Effect of surface curing timing on plastic shrinkage cracking of concrete

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Abstract

Surface curing of concrete is known to mitigate potential plastic shrinkage cracking. In this research, water and three curing compounds were used to investigate the efficacy of liquid curing on plastic shrinkage cracking mitigation. Water curing was applied at critical times during the development of plastic shrinkage cracks, namely: the start of capillary pressure build-up, the start of shrinkage, before the first visible surface crack, and during rapid crack growth. The performance of water curing was also compared to a wax emulsion, petroleum-based resin, and water-based acrylic solution curing compounds, all applied at the supplier specified times. Based on the findings of this research, any application of curing helps to relieve the associated potential plastic shrinkage cracking. The optimal timing of water curing application was based on the response of the various mechanisms of plastic shrinkage cracking. Water application at the start of the shrinkage period, about an hour after casting, prevented any shrinkage-related damage and proved to be most desirable. Water curing that was conducted too early or during rapid crack growth was not as effective. The performance of the different curing approaches in terms of settlement, shrinkage, final crack area, and percentage crack reduction was also compared to the uncured reference mix. The curing compounds performed better than water curing, with only the petroleum-based resin curing compound preventing crack formation, i.e. resulting in 100% crack reduction. However, it was concluded that applying water continuously after the drying point is more effective than most curing compounds.

Keywords: Plastic shrinkage · Plastic cracking · Water curing · Curing compounds · Curing timing · Capillary pressur

Introduction

Plastic shrinkage cracking is the unwanted result of volumetric shrinkage that takes place in freshly cast concrete elements with large, exposed surfaces [1, 2]. It is influenced by the consolidation of denser concrete constituents (aggregates, sand, and cement) in a fluid medium, causing water to rise to the surface in a phenomenon known as bleeding [3, 4]. The rate of bleeding versus that of evaporation becomes one of the deciding factors for plastic shrinkage cracking incidences [5,6,7]. In its plastic state, concrete is highly susceptible to cracking since it offers little resistance to the cracking phenomena; and once the shrinkage induced stresses/strains (due to the presence of restraint, such as reinforcement, mould friction, level differences, etc.) exceed the allowable capacities, cracking occurs [8,9,10]. The cracks can also align with the geometry in areas where there is a change in depth. Plastic shrinkage cracks are usually crisscrossed and of an irregular pattern, with lengths of 50–1000 mm, and widths that can exceed 1 mm [4]. These cracks, if unattended to, become paths for deleterious substances that may further impair the durability of concrete structures [11, 12].

There are several plastic shrinkage mitigation approaches, which can be categorised as either internal material design-based (active solutions) or externally applied techniques (passive solution) [13]. Active solutions rely on material properties modifications. These approaches involve the addition of mineral or liquid admixtures, such as shrinkage reducing admixtures, synthetic fibres, superabsorbent polymers and accelerators [14,15,16,17]. Active solutions reduce the impact of the mechanisms leading to plastic shrinkage cracking, whereas passive solutions are performed externally after the concrete is cast. The former can therefore adversely affect the material properties, such as the rheology and long-term strength and require a time-consuming design process [14, 15, 17]. It is for this reason that passive solutions are commonly preferred on-site.

Passive solutions, also known as curing measures, are aimed to prevent pore water evaporation [13, 18]. This can be achieved through fogging, water ponding, water-saturated coverings, or through the use of surface sealing such as plastic sheets, evaporative retarders and curing compounds. The general understanding is that passive solutions should be performed just before or immediately after the drying time is reached, i.e. when the bleeding water sheen has evaporated [18, 19]. This delays the development of capillary pore pressure, the precursor for plastic shrinkage and reduces cracking severity [4]. The application time of water-based curing methods (fogging, water ponding, water-saturated coverings) as well as curing compounds is critical for eliminating plastic shrinkage cracking [18]. The premature application can adversely affect the surface finish and long-term strength while the late application can be ineffective in preventing severe plastic shrinkage cracking. To avoid the mentioned disadvantage of a possible poorer surface finish due to these passive solutions, other curing measures such as windbreakers and shading can be considered to reduce the environmental evaporation load [20, 21].

Water curing provides additional water to the concrete surface that can be evaporated instead of the concrete pore water. However, curing compounds form a membrane on the concrete surface to prevent pore evaporation and are classified by the ASTM C 309 [22] standard. Many others have used curing compounds to mitigate the consequences of early age pore water loss. Wang et al. [23] compared various curing compounds to show that chlorinated rubber and resin-solvents are much more effective in reducing the pore water loss compared to wax-water based compounds. The study showed that early application is critical and recommended that the curing procedure is initiated immediately after placement. Löfgren and Esping [24] used a wax-based curing compound, applied to the surface, to significantly reduce plastic shrinkage cracking while Leemann et al. [25] added a paraffin-based curing compound to the concrete, like an admixture, arguing that paraffin dispersion can be effective in reducing evaporation and early age cracking. The study showed a clear reduction in the rate of capillary pressure development, mass loss as well as plastic shrinkage cracking. Recently, Ghourchian et al. [13] followed a similar approach to show that, although curing compounds are very effective in reducing plastic cracking, the protection provided against pore water evaporation only lasts for a few hours. The study also showed that the addition of curing compounds can retard cement hydration.

The effect of drying and wetting during water curing as well as the application of curing compounds influences the microstructure of the concrete. Conclusions from studies by Gajewicz et al. [26], Maruyama et al. [27], Maruyama et al. [28], and Takahashi et al. [29] suggest that the change of the calcium silicate hydrate (CSH) structure with drying or wetting may affect the volumetric change. The studies by Gajewicz et al. [26] and Maruyama et al. [27] investigated the microstructural changes in hardened or mature cement pastes at ages of 28 days and later using nuclear magnetic resonance (NMR) and small-angle X-ray scattering profiles. The study by Takahasi et al. [29] tested pore size distribution using Mercury intrusion porosimetry (MIP) in 5 mm cement mortar cubes hydrated for 24 h. The mentioned methods require small samples as well as hardened samples to obtain meaningful results. To the authors knowledge these methods have not been applied to concrete that has just been cast up to and age of 6 h, except for the work by Snoeck et al. [30] whom used NMR to track water distribution in plastic concrete along the specimen height. Although the agglomeration of CSH may affect the plastic shrinkage of the concrete at early ages, the current methods that can potentially quantitatively measure the micro- and nano-porosity of the concrete matrix where C–S–H agglomeration occurs are still not suitable for tests on plastic concrete.

With this in mind and since capillary pressure build-up in plastic concrete has been confirmed by many authors to dominate plastic shrinkage in the early ages (before final set) [4,5,6, 29, 31], it is argued that the capillary pressure remains one of the most valuable factors to investigate when water is evaporated from the capillary pore system of plastic concrete. Therefore in this study, capillary pressure measurements are used in combination with other measurements such as shrinkage, settlement, evaporation and cracking to determine the effect of externally applied curing methods on plastic shrinkage cracking in concrete from casting to an age of around 5 h.

This entailed investigating the efficacy of different water-based curing application times, with the aim of reducing crack severity. The capillary pressure, settlement, shrinkage and cracking are monitored while a fixed quantity of water is applied to the concrete surface at different times. The application timing is guided by capillary pore pressure development, shrinkage and the appearance of cracks. This study aims to show the importance of the timely application of water curing to concrete to prevent plastic shrinkage cracking which can result in durability issues that can even threaten the service life of a structure.

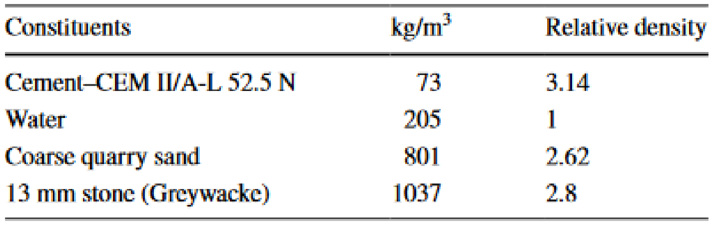
In addition to water-based curing, the efficacy of different commercially available curing compounds is investigated. The aim of this study with the curing compounds is to compare the curing compounds performance if applied as recommended by the supplier, which would be the same as done in practice. In addition, this study attempts to show that applying water to the surface of the concrete at the correct time can be just as effective in reducing plastic shrinkage cracking as curing compounds. This is significant since curing compounds can be harmful to humans and the natural environment where water curing is not [32]. Suppliers of curing compounds recommended waste management which is often neglected in practice in an effort to save time and cost.

There is limited research that experimentally shows how different water curing application times and different curing compounds compare and influence several of the factors known to influence plastic shrinkage cracking [33]. The aims and investigative approach of this study contributes to this knowledge gap by improving the understanding of the relationship between plastic shrinkage cracking and its influencing factors when external curing methods are applied.

Experimental approach

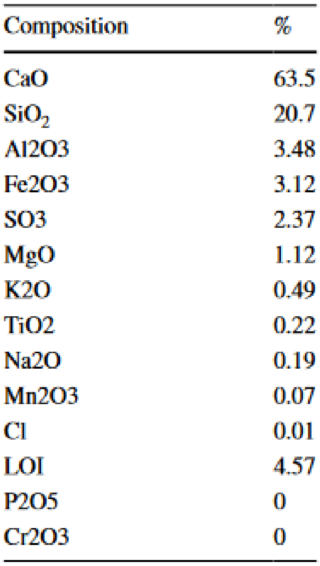
Uncured, water cured, and compound cured concrete samples were exposed to an external evaporation rate and the water loss, capillary pore pressure, horizontal shrinkage, vertical settlement and crack severity were monitored. Water was applied to the surface of the concrete at different application times that were based on the behaviour of the uncured sample. Three different curing compounds were applied according to the supplier's recommendation.

Table 1. Concrete mix constituents, proportions and properties



Constituents	kg/m^3	Relative density
Cement–CEM II/A-L 52.5 N	73	3.14
Water	205	1
Coarse quarry sand	801	2.62
13 mm stone (Greywacke)	1037	2.8

Table 2. Chemical composition of CEM II 52.5 N cement



Composition	%
CaO	63.5
SiO_2	20.7
Al2O3	3.48
Fe2O3	3.12
SO3	2.37
MgO	1.12
K2O	0.49
TiO2	0.22
Na2O	0.19
Mn2O3	0.07
Cl	0.01
LOI	4.57
P2O5	0
Cr2O3	0

Materials and mix design

A concrete mix with a 100 mm slump and water to cement ratio of 0.55 was used. The mix contained a CEM II/A-L 52.5 N cement and reached an average compression strength of 52 MPa at 28 days. CEM II/A-L consists of 80–94% clinker and contains 6–20% limestone. The other mix constituents and properties are shown in Table 1. The chemical composition of the concrete used in this study is shown in Table 2. All mix constituents used were from the same batch in order to minimise inconsistencies. The materials were stored in a climate-controlled room at 23 °C and 65% relative humidity, for 24 h before being mixed in a 50 L pan mixer. Sand, cement and aggregates were dry mixed for one minute, after which water was added and mixing continued for an additional four minutes at a constant rate. Next, all the necessary testing moulds were filled with concrete and vibrated on a shaking-table for two minutes before being placed in the environmental testing chamber. Mixing and specimen preparation were performed in the same manner for all tests.

Measurements

All measurements were performed in a climate-controlled chamber, as described by Combrinck et al. [34], with the chamber set to an air temperature of 40 °C, relative humidity of 10%, and wind speed of 6.25 m/s. In addition, the initial temperature of the concrete was 23 °C. The controlled chamber conditions caused an evaporation rate of approximately 1 kg/\({\mathrm{m}}^{2}/\mathrm{h}\), as calculated using the equation developed by Uno [19], as recommended by ACI 305R [35]. An evaporation rate of 1 kg/\({\mathrm{m}}^{2}/\mathrm{h}\) can be expected on-site in a typical Mediterranean climate [36].

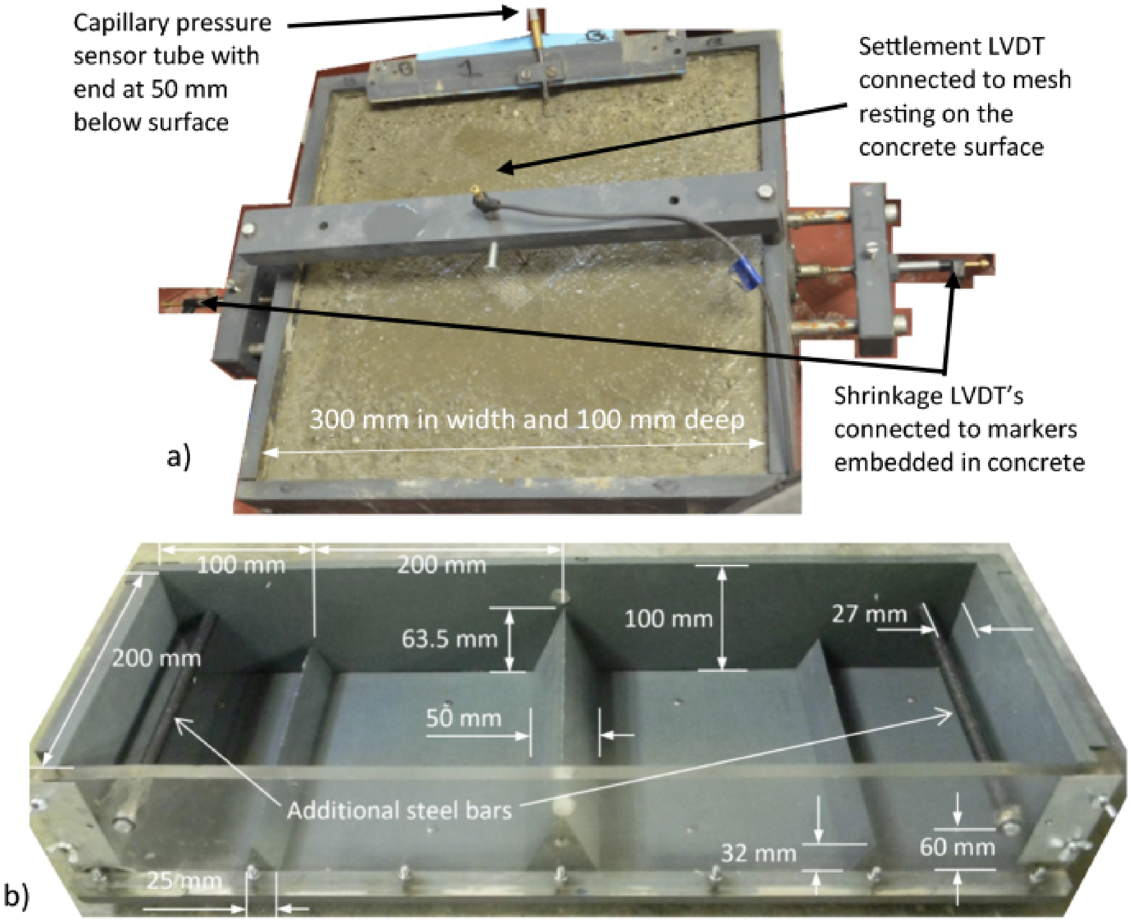


Fig. 1. a Shrinkage, settlement as well as capillary pressure measurement mould, **b** cracking mould [7, 34, 38]

All moulds were placed inside the climate chamber and the capillary pressure [4], rate of mass loss, horizontal shrinkage, vertical settlement as well as crack severity [37] were monitored. The capillary pressure was measured at 50 mm below the surface of the concrete. The mass loss, due to evaporation, was measured at a 20 min time interval, for all the specimen except the water cured test set. The standard moulds used to study plastic shrinkage cracking, settlement, shrinkage and capillary pressure development are shown in Fig. 1. It should be noted that no bleed water was removed except for the bleed water that was removed by evaporation during the test.

Plastic shrinkage crack areas were computed according to the ASTM C1579 [37] method using high-resolution photos taken at 20 min intervals. These photos were scaled and measured using CAD software as shown in Fig. 2. To eliminate the influence of the mould sides, 25 mm from each side were discarded. The remaining crack was then calculated by measuring the crack width of several line segments of around 10 mm in length. Special care was taken to use the same line segments and the position of crack width measurement for each photo of the crack at different time intervals. The widths were finally multiplied by the length of the lines and summed up to calculate the crack area.

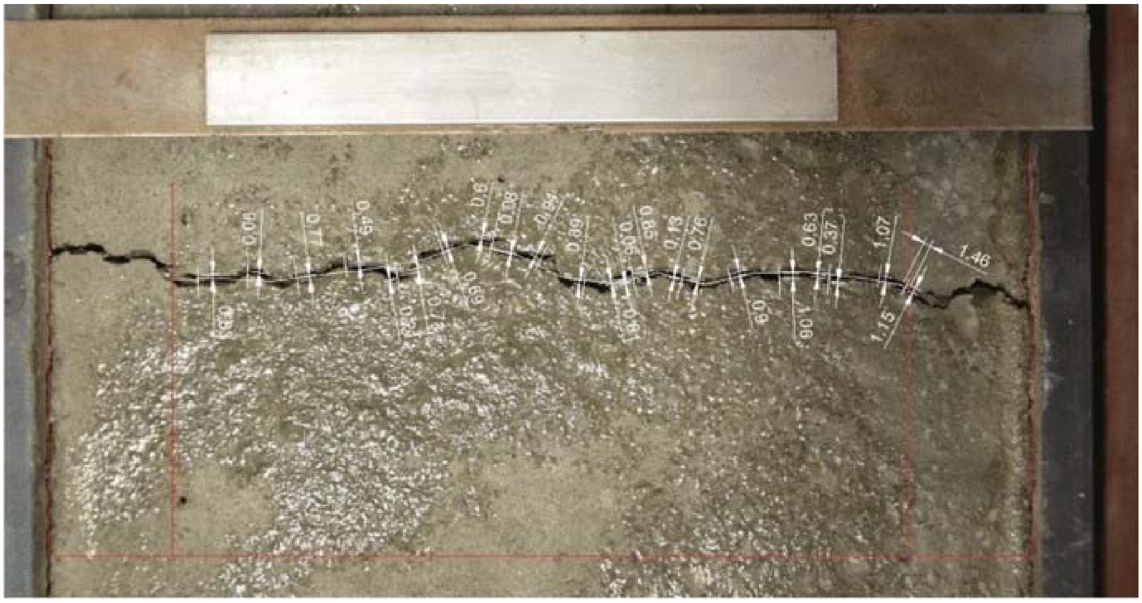


Fig. 2. Crack area calculation for a uniform crack

Two methods of curing were investigated to mitigate plastic shrinkage cracking, namely: water curing and compound curing. Five possible water curing application times were identified, namely: before the capillary pressure build-up (T1), at the start of the shrinkage period (T2), the start of crack growth (T3), at the first visible crack (T4) and during rapid crack growth (T5), as shown in Table 3. T1-T5 were identified graphically from the average results of the uncured reference as shown in Fig. 6. It should be noted that T1 was also specifically chosen at 30 min after casting to ensure that it was well before the start of significant capillary pressure build-up at around 50 min. In addition to the five single application times, water was also applied multiple times (MW) on one set. Water was applied as soon as the shrinkage started to increase.

Essentially, the application of water curing provides additional water to the pore system to delayed or reduce capillary pressure build-up by replacing the evaporated pore water.

Table 3. Curing regime design and designation

Curing type	Application time [min]	Test mechanism/application reasoning	Test designation
None	0	Uncured reference	Uncured
Water	30	Before capillary pressure build-up	WT1
	70	Start of shrinkage	WT2
	100	Before start of visible crack	WT3
	120	At first visible crack	WT4
	140	During rapid crack growth	WT5
	64, 91, 132, 163, 205, 235	At any increase in shrinkage	MW
Curing Compound	0	Evaporation protection	CA1*
	0	Evaporation protection	CA2*
	80	Disappearance of water sheen	CA3*

*Spray applied at dosage of 0.2 L per m^2 as prescribed by supplier

At least four samples were used for each test, except for capillary pressure where only two samples were used. Figure 3 shows a typical set of results for the WT3 test as well as the resulting average for typical settlement, shrinkage and crack area. The change in the shrinkage and settlement development at around 100 min is due to the application of water curing and is discussed later. Figure 3 indicates that the average can be used as a representative value of the various samples and that the tests are repeatable. Therefore, only the averages of the samples are shown and used to compare curing methods for the rest of this paper.

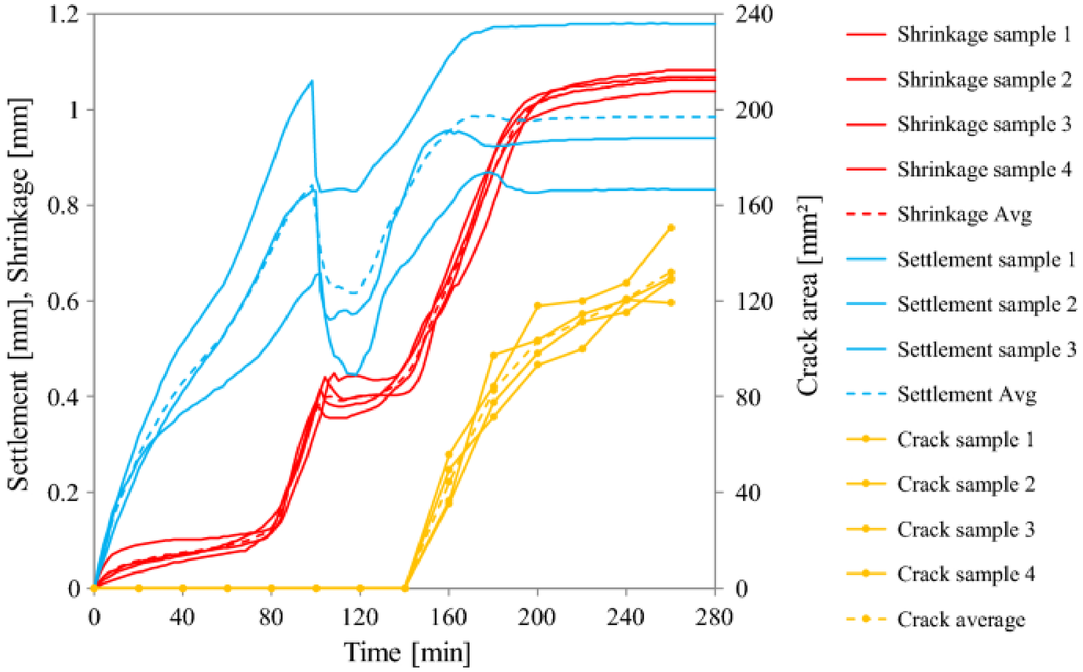


Fig. 3. Typical set of results and resulting averages for the WT3 test. The results are discussed later

To account for the differences in air entry for the two capillary pressure results, a representation using a compilation of average and interpolation lines was created. The representation is constructed using the average until the air entry pressure of Sample 2 occurs, that is, Point A (see Fig. 4). Thereafter a maximum point is created by linear interpolation between the max Points A and B of the two samples and connecting this new interpolated point using a straight line to the last point where the average pressure could still be calculated, as shown by the two red markers in Fig. 4.

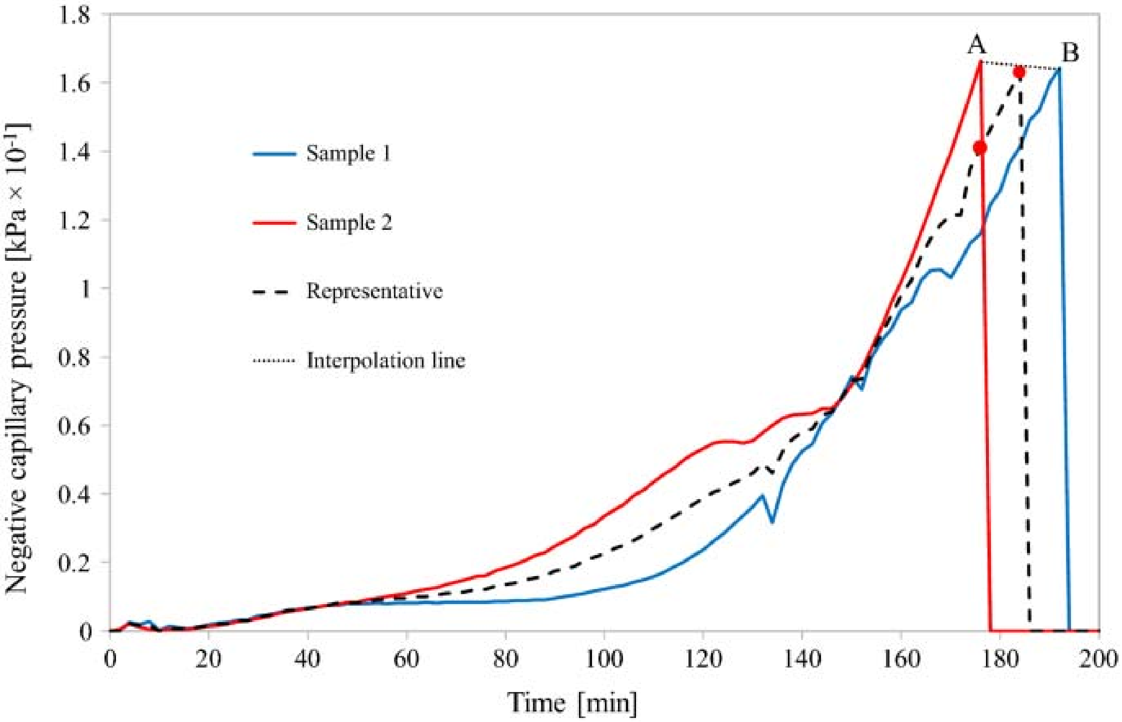


Fig. 4. Calculation of capillary representation for two samples

Uncured test

Three test sets were used in this study, namely: uncured, water cured and compound cured. Firstly, the capillary pore pressure, horizontal shrinkage, vertical settlement and crack severity was measured without any curing, referred to as the uncured set. The mechanism and magnitude of crack area reduction are determined by comparing the water cured and compound cured results to this uncured set. The results of the uncured set can be seen in Fig. 5 and was then used to identify possible water application times.

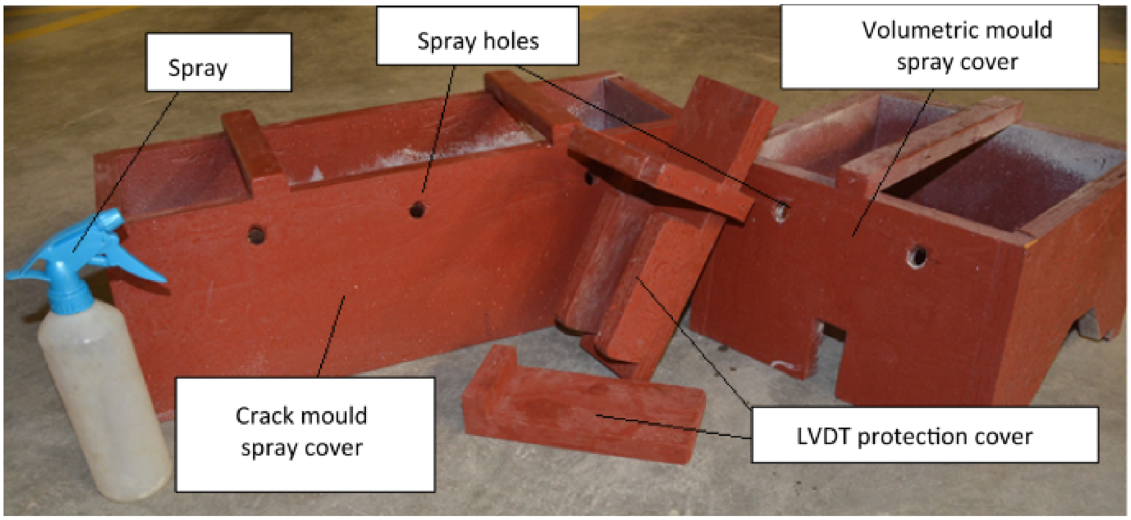


Fig. 5. Spray cover set-up

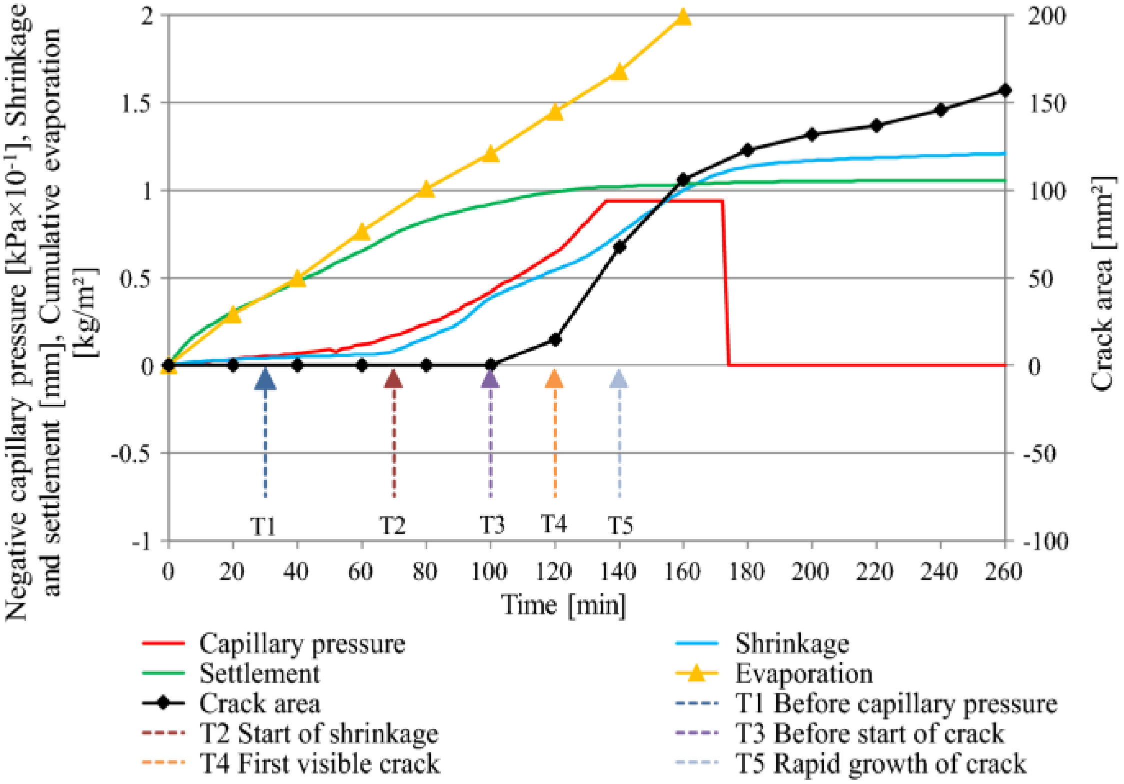


Fig. 6. Plastic shrinkage cracking response of the uncured reference mix and the chosen curing times, T1 to T5, for further testing

Water curing

As explained earlier, two methods of curing namely: water curing, and compound curing were investigated to mitigate plastic shrinkage cracking. Water curing was done by applying a measured amount of water on the surface of concrete at different application times. The process involved spraying an equivalent of 1 mm/mm^2 of water on the surface of concrete using a spray bottle as a misting device. The spray water was maintained at a temperature of 23 °C in a climate room and was applied using the spray covers as shown in Fig. 6. Spraying was done by fitting the spray nozzle through the holes in the cover. These spray covers were placed on top of use mould before applying the curing in order to minimise any water loss due to wind in the climate chamber.

Curing compounds

Three commercially available curing compounds were used in this investigation, namely: a wax emulsion-based compound (Chryso Cure WB) as CA1; a petroleum resin emulsion-based compound (Chryso Cure WP) as CA2 and a water-based acrylic emulsion-based compound (Chryso Cure Acrylic) CA3. According to the supplier, CA1 and CA2 are partially soluble in water while CA3 is dilutable in water. The suppliers do not provide further information on the effect of the dissolution of these products in water [39]. The effect of the dissolution of these curing compounds in water was not investigated in this study. However, the authors predict that the dissolution of these curing compounds will reduce the surface tension on the concrete surface, resulting in reduced effects of plastic shrinkage cracking [15,16,17].

The curing compound was only applied once, using the same procedure as water curing, at a dosage and application time recommended by the supplier (Table 3). According to the supplier, CA1 and CA2 should be applied immediately after placements where CA3 should be applied after the initial surface water sheen has disappeared [39].

Results and discussions

The plastic shrinkage behaviour of the reference mix was studied to understand the associated governing mechanisms. Thereafter, water curing and the use of curing compounds and the impact on typical plastic shrinkage cracking behaviour were investigated.

Uncured

The settlement, capillary pressure development, and crack area results of the uncured, reference mix are shown in Fig. 6. Cracking started between 100 and 120 min. Thereafter it entered the rapid growth period between 120 and 180 min and stabilised soon after. This behaviour is driven by the shrinkage, settlement and capillary pressure as described by Combrinck et al. [7] and the trends are similar to findings by other researchers [4].

Water curing

Water curing was applied once at five unique times (WT1–5), see Table 3 and Fig. 6. The impact of water curing on the vertical settlement, capillary pore pressure development, shrinkage, and crack area growth for the different water curing times are shown in Figs. 7, 8, 9, 10 and 11. The figures show both the water curing and uncured results for comparison. Figure 7 shows the effect of water curing when applied just at the start of capillary pore pressure build-up (WT1). Water curing at this point is observed to significantly lower both vertical settlement and capillary pressure as seen in Fig. 7.

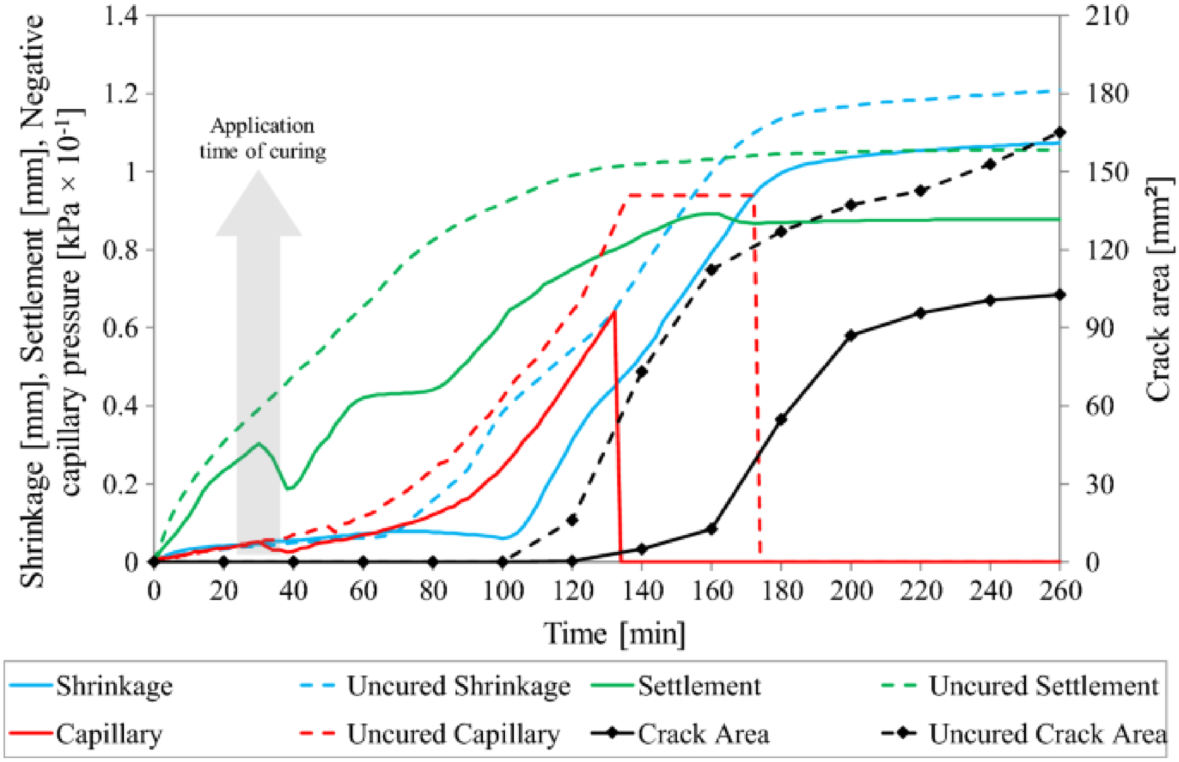


Fig. 7. Uncured Vs WT1: Settlement, capillary pressure, shrinkage and crack area

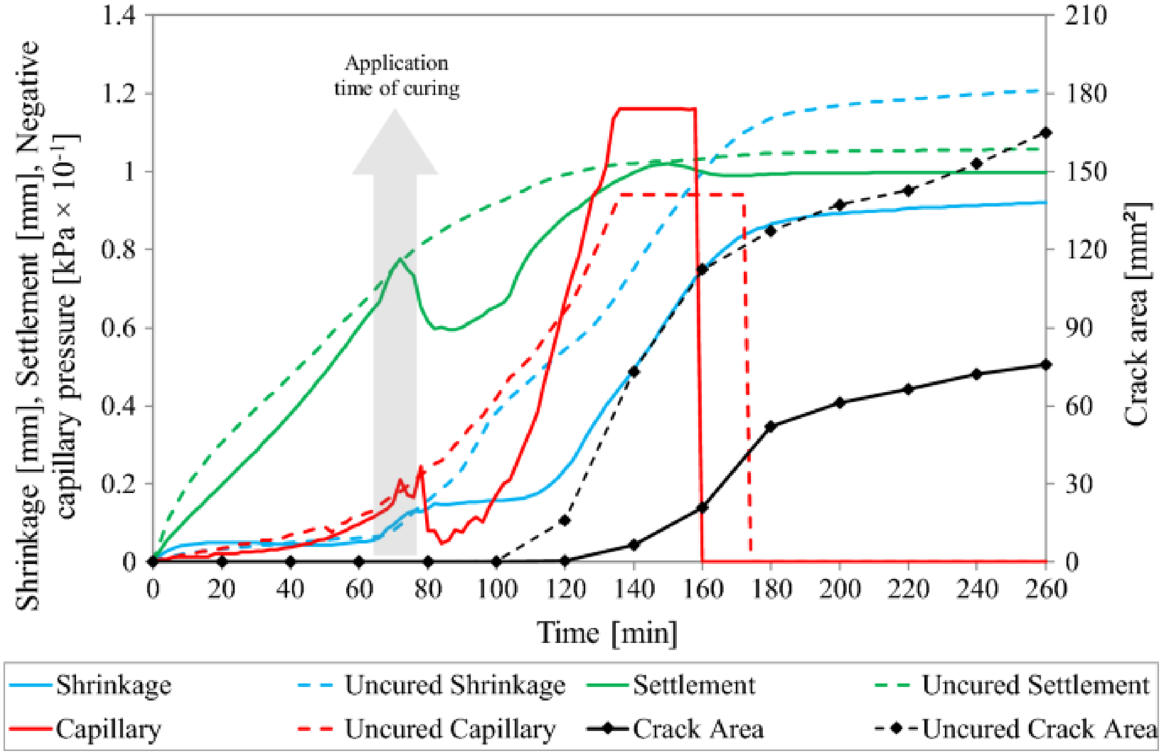


Fig. 8. Uncured Vs WT2: Settlement, capillary pressure, shrinkage and crack area

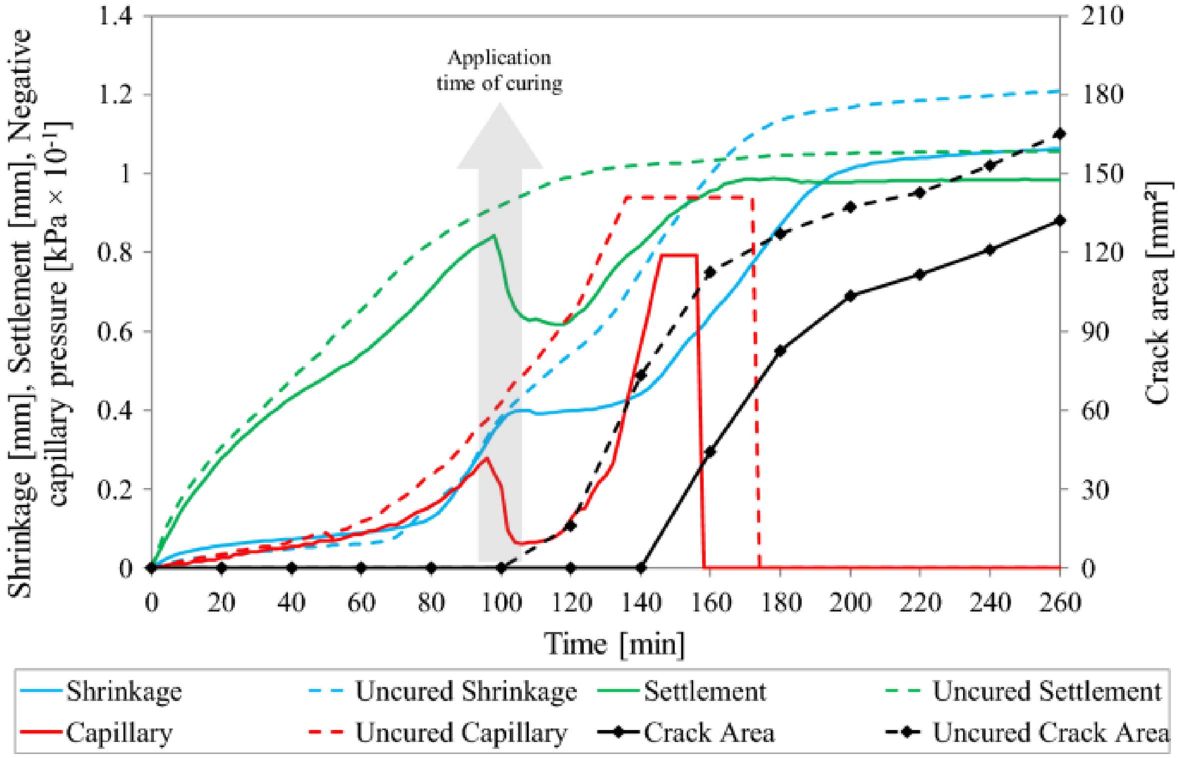


Fig. 9. Uncured Vs WT3: Settlement, capillary pressure, shrinkage and crack area

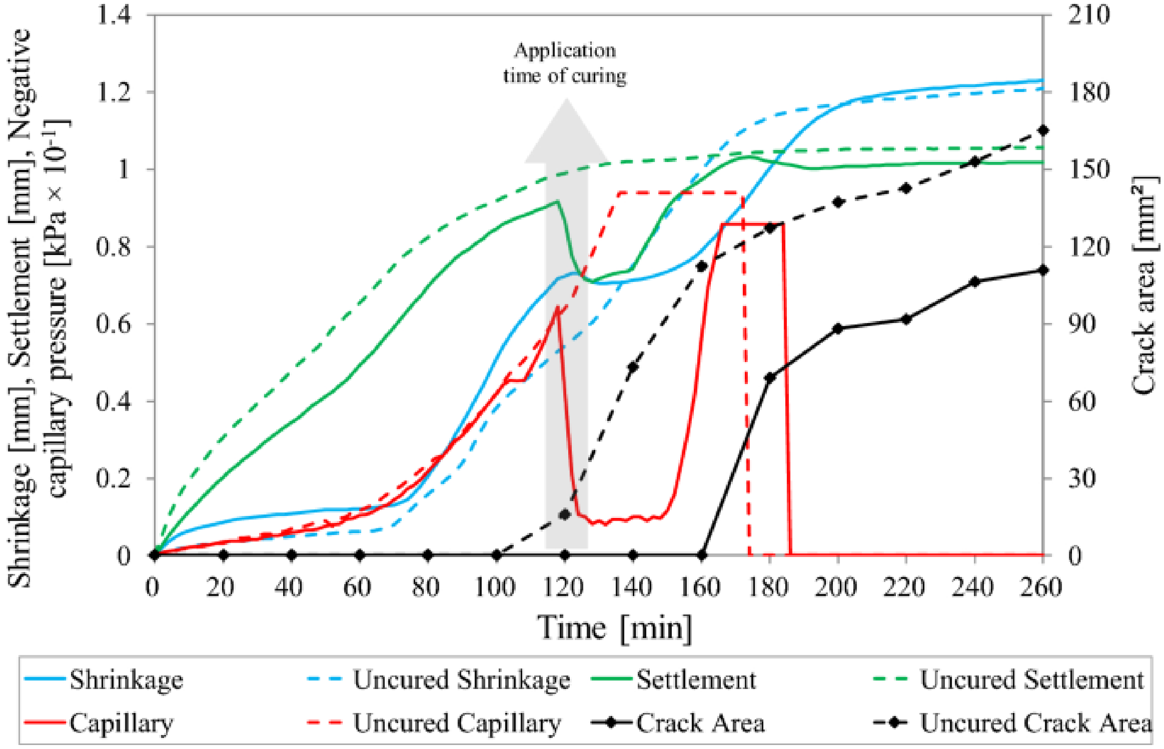


Fig. 10. Uncured Vs WT4: Settlement, capillary pressure, shrinkage and crack area

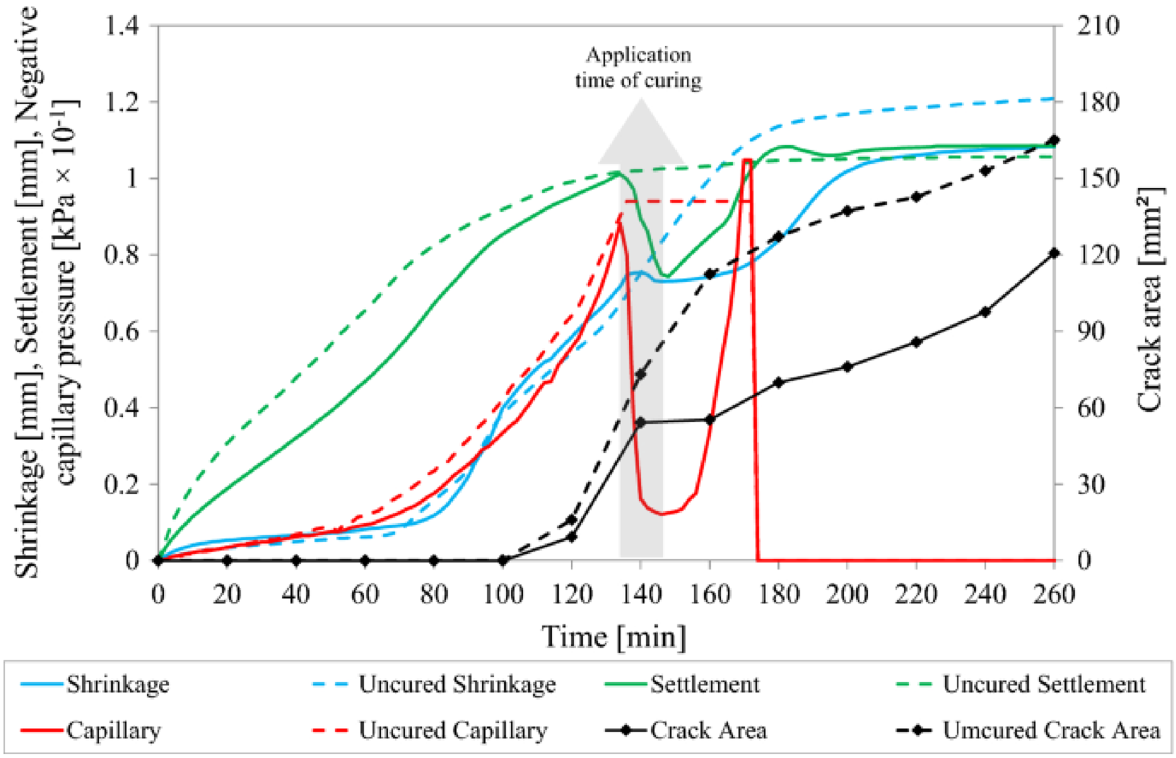


Fig. 11. Uncured Vs WT5: Settlement, capillary pressure, shrinkage and crack area

Figure 7 also reveals a momentary reduction in vertical displacement, for about 5–10 min, after which vertical settlement continues to increase at almost the same rate as before the application of curing. The reduction in vertical settlement is reasoned to be due to a slight swelling or reversal of the settlement of the top part of the concrete due to the applied curing water which relieves the capillary pressure. The same behaviour is observed to be consistent for all water curing application times, WT2-5, as seen in Figs. 8, 9, 10 and 11, respectively. However, the effect is more pronounced for later curing application times since more capillary pressure is relieved the later the curing is applied.

The result suggests that vertical settlement is also strongly influenced by capillary pressure which is normally only associated with horizontal shrinkage. A similar conclusion was reached by Combrinck et al. [7], whom showed that the settlement of concrete is caused by both gravity immediately after casting as well as the capillary pressure build-up after the drying time. Vertical shrinkage and the settlement results in plastic settlement cracking which is mainly caused by differential settlement [34]. Of the five single water application times (Figs. 7, 8, 9, 10 and 11), the least amount of vertical settlement occurred with WT2, when water was applied at the start of shrinkage (WT2). The reduction in vertical settlement reduced the potential plastic shrinkage cracking [7].

Capillary pore pressure development is similarly affected by the application of curing (Figs. 7, 8, 9, 10 and 11). Prior to water curing application, WT1 and the Uncured sample showed similar rates of capillary pore pressure development. The capillary pressure in the system is momentarily reduced to almost zero with water application. Thereafter, the rate slowly starts to increase to eventually reach a similar rate as the Uncured. Although the rate is similar, the magnitude of capillary pressure is delayed by approximately 15 min. Similar to WT1, WT2-5 all showed a similar response of capillary pore pressure development upon application of water curing. Before the application of water curing, the Uncured and respective water curing mixes all show similar trends and rates of capillary pore pressure development. At the point of application of water curing, a rapid drop in capillary pressure occurred, lasting for about 10–20 min. Thereafter, capillary pore pressure quickly increased and at an even higher rate than before, until the point of air entry. The increase in capillary pressure build-up is reasoned to be due to the decrease in the permeability of the plastic concrete mixture due to the continual production of hydration products. This leads to a decreased supply of water to the surface which is being lost at the surface due to evaporation. As a result, this leads to a higher rate of negative capillary pore pressure development.

As expected, the drop in capillary pressures delayered the development of horizontal shrinkage, as shown in Figs. 7, 8, 9, 10 and 11. For WT1, in Fig. 7, curing delayed the start of shrinkage by about 30 min compared to the Uncured trend. Thereafter, the shrinkage steadily increased at an almost similar rate to that of the Uncured. WT2, in Fig. 8, showed a delay in shrinkage. Both WT1 and WT2 delayed the shrinkage development when the magnitude was still small. Curing before WT1 and at WT2 the start of shrinkage increased the drying time of plastic concrete, delaying the start of the shrinkage. On the other hand, WT3-5 delay the shrinkage development at a higher shrinkage magnitude and was aimed to reduce the shrinkage-related damage. In fact, WT3 delayed the shrinkage at 0.4 mm, the same shrinkage magnitude at which cracking occurred in the Uncured sample.

All the water cured application times produced a lower final shrinkage when compared to Uncured, except WT4. WT1-2 performed better than WT3-5 in this regard. Based on these results, it is reasoned that there is an amount of shrinkage beyond which water curing may not significantly change the potential for plastic shrinkage cracking. This is because, at that level of shrinkage, a significant level of damage (micro cracking or internal tensile stress build-up) may already have occurred. After this critical point, additional water curing would not prevent plastic shrinkage cracking. It is clear from the crack results that extending the drying time (WT1-2) is more effective than attempting to reduce the shrinkage-related damage (WT3-T5). The best time to apply water curing is therefore just before the start of shrinkage.

Literature agrees that plastic shrinkage is a response to capillary pressure [4, 6]. At the start of the shrinkage period, the capillary pressure results in more shrinkage due to a lower Young's modulus, resulting in a more deformable concrete [8]. Young's modulus is a measure of the ability of a material to withstand changes along its length when under tension or compression. Bulk modulus is the ability of a material to resist the change in its volumes and explains settlement and plastic shrinkage behaviour well [40, 41]. Since the mould depth for the capillary pressure measurement mould is constant, the Young's modulus is sufficient to describe the concrete's resistance to change along its length. As the material stiffens, and the Young's modulus increase, the effect of the capillary pressures becomes less pronounced. Therefore, even if the rate of the second increase in capillary pressure is higher, the fact that it occurs later reduces the shrinkage response.

Ultimately, curing is intended to reduce plastic shrinkage cracking. The crack growth for WT1-5 is seen in Fig. 12. From the water curing crack area results, it is clear that the timing of application of curing is crucial in influencing the resultant amount of plastic shrinkage cracking. WT2 showed the least amount of shrinkage, settlement and cracking among the water cured sets. This further confirms that optimum curing should be done just before the start of shrinkage. This is evidenced by crack areas of WT1 and WT3-5. Water curing that is done after significant shrinkage has occurred may only delay surface crack initiation for a while, but it is believed that internal micro cracks or tensile stresses may already have developed. It is this damage that later manifests as cracks once shrinkage starts to increase. Furthermore, the results show that applying water curing just once, even at the critical time, is not enough to completely eliminate cracking in conditions with high evaporation rates.

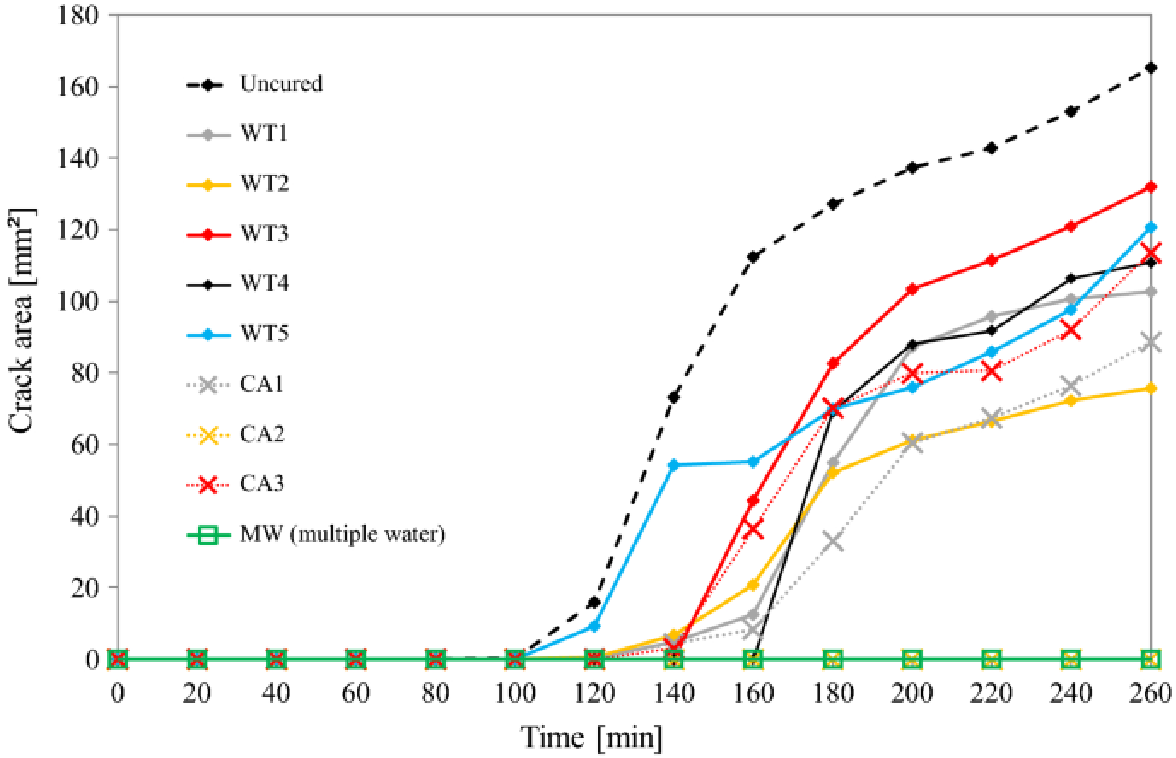


Fig. 12. Crack area growth for water curing WT1-5, curing compounds CA1-3 and MW

Based on the shrinkage performance of WT2, an additional test was conducted. Water was applied multiple times (MW) as soon as the shrinkage started to increase. In MW, water was applied at around a 30 min interval, at 64, 91, 132, 163, 205 and 235 min after casting. The shrinkage displacement results of all the tests can be seen in Fig. 13. Admittingly, the application at 205 min should have been applied earlier at around 191 min. Nevertheless, the shrinkage reduced 95% compared to the Uncured set. Applying the water multiple times (MW) also eliminated cracking, as seen in Fig. 12. This result further confirms that curing acts to relieve shrinkage and is best applied before any significant shrinkage has occurred. Figure 13 also compares the relative shrinkage performance of other curing approaches adopted in this research. It should also be noted that when the water is applied to the surface of the concrete, a temperature change occurs due to the temperature of the water and due to its later evaporation. The temperature change will only influence the upper layer of the concrete.

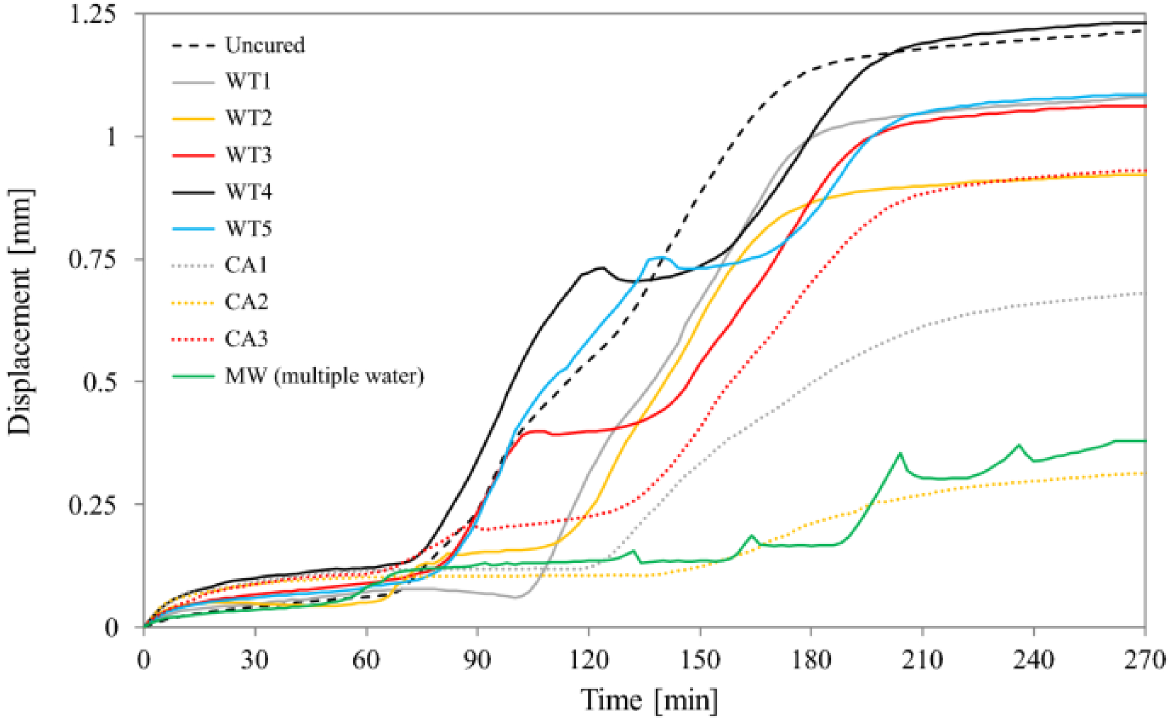


Fig. 13. Shrinkage measurements for single water curing (WT1-5), multiple water curing (MW) and curing compounds (CA1-3)

Curing compounds

Figures 14, 15 and 16 show the plastic shrinkage behaviour due to the application of curing compounds CA1-3 compared to the Uncured set. Curing compounds applied immediately after casting (CA1 and CA2) reduced the rate of capillary pore pressure development, delayed the shrinkage and crack growth for the 260 min test period. CA2 was more effective than CA1 in this regard. CA2 did not develop any measurable surface cracks and resulted in the least amount of horizontal shrinkage.

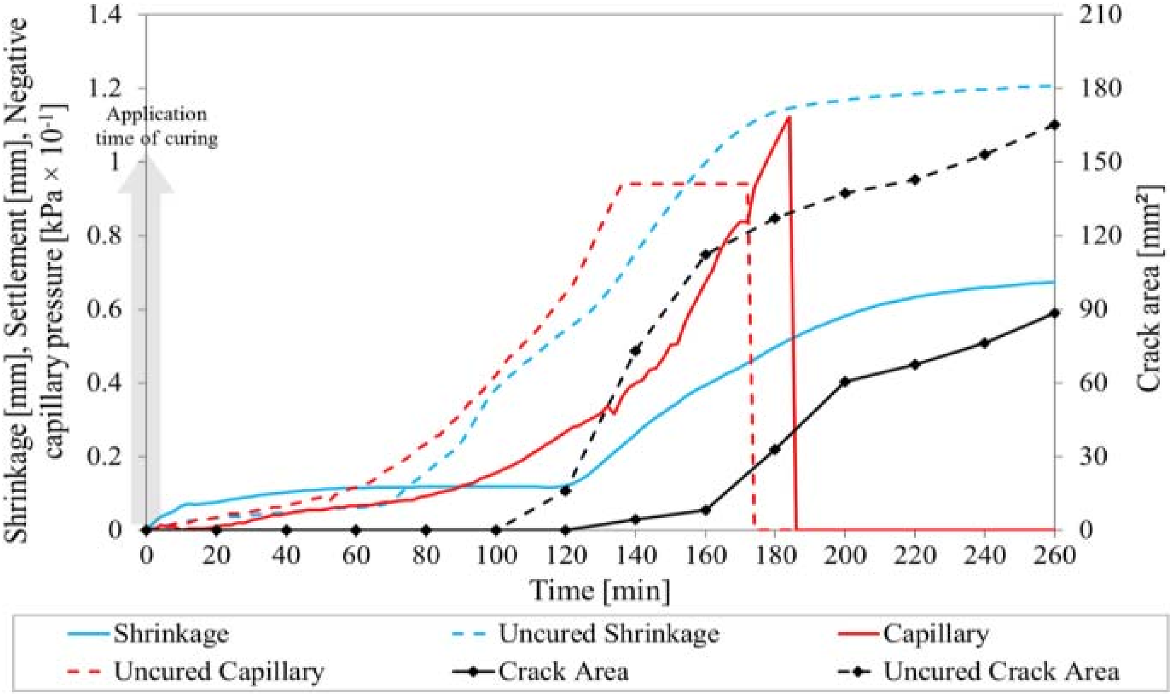


Fig. 14. Uncured Vs CA1: Capillary pressure, shrinkage and crack area

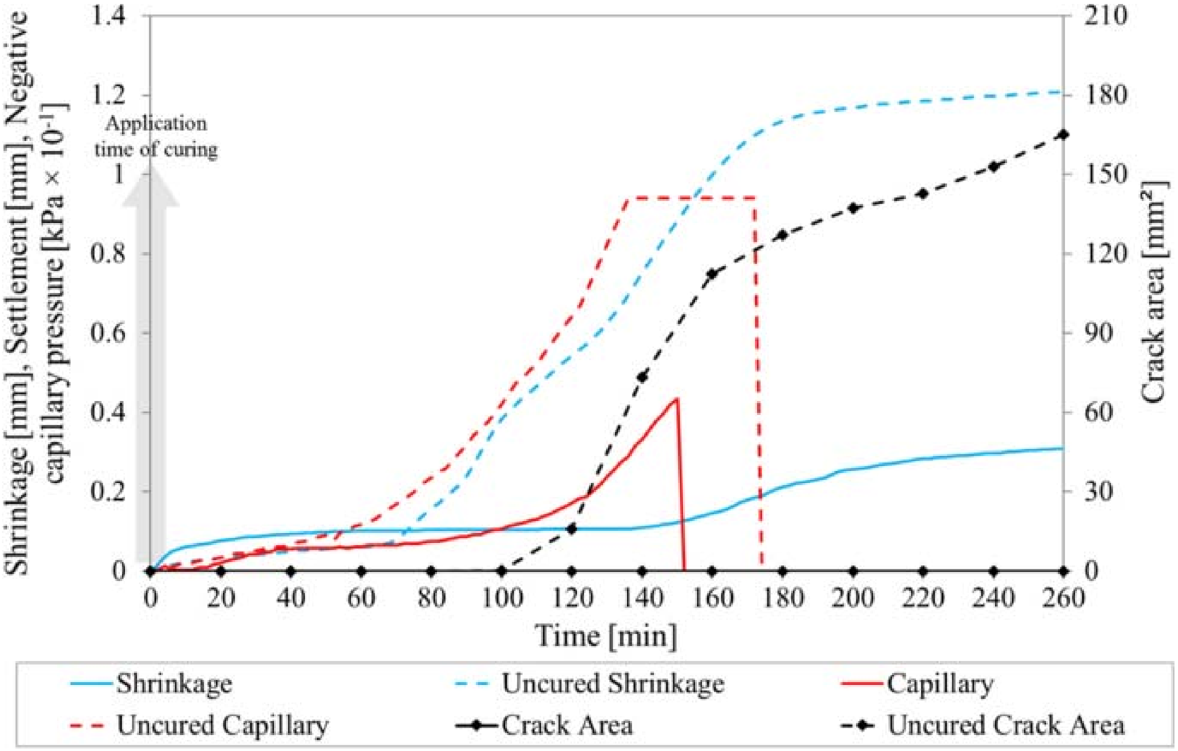


Fig. 15. Uncured Vs CA2: Capillary pressure, shrinkage and crack area

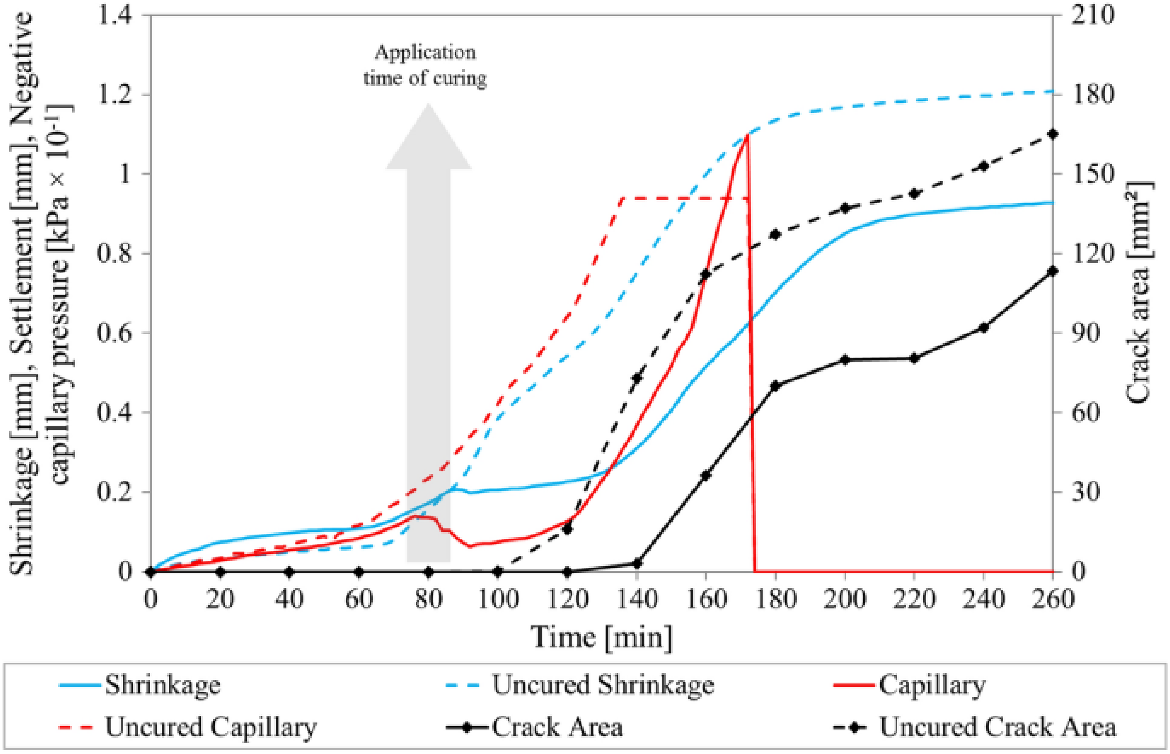


Fig. 16. Uncured Vs CA3: Capillary pressure, shrinkage and crack area

The water-based curing compound (CA3) (applied at 80 min) showed a similar drop in capillary pore pressure as the water cured sets (WT1-5). A momentary stabilisation of the plastic shrinkage can also be noticed in WT1-5 and CA3. CA3 was, however, more effective in reducing the shrinkage caused by the second increase in capillary pressure. Among the three curing compounds, CA2 was the most successful in delaying the shrinkage. It is this delay in shrinkage that prevented cracking in CA2.

The performance of CA1, CA2 and CA3 could be attributed to the differences in mass loss among the three curing compounds. Figure 17 shows the relative difference in mass loss when the curing compounds were sprayed onto the concrete. CA1 and CA2 notably reduced the mass loss when compared to the Uncured set with CA2 being marginally more effective. Ultimately, the pore water evaporation (indicated by mass loss) is what influences capillary pore pressure development, shrinkage and, eventually, cracking. The reduced crack area in CA2 can be attributed to the lower rate of mass loss. CA3, applied at 80 min, did not reduce the mass loss when compared to the Uncured set. Ghourchian et al. [13] and Nasir et al. [42] also attributed the shrinkage and cracking reduction caused by the application of a curing compound to the reduced evaporated water.

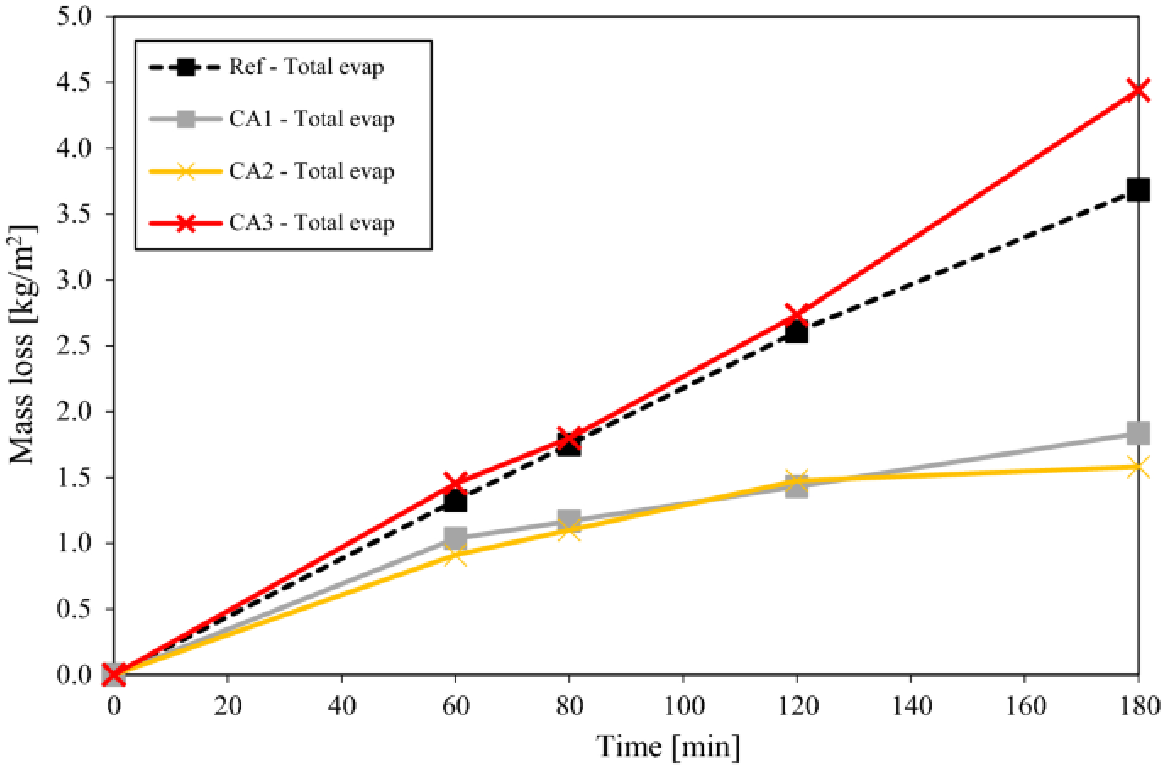


Fig. 17. The total mass loss due to evaporation from the Uncured (Ref) and the curing compound (CA1-3) sets

It should also be noted that the film formed by the three curing compounds created an aesthetically unpleasing layer on the specimen surface. This may also influence finishing operations and even quality, as increased signs of surface laitance was observed.

Comparison of water curing and curing compounds performance

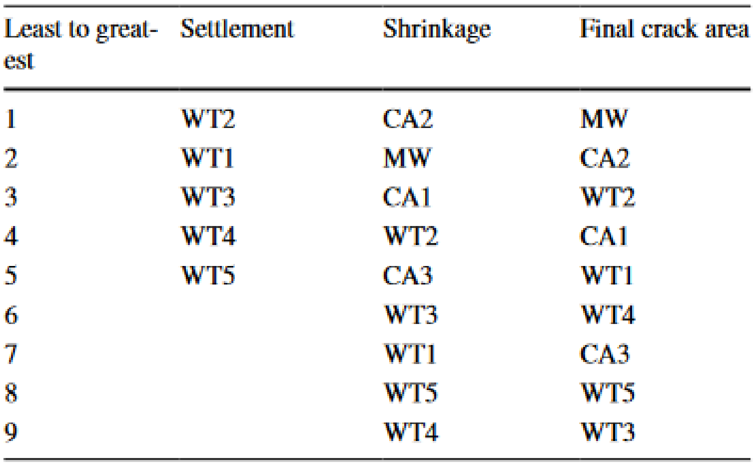
For the different water application times (WT1-5), the capillary pressure development trend only deviated from the Uncured trend at the point of curing, with a drop in capillary pressure reading. This is even more prominent for WT4 and WT5 (see Figs. 10 and 11, respectively) for which curing was applied much later. The drop in capillary pressure development should not be confused with air entry into the system as it soon recovers and attains actual air entry at a later time. This drop in capillary pressure to almost zero is responsible for the observed slight reduction and near stabilisation of the shrinkage.

It should be noted that sensors were always zeroed at the start of each test since the LVDT and capillary pressure sensors are controlled by one system. Thus, capillary pressure started from zero instead of a positive value (due to hydrostatic pressure) as is usually expected and then became negative as the capillary pore pressure developed. Consequently, the dropped value seen in the graphs, caused by the application of curing, is the true zero and thus the point of stabilisation or no pressure. While WT1, WT3, WT4 and CA2 showed lower air entry values compared to WT2, WT5, CA1 and CA2, this does not have a direct influence, since the variability of air paths deviates arbitrarily. The emphasis should rather be placed on the rate of capillary pressure development and change thereof, as seen for CA1 (Fig. 14) which shows a long steady growth before air entry occurs. This slow increase in the rate of capillary pore pressure results in a slow increase in shrinkage and, ultimately, less shrinkage at final set and less severe cracking. The sharp growth in capillary pressure, as seen for WT4 and WT5 (Figs. 10 and 11), is the cause of the more severe cracking.

For the water curing regimes WT1-5, the deviated capillary pressure at the point of curing application, caused a lower shrinkage value at the end of the testing period. WT4 registered a slightly higher final shrinkage value than the Uncured since it showed a slightly higher rate of shrinkage growth before the application of water curing. For curing compounds, the water-based curing compound (CA3), also reduced the capillary pressure momentarily, similar to the water curing regimes.

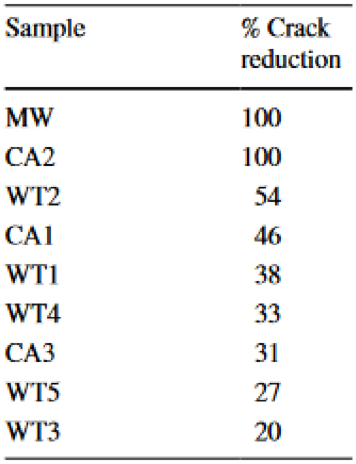
Curing acts by prolonging or delaying the first appearance of cracks. This behaviour is seen for all curing tests but is dominantly shown by WT1 and WT2 where cracking started approximately 20 min later than the Uncured. WT5 follows the Uncured closely and the crack stabilises for a short period after the application of curing. It should be noted that WT5, for which water curing was applied after crack growth started, crack area growth stabilised briefly and increased steadily thereafter, once again mimicking the trend of the Uncured but at a lower rate of growth. On the contrary, WT3 and WT4 do not completely follow the expected behaviour as WT3 ends with the highest crack area among all curing types. The performance of the different curing approaches in terms of settlement, shrinkage, final crack areas and percentage crack reduction compared to the Uncured are summarised and shown in Tables 4 and 5.

Table 4. Vertical settlement, horizontal shrinkage, final crack areas and % crack reduction compared to the Uncured



Least to greatest	Settlement	Shrinkage	Final crack area
1	WT2	CA2	MW
2	WT1	MW	CA2
3	WT3	CA1	WT2
4	WT4	WT2	CA1
5	WT5	CA3	WT1
6		WT3	WT4
7		WT1	CA3
8		WT5	WT5
9		WT4	WT3

Table 5. Crack reduction compared to the uncured sample



Sample	% Crack reduction
MW	100
CA2	100
WT2	54
CA1	46
WT1	38
WT4	33
CA3	31
WT5	27
WT3	20

CA1 and CA2 followed a different approach than water curing. CA2, and to a lesser extent CA1, successfully reduced the rate of water evaporation to retard the rate of capillary pressure development and significantly reduce all its consequences. Specifically, CA1 and CA2 delayed the start of the shrinkage period by about 50 and 70 min, respectively, compared to the reference. It is clear from the presented results that delaying the start of the shrinkage is very effective in reducing the total shrinkage. It is apparent that beyond a certain shrinkage threshold, delaying the shrinkage does not influence the final value. Generally, exceeding this threshold leads to an unredeemable amount of shrinkage leading to plastic shrinkage cracking.

The curing compounds generally performed better than the water curing, with the acrylic compound (CA3) performing similar to WT3 and WT4, the wax compound (CA1) performed similarly to the optimal water curing (WT2) while the petroleum-based compound (CA2) prevented the appearance of cracks. CA1 and CA3 both conformed to water curing, prolonging the appearance, and lessening the crack area, with the wax (CA1) having a greater influence than the acrylic (CA3). CA2 showed complete prevention of the crack on a surface visual level; however, internal cracks were observed to form beneath the surface as shown in Fig. 18. The use of CA2 (petroleum agent) greatly delayed and reduced the shrinkage and capillary pressure, which resulted in a low cracking potential. The shrinkage was, however, still large enough to result in an internal crack that started below the stress riser and propagated upwards, but did not reach the surface. This has also been reported by literature which confirmed, through X-ray radiography and microCT scanning, that cracks could potentially stop just below the surface of the concrete [43, 44]. Similar internal cracks were also observed by others [7, 34] and can be attributed to plastic settlement cracks that form due to differential settlement of the concrete due to the depth change caused by the stress raiser. Thus, it cannot be fully concluded that the CA2 curing compound completely prevented cracking.

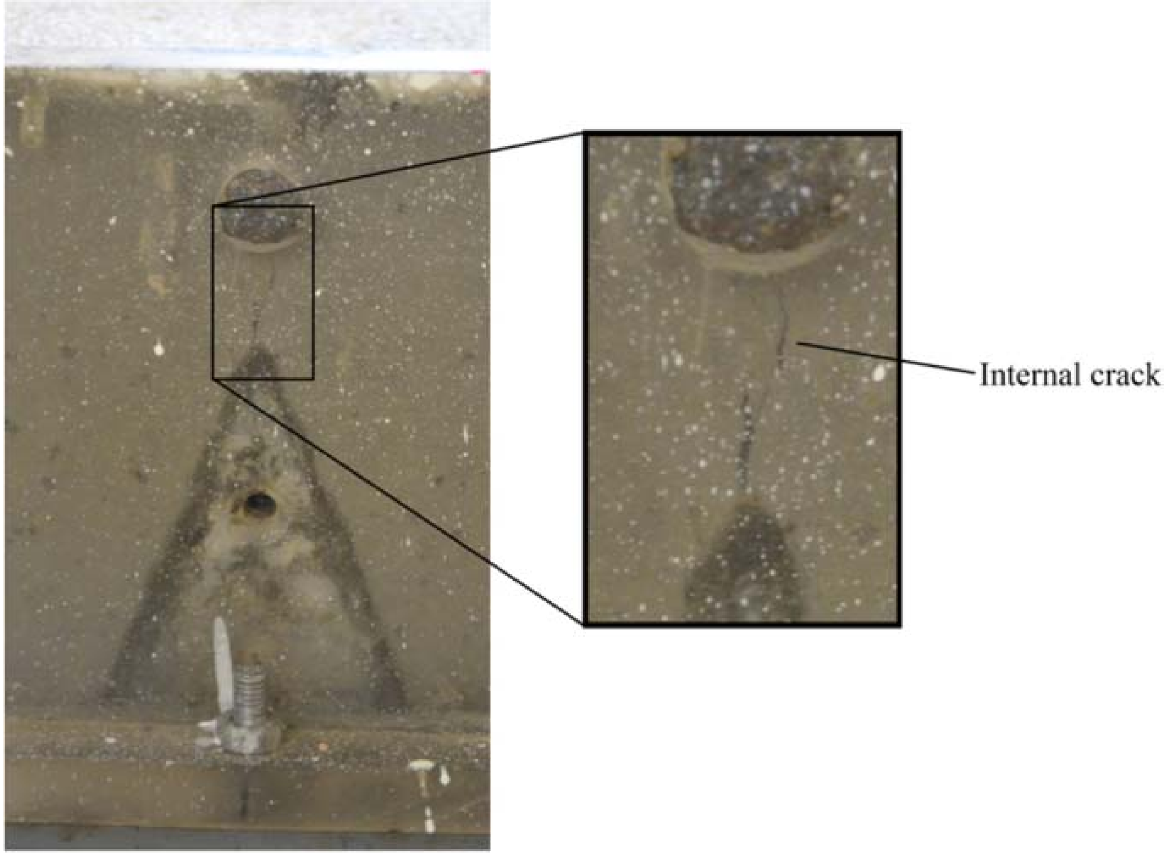


Fig. 18. CA2 internal crack below the surface as seen from the side

The results indicate that applying water multiple times (MW) was as effective in reducing the shrinkage and crack area as the best performing curing agent (CA2). MW prevented the shrinkage from exceeding the threshold beyond which the concrete is damaged unredeemable.

Conclusions

In this research, it is evident that curing concrete during the plastic phase, irrespective of application time or curing liquid/compound has a positive effect on cracking and lessened the resultant final crack area, as well as postponed the appearance of the crack for some of the curing regimes. This can be seen using shrinkage, settlement and capillary pressure results as a pre-emptive guideline, which are then confirmed by the crack area results. The results also reveal that complete prevention of plastic shrinkage cracking using curing was not possible; however, the testing of the samples was done under extreme climate conditions in which cracking is almost inevitable. The following conclusions can be drawn based on the results of this research.

- Curing directly impacts on the fundamental mechanisms of plastic shrinkage cracking, such as vertical settlement, volumetric shrinkage and capillary pore pressure development. Application of curing either caused a reduction in the rate of progression of plastic shrinkage phenomena or a stabilisation, eventually leading to a delay in the occurrence of plastic shrinkage cracking.

- A momentary reduction in vertical displacement occurred once water curing is applied, for about 5–10 min, after which, vertical settlement continues to increase at almost the same rate as before the application of curing. The reduction in vertical settlement is reasoned to be due to a slight swelling or reversal of the settlement of the top part of the concrete due to the applied curing water which relieves the capillary pressure. The same behaviour is observed to be consistent for all water curing application times, WT2-5, as seen in Figs. 8, 9, 10 and 11, respectively. However, the effect is more pronounced for later curing application times since more capillary pressure is relieved the later the curing is applied.

- The optimal application time of water curing is revealed to be just at the start of shrinkage and before any visible surface cracks, where in this study the curing at this timing led to a 54% crack size reduction.

- The results also show the importance and sensitivity of applying curing at the optimal time, and that applying curing only slightly before or after this optimal time, results in much less plastic cracking reduction.

- The petroleum resin emulsion, CA2, showed the best crack reduction performance, completely preventing surface crack development, though there were internal cracks that developed below the surface at the triangular restraint.

- The final size of the crack areas after curing is dominated by the shrinkage behaviour of the sample. Thus, the closer the curing is applied to the start of shrinkage, the greater effect curing will have. Similarly, the appearance of cracks can be postponed by curing the sample just before the first appearance of cracks. These effects on shrinkage and crack appearance are verified by both water curing (WT2) and curing compounds (CA1-2) which greatly influenced the crack area and postponed the appearance of cracks.

- Applying water curing multiple times can be just as effective in mitigating the internal damage caused by severe shrinkage. In fact, applying water at an interval of 30 min after the start of the shrinkage period (at about initial setting time) was be just as effective in reducing the crack area as the best performing curing compound. This method is also a more cost-effective and environmentally friendly approach.

The use of these curing regimes and compounds in everyday concrete practice should prove to be effective and could even prevent plastic shrinkage cracking if applied correctly and timely. However, the use of curing compounds may require prior testing on the influence on surface finishing operations and quality, due to the thin film left on the surface of the concrete. There are also practical difficulties with application of the water curing methods on-site due to poor workmanship, mix proportion, environmental conditions and no special attention to the time water curing is applied. The authors recommend that curing times could be provided by concrete batch plants accompanied by controlled tests before the start of any construction project.

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Ethics declarations

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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