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Preventing plastic shrinkage cracking by monitoring the capillary pressure build-up in self-compacting concrete

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Abstract. Plastic shrinkage cracking is a problem for the service life, aesthetics and durability of concrete members. It occurs when tensile stresses are induced in fresh concrete, through plastic shrinkage that is restrained. Plastic shrinkage is caused by negative capillary pressure build-up, but the capillary pressure of fresh concrete can be controlled to prevent plastic shrinkage. In this paper, the control of capillary pressure to prevent plastic shrinkage cracking using high-capacity capillary pressure sensors is explored. The capillary pressure behaviour of a self-compacting concrete mix design in various evaporation rates was determined. Capillary pressure boundaries for concrete wetting to relieve tensile stresses were identified. The effectiveness of wetting fresh concrete at a predefined capillary pressure boundary was investigated.

1 Introduction

Plastic shrinkage is an early age property of concrete. It occurs when the cumulative evaporation exceeds the cumulative amount of bleeding of the concrete. When plastic shrinkage occurs and the concrete is restrained, tensile stresses are induced and if the concrete did not develop sufficient strength to withstand the induced stresses, plastic shrinkage cracks will form [1, 2]. The induced tensile stresses are caused by the build-up of negative capillary pressure within the fresh concrete [3]. If the negative capillary pressure builds up at a high rate and reaches a critical capillary pressure, plastic shrinkage cracking may occur [4].

Depending on the evaporation rate, plastic shrinkage cracks will either form before or at initial set and will stabilise at final set and widen at a lower rate [5, 6]. When plastic shrinkage cracks have formed, the cracks can be aggravated further by drying shrinkage which can extend these cracks throughout the depth of the concrete member [1]. Therefore, making these cracks a major problem for the services life, aesthetics and durability of a concrete member [7-9].

Capillary pores are small liquid filled pockets within the fresh concrete. These liquid pockets form between solid particles in the concrete, resulting in a pressure build-up, known as capillary pressure [10, 11]. The negative capillary pressure build-up in concrete can be illustrated in Fig. 1. The figure shows how plastic shrinkage cracks form as the negative capillary pressure builds up when concrete is exposed to a constant evaporation rate. In Fig. 1, as the bleed water on the concrete surface evaporates, the internal pore water decreases, resulting in water menisci forming between the solid particles. As the ongoing evaporation continues to reduce the radius of the menisci between the solid particles, leading to a build-up of negative capillary pressure [4]. This build-up of negative capillary pressure draws the particles together, resulting in plastic shrinkage [12]. When the negative capillary pressure continues to build up at an increasing rate and passes a critical capillary pressure, cracks may form as shown in the figure [4].

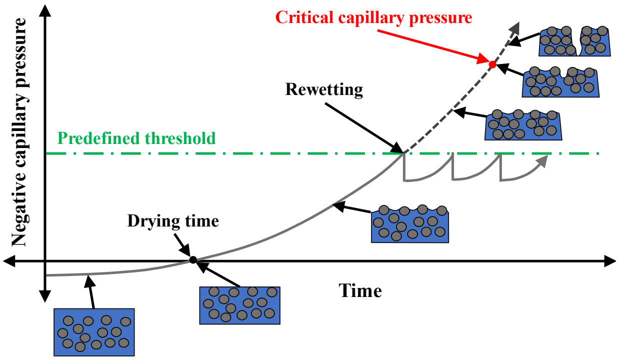

Fig. 1. Negative capillary pressure build-up and plastic shrinkage cracking [4,13,14].

The negative capillary pressure is significantly influenced by the evaporation rate. Increasing the evaporation rate increases the build-up rate of the negative capillary pressure in concrete and vice versa when the evaporation rate is decreased [4]. Numerous researchers have also shown that the negative capillary pressure build-up is affected by factors such as particle size distribution, bleeding, admixtures, additions, specimen geometry and the water/cement ratio [3, 6, 12, 14-17]. Due to all these factors influencing the negative capillary pressure build-

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up, the capillary pressure mechanism has been identified in the literature as the primary mechanism for plastic shrinkage [4, 10, 14, 18].

Studies have shown that by rewetting the concrete surface before a predefined capillary pressure threshold is reached, the negative capillary pressure build-up in concrete can be delayed [4, 12, 14, 19]. Delaying the build-up of negative capillary pressure gives the concrete time to develop strength and minimises the risk of plastic shrinkage cracks forming [4, 19]. Fig. 1 also demonstrates how the negative capillary pressure build-up and the risk for plastic shrinkage cracking are affected by rewetting the concrete.

Deysel *et al.* [19] proposed an empirical model for determining a boundary for when fresh concrete should be rewetted to prevent plastic shrinkage cracking. The model is known as the No Cracking Capillary Pressure Boundary Model and uses the area under the negative capillary pressure build-up of concrete that did not crack between the drying time and initial setting time. This area is then used to determine a capillary pressure limit required for that evaporation rate (for the same concrete mix). A no cracking capillary pressure boundary (the predefined threshold) is then applied which marks the limit for when the concrete surface should be rewetted. The drying time is known as the point in time when the cumulative evaporation is equal to the cumulative amount of bleeding of the concrete [20]. However, the drying time term used in the model refers to the point in time when the capillary pressure reached 0 kPa. More information on the model can be found in Deysel *et al.* [19].

In previous literature, the capillary pressure in concrete was measured using either an electrical pressure sensor or a wireless capillary pressure sensor [4, 13, 14, 21]. The electrical pressure sensors consist of a pressure transducer connected to a metal tube filled with water. The disadvantage of this sensor is that a specific mould (where the sensor is horizontally attached at half the depth) had to be used to measure the capillary pressure [13, 14, 21]. Another disadvantage noticed, was that the sensors were only able to measure the negative capillary pressures up to -80 kPa [14].

The wireless capillary pressure sensor consists of a pressure transducer connected to a measurement tip filled with water. An advantage of this sensor is that the sensor is also capable of measuring temperature and humidity [4]. The sensor is inserted into the surface of the concrete and measures the capillary pressure from the surface. However, the result in this paper indicates that the sensors were only able to measure the negative capillary pressure up to -34 kPa [4].

In soil, suctions (negative pore pressures) are measured directly with pressure sensors known as tensiometers [22]. A tensiometer is a small sensor shown in Fig. 2 which consists of a high air entry porous ceramic tip connected to a pressure gauge and protected by a stainless-steel cap.

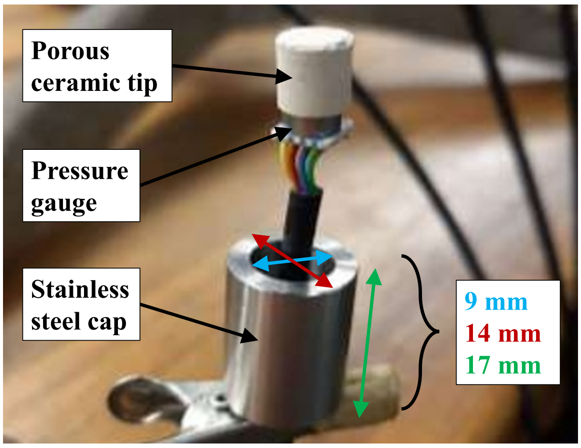

Fig. 2. An example of the components of a tensiometer.

Toll *et al.* [22] stated that tensiometers are capable of measuring suction of up to 2500 kPa in soil. However, most of the soil measurements were limited to suctions of up to 1000 kPa. Tensiometers are low-cost devices and can be built for the required negative pressure measurements [23]. In addition, tensiometers can be used on-site or in the laboratory [22, 23]. The only disadvantages of tensiometers are the saturation and calibration procedures which are rather tedious [22]. Although tensiometers are typically used for measuring high suction measurements in soil, this sensor can prove to be beneficial for measuring the negative capillary pressure in concrete.

The purpose of the study is to monitor the negative capillary pressure using tensiometers and prevent plastic shrinkage cracking in self-compacting concrete. The effectiveness of rewetting the concrete is also investigated.

2 Experimental procedures

2.1 Experimental Outline

The experimental procedures conducted consist of evaluating the plastic shrinkage cracking and capillary pressure behaviour of a self-compacting concrete mix. This was achieved by conducting a set of Control and Rewetting tests. The Control tests consisted of exposing the concrete to two distinct evaporation rates to evaluate the plastic shrinkage cracks behaviour. Whereas in the Rewetting tests, two tests were conducted which consisted of rewetting the concrete surface when a boundary was reached to prevent plastic shrinkage cracking. In both the Control and Rewetting tests, the evaporation rate, capillary pressure and plastic shrinkage cracks were measured for 9 hours. Time zero for the Control and Rewetting tests started just after the casting and placing of the specimens in their testing positions.

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2.2 Mix Design

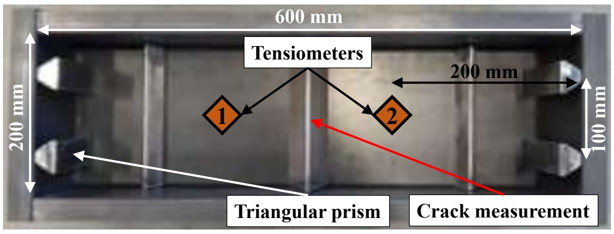
Table 1 shows the material constituents used for the self-compacting concrete. Some of the guidelines provided by Aggarwal *et al.* [24] were used to design the concrete mix. The self-compacting concrete had a water/binder ratio of 0.76. The properties such as the compressive strength [25], slump flow [26] and the setting times [27] of the concrete are also provided in the table. The standard deviation for the 28-day compressive strength is 1.21 MPa. Time zero for the setting time occurred when the water and cement made contact.

Table 1. Material constituents and concrete properties.

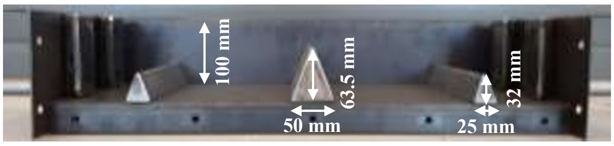
Material constituents	Water [kg/m^3]	174
	CEM I 52.5 R [kg/m^3]	430
	Fly ash [kg/m^3]	163
	Silica fume [kg/m^3]	38.7
	9.5 mm Dolomite crusher stone [kg/m^3]	504
	Dolomite crusher sand [kg/m^3]	1174
	Superplasticiser [kg/m^3]	6.10
Properties	28-day Compressive strength [MPa]	101
	Slump flow [mm]	590
	Initial setting time [min]	511
	Final setting time [min]	601

The mixing procedure of the self-compacting concrete consisted of mixing the dry materials for 60 seconds before adding the water and then the superplasticiser. The concrete was then mixed for an additional 4 minutes, adding up to 5 minutes in total.

The four tests were conducted on three cylindrical evaporation and three plastic shrinkage cracking specimens [19, 21, 28]. Fig. 3 shows the modified ASTM C1759 mould used for plastic shrinkage cracking, the tensiometer placement and where the crack measurements were done. As shown in the figure the modified ASTM C1759 mould is a slimmer design than the original ASTM C1759 mould [29] with additional triangular prism restraints at the endpoints. In this study, the triangular prism restraints at the endpoints were not used.



Top view



Side view

Fig. 3. Dimensions of the modified ASTM C1759 mould.

The evaporation moulds were cylindrical PVC moulds having a diameter of 55 mm and a height of 100 mm. All the moulds and concrete materials needed for each test were stored in a temperature-controlled room (set at 24±1 °C) for 24 hours before testing.

2.3 Experimental Set-up and program

A humidity-controlled room and a climate chamber were used to create the different evaporation environments needed for the four tests.

Two tensiometers were placed in the plastic shrinkage cracking specimens to monitor the capillary pressure. Fig. 4 shows the set-up used for embedding the tensiometers in the fresh concrete. The tensiometers were placed in 3D printed tenstal, to keep the sensor at the desired position. The tensiometers were kept at a depth of 32 mm and spaced at 200 mm (as shown in Fig. 3) in the modified ASTM C1579 moulds.

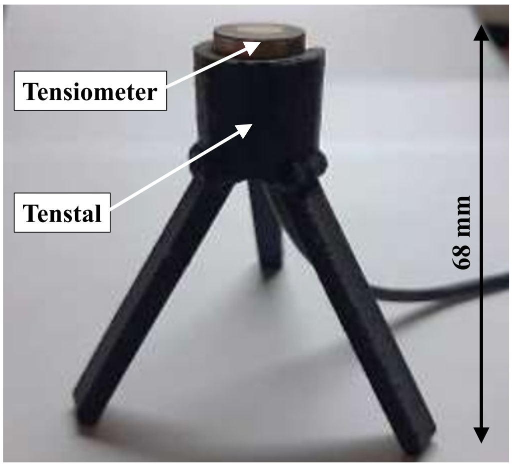


Fig. 4. Tensiometer set-up used for the experimental work.

The concrete was cast in two layers, to allow air bubbles to escape. The two tensiometers were then embedded and covered with the second layer of concrete.

The concrete evaporation rate was determined by weighing the evaporation specimens every 20 minutes once the test started. A Jadever JWA 30K scale was used for weighing the specimens. The scale had a resolution of 0.001 kg and a range from 0.2 to 30 kg.

Plastic shrinkage cracks were measured at the centre of the mould as illustrated in Fig. 3. The cracks were measured with a crack width card which could measure cracks width from 0.05 to 10 mm.

In the Control test set, the concrete was exposed to two evaporation rates for 9 hours and was allowed to crack. Control-1 (the first test) was conducted at a low evaporation rate to find a negative capillary pressure build-up where no cracks will form. This no cracking negative capillary pressure build-up along with the initial setting time was required to use the model and determine a no cracking capillary pressure boundary [19]. Control-2 (the second test) was done to determine at what

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evaporation rate the plastic shrinkage cracking would occur. Throughout the tests, the evaporation rate, plastic shrinkage crack width and capillary pressure were measured.

In the Rewetting test set, two tests were conducted where the concrete was exposed to two different evaporation rates for 9 hours and rewetted at a determined boundary to prevent plastic shrinkage cracking. In Rewetting-1 (the first test in this set), the concrete was exposed to a similar evaporation rate to that of Contol-1. In Rewetting-2, the concrete was exposed to a significantly higher evaporation rate. As soon as the concrete was exposed to an evaporation rate in Rewetting-1 and 2, the model [19] was applied and used to determine the boundary. Once the no cracking capillary pressure boundary was reached the surface of the concrete was rewetted with water to prevent plastic shrinkage cracks. In both tests, the surface was only rewetted up until 480 minutes to observe the capillary pressure behaviour after rewetting. In the rewetting tests the evaporation rate, plastic shrinkage cracks and capillary pressure were also measured for 9 hours. Table 2 summarises the total amount of properties measured throughout the Control and Rewetting tests.

Table 2. Properties measure for the Control and Rewetting tests.

Properties	**Control**		**Rewetting**	
	1	**2**	**1**	**2**
Evaporation rate	3		3	
Plastic shrinkage cracks	3		3	
Capillary pressure	6		6	

3 Results and Discussions

3.1 Control Tests

Fig. 5 shows the negative capillary pressure build-up and the crack width of the two Control tests. Each line represents the capillary pressure measurements obtained by a tensiometer in that Control test. The findings clearly show that the higher the evaporation rate the higher the negative capillary pressure build-up in the concrete. Therefore, the findings correlate with the literature from Slowik *et al.* [4] which showed that the negative capillary pressure build-up rate would increase with the increase in the evaporation rate. When comparing the curvatures of the negative capillary pressure build-up between Control-1: 0.11 kg/m^2/h and Control-2: 0.38 kg/m^2/h. Control-2 obtained a more linear curvature than Control-1.

The capillary pressure measurements also show that the higher the negative capillary pressure build-up rate, the earlier the tensiometers will cavitate. The noise seen in the capillary pressure measurements of Control-2 is possibly due to the cycles of the dehumidifier in the climate chamber and the self-compacting concrete, allowing movement.

The figure shows that the concrete exposed to the lower evaporation rate in Control-1 did not crack. Whereas the concrete exposed to a slightly higher evaporation rate started cracking significantly. The plastic shrinkage crack continued to widen until reaching a crack width of 0.49 mm after the initial setting time. Another aspect noticed in the figure is the significant increase in the crack growth when increasing the evaporation rate by 0.27 kg/m^2/h from Control-1 to Control-2. The findings are in agreement with Combrinck and Boshoff [6] when exposing concrete to an evaporation rate, the concrete will start cracking close to initial set and will continue widening until final set.

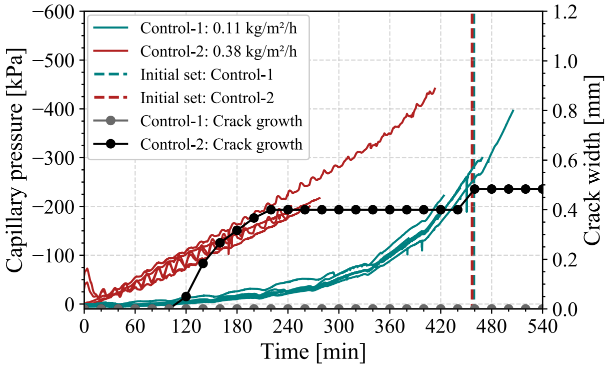

Fig. 5. Negative capillary pressure build-up and crack width over time for the two Control tests.

Table 3 provides the average capillary pressure values before cracking, at the start of cracking and at initial set for the two different evaporation rates. In addition, the tables provide the average drying time obtained for the two evaporation rates. The drying time was determined as the point in time when the capillary pressure reached 0 kPa. The results show that at Control-2, plastic shrinkage cracking occurred between a capillary pressure range of -78.7 and -89.4 kPa. This implies that a critical capillary pressure value where plastic shrinkage cracking occurs exists within this pressure range. Slowik *et al.* [4] stated that when a critical capillary pressure is reached plastic shrinkage cracking will occur. The findings, therefore, confirm this statement.

Table 3. Capillary pressures and drying times for Control tests.

Conditions	**Control-1: 0.11 kg/m^2/h**	**Control-2: 0.38 kg/m^2/h**
Capillary pressure before cracks, kPa	No cracks	-78.7
Capillary pressure at the start of cracking, kPa	No cracks	-89.4
Capillary pressure at initial set, kPa	-268	Tensiometer cavitation
Capillary pressure drying time, min	75.6	3.12

The negative capillary pressure build-up of the concrete in Control-1 did not crack and will be used in the model to determine the boundaries required for the two Rewetting tests.

3.2 Rewetting Tests

Fig. 6 and Fig. 7 show the individual capillary pressure and average crack width over time for the concrete in each Rewetting test. The no cracking capillary pressure boundary determined with the model is also shown in the figures. The pressure drops in the capillary pressure measurements are caused by rewetting the concrete surface when the boundary was reached. The capillary pressure before cracks, at the start of cracking and the no cracking boundary are provided in Table 4.

The evaporation specimens of Rewetting-2 (Fig. 7) were compromised by water that fell on it. Therefore, the evaporation rate for Rewetting-2 was estimated using Uno's equation [30]. The estimated evaporation rate obtained was found to be 0.73 kg/m^2/h, thus an evaporation rate of >0.70 kg/m^2/h will be used as a reference for Rewetting-2.

In Fig. 7, the capillary pressure measurements of two tensiometers were significantly higher than that of the other tensiometers and above the no cracking capillary pressure boundary. The reason for this might have been that the tensiometers might have moved in the concrete and measured at a different position.

The two figures show that the tensiometers were able to measure the slightest changes in the capillary pressure (pressure drops) as the water was added to the surface of the concrete.

Fig. 6 shows that no cracks formed when the negative capillary pressure build-up was maintained below the no cracking capillary pressure boundary while being exposed to an evaporation rate of 0.36 kg/m^2/h in Rewetting-1.

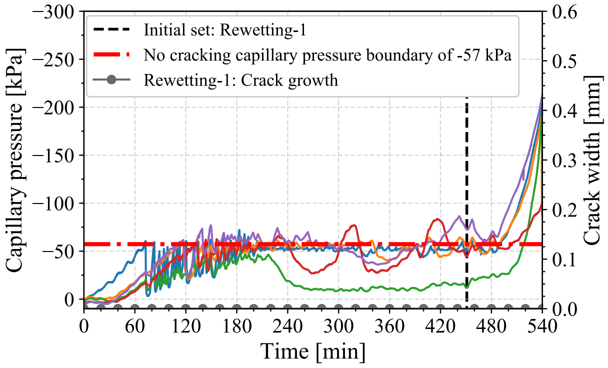

Fig. 6. Negative capillary pressure build-up and crack width over time for Rewetting-1: 0.36 kg/m^2/h.

Fig. 7 shows that even after applying the no cracking capillary pressure boundary, the concrete still cracked. It should be noted that only one of the three plastic shrinkage cracking specimens slightly cracked, which means that the crack might have been due to other influences such as plastic settlement. However, the figure shows that the crack only widened between 80 and 140 minutes and thereafter remained constant at a crack width of 0.05 mm. Therefore, it can be argued that applying a boundary and maintaining the negative capillary pressure build-up below that boundary by rewetting the surface, assist in reducing plastic shrinkage cracking.

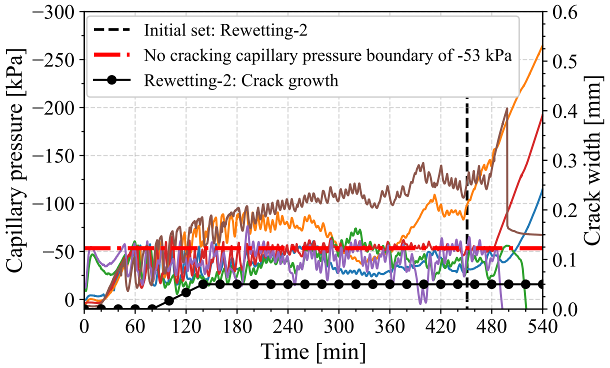

Fig. 7. Negative capillary pressure build-up and crack width over time for Rewetting-2: >0.70 kg/m^2/h.

The figures show that the negative capillary pressure build-up can effectively be delayed by rewetting the concrete surface when the boundary was reached. It can also be seen that the no cracking capillary pressure boundary decreased as the evaporation rate increased. The reason for this is the model [19] calculates a lower boundary as the negative capillary pressure build-up rate increases. It should also be noted that the calculated boundaries are lower than the pressure range (between -78.7 and -89.4 kPa) where cracking occurred in Control-2.

Table 4 shows that the capillary pressure ranges where cracking occurred for Rewetting-2 were between -23 and -33.4 kPa. When comparing this pressure range with the pressure range found in Control-2. The pressure ranges from Rewetting-2 is significantly lower than that of Control-2, which also implies that the cracking might have been due to other factors as previously mentioned.

Table 4. Summarised capillary pressure measurements.

Conditions	**Rewetting-1: 0.36 kg/m^2/h**	**Rewetting-2: >0.70 kg/m^2/h**
Capillary pressure before cracks, kPa	No cracks	-23
Capillary pressure at the start of cracking, kPa	No cracks	-33.4
No cracking capillary pressure boundary, kPa	-57	-53

The figures show that the negative capillary pressure build-up after ceasing the addition of water to the concrete (from 480 to 540 minutes) had a steep build-up rate. The figures also show that the build-up rate in both tests is similar which might be due to cement hydration. This implies that after a certain time period the negative capillary pressure build-up is no longer dependent on the evaporation rate and more dependent on hydration.

4 Conclusion

Tensiometers were used to monitor the capillary pressure and identify when the self-compacting concrete should be rewetted to prevent plastic shrinkage cracking. The following conclusions were drawn from the findings:

- As the evaporation rate increased, the rate of the negative capillary pressure build-up increased and the intensity of the plastic shrinkage cracking increased.
- Plastic shrinkage cracking can be minimised by wetting the surface of the concrete when a specific no cracking capillary pressure boundary is reached.
- The No Cracking Capillary Pressure Boundary Model proved to be a useful tool in determining a threshold for when the concrete should be rewetted.
- Tensiometers were able to measure the capillary pressure in concrete and measure the slightest changes in the pressure.

References

1. J. Lamond, J. Pielert, ASTM International. *Significance of Tests and Properties of Concrete and Concrete-Making Materials,* (2006)
2. M. Soutsos, P. Domone, *Construction materials: their nature and behaviour*, E **5**, (CRC Press, Roca Raton, 2017)
3. F. Sayahi, M. Emborg, H. Hedlund, A. Cwirzen, Nordic Concrete Research, *Plastic Shrinkage Cracking of Self-compacting Concrete: Influence of Capillary Pressure and Dormant Period.* **60**(1):67-88, (2019)
4. V. Slowik, M. Schmidt, D. Kässler, M. Eiserbeck, Transportation Research Record: Journal of the Transportation Research Board, *Capillary Pressure Monitoring in Plastic Concrete for Controlling Early-Age Shrinkage Cracking*, **2441**(1):1-5, (2014)
5. P. Turcry, A. Loukili ACI Materials Journal, *Evaluation of Plastic Shrinkage Cracking of Self-Consolidating Concrete*, **103**(4):272-279, (2006)
6. R. Combrinck, W. Boshoff, Magazine of Concrete Research, *Typical plastic shrinkage cracking behaviour of concrete*, **65**(8):486-493, (2013)
7. V. Dao, P. Dux, P Morris, L. O'Moore, Australian Journal of Structural Engineering, *Plastic Shrinkage Cracking of Concrete*, **10**(3):207-214, (2010)
8. C. Qi, *Quantitative assessment of plastic shrinkage cracking and its impact on the corrosion of steel reinforcement.* (Dissertation, Purdue University, 2003)
9. M. Otieno, M. Alexander, H. Beushausen, Magazine of Concrete Research, *Corrosion in cracked and uncracked concrete – influence of crack width, concrete quality and crack reopening*, **62**(6):393-404, (2010)
10. F. Wittmann, Cement and Concrete Research, *On the action of capillary pressure in fresh concrete*, **6**(1):49-56, (1976)
11. J. Knappett, R. Craig, *Craig's soil mechanics*, E **8**:22-23, (Spon Press, New York, 2012)
12. M. Schmidt, V. Slowik, Proceedings of the 2nd International RILEM Workshop on Concrete Durability and Service Life Planning – ConcreteLife'09, *Capillary shrinkage cracking and its prevention by controlled concrete curing*, (**1**):8 (2009)
13. R. Combrinck, *Cracking of Plastic Concrete in Slab-Like Elements*, (Dissertation, University of Stellenbosch, 2016)
14. V. Slowik, M. Schmidt, R. Fritzsch, Cement and Concrete Composites, *Capillary pressure in fresh cement-based materials and identification of the air entry value*, **30**(7):557-565, (2008)
15. E. Holt, M. Leivo, Cement and Concrete Composites, *Cracking risks associated with early age shrinkage*, **26**(5):521-530, (2004)
16. S. Leonovich, Concrete. Science & Technique *Modeling of Capillary Shrinkage and Cracking in Early-Age*, **17**(4):265-277, (2018)
17. F. Sayahi, M. Emborg, H. Hedlund, A. Cwirzen, ACI Materials Journal, *Effect of Admixtures on Mechanism of Plastic Shrinkage Cracking in Self-Compacting Concrete*, **117**(5):51-60, (2020)
18. S. Ghourchian, M. Butler, M. Krüger, V. Mechtcherine, Cement and Concrete Research, *Modelling the development of capillary pressure in freshly 3D-printed concrete elements*, **145**:106457, (2021)
19. R. Deysel, W. Boshoff, M. Smit, Mater. Struct., *Utilising an empirical model to assist in controlling the live capillary pressure in concrete to prevent plastic shrinkage cracking*, (to be published)
20. H. Kwak, S. Ha, Magazine of Concrete Research, *Plastic shrinkage cracking in concrete slabs. Part II: numerical experiment and prediction of occurrence*, **58**(8):517-532, (2006)
21. R. Combrinck, *Plastic Shrinkage Cracking in Conventional and Low Volume Fibre Reinforced Concrete*, (Dissertation, University of Stellenbosch, 2011)
22. D. Toll, S. Lourenço, J. Mendes, Engineering Geology, *Advances in suction measurements using high suction tensiometers*, **165**:29-37, (2013)
23. P. le Roux, *The Measurement of Soil-Water Retention Curves using the Tensiometer Method*, (Dissertation, University of Pretoria, 2020)
24. P. Aggarwal, Y. Aggarwal, S. Gupta, Leonardo Electronic Journal of Practices and Technologies, *Self-Compacting Concrete - Procedure for Mix Design*, (**12**):15-24, (2008)
25. EN 12390-3, *Testing hardening concrete. Part 3: Compressive strength of test specimens*, (2002)
26. EN 12350-5, *Testing Fresh Concrete – Flow Table Test*, (2009)
27. ASTM C403/C403M-16, *Standard Test Methods for Time of Setting of Concrete Mixtures by Penetration Resistance*, (ASTM International, West Conshohocken, 2016)
28. R. Combrinck, L. Steyl, W. Boshoff, Construction and Building Materials, *Interaction between*

settlement and shrinkage cracking in plastic concrete, **185**:1-11, (2018)

29. ASTM C 1579, *Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete*, (ASTM International, West Conshohocken, 2013)
30. P. Uno, ACI Materials Journal, *Plastic Shrinkage Cracking and Evaporation Formulae*, **95**(4):365-375, (1998)