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ABSTRACT

Solar radiation is electromagnetic energy emitted by the sun. Exposing early age concrete to solar radiation can increase the concrete temperature significantly. This increase in concrete temperature can increase the early age pore water evaporation, the driving force of plastic shrinkage cracking (PSC). The increase in concrete temperature can also increase the rate of hydration that can reduce PSC. This study investigates the influence of solar radiation on PSC by measuring the concrete temperature, pore water evaporation and PSC severity. The direct normal radiation was eliminated by placing one set of specimens in the sun and the other in the shade while keeping all other external variables constant. It was observed that direct normal solar radiation exposure significantly increased the surface temperature as well as the core temperature of early age concrete. The evaporation of pore water was much higher when exposed to the sun. PSC was more severe in the presence of direct normal radiation even though the setting time was reduced. The results indicate that eliminating direct normal radiation can significantly reduce PSC.

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ABSTRACT

Solar radiation is electromagnetic energy emitted by the sun. Exposing early age concrete to solar radiation can increase the concrete temperature significantly. This increase in concrete temperature can increase the early age pore water evaporation, the driving force of plastic shrinkage cracking (PSC). The increase in concrete temperature can also increase the rate of hydration that can reduce PSC. This study investigates the influence of solar radiation on PSC by measuring the concrete temperature, pore water evaporation and PSC severity. The direct normal radiation was eliminated by placing one set of specimens in the sun and the other in the shade while keeping all other external variables constant. It was observed that direct normal solar radiation exposure significantly increased the surface temperature as well as the core temperature of early age concrete. The evaporation of pore water was much higher when exposed to the sun. PSC was more severe in the presence of direct normal radiation even though the setting time was reduced. The results indicate that eliminating direct normal radiation can significantly reduce PSC.

1. INTRODUCTION

In South Africa, concrete is often placed in hot, dry and windy conditions that can lead to plastic shrinkage cracking (PSC). Plastic shrinkage cracks can serve as a direct pathway for the ingress of harmful agents into the concrete, resulting in the corrosion of reinforcement and the deterioration of the microstructure[1,2,3]. Placing concrete at elevated temperatures can also result in an inferior microstructure and reduce long-term strength[2,3,4,5]. Exposing concrete to high evaporation rates for prolonged periods in the first 28 days after casting would also increase the long-term drying shrinkage.

When concrete is placed, bleeding water rises to the surface, causing a vertical dimensional reduction known as plastic settlement[6,7,8]. Cracks can form if differential settlement occurs, at horizontal reinforcement or where the concrete element changes depth[7]. These cracks are referred to as plastic settlement cracks. Plastic shrinkage, on the other hand, is a three-dimensional volume reduction caused by pore water evaporation. A high wind speed, low relative humidity and high ambient temperature can lead to a high evaporation rate that dissipates the bleeding water and increases the early age pore water loss in the concrete[9,10,11]. When the pore water evaporates a negative capillary pressure is created that contracts the particles in the paste, leading to plastic shrinkage[12]. Plastic shrinkage cracks only occur if the shrinkage is restrained, for example, by tensile reinforcement or by frictional resistance provided by the concrete base[13].

In literature, the influence of solar radiation on plastic shrinkage cracking is often disregarded, with most studies conducting experiments in a laboratory with constant air temperature. On-site, the presence of solar radiation can increase the concrete temperature significantly above the air temperature, resulting in much higher evaporation rates[14]. During the day when the concrete is exposed to solar radiation, the surface of the concrete absorbs solar heat flux, and heat energy accumulates inside the concrete body. The energy dissipation of the heated concrete is governed by the convection parameters, which include the ambient temperature and the convection heat transfer coefficient[15]. Concrete's inability to dissipate this accumulated energy effectively via thermal diffusivity ($\alpha = \frac{\kappa}{\rho C_p}$) results in a core temperature that is much higher than the air temperature[16]. The temperature difference increases as the air temperature decreases in the afternoon, as the heat released by the exothermic hydration reaction increases the core temperature even further. The extent to which solar radiation increases the core temperature has not received much attention from other researchers in the past.

The increased core temperature can be advantageous in terms of plastic shrinkage cracking. Literature[1,17] suggests that plastic shrinkage typically starts after the initial set and subsides at the final set. The period between the initial and final set is defined as the critical period for plastic shrinkage cracking[1]. The plastic shrinkage generally starts once the bleeding water has evaporated and decreases as the concrete stiffens. It is well known that the rate of the hydration reaction, responsible for the stiffening, is dependent on the concrete's temperature. Therefore, increasing the concrete temperature can also decrease the likelihood of plastic shrinkage cracking by reducing the time of the critical period, as suggested by some literature[18].

Several internal and external factors may influence the temperature of concrete during its early age. Internal factors include the mix constituents as well as the influence of the constituents on the hydration reaction. The hydration process is an exothermic chemical reaction that influences the temperature of the concrete, as it generates heat over time. The initial temperature of the constituents used can also dramatically affect the temperature of the concrete for the first few hours. External factors include the air temperature, formwork, solar radiation, evaporative cooling and construction methods[1,19]. Of these, solar radiation is one of the most influential factors[14].

Solar radiation is a form of electromagnetic energy emitted by the sun and is measured in energy over time per unit area or watt per square meter (W/m2). Global horizontal radiation (GHI) is the total amount of short-wave radiation received by any surface horizontal to the ground.

The two primary forms of GHI include direct normal radiation (DNI) and diffuse horizontal radiation (DHI). DNI is the total radiation measured at the surface of the earth, excluding the atmospheric losses due to absorption and scattering. The diffused component of GHI is known as DHI. The ratio of DHI to DNI tends to increase with an increase in cloud cover[16].

The absence of relevant literature necessitates this research. Some researchers have exposed concrete to the sun to investigate PSC. However, no research could be found that quantified the solar radiation in its GHI, DHI and DNI components. The main objective of this study is to determine the extent to which quantified solar radiation influences the temperature of freshly placed concrete, the rate of pore water evaporation as well as the effects these factors have on PSC.

2. EXPERIMENTAL FRAMEWORK

2.1. Experimental test program

To achieve the objective of this study, a test was performed in an open-air outside environment where one set of concrete samples were exposed to the sun and the other set of samples were placed in the shade.

2.2. Mixture properties and mixing procedure

The mixture used during the experiment is displayed in Table 1. CEM II 52.5N cement is the South African equivalent of the Type II cement in the USA and GB cement in Australia. CEM II contains between 6 and 20% limestone extender. The high cement content was selected to increase the contribution of the hydration reaction to the internal temperature of the concrete as well as to provide a high paste content which gives more potential for plastic shrinkage cracking. Even though a lower cement content and admixtures are typically used in the marketplace, a mixture without an admixture and with a high cement content was beneficial in this study.

All the materials used in the concrete mixture were stored in a climate-controlled room for 24 hours before the test, with a controlled ambient temperature of 23°C and a relative humidity of 60%. This ensured that the casting temperature of the concrete was constant. The aggregates were added in a saturated surface dry state with constant moisture content. The dry materials were mixed for one minute in a pan mixer, whereafter water was slowly added and then mixed for another two minutes. After a total mixing time of three minutes, the concrete was placed into several moulds and vibrated and finished on a laboratory vibrating table. To reduce the finishing time, multiple specimens were vibrated at once. The large weight of about 50 kg on the table resulted in a low vibration intensity. It therefore took 5 minutes of vibrating to remove the majority of the entrapped air within the specimens at this low intensity. No segregation was noticed while demoulding the specimens after the experiment with the coarse aggregates being evenly distributed in the cement paste, as also shown in Figure 2. The concrete samples were finished using a steel float.

Table 1: Material constituents and mixture properties.

Constituents	Quantity (kg/m^3)
Water	205
Cement (CEM II 52.5 N)	466
Coarse aggregate (13 mm Greywacke stone)	900
Fine aggregate (Natural quarry sand)	850

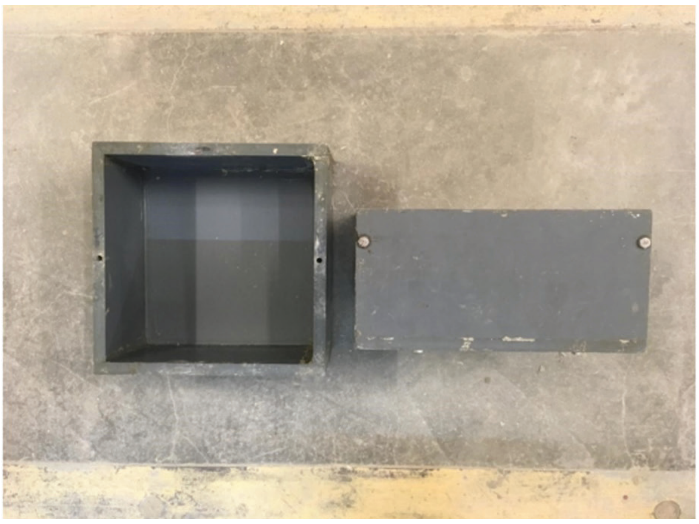
2.3. Moulds

PVC moulds, with inner dimensions of 200 x 200 x 100 mm, were used to measure the evaporation rate during this study. A similar mould was also used to measure the concrete temperature during the test. Figure 1a shows the moulds used for these tests. Figure 1b shows the PSC mould that was used to induce a single crack by creating a weak spot in the concrete. These moulds were used in accordance with ASTM C1579[20] with two additional steel bars at the end to increase restraint[17].

Each mould was adequately cleaned and sealed with a silicone sealant to prevent moisture leakage and placed in the same climate-controlled room with the materials. Mould release oil was applied to the inside of the moulds prior to placement to simplify the demoulding of the specimens.

2.4. Measurements

During each experiment, the mass loss due to evaporation, concrete temperature, as well as the crack area of the concrete samples was measured as discussed in the following sections.



(a)

(b)

Figure 1: Moulds used during (a) evaporation and temperature tests; (b) PSC test to induce cracks.

Evaporation test

For measuring the evaporation rate, three samples were placed in the sun and three in the shade. The rate of evaporation was determined by weighing each concrete sample every 30 minutes and using the average between the three samples. An electronic scale with a resolution of 0.1 g was used to measure the mass loss.

Temperature test

Temperature sensors, with a resolution of 0.1 °C, were cast in the samples to measure the temperature of the concrete during the test. Five sensors were cast over the depth of the concrete samples, with a spacing of 20 mm between each sensor. Figure 2 shows the spacing of the sensors within the concrete. Each sensor was connected to a data logger that logged a temperature reading every minute on a computer throughout the entire test.

The top sensor, located 5 mm below the surface, was used as the concrete surface temperature and the middle sensor, located 45 mm below the surface, as the core temperature.

Crack test

The crack development was observed by taking a high-resolution picture every 15 minutes. These pictures were scaled using Matlab software to measure the crack area that formed in the two concrete samples in the sun and the two in the shade.

2.5. Test conditions

The test was performed in an open area near the Sonbesie weather station (http://weather.sun.ac.za/) in Stellenbosch that measured the air temperature, relative humidity wind speed and solar radiation. These measurement instruments were located 1.5 m above the evaporation specimens. Figure 3a shows the full experimental setup in the sun, and Figure 3b the setup in the shade.

The test was started at approximately 12:00 pm when the direct solar radiation would typically reach its maximum value if no clouds are present. The testing day was selected according to the weather forecast. A hot day with minimal cloud cover was selected as the ideal testing conditions in order to investigate the full effect of solar radiation on the concrete specimens.

Weather conditions

Figure 4 shows the average air temperature, relative humidity, wind velocity and global horizontal as well as diffused normal radiation during the test.

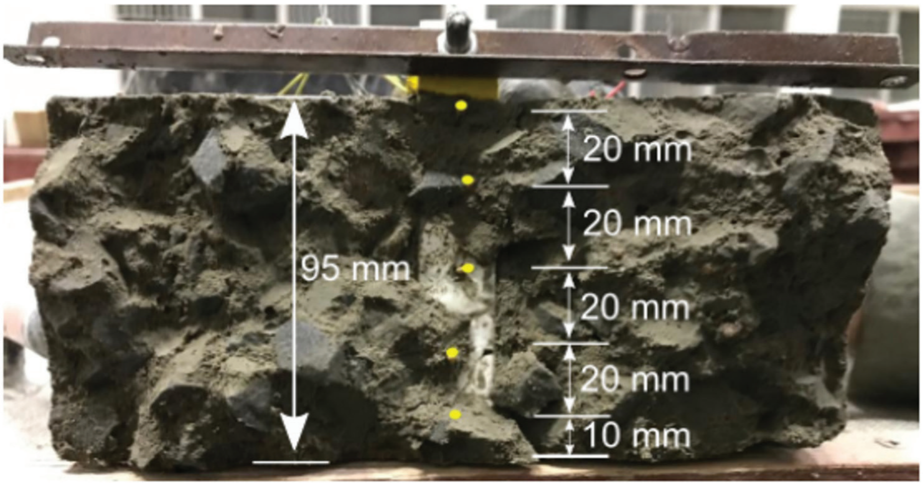


Figure 2: The spacing of the temperature sensors in the concrete samples.

(a) (b)

Figure 3: Test setup of (a) specimens in the sun; (b) specimens in the shade.

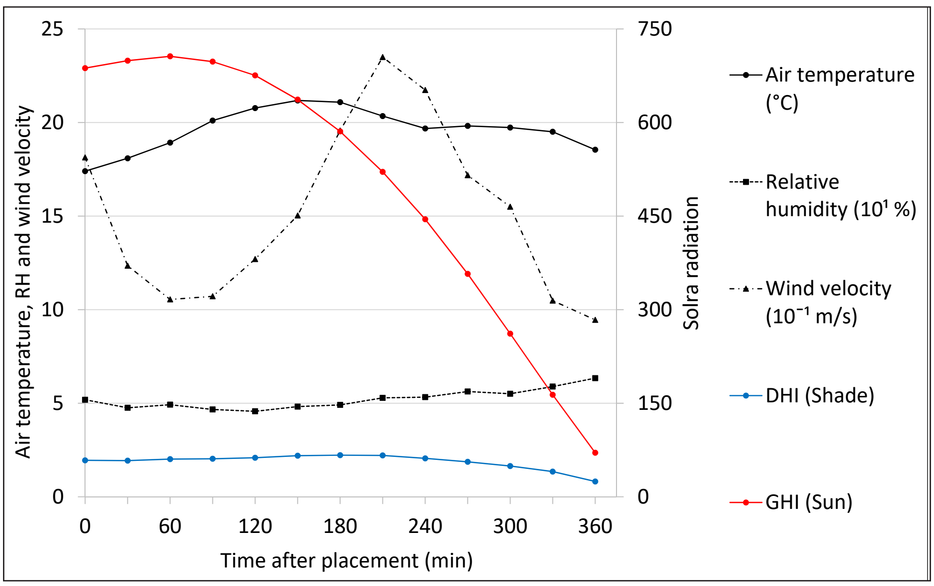


Figure 4: Weather conditions during the duration of the test.

Solar radiation

The difference in solar radiation experienced by the concrete specimens in the sun and the shade can also be seen in Figure 4. The concrete samples in the sun were exposed to a much higher level of solar radiation compared to those in the shade.

The samples in the sun were exposed to GHI and those in the shade only to DHI; the DNI was therefore eliminated for the samples in the shade. As the test was started in the middle of the day, the concrete samples experienced the peak solar radiation at the beginning of the test. A maximum peak difference of 600 W/m² was experienced between the two samples within 30 minutes after placement.

3. TEST RESULTS

3.1. Concrete temperature

Figure 5 shows the difference in concrete temperature between the samples that were placed in the sun (exposed to GHI) and the samples placed in the shade (exposed to DHI). A significant increase in the concrete temperatures of the specimens exposed to the sun was noted during the test.

The concrete temperature of the samples exposed to the sun was significantly higher compared to the samples in the shade. A maximum difference of about 10°C between the two samples occurred over the six-hour test. This was due to the effects of solar radiation experienced by the specimen in the sun. The specimen in the shade experienced a drop in temperature of about 3°C within the first three hours after placement. This drop in temperature was mainly due to the evaporative cooling effect caused by the wind flowing over the specimen. The hydration heat, produced by the high cement content, did not increase the core temperature of the shaded specimen in the first 6 hours after placement.

The surface temperature of the concrete was more variable than the core temperature as it was directly exposed to the surrounding conditions. Initially, the surface temperature in the sun was higher compared to the core temperature, but as the solar radiation gradually decreased over the day, the surface temperature also decreased. Ultimately the core temperature of the concrete was higher due to the insulating effect of the concrete in both the sun and shade samples.

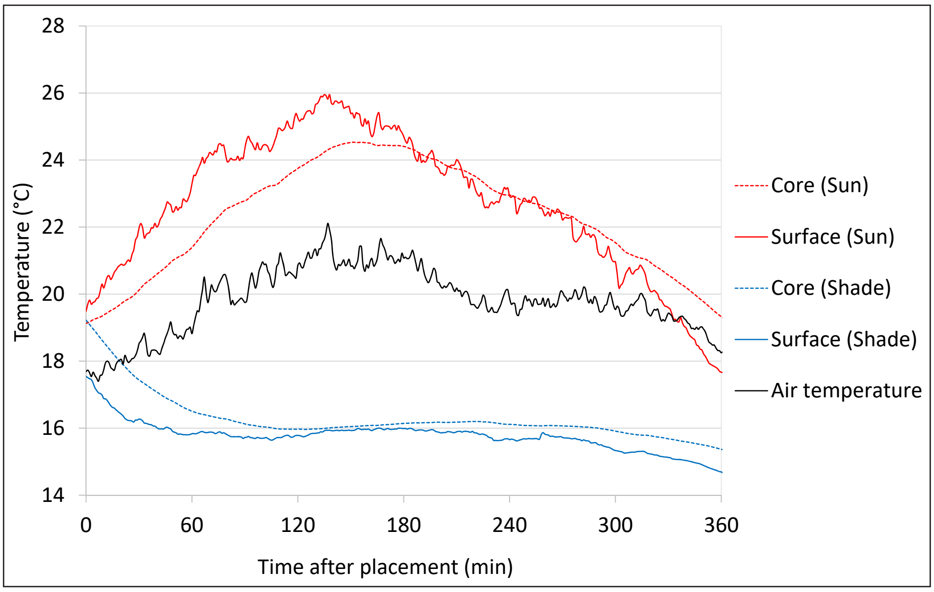


Figure 5 - Air temperature, concrete surface and core temperature over time.

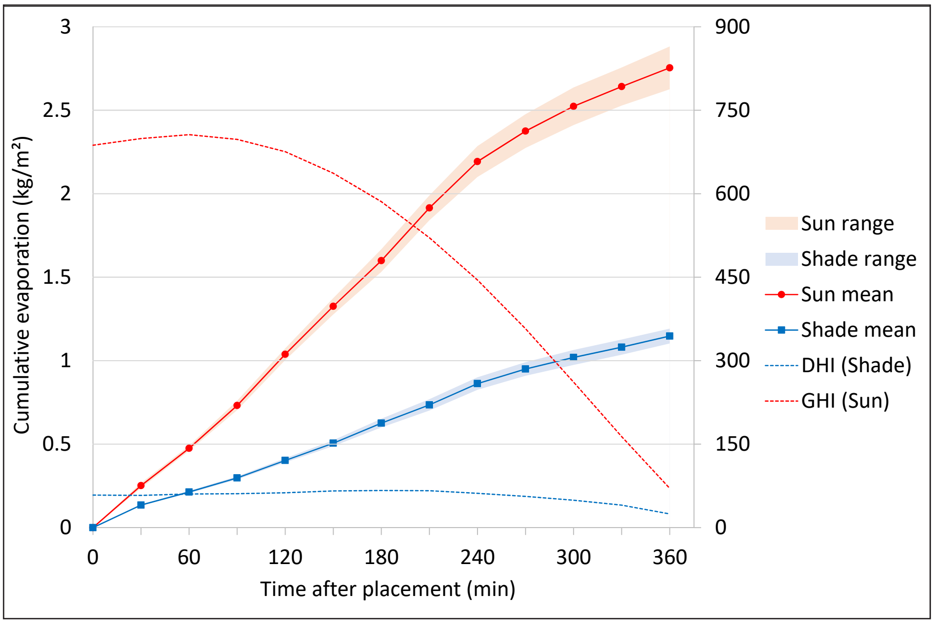


Figure 6: Cumulative mass loss and solar radiation over time.

3.2. Evaporation

Figure 6 shows the difference in the cumulative evaporation between the samples exposed to the sun and the shade. These mass losses over time are also in agreement with the amount of solar radiation experienced by each concrete sample. As expected, the concrete samples exposed to the sun resulted in a higher amount and rate of evaporation when compared to the samples in the shade.

Exposure to the sun significantly increased the rate of evaporation experience by the concrete specimens. Exposure to the sun resulted in a mean increase in mass loss of 95% within the first 60 minutes when compared to the samples in the shade and a peak of increase of 120% occurring after 180 minutes. It is clear from these results that exposure to the sun produced a higher evaporation rate compared to specimens in the shade.

3.3. Plastic shrinkage cracking

Figure 7 shows the plastic shrinkage crack area development as well as the cumulative evaporation over time. The severity of the PSC was determined by measuring the area of the cracks forming on the surface of the concrete.

PSC only occurred in the samples exposed to the sun with no cracks occurring in the concrete samples that were placed in the shade. Exposure to the sun resulted in an increase in concrete temperature that led to a higher evaporation rate. This increase resulted in more plastic shrinkage and, therefore, larger cracks. These cracks first appeared around 270 minutes after the concrete has been placed.

The concrete was still in a plastic state and did not have sufficient tensile strength to resist the strain that developed due to shrinkage.

4. CONCLUSION

An experimental program was executed to investigate the influence of solar radiation on the surface and core temperature of concrete, the rate of pore water loss as well as PSC. The following main conclusions can be drawn from this study.

Exposure to direct solar radiation can significantly increase the surface and core temperature of concrete. The surface temperature of the concrete was initially higher compared to the core temperature but gradually decreased as the solar radiation decreased. The core temperature was ultimately higher due to the insulating effect of the concrete. The concrete surface temperature was dominated by solar radiation with evaporative cooling being notable only in the shaded specimen.

The evaporation of free pore water was much higher when exposed to the sun (GHI) than in the shade (DHI). More energy was provided to the water molecules exposed to the sun, giving them the ability to overcome their intermolecular bond and transform into a gas.

Plastic shrinkage cracking occurred in the samples exposed to the sun (GHI), with no cracking in the samples placed in the shade. Exposing early age concrete to the sun leads to higher concrete temperatures and evaporation rates that ultimately results in more severe plastic shrinkage cracking. **CB**

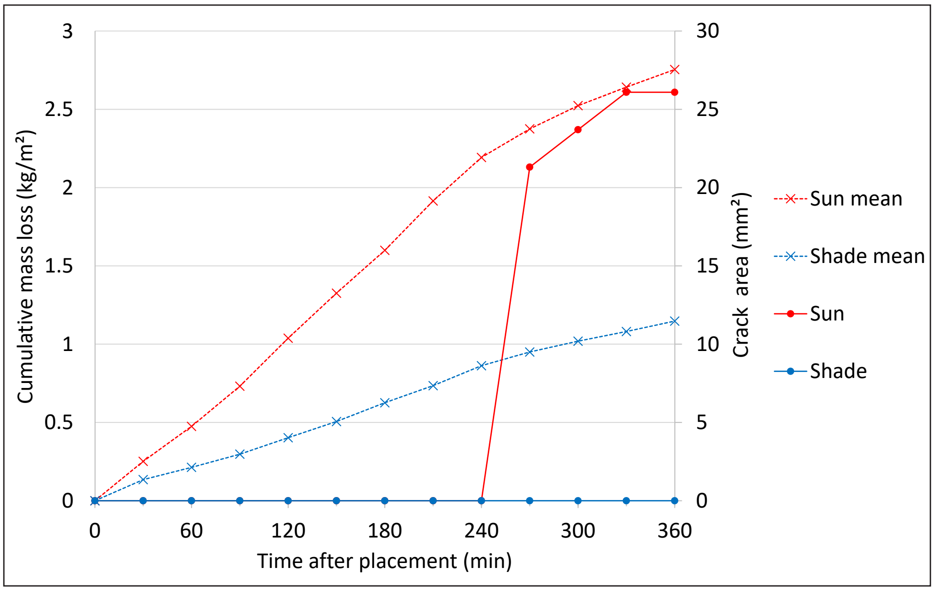


Figure 7: Plastic shrinkage crack area development and cumulative mass loss over time.

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