Degani I
*Cardiff University*
*School of Engineering*

Maddalena R
*Cardiff University*
*School of Engineering*

Kulasegaram S
*Cardiff University*
*School of Engineering*

NET ZERO

# The Effect of Curing Temperature and Supplementary Cementitious Materials on Chloride Permeability of Self-Compacting Concrete

In recent years, self-compacting concrete (SCC) has gained popularity due to its high flowability and reduced energy demand in construction. With a notable paste content, SCC undergoes intensified hydration reactions, resulting in a distinct microstructure compared to traditional concrete. When exposed to varying curing temperatures, SCC exhibits unique mechanical traits. However, the influence of curing temperature on SCC with supplementary cementitious materials (SCMs) remains underexplored. This study evaluates SCC performance with diverse SCMs, substituting specific volume fractions of cement with 10% silica fume (SF) and 40% fly ash (FA), under different curing temperatures. Emphasis lies on assessing the durability of these compositions for concrete structures. For evaluating critical chloride permeability, high-strength SCC specimens were cured underwater at 10 °C, 20 °C, and 50 °C. Incorporating supplementary cementitious materials (SCMs) enhances SCC's resistance to chloride permeability and mitigates the adverse effects of elevated curing temperatures. The study showcased remarkable enhancements in concrete performance with the addition of silica fume (SF) and fly ash (FA) compared to plain SCC. Particularly, at 10 °C, SCC with SF exhibited a significant increase rate of 78.89% over SCC without SF. These results underscore the pivotal role of SF and FA in bolstering the electrical resistance of SCC under different curing temperatures.

*Keywords:*
*Self-compacting concrete, chloride permeability, curing temperature, electrical resistivity.*

*Corresponding author:*
*DeganiIM@cardiff.ac.uk*



I. Degani, R. Maddalena, and S. Kulasegaram, ‘The Effect of Curing Temperature and Supplementary Cementitious Materials on Chloride Permeability of Self-Compacting Concrete’, *Proceedings of the Cardiff University School of Engineering Research Conference 2024*, Cardiff, UK, pp. 38-41.

**doi.org/10.18573/conf3.j**

## INTRODUCTION

The development of new types of concrete has opened up new possibilities in the construction field. One of these innovations is self-compacting concrete (SCC), first developed in Japan in the 1980s. SCC is a type of concrete that flows naturally through formwork without the need for vibration, filling it in a seamless manner and compacting under its own weight as it passes through reinforcing bars [1]. SCC boasts excellent deformability, passing ability, and high segregation resistance, making it suitable for heavily reinforced applications and self-compaction. Additionally, SCC enhances construction productivity, reduces the total cost of structures, improves the work environment, and exhibits sustainable characteristics [2]self-compacting concrete (SCC [3]. Several factors influence concrete properties, notably the composition of self-compacting concrete (SCC), where the high volume of paste in SCC is considered the major cause of porosity in the concrete, whereby replacing aggregates with paste increases the volume of porous material per volume of concrete, and thus the new concrete is more porous. Various harmful substances like water, chloride ions, acids, and other hazardous elements can easily penetrate concrete through these cracks and the pore system, leading to a degradation of its strength and overall durability [4][5].

The deterioration of concrete structures induced by chlorides is widely recognized as one of the most common causes of degradation [6] [7] .

Temperature, whether arising from internal reactions, curing conditions, or ambient surroundings, constitutes another influential factor impacting the properties of concrete, shaping its microstructure. Temperature significantly influences concrete properties by affecting hydration rates and microstructure. Lower curing temperatures initially increase porosity but lead to densification over time, reducing water absorption and permeability. In contrast, higher temperatures accelerate hydration, initially creating a denser microstructure but ultimately leading to increased porosity with prolonged exposure. This dual impact of temperature on concrete properties is detailed by [8] [9].

Incorporating cementitious materials SCMs such as SF and FA into concrete mixes results in the formation of concrete with a denser and finer structure due to very fine particle size of these SCMs, consequently enhancing mechanical properties [10] [11] . Moreover, FA mitigates the impact of high temperatures on concrete, slows down the hydration reaction [12] [13] [14] [15] [16]. The mechanical and durable properties of SCC containing mineral admixtures may exhibit more pronounced variations across different temperature conditions compared to conventional concrete.

The aim of this research is to evaluate the performance of SCC containing supplementary cementitious materials (SCMs) under different curing temperatures. Specifically, the study seeks to assess the durability of SCC compositions incorporating SF and FA by analysing chloride permeability through bulk electrical resistivity testing. The research aims to investigate how variations in curing temperatures affect the mechanical and durability properties of SCC, with a focus on understanding the influence of SCMs on mitigating the adverse effects of elevated curing temperatures.

## MATERIALS AND METHODS

*Materials*

Portland cement (CEM I 52.5) was used as a binder, where Portland cement has a fineness of 384 m2/kg. Silica fume (SF) and fly ash (FA) with specific gravities of 2.4 and 2.2, respectively, were used. A poly-aryl-ether-based superplasticiser (SP) with a specific gravity of 1.07 was utilized. The fine aggregate used in this experiment is river sand sieved to a diameter of 2.0 mm and a specific gravity of 2.55; approximately 30% of the fine aggregate was replaced with limestone dust (limestone dust) with a specific gravity of 2.6 and a size ranging from 0.125 mm to 2 mm. The coarse aggregate has a specific gravity of 2.65 and a maximum size of 10 mm. Superplasticiser with a specific gravity of 1.07 was used.

*Test methods*

The fresh properties were investigated according to [17]. Cubes with a size of 100×100×100 $mm^3$ were prepared for the compressive strength test in compliance with established standards outlined in BS EN 12390–3. For the bulk electrical resistivity test, 12 cylinders with 100 mm diameter and 200 mm height for each mix were performed. The test was conducted according to ASTM C1760. Nine samples for each mix were prepared: 3 samples for each curing temperature. The samples were wrapped with a plastic sheet and cured in water directly after casting. The samples were cured at 10 °C, 20 °C, 35 °C, and 50 °C for 90 days, and the tests were done at ages 1, 3, 7, 14, 28, 56, and 90 days.

## RESULTS AND DISCUSSIONS

*Fresh and hardened properties*

Table 1 presents the findings from tests on fresh properties and compressive strength after 28 days. These tests, including slump flow, J-ring, and compressive strength, were carried out as part of quality control measures to verify that the mixture attained self-compacting concrete properties and the anticipated strength.

| Mix code | (mm) | (mm) | D_slump-D_(J-ring) (mm) | Compressive strength at 28 days (MPa) | STDEV |
|---|---|---|---|---|---|
| SCC-C | 660 | 617.5 | 42.5 | 71.23 | 1.323 |
| SCC-SF-10% | 645 | 602.5 | 42.5 | 78.5 | 2.324 |
| SCC-FA-40% | 715 | 710 | 5 | 51.25 | 1.979 |

Table 1. Fresh and compressive strength results.

*Bulk Electrical Resistivity*

Figures 1 and 2 describe the results of the Bulk Electrical Resistivity test conducted on all mixes. This test is typically carried out to assess the chloride permeability in concrete samples. Observing the figures, it is clear that the electrical resistivity of all samples rises with increased curing time. Notably, the electrical resistivity of the SCC-C mix obtained the lowest electrical resistivity compared with other mixes for all curing temperatures. After 90 days of curing, the samples cured at 10 °C exhibited the highest electrical resistivity value (8.4 kΩ.cm), representing an increase of 79.7 from the 3-day curing age value of (1.7 kΩ.cm). While at for SCC-C-20 °C, the average electrical resistivity value ranges from 2.9 kΩ.cm to 7.2 kΩ.cm, showing an increased rate of 59 %. The SCC-C-50° exhibited the highest resistivity value at early ages (3.03 kΩ.cm), but later, it achieved the lowest value (4.26 kΩ.cm) compared to other SCC-C samples, showing an increase rate of 28.9 %.

This trend can be attributed to the significant impact that long-term exposure to low curing temperatures has on the hydration reaction. As the curing period extends, a microscopic structure begins to form, resulting in a denser microstructure with smaller, more uniform pores. Consequently, this transformation leads to a reduction in the porous structure, hindering ion movement and subsequently increasing electrical resistance. In contrast, high curing temperatures initially accelerate the hydration reaction, resulting in faster formation of hydration products creates pore structure and a temporary increase in electrical resistivity. Over the time, the differences in pore structure and hydration products due to the high curing temperature result in a less dense microstructure. This less dense structure allows for easier ion flow, which ultimately contributes to lower electrical resistivity. [1] [2] [3] [4].

It is observed that the addition of supplementary cementitious materials significantly enhanced the performance of concrete in terms of electrical resistivity. The SF mix achieved the highest electrical resistivity values at later curing ages. SF samples revealed that those cured at a lower temperature of 10 °C exhibited higher electrical resistivity compared to those cured at higher temperatures. The electrical resistivity value for SCC-SF-10 °C was 39.83 kΩ.cm, while for SCC-SF-20 °C it was 36.2 kΩ.cm. SCC-SF-50 °C exhibited lower electrical resistivity of 28.8 kΩ.cm. These values were higher than SCC-C values cured at the same temperature, with a rate of 78.8%, 80 %, and 85.20% higher, respectively. The electrical resistivity values of SF concrete samples cured at 10 °C and 20 °C, are highest due to the slower cement hydration rate at these temperatures, allowing for a more effective pozzolanic reaction of silica fume. This results in a denser and refined pore structure, restricting ion and electron movement and increasing resistivity. However, SF concrete samples cured 50 °C exhibit higher lower resistivity values. The higher temperatures accelerate cement hydration and initial strength development but may lead to less effective pozzolanic reaction of SF, resulting in larger pores. This facilitates easier ion and electron movement decreasing resistivity [5] [1] [6].

The addition of FA to SCC mixtures enhanced the electrical resistance performance of concrete. Its effect varied from that of SF in terms of resistance performance with temperatures. FA samples cured at 50 °C achieved the highest electrical resistivity value (36.93 kΩ.cm), This is attributed to the higher temperatures activate pozzolanic reactions in fly ash, leading to the creation of additional cementitious compounds like calcium silicate hydrate (CSH) gel, resulting in a denser and less porous concrete matrix. This denser matrix impedes ion movement, thus increasing electrical resistivity. while at lower curing temperatures, the pozzolanic reactions in fly ash are less activated compared to higher temperatures.

As a result, there is a reduced formation of additional cementitious compounds such as calcium silicate hydrate (CSH) gel, which contributes to a less dense microstructure and lower electrical resistivity [7] [8] [9] [10]. This was evident in the results of FA samples cured at 20 °C and 10 °C, which obtained much lower resistance values of 26.76 kΩ.cm and 13.46 kΩ.cm respectively. The increase rate of SCC-FA at 10 °C, 20 °C, and 50 °C compared to SCC-C at the same curing temperatures was 37.5%, 73.2%, and 88%, respectively.

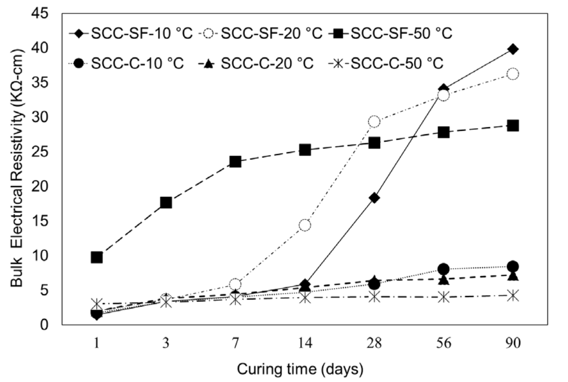


Fig. 1. Results of electrical resistivity of cement mix and SF mix cured at 10 °C, 20 °C and 50 °C.

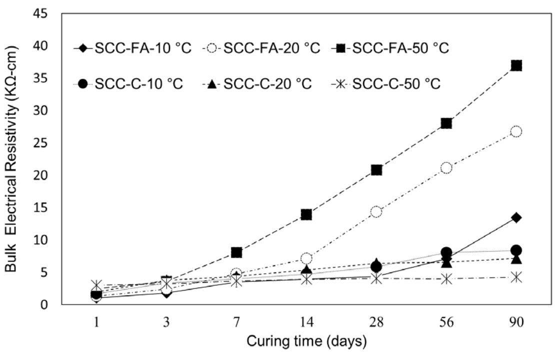


Fig. 2. Results of electrical resistivity of cement mix and FA mix cured at 10 °C, 20 °C and 50 °C.

## CONCLUSION

This study emphasizes the significant impact of curing temperatures and supplementary cementitious materials (SCMs) on self-compacting concrete (SCC) properties. It highlights the importance of considering factors such as hydration reactions, pore structure development, and ion movement when evaluating SCC performance and durability across different curing conditions. Lower curing temperatures promote the formation of a denser microstructure over time, enhancing electrical resistance, while higher temperatures can lead to larger pores and decreased resistivity.

The incorporation of SCMs like silica fume (SF) and fly ash (FA) improves SCC resistance, though effects vary with temperature. SF contributes to denser concrete matrices, especially at lower temperatures, while FA enhances resistance, particularly at higher temperatures, through activated pozzolanic reactions. These findings underline the complex relationship between curing conditions, SCMs, and concrete properties, offering valuable insights for optimizing SCC performance in diverse construction scenarios.

***Conflicts of Interest***
*The authors declare no conflict of interest.*

## REFERENCES


[1] H. Okamura and K. Ozawa, 'Self-Compacting High Performance Concrete', *Structural Engineering International*, vol. 6, no. 4, pp. 269–270, Nov. 1996. doi.org/10.2749/101686696780496292

[2] W. Zhu, J. C. Gibbs, and P. J. M. Bartos, 'Uniformity of in situ properties of self-compacting concrete in full-scale structural elements', *Cement and Concrete Composites*, vol. 23, no. 1, pp. 57–64, Feb. 2001. doi.org/10.1016/S0958-9465(00)00053-6

[3] H. Okamura and M. Ouchi, 'Self-Compacting Concrete', *ACT*, vol. 1, no. 1, pp. 5–15, 2003. doi.org/10.3151/jact.1.5

[4] S. Kolias and C. Georgiou, 'The effect of paste volume and of water content on the strength and water absorption of concrete', *Cement and Concrete Composites*, vol. 27, no. 2, pp. 211–216, Feb. 2005. doi.org/10.1016/j.cemconcomp.2004.02.009

[5] W. Sun, H. Chen, X. Luo, and H. Qian, 'The effect of hybrid fibers and expansive agent on the shrinkage and permeability of high-performance concrete', *Cement and Concrete Research*, vol. 31, no. 4, pp. 595–601, Apr. 2001. doi.org/10.1016/S0008-8846(00)00479-8

[6] U. Angst, B. Elsener, C. K. Larsen, and Ø. Vennesland, 'Critical chloride content in reinforced concrete — A review', *Cement and Concrete Research*, vol. 39, no. 12, pp. 1122–1138, Dec. 2009. doi.org/10.1016/j.cemconres.2009.08.006

[7] L. Basheer, J. Kropp, and D. J. Cleland, 'Assessment of the durability of concrete from its permeation properties: a review', *Construction and Building Materials*, vol. 15, no. 2–3, pp. 93–103, Mar. 2001. doi.org/10.1016/S0950-0618(00)00058-1

[8] D. J. Naus and H. L. Graves, 'A Review of the Effects of Elevated Temperature on Concrete Materials and Structures', in *Volume 1: Plant Operations, Maintenance and Life Cycle; Component Reliability and Materials Issues; Codes, Standards, Licensing and Regulatory Issues; Fuel Cycle and High Level Waste Management*, Miami, Florida, USA: ASMEDC, Jan. 2006, pp. 615–624. doi.org/10.1115/ICONE14-89631

[9] D. Wang, X. Zhou, Y. Meng, and Z. Chen, 'Durability of concrete containing fly ash and silica fume against combined freezing-thawing and sulfate attack', *Construction and Building Materials*, vol. 147, pp. 398–406, Aug. 2017. doi.org/10.1016/j.conbuildmat.2017.04.172

[10] R. Madandoust and S. Y. Mousavi, 'Fresh and hardened properties of self-compacting concrete containing metakaolin', *Construction and Building Materials*, vol. 35, pp. 752–760, Oct. 2012. doi.org/10.1016/j.conbuildmat.2012.04.109

[11] N. Chahal, R. Siddique, and A. Rajor, 'Influence of bacteria on the compressive strength, water absorption and rapid chloride permeability of fly ash concrete', *Construction and Building Materials*, vol. 28, no. 1, pp. 351–356, Mar. 2012. doi.org/10.1016/j.conbuildmat.2011.07.042

[12] N. Lahmar *et al*., 'Experimental and finite element analysis of shrinkage of concrete made with recycled coarse aggregates subjected to thermal loading', *Construction and Building Materials*, vol. 247, p. 118564, Jun. 2020. doi.org/10.1016/j.conbuildmat.2020.118564

[13] E. Rozière, S. Granger, Ph. Turcry, and A. Loukili, 'Influence of paste volume on shrinkage cracking and fracture properties of self-compacting concrete', *Cement and Concrete Composites*, vol. 29, no. 8, pp. 626–636, Sep. 2007. doi.org/10.1016/j.cemconcomp.2007.03.010

[14] M. Nasir, O. S. Baghabra Al-Amoudi, and M. Maslehuddin, 'Effect of placement temperature and curing method on plastic shrinkage of plain and pozzolanic cement concretes under hot weather', *Construction and Building Materials*, vol. 152, pp. 943–953, Oct. 2017. doi.org/10.1016/j.conbuildmat.2017.07.068

[15] J. Tang, H. Cheng, Q. Zhang, W. Chen, and Q. Li, 'Development of properties and microstructure of concrete with coral reef sand under sulphate attack and drying-wetting cycles', *Construction and Building Materials*, vol. 165, pp. 647–654, Mar. 2018. doi.org/10.1016/j.conbuildmat.2018.01.085

[16] Y. Li, J. Bao, and Y. Guo, 'The relationship between autogenous shrinkage and pore structure of cement paste with mineral admixtures', *Construction and Building Materials*, vol. 24, no. 10, pp. 1855–1860, Oct. 2010. doi.org/10.1016/j.conbuildmat.2010.04.018

[17] EFNARC, 'Specification and Guidelines for Self-Compacting Concrete' Rep. from *EFNARC*, vol. 44, no. February, p. 32, 2002, [online]. Available: https://wwwp.feb.unesp.br/pbastos/c.especiais/Efnarc.pdf

E. Spezi and M. Bray (eds.) 2024. *Proceedings of the Cardiff University School of Engineering Research Conference 2024.* Cardiff: Cardiff University Press.
doi.org/10.18573/conf3

*Cardiff University School of Engineering Research Conference 2024* was held from 12 to 14 June 2024 at Cardiff University.

The work presented in these proceedings has been peer reviewed and approved by the conference organisers and associated scientific committee to ensure high academic standards have been met.

First published 2024

Cardiff University Press
Cardiff University, Trevithick Library
First Floor, Trevithick Building, Newport Road
Cardiff CF24 3AA

cardiffuniversitypress.org

Editorial design and layout by
Academic Visual Communication

ISBN: 978-1-9116-5351-6 (PDF)