A comparison of bleeding measurement techniques with a proposed method utilising super absorbent polymers

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Abstract

Bleed water measurement is a critical part for the determination and prediction of the incidence of plastic shrinkage cracking in concrete. This research discusses the different bleeding measurement methods that are largely in use today. The effect of different intervals of bleed water extraction from the surface is experimentally studied and correlated with the non-extractive approaches. The findings reveal a difference in bleed water measurement results among the different methods, as well as the phenomenon of bleed water re-absorption. Additionally, a novel surface bleed water extraction approach using superabsorbent polymers (SAP) is proposed and used to compare with the direct water extractive methods. It was found that bleed water extractive approaches with smaller time intervals resulted in significantly higher bleeding amounts. However, for much longer measurement intervals, bleed water extractive approaches revealed that bleeding is similar to settlement due to self-weight as suggested in the non-contact laser approach. The SAP extraction method was found to be a viable alternative for measuring the bleeding in concrete.

Keywords: Bleeding; Concrete; Testing; Review; Superabsorbent polymers

1 Introduction

Plastic shrinkage cracking of concrete is largely understood to be a result of the volumetric changes that take place during its plastic state [1,2,3]. The window of occurrence lasts for about 3 – 8 h after casting and yet once it occurs, presents long-lasting durability challenges to an entire concrete structure [4, 5]. Plastic shrinkage cracking is most severe if large exposed concrete elements interface with high evaporation rate conditions [6, 7]. Cracks are not only aesthetically unappealing but also pathways for deleterious elements into the deeper zones of the structure [5]. This study acknowledges the great volume of literature evaluating the various mechanisms leading to plastic shrinkage cracking. These mechanisms have largely been identified as settlement [3, 8], bleeding [9,10,11], evaporation [12,13,14], and capillary pressure [10, 15, 16]. The evaluation and prediction of the incidence of plastic shrinkage cracking usually relies on the quantification of each of these mechanisms. This study critically identifies and discusses the bleeding measurement techniques existing in literature, either as proposed methods/procedures or standardised tests [17,18,19,20,21,22,23,24].

The genesis of bleeding of fresh concrete lies in the intrinsic nature of concrete being a mixture of water and solid particles. Bleeding, as one of the mechanisms leading to plastic shrinkage, is said to be induced by free settlement of the concrete's solid constituents in a fluid media [1]. This process causes water displacement through the several interconnected spaces between the particles, to the surface of the concrete where it ponds [10]. Bleeding is also said to progress by the capillary pore pressure suction effect which is facilitated by the drying of the surface ponding water due to evaporation [1, 8, 9, 11]. Ideally, the termination of these processes directly impact the progression of the bleeding phenomenon. In addition, setting of concrete is also said to stop the bleeding process [10, 25, 26]. In the prediction of the likelihood of plastic shrinkage, bleeding rate is usually compared to that of evaporation and is related to what is known as drying time [9, 13]. The progression of bleeding is usually influenced by the characteristics of the cementitious material (or other) as well as sectional dimensions such as depth [1, 7, 27,28,29]. Quantification of bleeding amounts is therefore important in estimating the occurrence and severity of plastic shrinkage cracking.

The known methods used to determine the quantity of bleed water could be divided into two; one where water is extracted, such as according to ASTM C232 [22] and EN 480–4:2005[23] or one where the bleed water volume is determined by a non-contact laser device as in [17,18,19,20,21]. These two approaches could be categorised into 'extractive' and 'non-extractive' methods based on how the measurement of bleed water volume is done. ASTM C232 (2004) is a standard method of measuring the volume of bleed water for plastic concrete. It involves extraction of bleed water from the surface of concrete at certain time intervals and differs from the modified version by Josserand and De Larrard [24] only via the method of extraction. The bleed water extraction methods could be referred to as direct methods of measuring bleeding, while the non-contact laser approach as an indirect one. The choice of method of bleeding measurement requires an understanding of the implication of either extracting or leaving the bleed water on the surface. This choice however, brings in view the known phenomenon of bleed water re-absorption that occurs during the time of measurement [3]. In view of this, a novel water extraction approach that minimises bleed water re-absorption is also proposed as part of this research. This approach involves the utilisation of superabsorbent polymers enclosed in a permeable membrane bag (tea bag) that is placed on the surface of concrete. This paper attempts to bring into focus the implications of the choice in bleed water measurement methods in order to guide future research. This is achieved by highlighting and comparing the differences among the bleeding measurement methods in use today in addition to proposing a new bleed water extraction approach.

2 Typical bleeding measurement methods

2.1 Extractive methods

Concrete bleeding usually leads to the accumulation of a water layer on the surface of concrete. Thus, extractive bleed water measurement methods involve removing and measuring the volume of this water. ASTM C232:2004 [22] and EN 480–4:2005[23], are standardised tests for the determination of concrete bleed volume by physically extracting surface accumulated water. Another bleed water extractive method is that proposed by Josserand and De Larrand [24]. Their method is a modification of ASTM C232. Figure 1 shows the typical cylindrical mould that is used for the two methods (ASTM and Josserand). Both methods involve covering a concrete filled mould to minimise evaporation of bleed water. Thereafter, the collected surface bleed water is continuously extracted (using a pipette or syringe) and measured at specified time intervals, for example in ASTM C232 it is every 10 min for the first 40 min and at 30 min intervals thereafter. To account for any water loss due to evaporation during the procedure, the filled mould is weighed both before and after bleed water extraction at all measurement intervals. The two methods vary by way of water extraction. The ASTM C232 method [22] involves tilting the bleed mould to gather before it is collected. Tilting is done by hinging the concrete-filled bleed mould on a 50 mm block for two minutes to allow bleed water collect on one side of the mould. This method involves movement of the mould (tilting process) at every measurement interval, and this can easily influence the bleeding process. In the Josserand and De Larrard method [24] a star shaped stencil (see Fig. 1) is used to create grooves on the surface of concrete where water collects. These grooves direct bleed water to the centre of the mould where it collects and is extracted without tilting or moving the mould. However, this method presents a challenge in creating consistent grooves where the water collects [1].

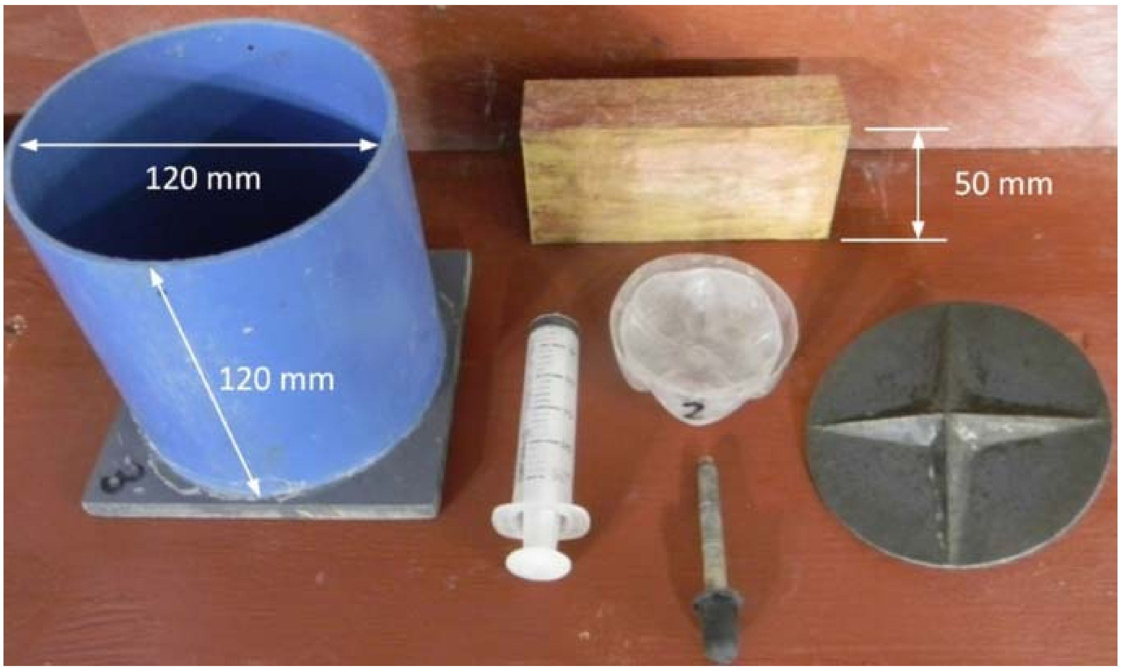

Fig. 1. Bleeding measurement apparatus: based on ASTM C232 [22] and Josserand and De Larrard [24]

2.2 Non-extractive methods

Kayir and Weiss [17] developed and proposed a non-extractive method of bleeding water measurement using a non-contact laser surface profiling approach. By this method, free settlement is also said to be measured. The device is fixed on a moving table that continuously scans the surface of concrete, measuring the distance from laser to surface of concrete (see Fig. 2) [17]. By this method, a laser beam is shot towards the fresh concrete surface and the reflected beam is read by a sensor. Measurements are then taken by a data acquisition system at set time intervals, for example every 30 s. Basic principles of optics are then used to measure the relative distances, including the extent of bleeding [3]. This method provides an automated and non-extractive approach of measuring concrete bleeding which is said to be nearly identical to settlement due to self-weight [1, 3, 17,18,19,20,21].

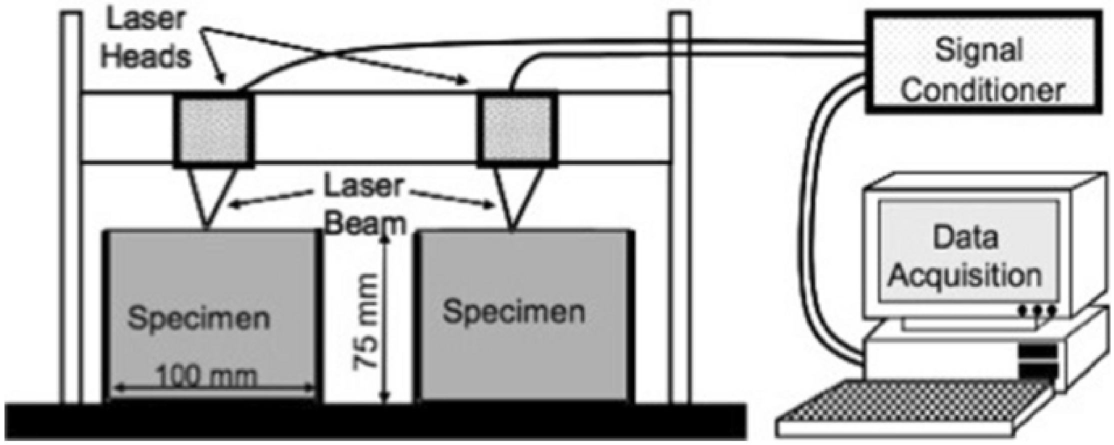

Fig. 2. Non-contact laser set-up for measuring plastic settlement [17]

2.3 Alternative methods

Ji et al. [30] used nuclear magnetic resonance (NMR) to investigate the microstructure development of cementitous paste during bleeding. The study showed that the void ratio at the top of the sample remains nearly constant while it gradually decreased at the bottom until it reached a constant value. Although this study provided valuable insights into bleeding of cement pastes, methods utilising NMR and x-ray scanning are expensive and requires specialized facilities not readily available for industry users.

Massoussi et al. [31] showed that bleeding is not only a consolidation of a soft porous material, but is of a heterogenous nature which leads to the formation of water channels in the cement paste. The formation of such channels increases the permeability of cement pastes whereafter the water is extracted at a constant rate until it is not able to consolidate any futher. There is also a good correlation between the permeability of cementitious materials and the void ratio, which reduces the amount of bleeding [32]. It is however difficult to measure and asssess the permeability of concrete and cement pastes, especially in its fresh state. Studies [33,34,35] indicate that the permeation of water is usually quatified by the permeation of the material. Therefore, an improvement of the particle dispersion and water retaining ability of cementitous materials through the use of cellulose ether, lignosulfonate or polycarboxylate (typically used as admixtures for self-compacting concrete) decrease the permeability, which limits the amount of bleeding.

Peng et al. [34] studied sedimentation and bleeding of cement pastes using hydrostatic pressure tests (HYSPT) and turbiscan measurements. The study showed that there are two phases of bleeding: (1) the first is a fast, initial phase, (2) followed by a phase with a diminishing sedimentaion rate. The first phase creates a turbid zone whereafter the top layer gradually becomes transparent. The results were also compared between the HYSPT, turbiscan and Kozeny-Carmen (K-C) equation. The K-C equation is based on liquid flow through a filter medium such as sand and can be used to equate the flow through cement paste as well [8]. The HYSPT showed higher bleeding rates compared to the K-C equation, while the turbiscan results showed a lower rate than the K-C equation.

The sedimentation theory presented by Kynch describes the behaviour of incompressible suspensions, and forms part of the general theory of compressible materials. Kynch's theory was based on a continuity balance and sedimentation velocity being a unique function of solid particulate concentration. However, this theory ignores the sediment rising from the bottom of a sample [36]. Perrot et al. [37] suggested that there is a correlation between the bleeding and the yield stress of fresh concrete. The results however showed that the correlation is indirect and therefore difficult to use in practice.

For all the methods mentioned, it is important to ensure that the size of the mould containing the concrete has suitable dimensions. This is since rate and amount of settlement is less at the wall or side of a mould than in the centre of the mould. This is because the wall influences the symmetry of the flow pattern of water around a particle and these particles near the wall also experience a greater upward viscous drag and therefore settle at a slower rate. The viscous drag on these wall particles are higher since the wall is generally smooth and vertical facilitating more effective water movement and since the wall is stationary and does not move downward with the particles. This lower settlement near the side of the mould can even lower the amount of settlement in the middle of the mould if the mould is too narrow. To avoid such effects on the settlement and bleeding measurements, the diameter of the mould should be at least greater than the depth of the mould [8]. Other research suggests that the range within which the settlement is influenced by the wall effect is 24% of the mould depth [3].

3 Methodology of comparison of bleeding test methods

3.1 Materials and testing approach

In order to clearly understand the possible differences between the bleeding measurement methods, the effect of bleed water extraction from the surface of concrete (using water extractive approaches) was the focus of this comparison. In the non-extractive method(s), bleed water is known to be re-absorbed due to the cement hydration process demand, causing chemical shrinkage and possibly additional shrinkage or swelling effects [3]. In the bleed water extractive methods, not all the bleed water is available for re-absorption. In order to investigate the influence of water extraction, the ASTM C232 [22] method was used to measure bleeding at constant time intervals of 20 min, 1, 2, 3 and 4 h respectively for each test. This differs slightly from the ASTM C232 [22] method which specifies that the water must be extracted every 10 min for 40 min and every 30 min thereafter. The reason this study varied from the standard method was to determine the impact of using varying extraction intervals. At each of these time intervals, bleed water was extracted and measured using two different concrete samples. These samples were left undisturbed and covered between time intervals. In addition, the mass of the samples was measured at every interval to account for any evaporation. The ASTM C232 (involving tilting of the mould) was preferred against the stencil method (Josserand and De Larrand) because it was difficult to create similar groove patterns on the concrete surfaces as shown in Fig. 3 a). Additionally, settlement was measured using the method described in [38, 39], but was modified to be done using a bleeding mould (as shown in Fig. 3b). Figure 3b) shows a vertically mounted non-spring loaded LVDT which is connected to a 50 × 50 mm metallic wire mesh which weighs 5 g and has a mesh opening of 2 mm with a wire diameter of 0.6 mm. The mesh is lowered onto the concrete surface after casting and follows the concrete surface settlement while still allowing bleeding water to pass through the mesh. The settlement of two different samples were tested and the average reported in this manuscript. Tests were performed on concrete with mix proportions as shown in Table 1. The concrete was designed for an average 28-day strength of 37.5 MPa with a slump of 70 mm and a w/c ratio of 0.6.

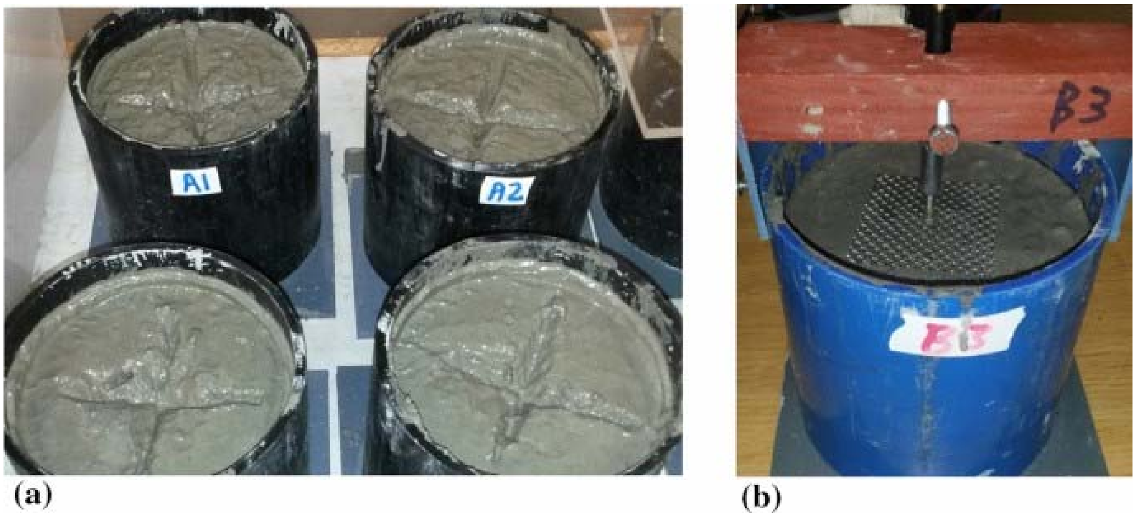

Fig. 3. a Inconsitent star-shaped groove patterns on four concrete samples using the bleeding method proposed by Josserand and De Larrand [24] **b** Settlement measurement in bleeding mould using an LVDT and mesh

Table 1. Material constituents and proportions of the mix

Material constituents	Relative density	Mix proportions [kg/m^3]
Water	1.00	205
CEM II 52.5 N Cement	3.05	342
13 mm Greywacke stone	2.80	1037
Natural quarry sand (FM = 2.6)	2.60	569
Greywacke crusher sand	2.70	244

In addition to bleeding and settlement tests, capillary pressure tests were also conducted using the bleeding mould, to study the influence of bleed water extraction at 30 and 60 min intervals as well as no extraction. The capillary sensors and method used is similar to that used by Slowik et al. [10]. These tests were carried out on only one sample per extraction interval, except for the 30 min interval, where two samples were tested. Capillary pressure measurements were conducted using capillary pressure sensors inserted in the bleeding mould. Capillary pore pressure sensors were placed at 15 mm below the surface of concrete. The moulds were initially filled with concrete up to the capillary sensor position, vibrated for 30 s, filled up and re-vibrated. Tests were carried out in climate conditions of 23 °C and relative humidity of 60%.

3.2 Use of superabsorbent polymers

In order to simulate the water extractive process of both ASTM C232 [22] and the Josserand and De Larrand [24] method, an alternative approach using superabsorbent polymers is proposed and used to collect bleed water from the surface of concrete. Superabsorbent polymers (SAP) are known to hold large amounts of water in relation to their size [40, 41]. It is this property that is utilised to extract the accumulating bleed water on the surface of fresh concrete. To achieve this, Starvis S 3911-F SAP powder was placed in tea bags and placed on the surface of fresh concrete. The following steps were followed:

1. Four tea bags of dimension 70 × 60 mm were used and numbered.
2. Each tea bag was filled with 2 g of SAP and closed with two staples, as shown in Fig. 4a).

3. The mass of each dry tea bag containing SAP was measured.
4. The tea bags were equally spaced on top of the fresh concrete surface just after the placement of the concrete.
5. The tea bags were carefully removed at the predetermined measurement intervals, weighed and replaced on the surface.

(a) (b)

Fig. 4. a A single tea bag having SAP powder **b** Four tea bags arranged on the surface of concrete in the bleeding mould

Figure 4 shows SAP-filled tea bags that were placed on the surface of concrete to collect bleeding water. Four different concrete samples were tested and the average reported. The moulds were at all times covered with plastic bags to minimise evaporation of bleed water during the test. This approach did not require tilting the mould or creating grooves in the concrete for water ponding and collection. The gain in mass of the tea bags containing SAP was taken as the bleed water accumulation at the surface of the concrete.

4 Results and discussions

4.1 ASTM C232 and settlement results

Results of bleeding measurements using ASTM C232 [22] as well as settlement conducted in the bleeding moulds are shown in Fig. 5. The figure shows the average cumulative amount of bleeding as measured using the tilting method (ASTM C232 [22]) for five different measurement intervals.

The results of the first measurement for each measuring interval are indicated in red in Fig. 5. From Fig. 5, it is revealed that the cumulative bleeding measured at 20 min intervals is clearly higher than the measured bleeding and the 1, 2, 3 and 4 h intervals respectively. The reasons for the difference are due to the extraction of bleed water from the concrete surface every 20 min, 1, 2, 3 and 4 h for the bleeding test, whereas no bleed water is extracted for the settlement tests. The difference in bleeding amounts clearly reduces and nearly becomes identical to settlement as measurement intervals become longer, as can be seen in Fig. 5.

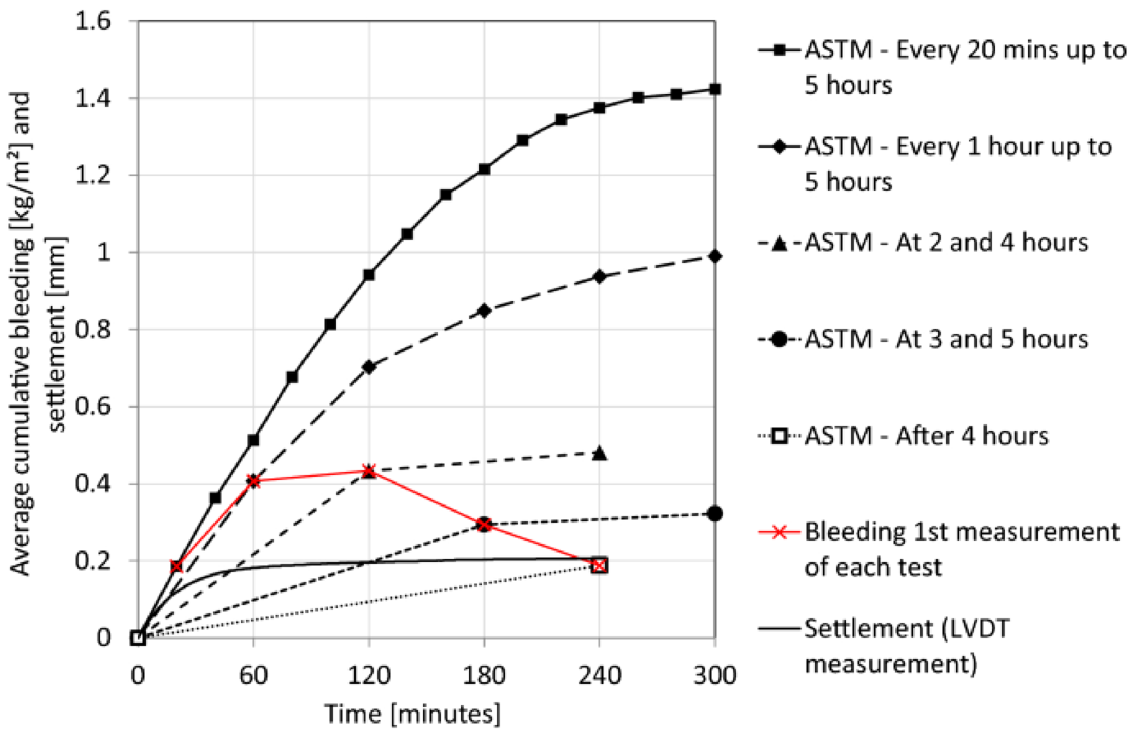

Fig. 5. Average cumulative bleeding using the tilting method, ASTM C323 [22] and average settlement using LVDT's

These results further suggest that the more frequently bleed water is removed from the concrete surface, the more bleed water becomes available. The results of the first measurement of bleeding at each measurement interval also suggest that if left undisturbed, bleed water at the surface of concrete will gradually decrease. The underlying mechanisms for these results are the re-absorption of bleed water into the concrete, as well as capillary pressure build-up. Figure 6 shows in situ capillary pressure measurements for two measurement durations of bleed water, 30 and 60 min' intervals as well as an undisturbed sample. At every interval of bleed water extraction, capillary pore pressure was observed to be affected, suggesting an impact of the water extraction process. Thereafter, capillary pore pressure was observed to rise again and normalise to the original growth trend. This process of capillary pressure normalisation acts to pull more water to the surface of concrete, thus causing more bleeding. For shorter extraction intervals, the process keeps re-occurring and more bleed water rises to the surface of concrete and can be removed – by any extractive approach. In contrast, the undisturbed scenario does not significantly impact capillary pore pressure development as seen in Fig. 6. The drop in the measured capillary pressure is due to the decrease in hydrostatic pressure due to the removal of the water from the surface of the sample. The increase in the measured pressure after the drops occur due to a redistribution of the water from below the sensor. This action is due to a combination of the settlement resulting in an upwards displacement of the water resulting in an increased hydrostatic pressure, as well as a capillary suction caused by the drying of the surface of the concrete due to the removal of the bleed water.

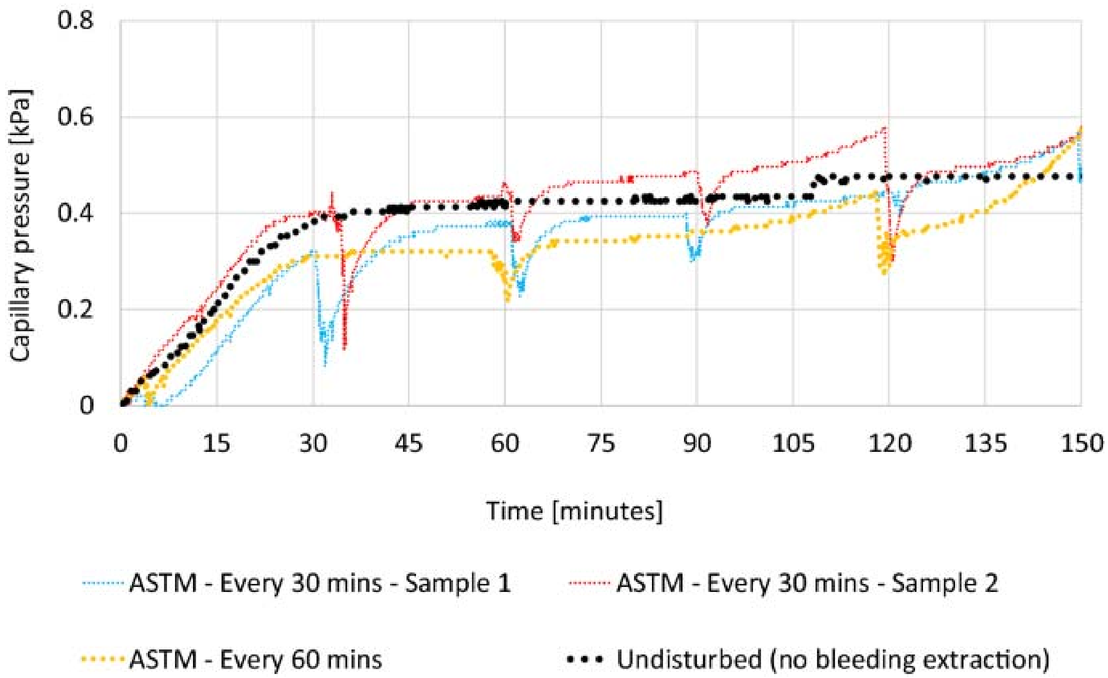

Fig. 6. Capillary pressure variation for undisturbed versus 30 and 60 min intervals of bleed water extraction

4.2 Reabsorption of bleed water

The red lines and markers in Fig. 5 show the first measurement of bleeding after the moulds were left undisturbed for 20 min as well as at 1, 2, 3 and 4 h respectively. These results show an initial increase to a maximum amount of bleed water on the concrete surface at around 1 h. This is then followed by a decrease in the amount of bleed water for later measurement intervals. This decrease is not due to evaporation of bleed water, since the evaporation is not only negligible at these climatic settings but also because it is taken into account during the bleeding calculations as discussed in Sect. 2.1. The results suggest that bleed water is drawn back or re-absorbed into the concrete specimen and this was observed to start at about 60 min after casting. This timing also coincides with the start of stabilisation of measured settlement as can be seen in Fig. 5.

Similar observations to these were made by Kwak et al. [3] who measured both bleeding and settlement simultaneously on a mortar specimen using a method that involved the covering of a sample with a layer of paraffin oil and monitoring the displacement of both the mortar and liquid surfaces. In contrast, the bleeding and settlement results shown in Fig. 5 were measured using a bleed water extractive approach compared to the non-extractive approach used by Kwak et al. [3]. Nonetheless, the same conclusion can be drawn that, if left undisturbed, bleed water will be re-absorbed into concrete, potentially starting around the time when maximum settlement is reached. Furthermore, the start of the re-absorption is said to coincide with the start of hydration at the end of the dormant period [3, 42].

4.3 Use of SAP to extract bleed water

Results of using SAP to extract bleed water from plastic concrete are shown in Fig. 7 for the different intervals of weight measurements, that is, 30 min, 1 and 4 h. These are then compared to those of ASTM C232 [22] tilting method in the same figure. The use of SAP still reveals the effect of measurement time interval on total bleed water collected, but to a much lesser extent than for the extractive methods.

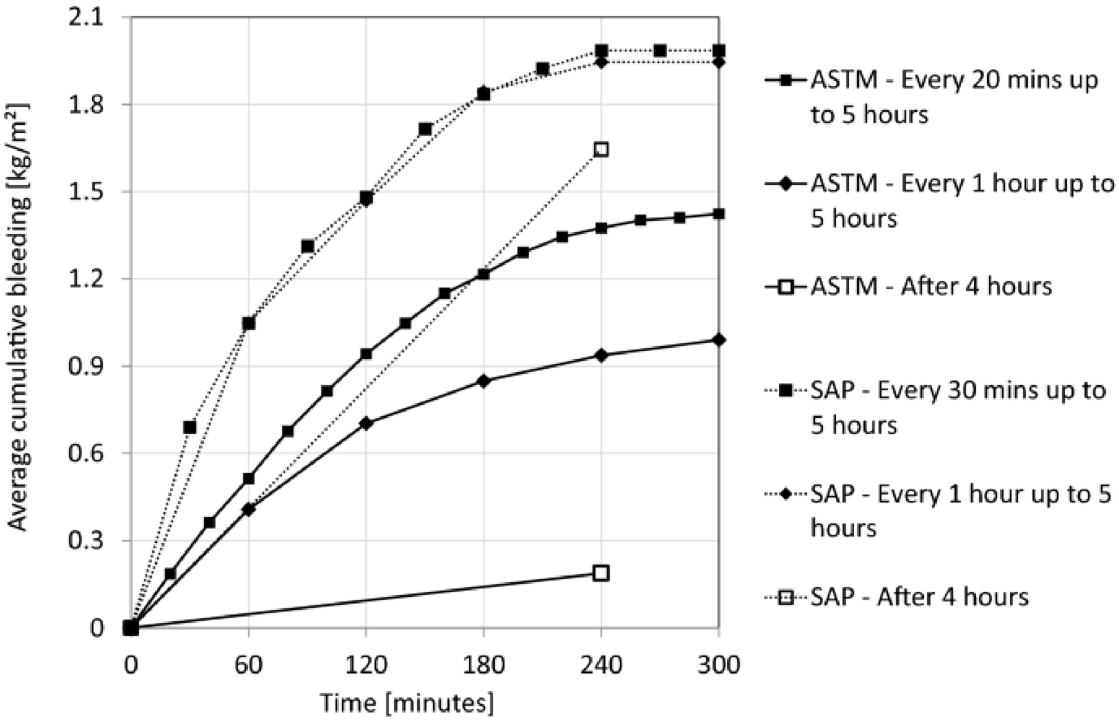

Fig. 7. Tilting method (ASTM C232 [22]) compared to use of SAP to extract bleed water at various measurement intervals

As discussed in Sect. 4.1, the results in Figs. 5 and 7 suggest that the more frequently bleed water is extracted using the ASTM method, the more the bleeding. The reasons for this are believed to be the upwards displacement of the water to the concrete surface due to settlement which increases the hydrostatic pressure as well as capillary suction due to the drying (or exposure) of the concrete surface each time the bleed water is extracted. As a consequence, and also due to the absence of significant amount of bleed water due to the extraction thereof, the effect of water re-absorption into the matrix becomes negligible, causing the upward movement or suction of water to the surface to outweigh the downward suction of bleed water due to chemical shrinkage (re-absorption).

For similar bleed water measurement intervals, it is evident that the use of SAP to extract bleed water resulted in almost twice as much bleeding as when it was extracted by the ASTM C232 [22] tilting approach. The SAP dries out the surface of the concrete continuously, thus causing a continuous increase of bleed water, which increases the total bleed water significantly. This is more realistic in certain cases as it mimics the same mechanism as in a high evaporation environment, which would have the surface permanently dry, even though there is bleeding. The SAP method would thus be able to give a more accurate indication of the drying time (the time the amount of water evaporated exceeds the cumulative bleeding water) in extreme evaporation conditions. The most realistic environment would however still be the actual wind, temperature and relative humidity of the air acting on the bleeding surface.

5 Significance of the different bleeding methods

The accurate measurement of bleeding volumes is critical to the development of the necessary prediction models or preventative courses of action for plastic shrinkage cracking. However, from the results of this critical study, it is quite evident that the currently used bleeding measurement approaches present varied results based on when and how the water is extracted. The standardised bleeding method of ASTM C232 [22] results in significantly higher bleeding measurements compared to non-extractive methods because it does not make surface bleed water available for re-absorption. The reason is also not only the re-absorption, but the increase of bleeding due to the dry surface and capillary action. The action of continuously extracting the accumulated bleed water at the surface (which is also obtained by using the SAP to extract the water), further on impacts capillary pore pressure variations, causing more bleeding to occur in order to re-set the capillary pressure balance. On the contrary, in the non-extractive bleed water approach, any bleed water is continuously maintained at the surface and becomes available for re-absorption.

The choice of bleeding method will however depend on the application. If the bleeding is to be obtained for an application where the environment is without any evaporation and the bleed water will remain on the surface, a non-extractive method is recommended. For an application with extreme evaporation rates (higher than 1 $kg/m^2/hour$), e.g. a bridge deck with a strong wind, the SAP method is proposed. For anything in between the ASTM C232 [22] is proposed.

6 Conclusions and recommendations

In this research, the main approaches to evaluate plastic concrete bleeding were reviewed, and in particular the effect of bleed water extraction on the total measured bleeding amount. A novel approach using SAP to extract the bleed water is also presented. Based on the findings, the following conclusions can be drawn.

- Bleed water extractive methods such as ASTM C232:2004 or EN 480–4:2005 conducted at different time intervals result in different total bleed water measurements. The shorter the interval of measurement, the more the total bleed water collected or measured. This behaviour is linked to the increase in hydrostatic pressure as water moves to the surface and capillary pressure acting to restore the status quo at every interval of water extraction, which in so doing draws more water to the surface. For longer measurement intervals the bleed water has more time to be re-absorbed into the concrete once hydration starts which then reduces the amount of bleeding measured.
- A novel bleed water extraction approach has been proposed. This approach utilises superabsorbent polymers placed in a permeable membrane (tea bag) and placed on the surface of fresh concrete. By using this approach, the re-absorption of bleed water is minimised as the SAP extracts the water continuously.
- The application of the fresh concrete determines the appropriate bleeding measurement technique. For an application where the bleed water will be remaining on top of the concrete member, a non-extractive bleeding test method is proposed. Where the application will be an environment where the bleed water will evaporate immediately, the SAP extraction method is proposed. For applications in between the two mentioned scenario's, the ASTM C232 or similar method is proposed.

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References

1. Kayondo M, Combrinck R, Boshoff WP (2019) State-of-the-art review on plastic cracking of concrete. Constr Build Mater 225:886–899
2. CCIP-048, Technical report No.22: non-structural cracks in concrete. (4th ed). surrey: the concrete society: a cement and concrete industry publication, (2010).
3. Kwak H-G, Ha S, Weiss WJ (2010) Experimental and numerical quantification of plastic settlement in fresh cementitious systems. J Mater Civ Eng 22:951–966
4. C Qi (2003) Quantitative assessment of plastic shrinkage cracking and its effect on the corrosion of steel reinforcement. Purdue University, Indiana, (PhD. thesis).
5. Otieno MB, Alexander MG, Beushausen H-D (2010) Corrosion in cracked and uncracked concrete - influence of crack width, concrete quality and crack reopening. Mag Concr Res 62(6):393–404
6. American Concrete Institute, Hot weather concreting, ACI manual of concrete practice, ACI, Detroit,ACI Committee 305 (2) (2010).
7. Kwak H-G, Ha S-J (2006) Plastic shrinkage cracking in concrete slabs Part II: numerical experiment and prediction of occurrence. Magazine Concrete Res 58(8):517–532
8. Powers TC (1968) The properties of fresh concrete. John Wiley & Sons, Inc New York, USA
9. Dao V, Dux P, Morris P, O'Moore L (2010) Plastic shrinkage cracking of concrete. Aust J Struct Eng 10(3):207–214
10. Slowik V, Schmidt M, Fritzsch R (2008) Capillary pressure in fresh cement-based materials and identification of the air entry value. Cement Concr Compos 30:557–565
11. Combrinck R, Boshoff WP (2013) Typical plastic shrinkage cracking behaviour of concrete. Mag Concr Res 65(8):486–493
12. Menzel CA (1954) Causes and prevention of crack development in plastic concrete. Proc Portland Cement Assoc 130:136
13. Uno PJ (1998) Plastic shrinkage cracking and evaporation formulas. ACI Mater J 95(4):365–375
14. ACI 305R (1999) "Hot weather concreting", ACI manual of construction practice, Part 2, Farmington Hills: American concrete institute international.
15. Wittmann FH (1976) On the action of capillary pressure in fresh concrete. Cem Concr Res 6(1):49–56
16. Combrinck R, Boshoff WP (2019) Tensile properties of plastic concrete and the influence of temperature and cyclic loading. Cement Concr Compos 97:300–311
17. H Kayir, and WJ Weiss (2002) 'A fundamental look at settlement in fresh systems: role of mixing time and high-range water reducers', First North American conference on self-consolidating concrete, Chicago, IL, November 27–32.
18. P. Lura, G.B. Mazzotta, F. Rajabipour, J. Weiss, Evaporation, settlement, temperature evolution and development of plastic shrinkage cracks in mortars with shrinkage-reducing admixtures. In: proceedingsof the international RILEM-JCI seminar on

concrete durability and service life lanning (ConcreteLife006), Ein-Bokek, Israel; March 14–16 (2006) 203–13.
19. Yim HJ, Kim JH, Kwak HG, Kim JK (2013) Evaluation of internal bleeding in concrete using a self-weight bleeding test. Cement Concrete Res 53:18–24
20. Yim HJ, Kim JH, Kwak HG (2014) Experimental simulation of bleeding under a high concrete column. Cem Concr Res 57:61–69
21. Qi C, Weiss J, Olek J (2005) Assessing the settlement of fresh concrete using a non-contact laser profiling approach. In: Proceedings of the 3rd International Conference on Construction Materials: Performance, Innovation and Structural Implications, Vancouver, Canada
22. ASTM C232 (2004) Standard test method for bleeding of concrete. West Conshohocken: ASTM International.
23. BS EN 480–4:2005, Admixtures for concrete, mortar and grout. Test Methods. Determination of bleeding of concrete, (2005).
24. Josserand L, De Larrard F (2004) A method for concrete bleeding measurement. Mater Struct 37:666–670
25. Kronlöf A, Leivo M, Sipari P (1995) Experimental study on the basic phenomena of shrinkage and cracking of fresh mortar. J Cement Concr Res 25(8):1747–1754
26. Almusallam A, Abdul-Waris M, Maslehuddin M, A AL-Gahtani, (1999) Placing and shrinkage at extreme temperatures. Concrete Int 21(1):75–79
27. Meyer DM, Boshoff WP, Combrinck R (2020) Utilising super absorbent polymers as alternative method to test plastic shrinkage cracks in concrete. Constr Build Mater 248:118666
28. Schmidt M, Slowik V (2013) Instrumentation for optimizing concrete curing. Concr Int 35(8):1377
29. Combrinck R, Steyl L, Boshoff WP (2018) Influence of concrete depth and surface finishing on the cracking of plastic concrete. Constr Build Mater 175:621–628
30. Ji Y, Pel L, Sun Z (2019) The microstructure development during bleeding of cement paste: an NMR study. Cem Concr Res 125:105866
31. Massoussi N, Keita E, Roussel N (2017) The heterogeneous nature of bleeding in cement pastes. Cem Concr Res 95:108–116
32. Picadent V, Rangeard D, Perrot A, Lecompte T (2011) Permeability measurement of fresh cement paste. Cem Concr Res 41:330–338
33. Pierre A, Perrot A, Picadent V, Guevel Y (2015) Cellulose ethers and cement paste permeability. Cem Concr Res 72:117–127
34. Peng Y, Lauten RA, Reknes K, Jacobsen S (2017) Bleeding and sedimentation of cement paste measured by hydrostatic pressure and Turbiscan. Cement Concr Compos 76:25–38
35. Perrot A, Rangeard D, Picadent V, Melinge Y (2013) Hydro-mechanical properties of fresh cement pastes containing polycarboxylate superplasticizer. Cem Concr Res 53:221–228
36. Tiller FM (1981) Revision of kynch sedimentation theory. AIChE J 27(5):823–829. https://doi.org/10.1002/aic.690270517
37. Perrot A, Lecompte T, Khelifi H, Brumaud C, Hot J, Roussel N (2012) Yield stress and bleeding of fresh cement pastes. Cem Concr Res 42:937–944
38. Olivier G, Combrinck R, Kayondo M, Boshoff WP (2018) Combined effect of nano-silica, super absorbent polymers, and synthetic fibres on plastic shrinkage cracking in concrete. Constr Build Mater 192:85–98

39. Combrinck R, Kayondo M, le Roux BD, de Villiers WI, Boshoff WP (2019) Effect of various liquid admixtures on cracking of plastic concrete. Constr Build Mater 202:139–153
40. Snoeck D, Van Tittelboom K, Steuperaert S, Dubruel P, De Belie N (2014) Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers. J Intell Mater Syst Struct 25:13–24
41. Mignon A, Graulus G-J, Snoeck D, Martins J, De Belie N, Dubruel P, Van Vlierberghe S (2015) pH-sensitive superabsorbent polymers: a potential candidate material for self-healing concrete. J Mater Sci 50:970–979
42. Sant G, Dehadrai M, Bentz D, Lura P, Ferraris CF, Bullard JW, Weiss J (2009) Detecting the fluid-to-solid transition in cement pastes. Concr Int 31(6):53