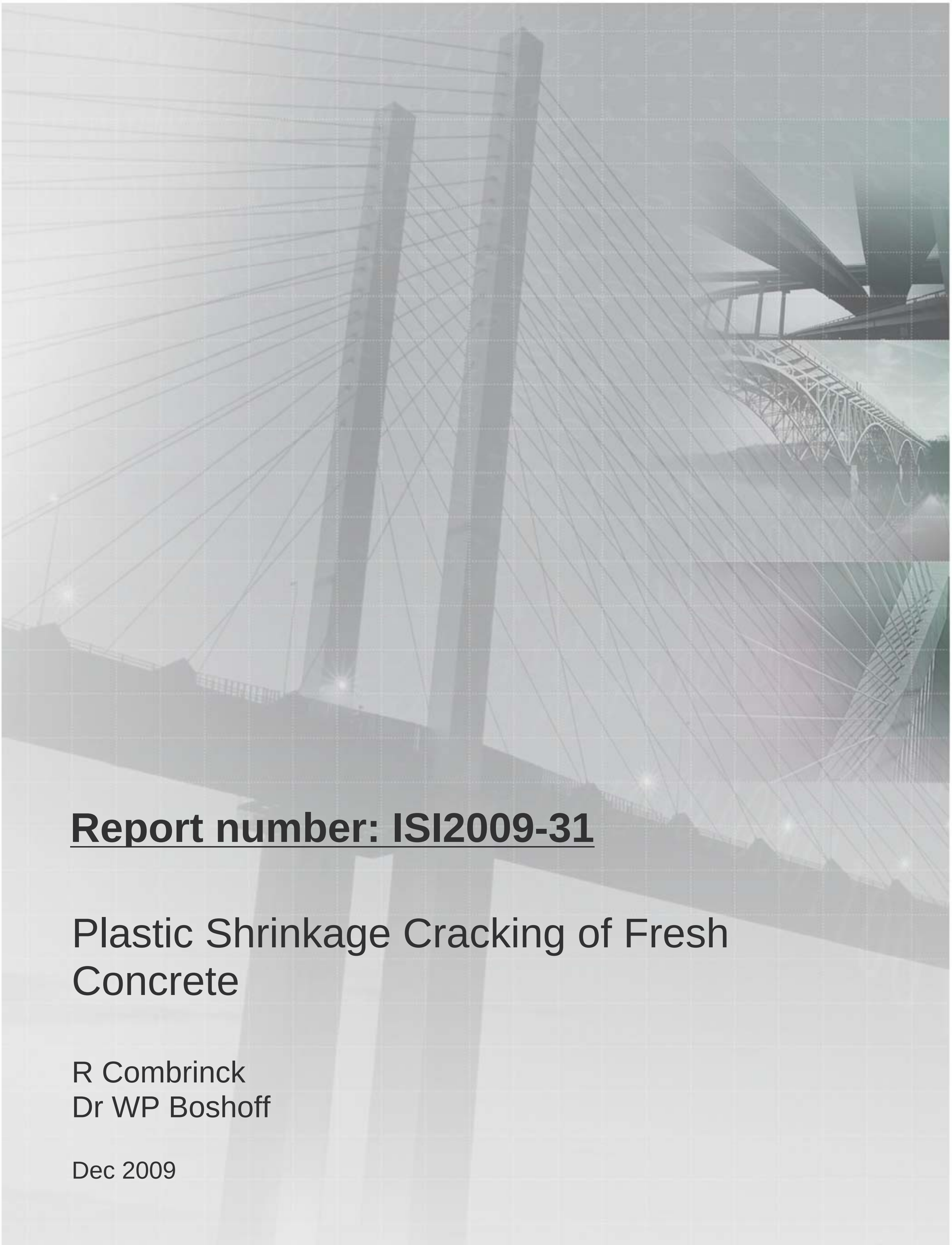

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Plastic Shrinkage Cracking of Fresh Concrete

R Combrinck
Dr WP Boshoff

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INSTITUTE OF STRUCTURAL ENGINEERING

Contents

1. Introduction

This report gives the basic knowledge to understand plastic shrinkage cracking in freshly cast concrete. It starts with a brief overview on plastic shrinkage cracking as background. This is followed by sections discussing the mechanisms causing and influencing plastic shrinkage cracking.

2. Brief Overview of Plastic Shrinkage of Concrete

This section gives brief answers to questions typically asked concerning plastic shrinkage cracking.

2.1. What is plastic shrinkage cracking in concrete?

The term *plastic shrinkage cracking of concrete* is self explanatory if it is broken down into its components.

Firstly, plastic shrinkage cracking occurs in *concrete*, where *concrete* is a mixture of cement, water, fine aggregate (sand) and coarse aggregate (gravel or crushed rock) in which the cement and water have hardened by a chemical reaction called hydration (Illston et al., 2001).

Secondly, *plastic* refers to the state of matter in which the concrete finds itself. It is agreed that a material capable of being moulded or shaped it is plastic (Powers, 1968) and more or less behaves like a fluid or liquid. A plastic concrete is therefore still in the liquid or fluid phase which occurs only for a few hours after water has been added to the concrete. The plastic phase ends when the concrete becomes unworkable, which means that concrete placement, compaction and finishing becomes difficult. This point in time is called the initial set of concrete (Garcia et al., 2008).

Thirdly, shrinkage refers to a volume reduction. This volume reduction of the concrete during the plastic phase is mainly due to the loss of water due to evaporation.

Finally, cracking tells us that the concrete cracked due to this shrinkage or volume reduction. These cracks can only form if the concrete is restraint because if no restraint is present the concrete will shrink freely with no cracks (Addis, 1998).

2.2. Where is it a problem?

Plastic shrinkage is mainly a problem with large exposed surfaces like floor slabs and paving placed in environmental conditions with a high evaporation rate. The faster water evaporates from the concrete surface the more the shrinkage, which gives a bigger potential for cracking. A high evaporation rate is caused by conditions with high temperature (often associated with direct sunlight), high wind speeds and low relative humidity (Addis, 1998). The potential for plastic shrinkage cracking is also high for mixes with a high fine content, like high strength concrete and Self Compacting Concrete.

2.3. *Why is it a problem?*

From an aesthetical point of view plastic shrinkage results in unsightly surface cracks which give a non-uniform appearance of the concrete surface. In some cases cracks that penetrate the full depth of the concrete slab has been reported.

More importantly, plastic shrinkage results in serious durability issues due to the possibility of corroding agents infiltrating the concrete through the cracks. This accelerates concrete deterioration and consequently gives a reduction in the performance, serviceability and durability of the concrete structure (Wongtanakitcharoen, 2005).

2.4. *What is being done to prevent it?*

Since the conditions that give rise to plastic shrinkage cracking are common in South Africa it is very important that we know what can be done to prevent it. The standard precautions used to minimize plastic shrinkage cracking can be divided into two groups. One influences the internal and the other the external factors that influence plastic shrinkage cracking.

External precautions measures (Uno, 1998 and Clobo, 2006):

- Temporary wind breaks are used to reduce the air flow over the concrete surface which hinders rapid evaporation
- Casting of concrete early in the morning, late in the afternoon or at night as well as using sunshades and adding ice to the mixing water, all minimizes the concrete temperature which reduces evaporation
- Curing the concrete surface during the plastic stage with a fog spray, liquid membrane curing compound or covering the surface with wet burlap or polyethylene sheeting also reduces evaporation
- Using evaporative retarders such as aliphatic alcohols
- Lightly damping the sub-grade and formwork prior to casting to minimize their water absorption reduces water loss

Internal precautions measures (Uno, 1998):

- Adding random distributed fibres in the concrete mix, especially synthetic fibres in low volume fractions (0.1 - 0.25%) reduces the size and distribution of plastic shrinkage cracks
- Avoid excess use of retarders which prolongs the setting time and therefore increases the risk for plastic shrinkage cracks
- Accelerators can be used to shorten the setting time and hence decreasing the risk for plastic shrinkage cracking
- Avoid or limit excessive fine content (cement and cement replacement material like fly ash and silica fumes) which reduces the bleeding rate and also induces an bigger shrinkage or volume reduction, all of which increases the risk for plastic shrinkage cracking

3. Mechanisms Causing Plastic Shrinkage Cracking

This section concentrates on the three factors that are a necessity for plastic shrinkage cracking. If one of these factors were missing, no plastic shrinkage cracks will form.

3.1. Plastic Shrinkage Mechanism

It is widely acknowledged that the origin of plastic shrinkage is capillary pressure. This was confirmed by Wittman as far back as 1976. It is therefore safe to say that the main mechanism which causes plastic shrinkage is capillary pressure. Capillary pressure is caused by water evaporation from the concrete surface. The more water evaporates the more concave the water surfaces between the particles become. These concave water surfaces are called water menisci which causes a negative pressure in the capillary water. According to the Gauss-Laplace equation (Eq.1), the pressure P is inversely proportional to the main radii of the water surface as well as the surface tension σ of the liquid. This pressure acts on the surrounding particles and tends to suck all these particles closer together (Slowik et al., 2008). This is called plastic or capillary shrinkage. Figure 1 shows the meaning of the radii in Equation 1.

$$P = -\sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$ ………………………………………………………………………..Equation 1

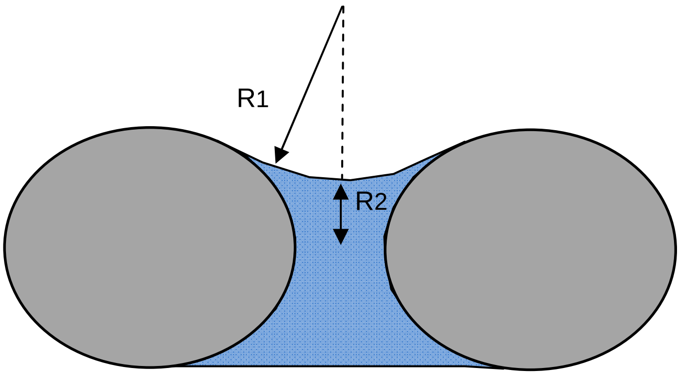

Figure 1. Meniscus forming in a capillary pore.

3.2. Crack initialization

Evaporation continuously decreases the main radii of the menisci between the solid particles which causes a rising capillary pressure build-up. The positions on the concrete surface where the particles are further apart or in other words the positions with larger pores, form weak spots because the suction forces between these particles are smaller than with particles that are closer to each other. Then at a certain capillary pressure air enters the concrete surface at these so-called weak spots. This happens locally and not simultaneously over the entire concrete surface because of the irregular arrangement of solid particles. The air enters because the radius of meniscus between the particles becomes too small to the bridge the gap between the particles. The system has now become unstable which causes a relocation of pore water. Since the positions of where air entry happened are weak spots, they also become the positions of where cracks will form. This air entry pressure was first observed by Wittman in 1976 and more research was done by Slowik in 2008, where he also stated that cracks are impossible to form without air entry into a drying surface. This tells us that the event that initializes cracks associated with plastic shrinkage is air entry.

3.3. Crack forming

Remember the position of air entry is not a crack, it is just a pore filled with air instead of water. Capillary shrinkage alone will also not form any cracks, because the material will shrink uniformly with no cracks and just a change in size (shrinkage). The other factor needed to form a physical or visible crack after the crack has been initialized by air entry is restraint (Addis, 1998). If the shrinkage is restraint, cracks will from to facilitate the change in size of the material. The restraint is ever present and can be a result of external and internal boundary conditions. See factors influencing plastic shrinkage cracking for more details on restraint.

4. Factors influencing plastic shrinkage cracking

The factors that influence plastic shrinkage cracking are diverse and all seem to be interdependent. This means that by changing one aspect, you could have an influence on several other factors that also influences plastic shrinkage cracking. For example just by using a different cement type, your are changing the bleeding, capillary pressure build-up, mobility as well as the heat of hydration which influences the evaporation and setting times. Time makes matters even more complex, because most of these factors changes continuously with time due to hydration. It is very important to keep all of this in mind to truly understand the influence that a certain change might have on plastic shrinkage cracking.

4.1. Capillary Pressure build-up

Since capillary pressure is the main mechanism that causes plastic shrinkage cracking, it is important to know what influences it.

4.1.1. Rate of Water Loss

The rate at which water is lost at the surface of the concrete depends on the rate of evaporation and bleeding. Water that evaporates from the surface is constantly replenished by bleeding water from inside the concrete paste. It is further commonly known that cracking can start as soon as the rate of evaporation of surface water exceeds the rate at which bleeding water is supplied to the surface. Therefore, the bigger the rate of water loss out of a concrete specimen, the faster the capillary pressure builds up, which is the main mechanism that causes plastic shrinkage cracking. We will now look at what influences evaporation and bleeding.

4.1.2. Evaporation

Evaporation is the process by which a liquid is converted into a vapor of gas. The liquid molecules can escape the liquid as vapor through heat absorption by solar radiation or where the pressure above the liquid surface is less than in the liquid (Uno, 1998). The bigger the evaporation rate the faster capillary pressure can build up which causes plastic shrinkage cracks. Evaporation is mainly influenced by the following environmental factors:

Wind

Wind is one of the critical factors influencing evaporation and therefore also plastic shrinkage cracking. It accelerates the evaporation process by continually removing escaping water molecules from the liquid into the atmosphere (Uno, 1998). Protecting a freshly cast concrete specimen from wind, is considered to be one of the most effective ways to reduce plastic shrinkage cracking (Kwak et al., 2006).

Relative Humidity

The relative humidity has to do with the combination of air temperature and water vapor in the air. This means that air with a certain temperature can only hold a certain amount of water vapor. The higher the air temperature the more water vapor can evaporate into the air. A 100% relative humidity means that the air is already fully saturated with water vapor and therefore does not allow any additional evaporation (Uno, 1998). If the temperature increases suddenly it lowers the relative humidity for example from 100% to 90%, which now allows more water to evaporate into the air. The lower the relative humidity the faster water will evaporate.

Air temperature

Air temperature influences the relative humidity as well as the concrete temperature. It should be noted that air temperature does not make provision for the direct solar radiation component (Uno, 1998). A higher air temperature increases the rate of water evaporation.

Concrete temperature

The concrete temperature is mostly influenced by the temperature of all the concrete components (water, cement, fine and coarse aggregate) when mixed together as well as the air temperature and the solar radiation after casting. It can also be influenced by the heat released by the hydration reaction between cement and water which will increase the concrete temperature. The higher the temperature of the concrete the faster water will evaporate. Since it is difficult to measure the water temperature of the concrete separately from the concrete, it is normally assumed that the concrete temperature is the same as that of the water in the concrete (Uno, 1998). Reducing the temperature of freshly cast concrete, is considered to be one of the most effective ways to reduce the evaporation rate (Kwak et al., 2006).

Solar Radiation

Water surfaces exposed to direct sun rays (solar radiation) evaporate much faster than without direct sun rays. This is also true for freshly cast concrete surfaces, but the opinions still differ concerning its effect on plastic shrinkage cracking. Some researcher say shielding concrete specimens from the sun will reduce the evaporation rate, which in turn will reduce the risk for plastic shrinkage cracks. Other researchers found that although specimens exposed to direct sunlight had increased evaporation, they also showed an increased rate of hydration which shortens the time available for plastic shrinkage cracking and therefore reduced the risk (Uno, 1998). It can however be speculated that increased evaporation rate due to direct sunlight will increase the risk for plastic shrinkage cracks, since these cracks normally happen within 2 to 3 hours after casting, when the degree of hydration is still low even with an increased rate of hydration. Especially considering that the extra hydration heat will increase the concrete temperature, which will further increase the evaporation rate.

4.1.3. Bleeding

Bleeding water accumulates at the surface of freshly poured concrete and is described as the upward displacement of water because of particle (mostly aggregate) settlement in the concrete (Illston, 2001). The slower the bleeding rate the faster the capillary pressure will build up which causes plastic shrinkage cracking. The rate of bleeding is influences by the following factors:

Amount of fines

The more fine content concrete has the slower the bleeding rate (Uno, 1998). Fines are mostly cement, fly ash and fine sand like crusher dust. The reason for the slower bleeding rate with increasing fine content is as follows (Suhr et al., 1990):

- The finer particles give retarded sedimentation which leads to less bleeding water
- Finer content also gives increased hydration and reacting products which makes the paste less permeable
- The fines also retards movement of water by being less permeable

Aggregate content

Since aggregate has relative densities of almost three times that of water it tends to fall to the bottom of freshly cast concrete, which displaces the water upwards (Addis, 1998). This is called bleeding, and is greatly influenced by the amount and size of the aggregate. The bleeding rate increases with increasing aggregate size and quantity (Kwak et al., 2006).

Unit water content

The more water in a concrete mix, the more capacity or potential there is for bleeding (Kwak et al., 2006).

Slab depth

The amount of bleeding water is proportional to the depth of the concrete specimen (Kwak et al., 2006). This means that it can be expected that a deeper concrete specimen will give more bleeding. The reason is that more settlement of particles can occur, which result in more bleeding water being displaced to the surface.

4.1.4. Material Composition

This concerns the size and distribution of the small solid particles in a concrete paste like cement, fly ash and fine sand.

Size

It is clear from Equation 1 that the capillary pressure gets bigger the smaller the radii of the menisci becomes. The smaller the solid particles, the smaller the radius of the menisci between them can become. This means that the smaller the solid particles in a concrete specimen, the higher the capillary pressure (Slowik et al., 2009).

Distribution

The distribution and quantity of the particle size through the concrete have a large effect on the magnitude of the pressure values reached (Slowik et al., 2009). If, for example, a certain volume of small particles are located next to each at the surface of the concrete, it will give a very high capillary pressure value. This is because there are many small particles present with small menisci between them, which results in a much higher capillary pressure than what would have resulted if the same volume was filled with larger particles. This is because the larger particles would be less over the same volume with bigger menisci between them.

4.2. Paste Mobility

This is term that describes how mobile the concrete paste is or in other words how easily does the material move or deform when subjected to a force. For a concrete paste to be mobile, the particles it consist of need to be able to move easily in relationship to each other. The mobility therefore depends on the properties of the solid particles as well as the water to solid ratio.

4.2.1. Solid Particle Properties

This concerns the physical properties like shape, size and self-weight.

Shape

The ideal shape for maximum mobility is a smooth as possible sphere. Anything not spherical or rougher is less mobile. Naturally weathered aggregate would normally be more mobile that crushed aggregates.

Size and Self-Weight

Finer particles are more mobile than larger ones because of their comparably smaller self-weight. This is because the capillary pressure needed to move these particles horizontally is must smaller than the gravitational force acting on these particles (Slowik et al., 2009).

4.2.2. Water-Solid Ratio

Here solid refers to any solid in the concrete mixture, especially the hydration products that form with time due to the reaction between water and cement. The higher the degree of hydration, the more hydration products have formed and the less mobile the paste becomes. This is because hydration gives the concrete a solid skeleton which resists movement.

4.3. Restraint

The restraint is responsible for crack forming as stated before. The restraint can be internal or external.

4.3.1. Internal restraint

The internal restraint is a result of the differential volume reduction, which means that the upper part of the concrete where evaporation takes place undergoes more shrinkage than the lower part of the concrete. The shrinkage of the upper part is restraint by the underlying concrete, which results in cracks forming from the surface downwards (Addis, 1998).

4.3.2. External Restraint

The external restraint is due to the physical casting conditions. The shape and surface roughness of the formwork or sub-grade on which the concrete is cast on has a great influence on the restraint. Irregular formwork shapes can cause additional restraint as well as formwork with a rough surface finish. Rebar also causes additional restraint, especially if used in large quantities.

4.4. Setting Time

There are two defined setting times with regard to concrete, namely, the initial setting time and the final setting time. The initial setting time is defined as the time when the concrete ceases to be liquid. This is when the concrete has stiffened so much that it can no longer be vibrated without damaging the internal structure (Garcia et al., 2008). The final setting time is when hardening begins (Ahmadi, 2000).The point at which plastic shrinkage cracking ceases is somewhere between the initial and final set of concrete. These setting times are greatly influenced by temperature, an increase in temperature will make the mixture mature more quickly and therefore decrease the setting times. The temperature is mostly influenced by the following: The heat of hydration, which differs for each type of cement, generally the finer the cement the more heat it releases during hydration. The air temperature as well as solar radiation also has a big influence on the setting times.

4.5. Building procedures

Building producers can have a great influence in plastic shrinkage cracking. It can almost be said that if the correct building procedures are followed, there will be no problem with plastic shrinkage cracking. Doing simple things like casting under the correct environmental conditions and curing can reduce plastic shrinkage cracks every time.

5. Conclusions

This report is a literature study on phenomenon of plastic shrinkage cracking and the mechanisms causing this early age cracking. It can be concluded that the most significant mechanisms that influence the occurrence of plastic shrinkage cracking is:

- **The evaporation of water from fresh concrete**. This is in turn influenced by the wind speed, ambient temperature, concrete temperature, relative humidity and solar radiation.
- **The bleeding of concrete.** This is influenced again by the amount of fines, aggregate content, water content and slab thickness.
- **The material constituents.** This refers to the particle shapes and particle shape distribution of the constituents.
- **The paste mobility.** This is the ability of concrete to deform.
- **Restraint.** This could be internal or external restraint.

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