50}$ (s)		-	Fresh
	$V_{funnel}$ time (s)	EN 12350-9	-	Fresh
<i>Passing ability</i>	$J_{Ring}$ flow (mm)	ASTM C 1621 [39]	-	Fresh
	<i>L-box</i> flow	EN 12350-10	-	Fresh
<i>Stability</i>	<i>Sieve segregation</i> (%)	EN 12350-11	-	Fresh
<i>Air content</i> (%)		ASTM C 231 [40]	-	Fresh
<i>Unit weight</i> ( $\text{kg}/\text{m}^3$ )		ASTM C 138	-	Fresh
<b>Hardened mechanical properties</b>				
<i>Compressive strength</i>		ASTM C 39 [41]	100 Ø 200 mm	3, 28, 56, and 91 days
<i>Split tensile strength</i>		ASTM C 496 [42]		
<b>Durability properties</b>				
<i>Mercury porosimetry</i>		NF P18- 459	Inner fragments	91 days
<i>Electrical resistivity</i>		ASTM C 1760 [43]	100 Ø 200 mm	3, 28, 56, and 91 days
<i>Rapid chloride ion penetrability</i>		ASTM C 1202 [44]	100 Ø 50 mm	91 days
<i>Absorption and sorptivity</i>		ASTM C 1582 [45]	100 Ø 50 mm	-
<i>Drying shrinkage</i>		ASTM C 157 [46]	25 mm <sup>2</sup> x 285 mm	-
<i>External sulfate attack</i>		ASTM C 1012 [47]	25 mm <sup>2</sup> x 285 mm	-
<i>Alkali silica reaction (ASR)</i>		ASTM C 1260 [48]	25 mm <sup>2</sup> x 285 mm	-
<i>Accelerated carbonation</i>		-	100 mm <sup>2</sup> x 50 mm	3, 28, 56, and 91 days

163 The accelerated carbonation tests were conducted using a special chamber in which 4.0% of carbon  
 164 dioxide was introduced at controlled relative humidity of  $55\% \pm 5\%$  and temperature of  $20 \pm 2^\circ\text{C}$ .  
 165 For each SCC mixture, three  $100\text{ mm}^2$  by  $400\text{ mm}$  prisms were tested. The prisms were prepared  
 166 and wet cured for 28 days. They were then left to dry for 14 days at 50% relative humidity before  
 167 carbonation testing. The carbonation depths ( $x_c$ ) were evaluated by spraying 1% phenolphthalein  
 168 alcohol solution on a specimen of  $100\text{ mm}^2$  by  $50\text{ mm}$  cut at different ages of the test. The non-  
 169 carbonated region is identified by purple color due to high alkalinity. The  $x_c$  was determined by  
 170 taking the average depth of colorless regions.

## 171 4. RESULTS AND DISCUSSIONS

### 172 4.1. Workability

173 The fresh properties of the investigated SCC mixtures are summarized in Table 1. As can be  
 174 observed, the investigated mixtures achieved a  $S_{\text{flow}}$  of  $690 \pm 5\text{ mm}$ , which corresponds to SCC  
 175 Class 2 (SF2) in accordance with EFNARC standard [49]. Also, all the investigated mixtures  
 176 exhibited a comparable  $T_{50}$  value of approximately 2 sec and good passing ability reflected by  
 177 difference between  $S_{\text{flow}}$  and  $J_{\text{Ring}}$  flow values (i.e.,  $S_{\text{flow}} - J_{\text{Ring}}$ ) less than 50 mm [50]. The mixtures  
 178 achieved a  $V_{\text{funnel}}$  flow time ranging between 6 and 8 s, and a blocking index  $H_2/H_1$  between 0.85  
 179 and 0.98 in the L-box test [51]. The investigated mixtures belong to passing ability class “PA1”,  
 180 except for the SCC-2. On the other hand, the segregation index of the investigated mixtures was  
 181 less than 10%. It is worth mentioning that during the test, no sign of bleeding was noticed at the  
 182 outer edge of the spread. This indicates that all the developed SCCs an adequate segregation and  
 183 bleeding resistance. The findings indicate that the investigated mixtures have good passing ability  
 184 and stability.

185 *Table 3: Fresh properties of the studied mixtures*

<i>Properties</i>		<i>SCC-R</i>	<i>SCC-1</i>	<i>SCC-2</i>
<i>Filling</i>	$S_{\text{flow}}\text{ (mm)}$	695	690	685

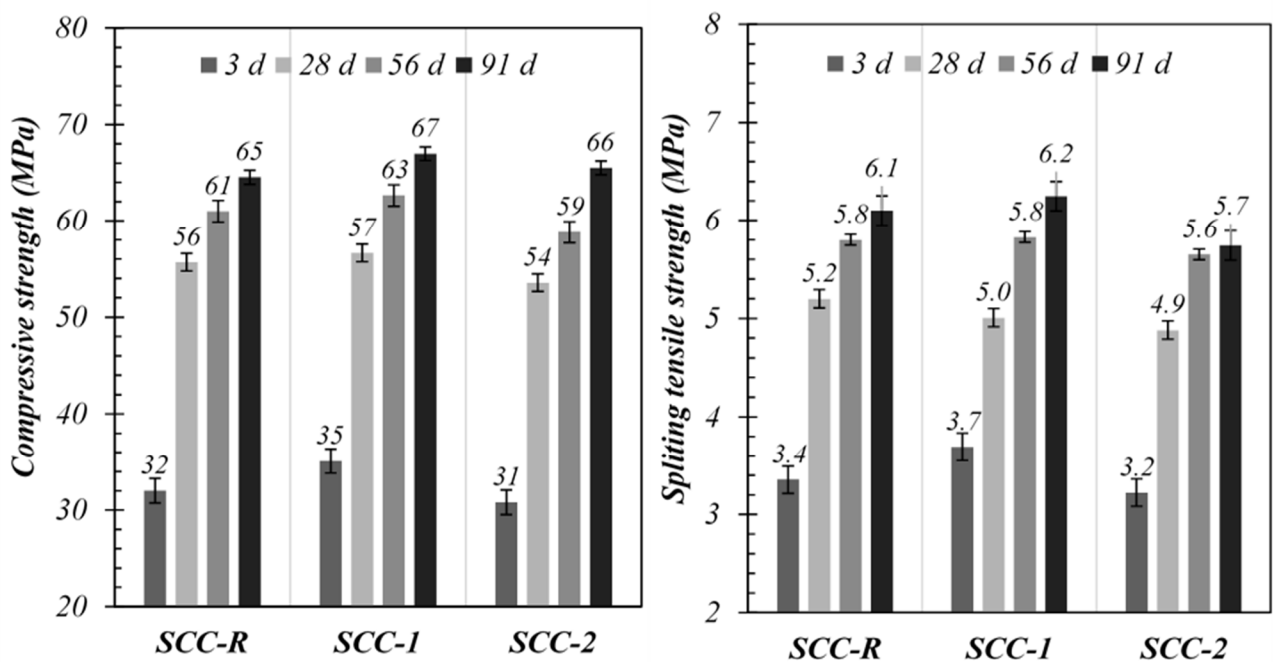
<i>ability</i>	<i>T<sub>50</sub></i> (s)	2.00	2.03	2.06
	<i>V<sub>funnel time</sub></i> (s)	8.10	7.41	6.66
<i>Passing ability</i>	<i>J<sub>Ring flow</sub></i> (mm)	655	660	665
	<i>L-box flow</i>	0.98	0.94	0.85
<i>Stability</i>	<i>Sieve segregation (%)</i>	6.6	8.5	6.2
<i>Air content (%)</i>		3.9	2.2	1.4
<i>Specific gravity (kg/m<sup>3</sup>)</i>		2310	2365	2380

## 186 4.2. Hardened properties

187 The average compressive and splitting tensile strength values of the SCCs mixtures are  
188 presented in Fig. 2. The investigated mixtures showed similar trend of strength development with  
189 time. The increase rate was rapid up to 28 days and then slowed down afterward. A previous study  
190 conducted on the same mixtures [22] reported the evolution of ultrasonic pulse velocity reflecting  
191 the ongoing hydration reactions toward the formation of a denser and interlocked microstructure.  
192 The investigated mixtures reached a velocity of 4900 m/s and exhibited similar compressive  
193 strength of  $66 \pm 1$  MPa at 91 days of age. The maximum strength was observed with SCC-1  
194 containing 10% TMS, regardless of the age. The oxides derived from TMS contribute to the  
195 pozzolanic reactivity and produce additional calcium silicate hydrate (C–S–H), hence leading to  
196 higher strength development [22]. The SCC-2 mixture containing 20% TMS showed a slower  
197 strength gain but reached comparable strength after 91 days of age. It is well known that the use of  
198 SCMs required longer curing time to achieve a given strength. Du and Tan [26] reported that  
199 concrete incorporating 60% of glass powder that contains 72% silica exhibited a compressive  
200 strength of 22 MPa after 7 days of age compared to 35 MPa obtained in the case of the reference  
201 mixture. However, after 365 days of age, the glass-powder concrete containing showed 12% greater  
202 compressive strength than the reference mixture.

203 The tensile strength of SCC-1 was comparable to that of the reference mixture. The increase of  
204 TMS content resulted in a slight decrease in splitting strength. This may be due to the low liberated  
205 quantity of lime during hydration compared to the available quantity of silica in the case of higher

206 substitutions of 20%. Also, the relatively higher finesse of TMS compared to that of cement can  
 207 induce higher water demand for a given workability that leads to lower strength [52]. The partial  
 208 replacement of cement by 20% of TMS can also result in lower C<sub>3</sub>S phases in blended cement,  
 209 hence reducing the volume of initial hydration products. After 91 days of age, the investigated SCC  
 210 mixtures exhibited a comparable tensile strength of 6 ± 0.3 MPa. Sharifi et al. [25] reported similar  
 211 results with the use of glass microparticles as partial replacement of cement (up to 30%, by weight).  
 212 The authors reported that the mixture containing 5% of ground waste glass exhibited the highest  
 213 compressive strength, regardless of the age of concrete. However, the use of substitution rates  
 214 higher than 20% resulted in decreasing the compressive strength development due to the excess  
 215 silica content.

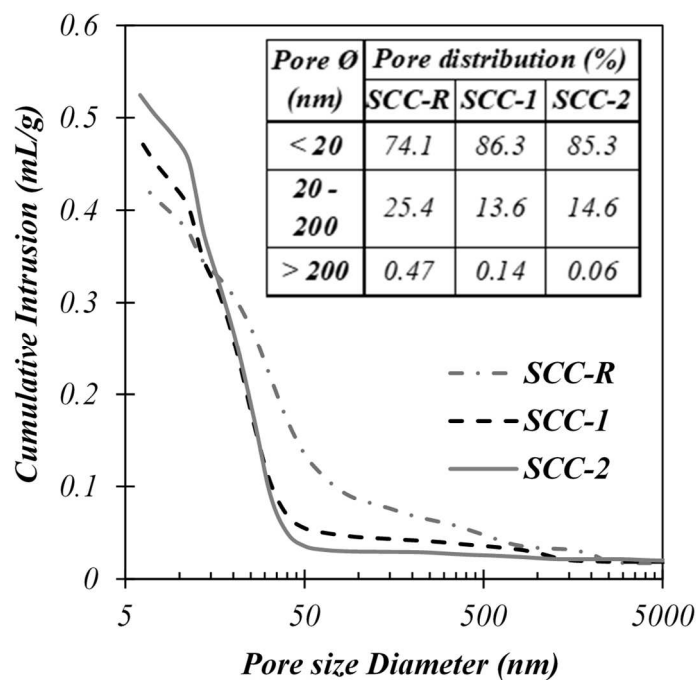


217 *Fig. 2: Compressive and tensile splitting strengths of SCCs at different ages*

### 218 4.3. Microstructure characteristics

219 Pore structure and porosity of cementitious materials depend mainly on the reactivity of  
 220 cement, *w/cm* ratio, curing temperature and condition and SCMs which refine the pore structure  
 221 [53]. The pore-size distribution of the investigated SCC mixtures is illustrated in Fig. 3. As can be  
 222 observed, the mixtures exhibited an average total porosity of 9.1%. SCC-R mixture showed the

223 lowest porosity (8.74%), while SCC-2 exhibited the highest one (9.57%). However, the TMS  
 224 mixtures exhibited more refined pores less than 20 nm compared to the reference mixture. This can  
 225 be explained by the densification of the ITZ caused by additional formed C-S-H gels attributed to  
 226 the high chemical activity and pozzolanic reaction of TMS. SEM observations show that SCC-1 is  
 227 denser than SCC-2 mixture (Fig. 4). Refined and denser ITZ is crucial to achieve durable concrete,  
 228 since it is the preferential pathway of transport properties (e.g. permeability, diffusion, etc.). In fact,  
 229 the use of TMS increased the capillary porosity because of the higher effective  $w/cm$  ratio in the  
 230 presence of TMS which required water to ensure the targeted workability [54]. Higher substitution  
 231 rate of cement by finer SCMs increases the nucleation zones, hence increasing hydration kinetics.  
 232 Similar findings were reported using glass powder that led to finer pores size with a comparable  
 233 total porosity [26].



234

235

Fig. 3: Pore structure and distribution of SCC fragments at 91 days

SCC-R	SCC-1	SCC-2
-------	-------	-------

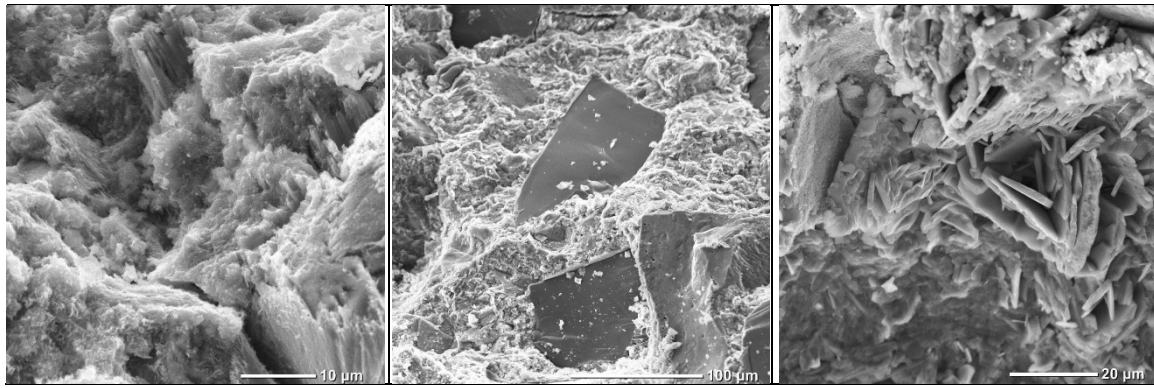


Fig. 4: SEM images of the investigated systems at 91 days

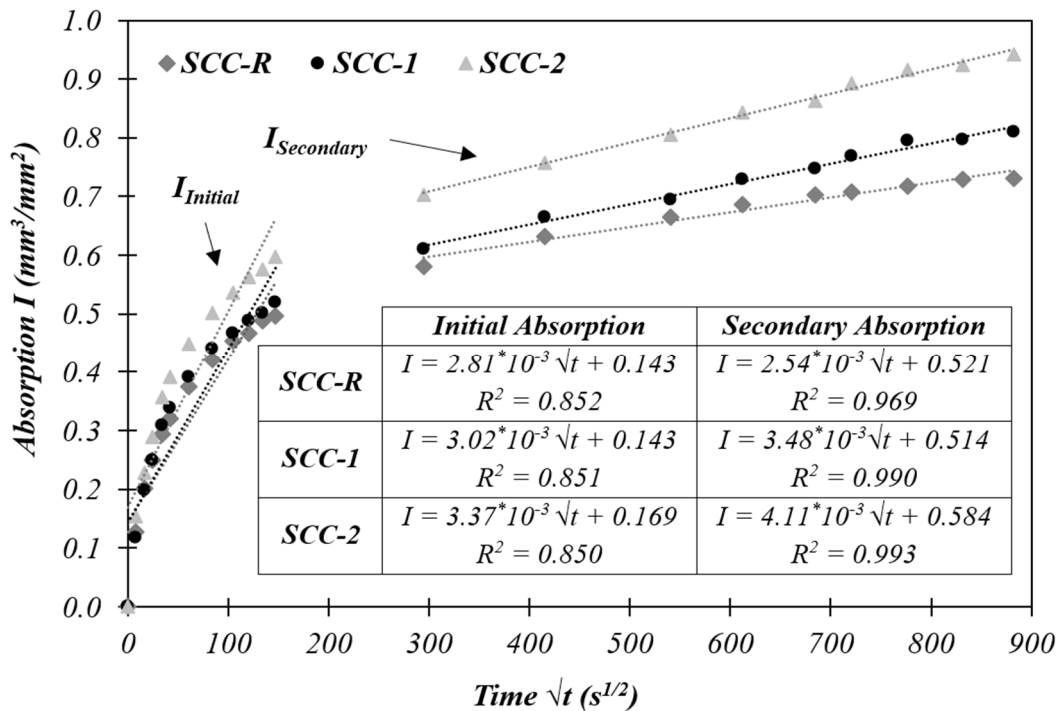
236

## 237 4.4. Transport Properties and Durability

### 238 4.4.1. Absorption and Sorptivity

239 Absorption and sorptivity are the principally transport mean of harmful agent (e.g. chloride,  
 240 acid, sulfate, etc.) in concrete. The reachable pore volume represents the average value ( $I$ ) obtained  
 241 on three different samples (Fig. 5). As expected, the water absorption increased with time,  
 242 regardless of the mixture type. The SCC-R and SCC-1 mixtures showed comparable initial  
 243 adsorption values, while SCC-2 mixture showed relatively higher value. The presence of TMS  
 244 increased the secondary absorption, which indicates a higher pores connectivity. The sorptivity  
 245 represents the slope of the cumulative absorbed volume of liquid per unit inflow surface versus  $t^{1/2}$   
 246 curve. This property was determined with accuracy of  $\pm 5 \text{ E}^{-5} \text{ mm}^3/\text{mm}^2.\text{s}^{1/2}$ . As shown  
 247 schematically in Fig. 5, the sorptivity test can be divided into two phases, a higher slope during the  
 248 first 6h of testing corresponding to the initial sorptivity ( $S_1$ ), which is related to the capillary  
 249 suction. The lower slope corresponds to the secondary sorptivity ( $S_2$ ), which is related to the filling  
 250 of pores and air voids [55]. The  $S_1$  values for the mixtures containing 10% and 20% of TMS are  
 251 higher than that of SCC-R mixture by 7.5% and 19.8%, respectively. On the other hand, the  $S_2$   
 252 values were 37% and 62% higher than that of SCC-R mixture, respectively. Nevertheless, for all the  
 253 investigated mixtures, sorptivity values were less than  $0.05 \text{ mm}^3/\text{mm}^2.\text{s}^{1/2}$ , which indicates a good  
 254 durability according to the Concrete Society criteria [56].

255 It is worthy to mention that a higher TMS substitution necessitates a higher  $w/c$ , hence resulting  
 256 in higher porosity and sorptivity as well as deep water penetration and higher absorption. Liu [57]  
 257 reported that sorptivities of SCC incorporating glass powder increased with substitution content.  
 258 On the other hand, Nassar and Soroushian [58] reported that concrete containing 20% of milled  
 259 glass showed 13% less water absorption after 56 days of age compared to the reference mixture.  
 260 This can be attributed to the pozzolanicity and filling effect of the glass powder. However, Matos  
 261 and Sousa-Coutinho [59] reported that the use of 20% of glass powder did not influenced the  
 262 sorptivities of concrete. This can be attributed to the fact that glass powder and cement had  
 263 comparable finesse.



264

265

Fig. 5: Capillarity absorption of the investigated SCC mixtures

266

#### 4.4.2. Electrical resistivity and chloride penetrability

267

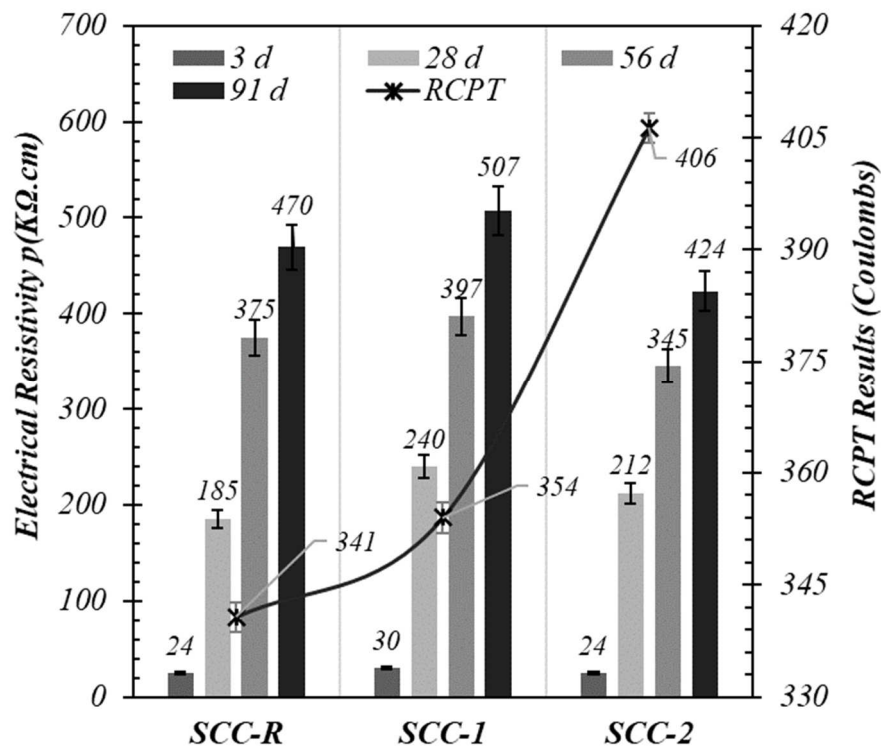
268

269

270

As can be observed in Fig. 6, the electrical resistivity of the investigated SCC increased with time, regardless of type and age of the mixture. This is probably due to the pore refinement induced by the pozzolanic reaction. SCC-1 mixture showed the highest resistivity compared to control mixture (+8.1% at 91 days). On the other hand, SCC-2 showed a comparable resistivity than control

271 mixture up to an age of 28 days but decreased by 8.0% and 9.8% after 56 and 91 days of age,  
 272 respectively. In general, the use of 10% TMS resulted in higher volume of micropores less than 20  
 273 nm, hence resulting in denser matrix and higher electrical resistivity. However, the use of 20%  
 274 TMS resulted in higher porosity and less compact matrix, thus inducing lower electrical resistivity.  
 275 Electrical resistivity is also affected by the pore solutions, principally the presence of  $\text{Ca}^{2+}$  and  $\text{OH}^-$   
 276 ions. The increase in TMS substitution content lowered the concentration of these ions, hence  
 277 lowering the electrical conductivity [26]. This is consistent with reported literature on the use of  
 278 pozzolanic materials to improve resistivity despite their low contribution to strength development of  
 279 concrete [60]. Overall, the electrical resistivity of the investigated mixtures was higher than  
 280 20 k $\Omega$ .cm, which indicates a low risk of corrosion [61].

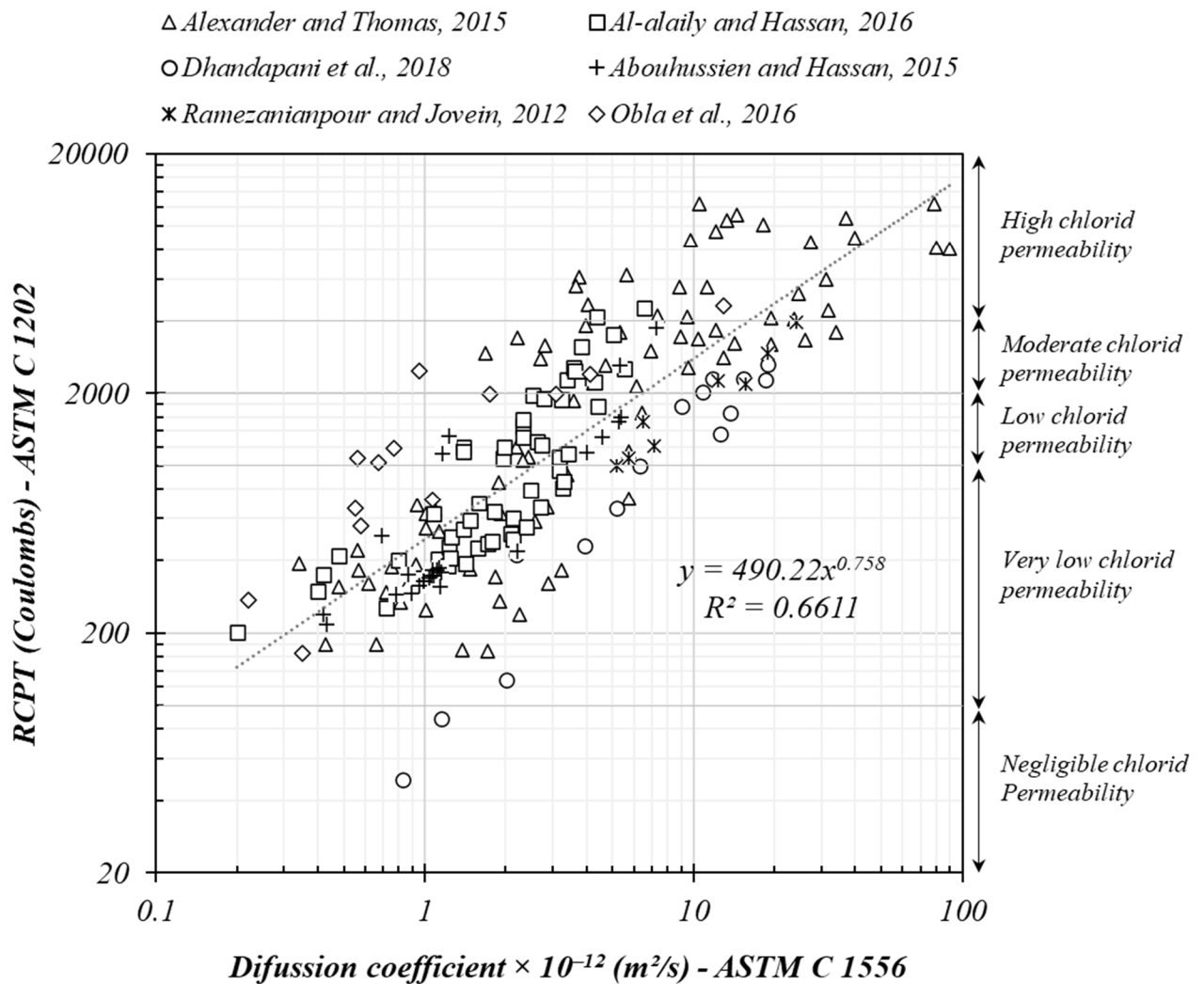


281

282 *Fig. 6: Electrical resistivity and chloride penetrability of SCC mixtures*

283 Chloride resistance is a key property that can affect the lifetime of steel in reinforced structure,  
 284 especially in marine conditions. Capillary suction, diffusion, penetrability, migration, or  
 285 combinations of these transport mechanisms can be used to assess chloride ions ingress into  
 286 concrete. Based on the Fick's 2<sup>nd</sup> law, the apparent diffusion coefficient is usually used for

287 measuring chloride penetrability. In this study, the “Rapid chloride penetrability test” (RCPT) was  
 288 conducted on SCC samples at 91 days of age to determine the apparent diffusion coefficient. The  
 289 results of the RCPT showed a reasonable correlation with the results of the diffusion coefficients;  
 290 however, a significant spread of data was obtained considering the log-log plot (Fig. 7). As reported  
 291 by Thomas [62], the relation between RCPT and diffusion coefficient is primarily governed by the  
 292 pore structure (volume, size, connectivity, and tortuosity of the pores), and to a lesser degree by the  
 293 composition of cement hydrates and pore solution.



294  
 295 Fig. 7: Correlation between 201 test data of RCPT and diffusion coefficient results (data of 28 days  
 296 were chosen) – cf. [63–68]

297 As can be observed in Fig. 6, the test results revealed that the investigated mixtures achieved RCPT  
 298 values lower than 1000 Coulomb, which indicates a very low chloride permeability (ASTM

299 C1202). SCC-1 and SCC-2 mixtures showed, however, 4% and 19% higher RCPT values,  
300 respectively, than control mixture (341 Coulombs). This tendency is similar to that observed with  
301 sorptivity values. Nassar and Soroushian [58] reported that the use of well ground glass powder ( $d_{50}$   
302 equal 13  $\mu\text{m}$ ) reduced chloride penetrability due to the pozzolanic reaction that refine the porosity  
303 of the matrix. The TMS used in this study is a fine powder having a  $d_{50}$  of 17  $\mu\text{m}$ , hence improving  
304 the microstructure and transport properties.

#### 305 **4.4.3. Unrestrained drying shrinkage**

306 Unrestrained shrinkage testing was carried out to determine the free volumetric change of  
307 concrete according to the ASTM C157 specifications [46]. As can be observed in Fig. 8, the  
308 investigated mixtures achieved comparable length change values at 7 days of exposure. However,  
309 drying shrinking developed quickly after 7 days of exposure, and stabilized after 21 days. SCC-R  
310 control mixture exhibited higher shrinkage of 8% and 5% after 49 days of exposure than SCC-1 and  
311 SCC-2 mixtures, respectively. The microstructure analysis is consistent with the shrinkage results  
312 reported in this study, where SCC-R showed the lowest volume of micro-pores and the highest  
313 volume of meso-pores. The test results revealed that the mass loss increased with TMS content  
314 compared to control mixture. Indeed, SCC-1 and SCC-2 mixtures showed 5% and 12% higher mass  
315 loss, respectively, than control mixture. These results are similar to those reported on the effect of  
316 red mud on drying shrinkage of concrete [5]. This reduction was attributed to the porosity of red  
317 mud and its ability to absorb a large volume of free water and thereafter released it, hence  
318 contribute to reducing drying shrinkage through internal curing process.

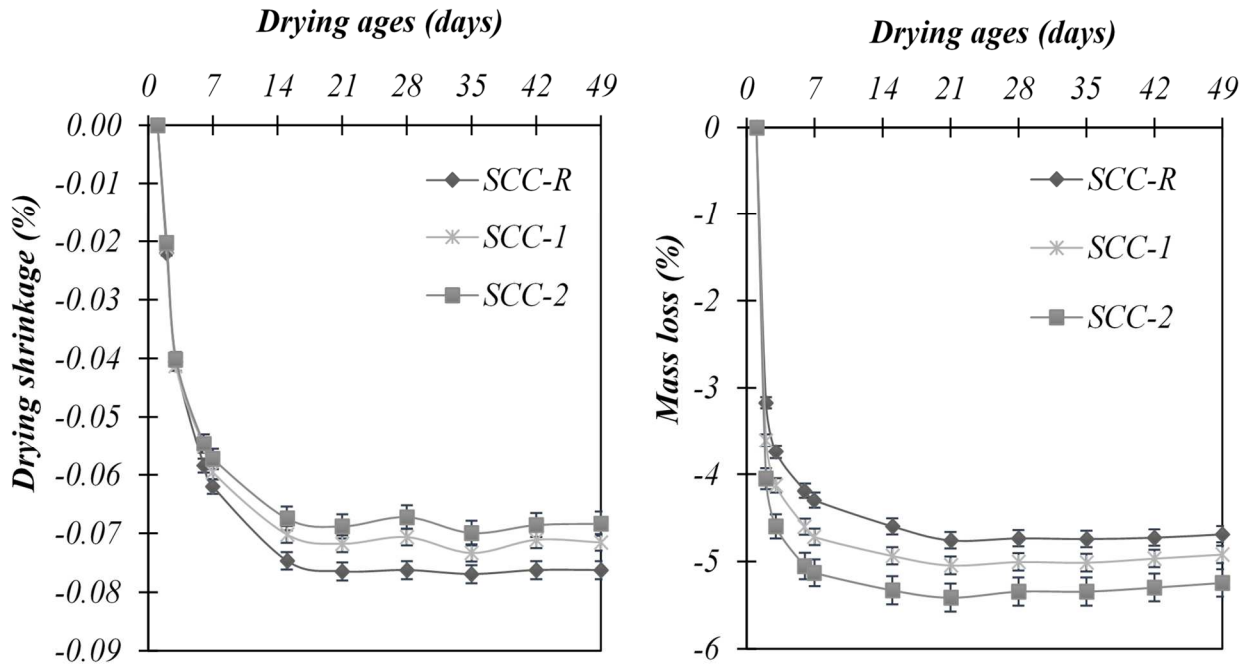


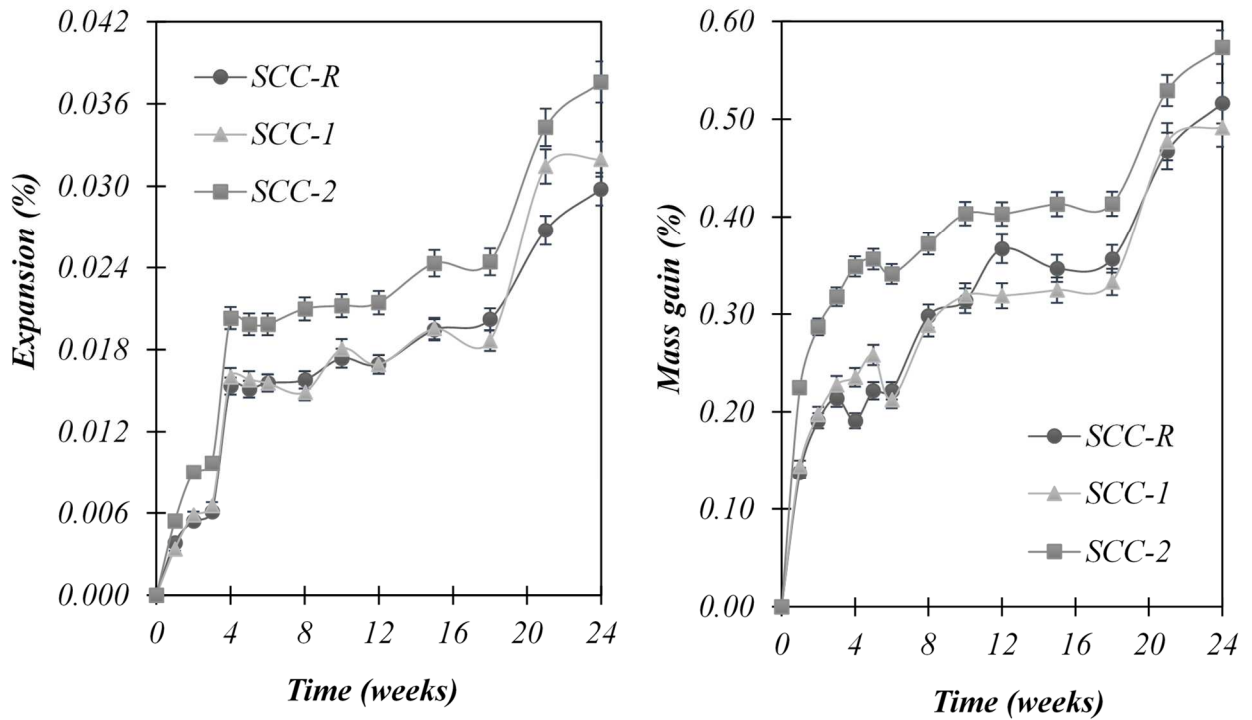
Fig. 8: Drying shrinking: length change (left) and mass loss (right)

Bouhamou et al. [19] investigated the influence of dredging sediments used as SCM on shrinkage of SCC. The authors reported that the calcined mud decreased the autogenous shrinkage due to the formation of expansive calcium aluminate hydrates. Furthermore, they reported that SCC incorporating calcined mud showed denser microstructure and finer pore sizes, hence resulting in lower porosity, permeability, water diffusivity, and drying shrinkage. Zhang et al. [70] demonstrated that drying shrinkage is well correlated with pore volume, where lower volume of the mesopores below 50 nm can significantly decrease drying shrinkage. On the other hand, Collins and Sanjayan [71] showed that increasing the volume of mesopore is responsible for increasing the drying shrinkage. Overall, it appears that the differences were not significant between the mixtures.

#### 4.4.4. External sulfate attack

The degradation of concrete due to external sulfate attack is primarily related to the expansion of gypsum ( $C\bar{S}H$ ) and ettringite ( $C_6A\bar{S}_3H_{32}$ ) formed by the reaction of unreacted  $C_3A$ , monosulfate, and portlandite ( $CH$ ) with sodium sulfate ( $Na_2SO_4$ ) or magnesium sulfate ( $MgSO_4$ ). The expansion results obtained after 24 weeks of exposure are shown in Fig. 9. As can be observed, a rapid initial expansion was noted during the first month of testing. Then, the expansion rate stabilized until the

336 12<sup>th</sup> week, where the expansion was limited to 0.022%. Another peak occurred at the 18<sup>th</sup> week  
337 until reaching 0.036% at the 24<sup>th</sup> week in the case of SCC-2. SCC-1 and SCC-R mixtures showed  
338 similar trend, while SCC-2 mixture showed higher expansion starting from the 4<sup>th</sup> week of  
339 exposure, even though it contains the lowest C<sub>3</sub>A content due to higher substitution of cement by  
340 TMS. This is probably due to the formation of ettringite following reaction of Na<sub>2</sub>SO<sub>4</sub> and C<sub>3</sub>A or  
341 CH. Indeed, SEM observations revealed that SCC-2 exhibits a disordered structure with numerous  
342 sulfate phases and large number of open pores [22]. Diverse CH crystals were observed in SCC-2,  
343 including thin hexagonal and globular crystals indicating the presence of alite and belite. In addition  
344 to SEM observations, XRD analyses showed that increasing the TMS content promoted the  
345 formation of ettringite. The pozzolanic activity binds CH released during hydration of C<sub>3</sub>S and C<sub>2</sub>S,  
346 hence leaving less available CH for reaction with sulphates and preventing the formation of gypsum  
347 [72]. Another possible explanation may be the higher effective *w/b* ratio, which could decrease the  
348 pH of the pore solution resulting in C-S-H instability and releasing of Ca<sup>2+</sup> ions. At lower pH,  
349 ettringite also become unstable and decompose to gypsum generating smaller expansion [73,74].  
350 The higher expansion and mass gain of SCC-2 specimens could also be explained by its higher  
351 porosity and sorptivity compared to those of SCC-R and SCC-1 mixtures, which provided an open  
352 pathway for sulfate ions. In general, the use of 10% TMS did not have a negative effect on sulfate  
353 attack.

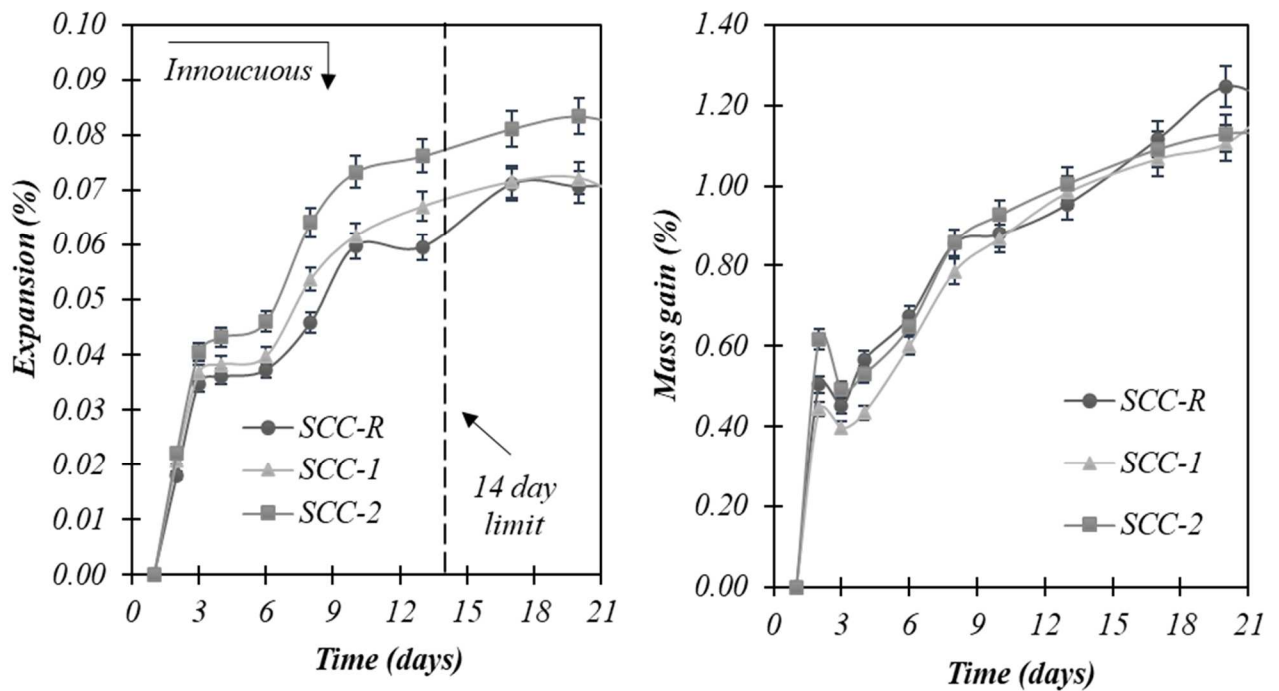


354

355 *Fig. 9: Resistance to external sulfate attack: left) length expansion and right) mass gain*

356 **4.4.5. Accelerated Alkali Silica Testing**

357 Mortar samples were prepared using a non-reactive sand and subjected to the accelerated  
 358 alkali-silica test according to the ASTM C1260 specifications. The expansion and mass gain results  
 359 are summarized in Fig. 10. As can be observed, a rapid expansion of 0.035% was observed after 3  
 360 days of exposure, regardless of the type of mixture. SCC-1 and SCC-R mixtures achieved  
 361 comparable expansion of 0.070%, while SCC-2 exhibited slightly higher expansion of 0.075% after  
 362 14 days of exposure. On the other hand, the investigated mixtures exhibited almost the same mass  
 363 gain where a slight increase of 1.0% was observed after 14 days of exposure. Overall, the  
 364 expansions of the investigated mortar mixtures are lower than 0.10% after 14 days of exposure,  
 365 hence reflecting an innocuous behavior according to the ASTM C1260 specifications [48]. These  
 366 results indicate that the use of up to 20% TMS will not cause more ASR expansion under normal  
 367 conditions, including the use of non-reactive aggregate.



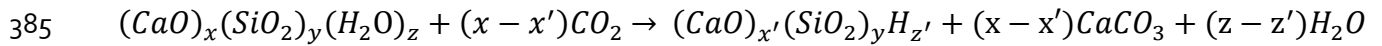
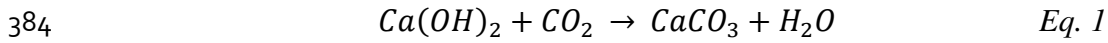
368

369 *Fig. 10: Resistance to alkali silica reaction: left) expansion and right) weight gain*

370 These results confirm the findings reported by Schwarz et al. [27] where expansion for mortars  
 371 containing ternary mixture of cement, fly ash, and glass powder (5%, 10%, and 15%) showed an  
 372 innocuous behavior less than 0.10%. Taha and Nounu [34] in their study on ASR testing of mortars  
 373 containing 10% glass powder, they explained the findings by the quick dissolving of reactive silica  
 374 during the pozzolanic reaction that agglomerated in the crystals of concrete minerals, hence may not  
 375 be available for the ASR that occurs in later stages. They argue that in the first 4 weeks of  
 376 pozzolanic reaction and hydration process, most of alkalis would have been consumed to catalyze  
 377 the pozzolanic reaction and act as chemical activators to compensate for the lower calcium content  
 378 in the glass powder.

379 **4.4.6. Accelerated carbonation**

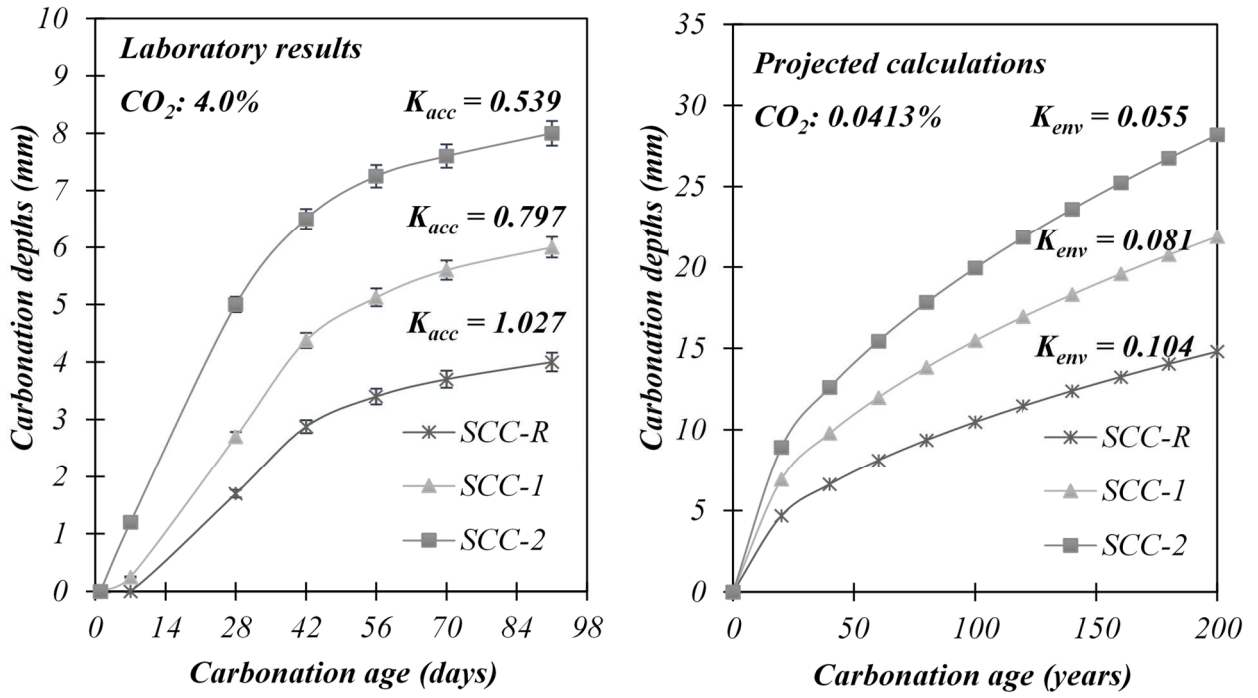
380 Carbonation is one of the major factors affecting durability of concrete by reducing its pH,  
 381 which can initiate the reinforcement corrosion. In fact, CO<sub>2</sub> in the air can react with hydration  
 382 products, such as CH and C-S-H dissolved in pore water, to form CaCO<sub>3</sub> and water [75,76]  
 383 according to the following equations:



387 The carbonation of  $Ca(OH)_2$  causes expansion, decreasing porosity, refining pores, increasing  
 388 strength, and improving durability of the matrix [77]. However, carbonation of C–S–H cause its  
 389 disintegration and loss of strength [78]. Assuming that carbonation process is steady, the depth ( $x_c$ )  
 390 can be calculated using the Fick's first law as shown in Eq. 3.

391 
$$x_c = k\sqrt{t} \quad Eq. 3$$

392 where  $k$  is the carbonation rate of concrete. The coefficient  $k_{acc}$ , which is related to the controlled  
 393 test conditions, was determined for all the investigated SCC mixtures (Fig. 11). The test results  
 394 revealed that the investigated mixtures showed seems to be proportional to the TMS replacement  
 395 percentage. After 91 days of exposure, the carbonation depth of SCC-R reached 4 mm, while those  
 396 of SCC-1 and SCC-2 reached 150% and 200% higher values, respectively. This can be due to the  
 397 higher porosity and sorptivity of SCC mixtures containing TMS. As discussed earlier, increasing  
 398 TMS content increases the effective  $w/b$  ratio, which results in lowering the pH of the matrix.  
 399 Gabrisova et al. [79] conducted potentiometric analysis and concluded that ettringite is unstable  
 400 below a pH of 10.7, while the monosulphate is unstable below 11.6; lowering the pH causes  
 401 dissociation of phases, thus providing more calcium hydroxide (CH) available for carbonation.  
 402 Matos and Sousa-Coutinho [59] reported similar carbonation trend, i.e. incorporating glass powder  
 403 by 10% to 20% generates a carbonation depth of 5 mm and 8 mm, respectively, after 4 months of  
 404 age. These values represent an increase of 165% and 265% compared to the reference, respectively.



405

406

407

408

409

410

411

412

413

414

415

416

417

418

419

Fig. 11 : Carbonation progress of the investigated SCC mixtures: left) in the tested atmosphere and right) the consequential calculated development in air

Sisomphon and Franke [80] proposed a relationship between  $k_{acc}$  and coefficient of environmental carbonation ( $k_{env}$ ), as follows:

$$k_{acc}/k_{env} = \sqrt{C_{acc}}/\sqrt{C_{env}} \quad \text{Eq. 4}$$

where  $C_{acc}$  is the CO<sub>2</sub> concentration used to carry out the test (4.0%), while  $C_{env}$  is the CO<sub>2</sub> concentration in the environment, which varies from 0.03% in a rural environment to 0.1% in urban areas [81]. According to NOAA Earth System Research Laboratory, the environment CO<sub>2</sub> concentration was fixed at 0.0413%. This scale up does not consider the influence of ambient temperature and humidity, moisture cycles, and surface geometry, which could affect the carbonation kinetics [24]. Using Eq. 3 and 4, the parameter  $k_{env}$  was calculated, and the carbonation progression in nature was evaluated based on the  $\sqrt{t}$ -function (Fig. 11). For example, in the case of 20-mm concrete cover, the carbonation can reach the reinforcing bars after 167 and 101 years in the case of SCC-1 and SCC-2 mixtures, respectively, compared to 365 years for the control mixture.

420 Even for the highest TMS content of 20%, the expected durability against carbonation is over 100  
421 years.

#### 422 **4.5. Discussions**

423 The high alkalinity of the pore solution rich in  $\text{Ca}^{2+}$ ,  $\text{SiO}_4^{2-}$ , and  $\text{OH}^-$  ions contribute to  
424 dissolving the amorphous silica in TMS (Si–O–Si bond), which can react with  $\text{Ca}^{2+}$  ions to form  
425 C–S–H gel with a lower Ca/Si ratio. Higher substitution rates lead to a lower availability of  $\text{Ca}^{2+}$  to  
426 accommodate the higher existing Si brought by TMS, which can therefore delay cement hydration  
427 [35]. Less available  $\text{Ca}^{2+}$  can result in a decrease of pH of the pore solution, as reported by Du and  
428 Tan [73]. The pozzolanic reactivity of TMS depends on the substitution percentage and the mixture  
429 parameters, including the mixing water. Indeed, SCC-2 mixture proportioned with 20% TMS  
430 substitution showed slower strength development but reached equivalent mechanical properties  
431 after 90 days of age.

432 The curing type and duration, as well as temperature are key factors affecting the performance  
433 of SCM in terms of the strength development, especially in the case of rich-silica medium, such as  
434 that containing glass powder or TMS investigated in this study. Shi et al. [83] investigated the  
435 compressive strength of mortars made with glass powder and cured at different temperatures of  
436 23°C, 35°C, and 65°C. As expected, mortar samples cured at 35°C and 65°C developed higher  
437 strength than those cured at 23°C, regardless of the age of mortar. This can be attributed to the  
438 higher apparent activation energy for pozzolanic reaction. Furthermore, Mirzahosseini and Riding  
439 [29] reported that mortar mixtures made with 25% glass powder and cured at 50 °C developed 25%  
440 higher compressive strength after 91 days than those cured at 23 °C. In the case of the investigated  
441 TMS, higher curing time can allow better mechanical performances.

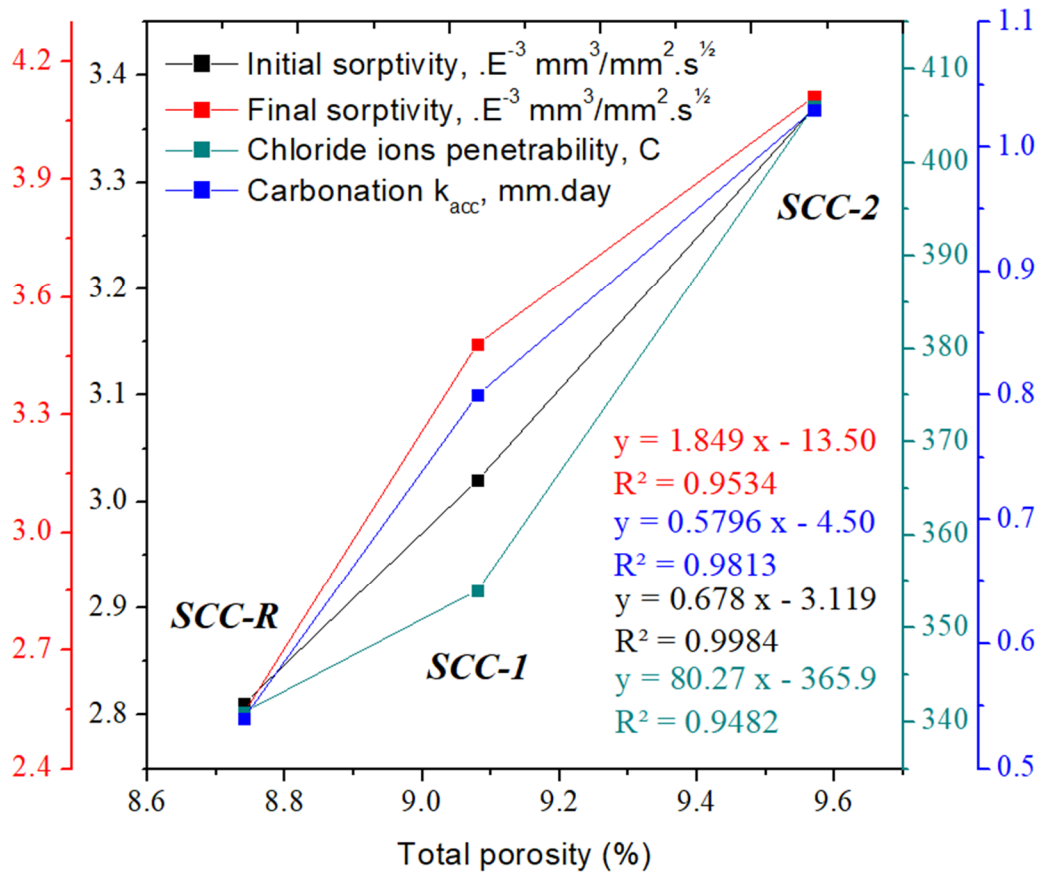
442 The degradation mechanisms are related to the transport properties, including the sorptivity,  
443 which is a fundamental parameter controlling liquid transport in porous materials. Laidani et al.  
444 [84] investigated the effects of calcined bentonite on SCC properties and reported a strong

445 correlation between the chloride diffusion and porosity, and gas permeability and porosity. A low  
 446 porosity was found to be associated with low passing charge and gas permeability coefficient.  
 447 Kanellopoulos et al. [85] found a strong linear correlation ( $R^2 = 0.94$ ) between sorptivity and open  
 448 porosity, sorptivity and chloride permeability ( $R^2 = 0.92$ ), as well as sorptivity and compressive  
 449 strength ( $R^2 = 0.93$ ). The authors [85] suggested that these durability properties are interrelated and  
 450 constitute good indicators for durability. They can also be used to avoid long-term durability tests.  
 451 Liu [57] also found a strong correlation between sorptivity and compressive strength ( $R^2 = 0.82$ )  
 452 and suggested that sorptivity could be used to predict the service life of concrete.

453 A correlation was established between the total porosity and transport properties, including  
 454 initial and final sorptivities, carbonation coefficient  $k_{acc}$ , and the chloride ions penetration. A strong  
 455 correlation ( $R^2 > 0.94$ ) between the total porosity and other transport properties was reported, as  
 456 shown in Fig. 12 and Table 4. As expected, lower porosity was associated with lower sorptivity,  
 457 carbonation permeability, and chloride diffusion. A high porosity was also related to a high  
 458 diffusion of sulfate and NaOH used for ASR, where more expansion was observed in the case of  
 459 SCC-2 due to its higher porous structure. Grinding TMS to meet a  $d_{50} < 5 \mu\text{m}$  can be interesting to  
 460 ensure more reactive particles, hence resulting in denser and less porous ITZ.

461 *Table 4: Transport properties of the investigated SCC mixtures*

<b>Mixes</b>	<b>Total porosity (%)</b>	<b>Initial sorptivity (<math>\text{mm}^3/\text{mm}^2 \cdot \text{s}^{1/2}</math>)</b>	<b>Final sorptivity (<math>\text{mm}^3/\text{mm}^2 \cdot \text{s}^{1/2}</math>)</b>	<b>Chloride ions penetrability (C)</b>	<b>Carbonation <math>k_{acc}</math> (mm.day)</b>
<b>SCC-R</b>	8.74	2.81 E <sup>-3</sup>	2.54 E <sup>-3</sup>	341	0.539
<b>SCC-I</b>	9.08 (+3.9%)	3.02 E <sup>-3</sup> (+7.5%)	3.48 E <sup>-3</sup> (+37%)	354 (+3.8%)	0.797 (+50%)
<b>SCC-2</b>	9.57 (+9.5%)	3.37 E <sup>-3</sup> (+20%)	4.11 E <sup>-3</sup> (+62%)	406 (+19%)	1.027 (+90%)



462

463

Fig. 12: Correlation between various investigated transport properties

464

465

466

467

468

469

470

471

The investigated SCCs met the criteria for high-performance SCC, including a fresh air content of 5–8% [86] for durability purposes, high-early compression strength of 20–28 MPa, 28-d compressive strength higher than 40 MPa (ASTM C39 [41]), low permeability of 500–2000 coulombs (ASTM C1202 [44]), low water absorption of 2–5%, expansion to sulfate attack below 0.10% after 6 months of exposure (ASTM C1012 [47]), high-elasticity modulus of 40 GPa (ASTM C469 [87]), a drying shrinkage lower than 400 millionths (ASTM C157 [46]) [88], ultrasonic pulse velocity higher than 4575 m/s [89], total porosity of 7–15% [90], and electrical resistance to corrosion higher than 5–10 kΩ.cm [61].

472

## 5. CONCLUSIONS

473

474

475

Key fresh and hardened properties, microstructure characterization, transport properties, and key durability indicators of SCC containing treated marine sediments (TMS) were assessed. Based on the results presented in this paper, the following conclusions can be pointed out:

- 476 1. The investigated SCC mixtures exhibited adequate self-consolidating characteristics with high  
477 filling and passing abilities, and good stability. Also, they exhibited comparable compressive  
478 splitting tensile strength values of  $66 \pm 1$  MPa and  $6 \pm 0.3$  MPa at 91 days, respectively.
- 479 2. An average total porosity of  $9 \pm 0.4\%$  was found for the investigated mixtures. However, the  
480 incorporation of TMS increased the micropores volume (16%), decreased mesopores volume  
481 (44%), and decreased macropores volume (90%) compared to the reference mixture. This was  
482 attributed to the pozzolanic reaction and filling ability that refined the ITZ.
- 483 3. All the investigated SCC mixtures showed adequate transport property reflected by sorptivity  
484 values lower than  $0.05 \text{ mm}^3/\text{mm}^2 \cdot \text{s}^{1/2}$ . The incorporation of TMS increased the absorption and  
485 sorptivity by 7.5% and 19.8% in the case of SCC-1 and SCC-2 containing 10% and 20% TMS,  
486 respectively, compared to control mixture ( $2.81 \text{ E}^{-3} \text{ mm}^3/\text{mm}^2 \cdot \text{s}^{1/2}$ ). In the case of the secondary  
487 sorptivity, higher increase of 37% (SCC-1) and 62% (SCC-2) were observed.
- 488 4. SCC mixture containing 10% TMS exhibited the highest electrical resistivity regardless of the  
489 age (8.1% higher than the reference of 470 k $\Omega$ .cm after 91 days). The use of higher TMS  
490 content resulted in higher chloride permeability by 19% compared to reference mixture (341  
491 Coulombs).
- 492 5. SCC mixtures incorporating TMS exhibited lower drying shrinkage compared to the reference  
493 mixture. Control SCC mixture exhibited higher shrinkage after 49 days of exposure compared  
494 with those containing TMS.
- 495 6. For external sulfate attack, the use of 20% TMS led to a higher expansion compared with the  
496 reference mixture. The use of 10% TMS resulted in comparable expansion to that of the control  
497 mixture; however, the expansion was less than 10% after 24 weeks of exposure.
- 498 7. The use of TMS increased the carbonation depth compared to control mixture (4 mm) after 91  
499 days of exposure by 150% (10% TMS) and 200% (20% TMS). The expected durability against  
500 carbonation of the investigated mixture is higher than 100 years.

501 8. Taken as a whole, incorporation up to 10% led to a comparable durability performance. A  
502 typical substitution rate of 10%-20% TMS can be considered without mitigating durability of  
503 non-reinforced concrete in moderate exposure class and no external aggression.

## 504 **DECLARATIONS**

### 505 **Competing interest**

506 We pledge that we are not involved in the interests of the financial, commercial, legal, or  
507 professional relationship with other organizations, or with the people we worked with them, that  
508 could influence this research.

### 509 **Data availability**

510 The data supporting the conclusions of this article are included within the article. Any queries  
511 regarding these data may be directed to the corresponding author.

### 512 **Funding**

513 The research work was accomplished as a part of a PhD program [91] in the laboratory of the  
514 *Department of Civil & Building Engineering* of the *Université de Sherbrooke*, Canada. The study  
515 was funded by the research funds of the *IMT Lille Douai*, grants from the *Natural Sciences and*  
516 *Engineering Research Council of Canada* (NSERC) and the “*Fonds de Recherche Nature et*  
517 *Technologies du Québec*” (FRQNT). A. M. Safhi thanks the *ACI-Quebec and East Ontario Chapter*  
518 for supporting this work through “*Michel Pigeon*” award. The authors would like to thank Sika  
519 Canada, Montreal, for providing the admixtures.

## 520 **REFERENCES**

521 [1] CEN/TC 104 “Concrete and related products” technical committee., EN 206+A1 : Concrete –  
522 Part 1: Specification, performance, production and conformity, (2016).

- 523 [2] J.G. Kessy, M.G. Alexander, H. Beushausen, Concrete durability standards: International  
524 trends and the South African context, *J. South Afr. Inst. Civ. Eng.* 57 (2015) 47–58.  
525 <https://doi.org/10.17159/2309-8775/2015/v57n1a5>.
- 526 [3] M. Cyr, 8 - Influence of supplementary cementitious materials (SCMs) on concrete durability,  
527 in: *Eco-Effic. Concr.*, Woodhead Publishing, 2013: pp. 153–197.  
528 <https://doi.org/10.1533/9780857098993.2.153>.
- 529 [4] J.M. Marangu, J.K. Thiong’o, J.M. Wachira, Chloride Ingress in Chemically Activated  
530 Calcined Clay-Based Cement, *J. Chem.* 2018 (2018) e1595230.  
531 <https://doi.org/10.1155/2018/1595230>.
- 532 [5] J.M. Marangu, J.K. Thiong’o, J.M. Wachira, Review of Carbonation Resistance in Hydrated  
533 Cement Based Materials, *J. Chem.* 2019 (2019) e8489671.  
534 <https://doi.org/10.1155/2019/8489671>.
- 535 [6] A.S. El-Dieb, D.M. Kanaan, Ceramic waste powder an alternative cement replacement –  
536 Characterization and evaluation, *Sustain. Mater. Technol.* 17 (2018) e00063.  
537 <https://doi.org/10.1016/j.susmat.2018.e00063>.
- 538 [7] M. Abed, R. Nemes, Long-term durability of self-compacting high-performance concrete  
539 produced with waste materials, *Constr. Build. Mater.* 212 (2019) 350–361.  
540 <https://doi.org/10.1016/j.conbuildmat.2019.04.004>.
- 541 [8] Z. Ahmadi, J. Esmaili, J. Kasaei, R. Hajialioghli, Properties of sustainable cement mortars  
542 containing high volume of raw diatomite, *Sustain. Mater. Technol.* 16 (2018) 47–53.  
543 <https://doi.org/10.1016/j.susmat.2018.05.001>.
- 544 [9] F.A. Sabet, N.A. Libre, M. Shekarchi, Mechanical and durability properties of self  
545 consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash,  
546 *Constr. Build. Mater.* 44 (2013) 175–184. <https://doi.org/10.1016/j.conbuildmat.2013.02.069>.

- 547 [10] P. Hou, S. Kawashima, D. Kong, D.J. Corr, J. Qian, S.P. Shah, Modification effects of  
548 colloidal nanoSiO<sub>2</sub> on cement hydration and its gel property, *Compos. Part B Eng.* 45 (2013)  
549 440–448. <https://doi.org/10.1016/j.compositesb.2012.05.056>.
- 550 [11] D. Kong, Y. Su, X. Du, Y. Yang, S. Wei, S.P. Shah, Influence of nano-silica agglomeration on  
551 fresh properties of cement pastes, *Constr. Build. Mater.* 43 (2013) 557–562.  
552 <https://doi.org/10.1016/j.conbuildmat.2013.02.066>.
- 553 [12] K. Jaglal, D.M. Crawford, S.W. Anagnost, B.E. White, Alternative Approaches for Managing  
554 Dredged Sediments, in: *Proceeding of the Western Dredging Association (WEDA)*,  
555 Vancouver, British Columbia, Canada, 2017.
- 556 [13] J. Harrington, J. Murphy, M. Coleman, D. Jordan, T. Debuigne, G. Szacsuri, Economic  
557 modelling of the management of dredged marine sediments, *Geol. Geophys. Environ.* 42  
558 (2016) 311. <https://doi.org/10.7494/geol.2016.42.3.311>.
- 559 [14] M. Benzerzour, M. Amar, N.-E. Abriak, New experimental approach of the reuse of dredged  
560 sediments in a cement matrix by physical and heat treatment, *Constr. Build. Mater.* 140 (2017)  
561 432–444. <https://doi.org/10.1016/j.conbuildmat.2017.02.142>.
- 562 [15] M. Amar, M. Benzerzour, N.-E. Abriak, Y. Mamindy-Pajany, Study of the pozzolanic activity  
563 of a dredged sediment from Dunkirk harbour, *Powder Technol.* 320 (2017) 748–764.  
564 <https://doi.org/10.1016/j.powtec.2017.07.055>.
- 565 [16] R. Snellings, Ö. Cizer, L. Horckmans, P.T. Durdziński, P. Dierckx, P. Nielsen, K. Van Balen,  
566 L. Vandewalle, Properties and pozzolanic reactivity of flash calcined dredging sediments,  
567 *Appl. Clay Sci.* 129 (2016) 35–39. <https://doi.org/10.1016/j.clay.2016.04.019>.
- 568 [17] F. Rozas, A. Castillo, I. Martínez, M. Castellote, Guidelines for assessing the valorization of a  
569 waste into cementitious material: dredged sediment for production of self compacting  
570 concrete, *Mater. Constr.* 65 (2015) 057. <https://doi.org/10.3989/mc.2015.10613>.

- 571 [18] E. Rozière, M. Samara, A. Loukili, D. Damidot, Valorisation of sediments in self-  
572 consolidating concrete: Mix-design and microstructure, *Constr. Build. Mater.* 81 (2015) 1–10.  
573 <https://doi.org/10.1016/j.conbuildmat.2015.01.080>.
- 574 [19] N.-E. Bouhamou, F. Mostefa, A. Mebrouki, K. Bendani, N. Belas, Influence of dredged  
575 sediment on the shrinkage behavior of self-compacting concrete, *Mater. Tehnol.* 50 (2016)  
576 127–135. <https://doi.org/10.17222/mit.2013.252>.
- 577 [20] A. el M. Safhi, M. Benzerzour, P. Rivard, N.-E. Abriak, Feasibility of using marine sediments  
578 in SCC pastes as supplementary cementitious materials, *Powder Technol.* (2018).  
579 <https://doi.org/10.1016/j.powtec.2018.12.060>.
- 580 [21] A. el M. Safhi, M. Benzerzour, P. Rivard, N.-E. Abriak, I. Ennahal, Development of self-  
581 compacting mortars based on treated marine sediments, *J. Build. Eng.* 22 (2019) 252–261.  
582 <https://doi.org/10.1016/j.jobe.2018.12.024>.
- 583 [22] A. el M. Safhi, P. Rivard, A. Yahia, M. Benzerzour, K.H. Khayat, Valorization of dredged  
584 sediments in self-consolidating concrete: Fresh, hardened, and microstructural properties, *J.*  
585 *Clean. Prod.* 263 (2020) 121472. <https://doi.org/10.1016/j.jclepro.2020.121472>.
- 586 [23] ASTM C150, Specification for Portland Cement, ASTM International, 2019.  
587 [https://doi.org/10.1520/C0150\\_C0150M-19A](https://doi.org/10.1520/C0150_C0150M-19A).
- 588 [24] ASTM C618, Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in  
589 Concrete, ASTM International, 2019. <https://doi.org/10.1520/C0618-19>.
- 590 [25] Y. Sharifi, I. Afshoon, Z. Firoozjaei, A. Momeni, Utilization of Waste Glass Micro-particles in  
591 Producing Self-Consolidating Concrete Mixtures, *Int. J. Concr. Struct. Mater.* 10 (2016) 337.  
592 <https://doi.org/10.1007/s40069-016-0141-z>.
- 593 [26] H. Du, K.H. Tan, Properties of high volume glass powder concrete, *Cem. Concr. Compos.* 75  
594 (2017) 22–29. <https://doi.org/10.1016/j.cemconcomp.2016.10.010>.

- 595 [27] N. Schwarz, N. Neithalath, Influence of a fine glass powder on cement hydration: Comparison  
596 to fly ash and modeling the degree of hydration, *Cem. Concr. Res.* 38 (2008) 429–436.  
597 <https://doi.org/10.1016/j.cemconres.2007.12.001>.
- 598 [28] Y. Shao, T. Lefort, S. Moras, D. Rodriguez, Studies on concrete containing ground waste  
599 glass, *Cem. Concr. Res.* 30 (2000) 91–100. [https://doi.org/10.1016/S0008-8846\(99\)00213-6](https://doi.org/10.1016/S0008-8846(99)00213-6).
- 600 [29] M. Mirzahosseini, K.A. Riding, Effect of curing temperature and glass type on the pozzolanic  
601 reactivity of glass powder, *Cem. Concr. Res.* 58 (2014) 103–111.  
602 <https://doi.org/10.1016/j.cemconres.2014.01.015>.
- 603 [30] M.C. Bignozzi, A. Saccani, L. Barbieri, I. Lancellotti, Glass waste as supplementary  
604 cementing materials: The effects of glass chemical composition, *Cem. Concr. Compos.* 55  
605 (2015) 45–52. <https://doi.org/10.1016/j.cemconcomp.2014.07.020>.
- 606 [31] H. Lee, A. Hanif, M. Usman, J. Sim, H. Oh, Performance evaluation of concrete incorporating  
607 glass powder and glass sludge wastes as supplementary cementing material, *J. Clean. Prod.*  
608 170 (2018) 683–693. <https://doi.org/10.1016/j.jclepro.2017.09.133>.
- 609 [32] J. Lu, Z. Duan, C.S. Poon, Combined use of waste glass powder and cullet in architectural  
610 mortar, *Cem. Concr. Compos.* 82 (2017) 34–44.  
611 <https://doi.org/10.1016/j.cemconcomp.2017.05.011>.
- 612 [33] A. Bouchikhi, M. Benzerzour, N.-E. Abriak, W. Maherzi, Y. Mamindy-Pajany, Study of the  
613 impact of waste glasses types on pozzolanic activity of cementitious matrix, *Constr. Build.*  
614 *Mater.* 197 (2019) 626–640. <https://doi.org/10.1016/j.conbuildmat.2018.11.180>.
- 615 [34] B. Taha, G. Nounu, Properties of concrete contains mixed colour waste recycled glass as sand  
616 and cement replacement, *Constr. Build. Mater.* 22 (2008) 713–720.  
617 <https://doi.org/10.1016/j.conbuildmat.2007.01.019>.
- 618 [35] B. Lothenbach, K. Scrivener, R.D. Hooton, Supplementary cementitious materials, *Cem.*  
619 *Concr. Res.* 41 (2011) 1244–1256. <https://doi.org/10.1016/j.cemconres.2010.12.001>.

- 620 [36] D.R. Gaskell, CHAPTER FOURTEEN - THE DETERMINATION OF PHASE DIAGRAMS  
621 FOR SLAG SYSTEMS, in: J.-C. Zhao (Ed.), *Methods Phase Diagr. Determ.*, Elsevier Science  
622 Ltd, Oxford, 2007: pp. 442–458. <https://doi.org/10.1016/B978-008044629-5/50014-8>.
- 623 [37] T. Sedran, F.D. Larrard, L.L. Guen, Détermination de la compacité des ciments et additions  
624 minérales à la sonde de Vicat, *Bull. Lab. Ponts Chaussées*. (2007) 155–163.
- 625 [38] ASTM C1611, Test Method for Slump Flow of Self-Consolidating Concrete, ASTM  
626 International, 2019. [https://doi.org/10.1520/C1611\\_C1611M-18](https://doi.org/10.1520/C1611_C1611M-18).
- 627 [39] ASTM C1621, Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring,  
628 ASTM International, 2017. [https://doi.org/10.1520/C1621\\_C1621M-17](https://doi.org/10.1520/C1621_C1621M-17).
- 629 [40] ASTM C231, Test Method for Air Content of Freshly Mixed Concrete by the Pressure  
630 Method, ASTM International, 2017. [https://doi.org/10.1520/C0231\\_C0231M-17A](https://doi.org/10.1520/C0231_C0231M-17A).
- 631 [41] ASTM C39, Test Method for Compressive Strength of Cylindrical Concrete Specimens,  
632 ASTM International, 2018. [https://doi.org/10.1520/C0039\\_C0039M-18](https://doi.org/10.1520/C0039_C0039M-18).
- 633 [42] ASTM C496, Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens,  
634 ASTM International, 2017. [https://doi.org/10.1520/C0496\\_C0496M-17](https://doi.org/10.1520/C0496_C0496M-17).
- 635 [43] ASTM C1760, Test Method for Bulk Electrical Conductivity of Hardened Concrete, ASTM  
636 International, 2012. <https://doi.org/10.1520/C1760-12>.
- 637 [44] ASTM C1202, Test Method for Electrical Indication of Concretes Ability to Resist Chloride  
638 Ion Penetration, ASTM International, 2019. <https://doi.org/10.1520/C1202-19>.
- 639 [45] ASTM C1582, Specification for Admixtures to Inhibit Chloride-Induced Corrosion of  
640 Reinforcing Steel in Concrete, ASTM International, 2017.  
641 [https://doi.org/10.1520/C1582\\_C1582M-11R17E01](https://doi.org/10.1520/C1582_C1582M-11R17E01).
- 642 [46] ASTM C157, Test Method for Length Change of Hardened Hydraulic-Cement Mortar and  
643 Concrete, ASTM International, 2017. [https://doi.org/10.1520/C0157\\_C0157M-17](https://doi.org/10.1520/C0157_C0157M-17).
- 644 [47] ASTM C1012, Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a  
645 Sulfate Solution, ASTM International, 2018. [https://doi.org/10.1520/C1012\\_C1012M-18B](https://doi.org/10.1520/C1012_C1012M-18B).

- 646 [48] ASTM C1260, Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar  
647 Method), ASTM International, 2014. <https://doi.org/10.1520/C1260-14>.
- 648 [49] Self-Compacting Concrete European Project Group, The European Guidelines for Self-  
649 compacting Concrete: Specification, Production and Use, International Bureau for Precast  
650 Concrete (BIBM), 2005.
- 651 [50] ACI Committee 237, ed., Self-consolidating concrete, American Concrete Institute,  
652 Farmington Hills, Mich, 2007.
- 653 [51] K.H. Khayat, J. Assaad, J. Daczko, Comparison of Field-Oriented Test Methods to Assess  
654 Dynamic Stability of Self-Consolidating Concrete, *ACI Mater. J.* 101 (2004).  
655 <https://doi.org/10.14359/13066>.
- 656 [52] B.V. Kavyateja, J. Guru Jawahar, C. Sashidhar, Effectiveness of alccofine and fly ash on  
657 mechanical properties of ternary blended self compacting concrete, *Mater. Today Proc.*  
658 (2020). <https://doi.org/10.1016/j.matpr.2020.03.152>.
- 659 [53] P. Duan, Z. Shui, W. Chen, C. Shen, Effects of metakaolin, silica fume and slag on pore  
660 structure, interfacial transition zone and compressive strength of concrete, *Constr. Build.*  
661 *Mater.* 44 (2013) 1–6. <https://doi.org/10.1016/j.conbuildmat.2013.02.075>.
- 662 [54] Q. Zeng, K. Li, T. Fen-Chong, P. Dangla, Analysis of pore structure, contact angle and pore  
663 entrapment of blended cement pastes from mercury porosimetry data, *Cem. Concr. Compos.*  
664 34 (2012) 1053–1060. <https://doi.org/10.1016/j.cemconcomp.2012.06.005>.
- 665 [55] N.S. Martys, C.F. Ferraris, Capillary transport in mortars and concrete, *Cem. Concr. Res.* 27  
666 (1997) 747–760. [https://doi.org/10.1016/S0008-8846\(97\)00052-5](https://doi.org/10.1016/S0008-8846(97)00052-5).
- 667 [56] C. Hall, Water sorptivity of mortars and concretes: a review, *Mag. Concr. Res.* 41 (1989) 51–  
668 61. <https://doi.org/10.1680/mac.1989.41.147.51>.
- 669 [57] M. Liu, Incorporating ground glass in self-compacting concrete, *Constr. Build. Mater.* 25  
670 (2011) 919–925. <https://doi.org/10.1016/j.conbuildmat.2010.06.092>.

- 671 [58] R.-U.-D. Nassar, P. Soroushian, Strength and durability of recycled aggregate concrete  
672 containing milled glass as partial replacement for cement, *Constr. Build. Mater.* 29 (2012)  
673 368–377. <https://doi.org/10.1016/j.conbuildmat.2011.10.061>.
- 674 [59] A.M. Matos, J. Sousa-Coutinho, Durability of mortar using waste glass powder as cement  
675 replacement, *Constr. Build. Mater.* 36 (2012) 205–215.  
676 <https://doi.org/10.1016/j.conbuildmat.2012.04.027>.
- 677 [60] K.O. Ampadu, K. Torii, Chloride ingress and steel corrosion in cement mortars incorporating  
678 low-quality fly ashes, *Cem. Concr. Res.* 32 (2002) 893–901. [https://doi.org/10.1016/S0008-  
679 8846\(02\)00721-4](https://doi.org/10.1016/S0008-8846(02)00721-4).
- 680 [61] Md. Safiuddin, J.S. West, K.A. Soudki, Hardened properties of self-consolidating high  
681 performance concrete including rice husk ash, *Cem. Concr. Compos.* 32 (2010) 708–717.  
682 <https://doi.org/10.1016/j.cemconcomp.2010.07.006>.
- 683 [62] M. Thomas, Specifying and Achieving Durable Concrete, in: *Concr. NZ Conf. 2018 Tech.*  
684 *Pap. TR71*, Claudelands, Hamilton, 2018.
- 685 [63] H.S. Al-alaily, A.A.A. Hassan, Time-dependence of chloride diffusion for concrete containing  
686 metakaolin, *J. Build. Eng.* 7 (2016) 159–169. <https://doi.org/10.1016/j.job.2016.06.003>.
- 687 [64] Y. Dhandapani, T. Sakthivel, M. Santhanam, R. Gettu, R.G. Pillai, Mechanical properties and  
688 durability performance of concretes with Limestone Calcined Clay Cement (LC3), *Cem.*  
689 *Concr. Res.* 107 (2018) 136–151. <https://doi.org/10.1016/j.cemconres.2018.02.005>.
- 690 [65] M. Alexander, M. Thomas, Service life prediction and performance testing — Current  
691 developments and practical applications, *Cem. Concr. Res.* 78 (2015) 155–164.  
692 <https://doi.org/10.1016/j.cemconres.2015.05.013>.
- 693 [66] A.A. Abouhussien, A.A.A. Hassan, Optimizing the durability and service life of self-  
694 consolidating concrete containing metakaolin using statistical analysis, *Constr. Build. Mater.*  
695 76 (2015) 297–306. <https://doi.org/10.1016/j.conbuildmat.2014.12.010>.

- 696 [67] K. Obla, C. Lobo, H. Kim, Tests and Criteria for Concrete Resistant to Chloride Ion  
697 Penetration, *ACI Mater. J.* 113 (2016). <https://doi.org/10.14359/51689107>.
- 698 [68] A.A. Ramezani-pour, H. Bahrami Jovein, Influence of metakaolin as supplementary  
699 cementing material on strength and durability of concretes, *Constr. Build. Mater.* 30 (2012)  
700 470–479. <https://doi.org/10.1016/j.conbuildmat.2011.12.050>.
- 701 [69] R.-X. Liu, C.-S. Poon, Utilization of red mud derived from bauxite in self-compacting  
702 concrete, *J. Clean. Prod.* 112 (2016) 384–391. <https://doi.org/10.1016/j.jclepro.2015.09.049>.
- 703 [70] W. Zhang, Y. Hama, S.H. Na, Drying shrinkage and microstructure characteristics of mortar  
704 incorporating ground granulated blast furnace slag and shrinkage reducing admixture, *Constr.*  
705 *Build. Mater.* 93 (2015) 267–277. <https://doi.org/10.1016/j.conbuildmat.2015.05.103>.
- 706 [71] F. Collins, J.G. Sanjayan, Effect of pore size distribution on drying shrinking of alkali-  
707 activated slag concrete, *Cem. Concr. Res.* 30 (2000) 1401–1406.  
708 [https://doi.org/10.1016/S0008-8846\(00\)00327-6](https://doi.org/10.1016/S0008-8846(00)00327-6).
- 709 [72] M. Sahmaran, O. Kasap, K. Duru, I.O. Yaman, Effects of mix composition and water–cement  
710 ratio on the sulfate resistance of blended cements, *Cem. Concr. Compos.* 29 (2007) 159–167.  
711 <https://doi.org/10.1016/j.cemconcomp.2006.11.007>.
- 712 [73] H. Du, K.H. Tan, Transport Properties of Concrete with Glass Powder as Supplementary  
713 Cementitious Material, *ACI Mater. J.* 112 (2015). <https://doi.org/10.14359/51687363>.
- 714 [74] D.J. De Souza, M.H.F. Medeiros, J. Hoppe, L.F.M. Sanchez, The Uses of Finely Ground  
715 Materials to Mitigate the External Sulphate Attack (ESA) on Cementitious Materials, in: E.  
716 Menéndez, V. Baroghel-Bouny (Eds.), *Extern. Sulphate Attack – Field Asp. Lab Tests*,  
717 Springer International Publishing, Cham, 2020: pp. 139–151. <https://doi.org/10.1007/978-3->  
718 [030-20331-3\\_11](https://doi.org/10.1007/978-3-030-20331-3_11).
- 719 [75] W.-J. Long, Y. Gu, F. Xing, K.H. Khayat, Microstructure development and mechanism of  
720 hardened cement paste incorporating graphene oxide during carbonation, *Cem. Concr.*  
721 *Compos.* 94 (2018) 72–84. <https://doi.org/10.1016/j.cemconcomp.2018.08.016>.

- 722 [76] M. Boumaaza, B. Huet, P. Turcry, A. Aït-Mokhtar, The CO<sub>2</sub>-binding capacity of synthetic  
723 anhydrous and hydrates: Validation of a test method based on the instantaneous reaction rate,  
724 Cem. Concr. Res. 135 (2020) 106113. <https://doi.org/10.1016/j.cemconres.2020.106113>.
- 725 [77] E.A.B. Khalil, M. Anwar, Carbonation of ternary cementitious concrete systems containing fly  
726 ash and silica fume, Water Sci. 29 (2015) 36–44. <https://doi.org/10.1016/j.wsj.2014.12.001>.
- 727 [78] B. Lu, C. Shi, J. Zhang, J. Wang, Effects of carbonated hardened cement paste powder on  
728 hydration and microstructure of Portland cement, Constr. Build. Mater. 186 (2018) 699–708.  
729 <https://doi.org/10.1016/j.conbuildmat.2018.07.159>.
- 730 [79] A. Gabrisová, J. Havlica, S. Sahu, Stability of calcium sulphoaluminate hydrates in water  
731 solutions with various pH values, Cem. Concr. Res. 21 (1991) 1023–1027.  
732 [https://doi.org/10.1016/0008-8846\(91\)90062-M](https://doi.org/10.1016/0008-8846(91)90062-M).
- 733 [80] K. Sisomphon, L. Franke, Carbonation rates of concretes containing high volume of  
734 pozzolanic materials, Cem. Concr. Res. 37 (2007) 1647–1653.  
735 <https://doi.org/10.1016/j.cemconres.2007.08.014>.
- 736 [81] A.M. Neville, Properties of Concrete, 5 edition, Prentice Hall, Harlow, England ; New York,  
737 2012.
- 738 [82] Chen Chun-Tao, Ho Chia-Wei, Influence of Cyclic Humidity on Carbonation of Concrete, J.  
739 Mater. Civ. Eng. 25 (2013) 1929–1935. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000750](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000750).
- 740
- 741 [83] C. Shi, Y. Wu, C. Riefler, H. Wang, Characteristics and pozzolanic reactivity of glass  
742 powders, Cem. Concr. Res. 35 (2005) 987–993.  
743 <https://doi.org/10.1016/j.cemconres.2004.05.015>.
- 744 [84] Z.E.-A. Laidani, B. Benabed, R. Abousnina, M.K. Gueddouda, E.-H. Kadri, Experimental  
745 investigation on effects of calcined bentonite on fresh, strength and durability properties of  
746 sustainable self-compacting concrete, Constr. Build. Mater. 230 (2020) 117062.  
747 <https://doi.org/10.1016/j.conbuildmat.2019.117062>.

- 748 [85] A. Kanellopoulos, M.F. Petrou, I. Ioannou, Durability performance of self-compacting  
749 concrete, *Constr. Build. Mater.* 37 (2012) 320–325.  
750 <https://doi.org/10.1016/j.conbuildmat.2012.07.049>.
- 751 [86] K.H. Khayat, Optimization and performance of air-entrained, self-consolidating concrete, *ACI*  
752 *Struct. J.* 97 (2000) 526–535.
- 753 [87] ASTM C469, Test Method for Static Modulus of Elasticity and Poissons Ratio of Concrete in  
754 Compression, ASTM International, 2014. [https://doi.org/10.1520/C0469\\_C0469M-14](https://doi.org/10.1520/C0469_C0469M-14).
- 755 [88] S.H. Kosmatka, B. Kerkhoff, W.C. Panarese, Design and control of concrete mixtures,  
756 Portland Cement Association, Skokie, 2002.
- 757 [89] M.S. Shetty, Concrete technology: theory and practice, S. Chand, Ram Nagar, New Delhi,  
758 2007.
- 759 [90] N. Hearn, R.D. Hooton, R.H. Mills, Pore Structure and Permeability, Significance Tests Prop.  
760 *Concr. Concr.-Mak. Mater.* (1994). <https://doi.org/10.1520/STP36424S>.
- 761 [91] A. el M. SAFHI, Valorisation des sédiments de dragage dans des bétons autoplaçants :  
762 optimisation de la formulation et étude de la durabilité, Recycling of dredged sediments in  
763 self-consolidating concrete: mix design optimization and durability study. (2020).  
764 <http://hdl.handle.net/11143/16937>.
- 765