State-of-the-art review on plastic cracking of concrete

E. Torsvik[a]

[a] *Universitat Politècnica de Catalunya, Barcelona, Spain, 08021*

Abstract

Plastic shrinkage cracking of concrete is the cracking that takes place in the plastic phase. The development within this field has mainly taken place after the beginning of the 2000s, but the first noticeable studies was already presented in the 50s. The current understanding of this cracking mechanism has developed around the understanding that the drivers are hydration, free settlement, bleeding, evaporation and capillary pressure. These in combination leads to a settlement in three dimension which tends to lead to cracks if the concrete is restrained. We separate the cracking into two different cracking types; plastic settlement and plastic shrinkage. Testing methods and models for shrinkage cracking has been developed and has contributed to a deeper understanding of the subject.

1. Introduction to plastic cracking

Concrete undergoes volumetric and other changes in its plastic state, which lasts about 3-8 hours after casting depending on the binder type, mix proportions and environment. Plastic settlement and plastic shrinkage are among these volumetric changes that in combinations with other factors can introduce cracks into the concrete. Other mechanisms are temperature variations, drying and autogenous shrinkage, whereas autogenous shrinkage is significant in concretes with a water-binder ratio less than 0.4. These mechanisms will not be described in this paper since these processes mainly takes place after the plastic phase; in the early age and onward. Early age refers to the time between final setting to 7 days [1] and it is therefore important to distinguish this phase from the plastic phase.

The problem with cracks is that they become a pathway for intruding particles such as chloride and carbon dioxide that can lead to reinforcement corrosion and carbonation in addition to the aesthetic damage. Plastic cracking is most likely to happen in concrete elements such as slabs because of the large surface area where water can evaporate from [2].

Plastic cracking has been researched since the 50's [3], and there has been a good understanding of the main reasons of plastic cracking since the early 2000s. It was understood that the rise of capillary pressure because of the evaporation of water at the surface caused the cracks [4]. Since the 2000s, more works has been carried out to investigate plastic cracking in different types of concrete such as high strength concrete, fibre-reinforced concrete, and self-compacting concrete.

It is now known that the plastic cracking mechanism starts with the settlement of solid particles in concrete which causes bleeding of free water to the surface, which is followed by evaporation from the surface. Evaporation causes high capillary pressures between the surface particles that lead to capillary shrinkage. Both capillary shrinkage and consolidation are associated to volume contractions that can lead to plastic cracking if the concrete is restrained by reinforcement, formwork, lower concrete layers or if there are high moisture differences through the concrete cross-section [5]. In the case of restraining by reinforcement, cracks is likely to develop in the same pattern s the reinforcement [7]. Several factors are known to have an accelerating or retarding effect on the plastic shrinkage. These are: concrete member size, properties regarding the mix proportions such as w/c-ratio, fines content, additives, admixtures, and environmental conditions such as relative humidity, wind velocity, air temperature and temperature of concrete surface [6]. Plastic cracks vary in size but can normally be between 50 to 1000 mm long and up to 1 mm wide. Sometimes they even split the cross-section of a structural element [7]. They are created first after the plastic shrinkage introduces tensile tresses in the concrete that exceeds the tensile capacity of the concrete [8].

Plastic settlement and plastic shrinkage are the main drivers for volumetric change in the plastic state of concrete. These are associated with plastic settlement, that is the vertical volumetric reduction in the gravitational direction, and plastic shrinkage that is a three-dimensional volumetric reduction.

2. Drivers for plastic cracking

2.1. Hydration

Hydration of concrete has an important influence on the plastic shrinkage of concrete because of the consumption of free water to form hydration products. In the hydration phase we also have water loss through evaporation and absorption in unsaturated aggregates. The water loss in this phase effects mechanisms such as free settlement, capillary pressure and bleeding. The plastic cracking behaviour is strongly affected by the stiffness development in the hydration phase [8].

2.2. Free settlement

Gravity is the main driver of the free settlement of solid particles in concrete while friction between the particles and the viscous matrix slows the process down. The settlement displaces water upwards which introduces an upward force due to the viscous drag of the moving water as illustrated in Figure 1. The process will stop once the hydration process creates hydrates or the settlement causes enough contact between the particles [5] [9].

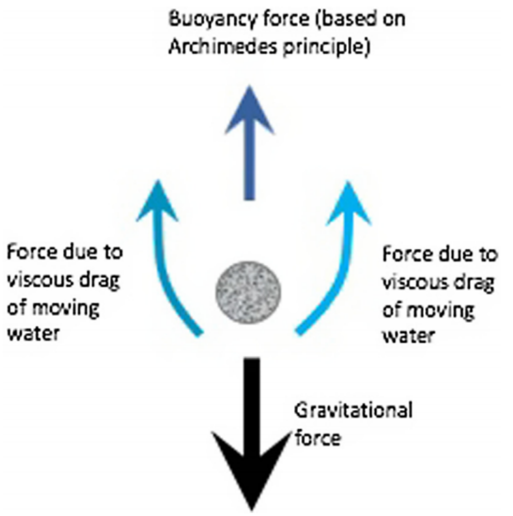

Figure 1: Forces acting on a solid particle in fresh concrete.

2.3. Bleeding

Bleeding is caused by the free settlement of particles which forces the water upwards to the surface [7]. Another driving mechanism is the suction because of the capillary pore pressure introduced when water starts evaporating on the surface [5]. Bleeding depends strongly on the w/c-ratio since it is the free mixing water that is displaced to the surface. Also, matrix viscosity, fines content, hydration rate and the cross-section shape determine the rate of bleeding [9].

2.4. Evaporation

The evaporation rate of surface bleeding water is determined by wind speed, air temperature, concrete temperature, difference between concrete and air temperature, solar radiation and relative humidity [10].

2.5. Capillary pressure

When surface water starts evaporating, the solid particles at the surface starts form a complicated system of menisci that causes a negative pressure in the capillary water determined by the increasing curvature of the menisci as shown in Figure 2. The negative pressure can be found by the Gauss-Laplace equation (1);

$$P = -(1/R_1 + 1/R_2) \tag{1}$$

Where P is capillary pressure [Pa], is surface tension of the pore liquid [N/m^2], R1 and R2 is the minimum and maximum radius of water surface curvature [mm].An important note is that a reduction of fines radius increases the number of menisci and reduces the radii of menisci, so we will get a bigger pore pressure.

The pore pressure tends to force more water to the surface and drags the particles closer together, but the drag between the particles is counteracted by the repulsive forces between the solids. If evaporation continues, the menisci will be reduced till a point where the tensile capacity of the plastic concrete is reached, and cracking will occur as shown in Figure 3 [8].

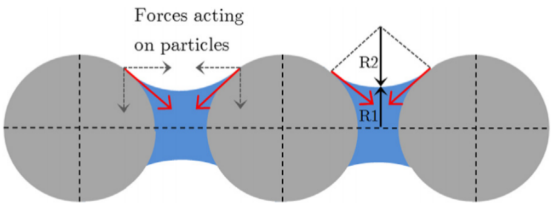

Figure 2: Capillary forces acting on particles

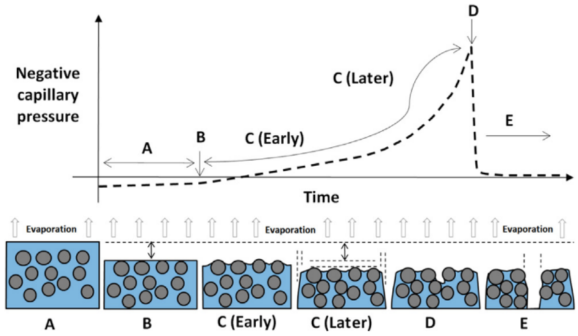

Figure 3: Relevant stages during the build-up of capillary forces within the pore structure

3. Plastic shrinkage mechanisms and their effect on fresh concrete

3.1. Plastic settlement

Plastic settlement is the volume change caused by the vertical settlement of solid particles in concrete while surface water evaporates [5]. Restraining of this mechanism by such as reinforcement or change of section depth tends to introduce cracks near the restraining as illustrated in Figure 4. Plastic settlement cracking can only occur if the concrete has settlement potential due to concrete mixture, evaporation and depth of cross-section. Settlement can be ceased completely or partly by hydration, viscosity altering admixtures and prevention of evaporation.

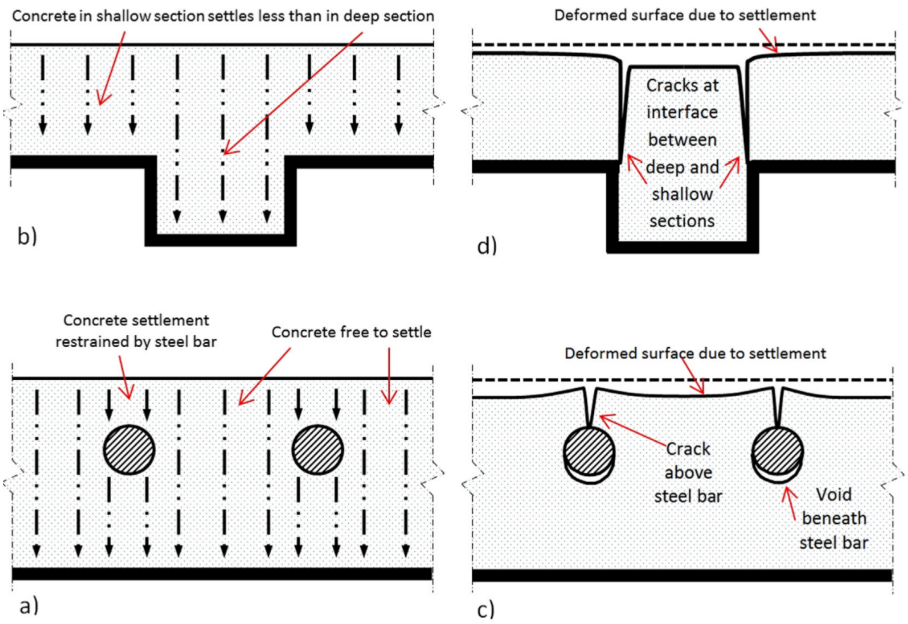

Figure 4: Cracks induced by settlement differences around a change of section depth in b) and d). Cracks induced by settlement near reinforcement bars in a) and c)

3.2. Plastic shrinkage

Plastic shrinkage is a three-dimensional volume reduction due to the suction of the capillary pores of plastic concrete [11]. During the evaporation process on the concrete surface, negative pore pressure builds up in the concrete and tends to empty the pores and lead the free water to the surface. This creates a negative capillary pressure which results in volume reduction.

4. Testing methods

4.1. Plastic settlement

The plastic settlements can be measured using a non-contact laser that measures the development of the distance from the laser to the surface over time [12]. Another method is to use a metallic wire mesh that follows the settlement of the aggregates while letting the free water pass. The displacement is measured using a linear differential transformer [11].

4.2. Bleeding

Bleeding can be measured by casting a cylinder of concrete, cover it, and extract the bleeding water accumulating on the surface with a certain time interval. The water is extracted by a pipette while the cylinder is tilted by placing a 50 mm block on one side and then weighted [13]. The tilting may disturb the sample, so there is also developed a method where one creates grooves on top of the concrete by a star shaped stencil where the water gathers, and where the water can be extracted [14]. Non-contact laser test method was developed also for this mechanism. There is no need for extraction of the bleed water or tilting in this test, so the concrete can re-absorb the water that is bled and is not disturbed by tilting.

4.3. Evaporation

To measure the evaporation rate, concrete can be casted in a form and placed on a scale. Then the weight loss due to evaporation can be measured in intervals of for example 20 minutes, and the total water loss can be obtained. Normally, a general rule that if the evaporation is less than 1 kg/m2/h there will be no cracking. It should be mentioned that this rule is empirical and almost 60 years old [15]. The evaporation rate can also be estimated by using this formula [10]:

$$ER = 5 * 10^{-6}(V + 4)[(T_c + 18)^{2,5} - r(T_a + 18)^{2,5}] \tag{2}$$

Where ER=evaporation rate [kg/m^2/h], V=wind velocity [km/h], T_c=concrete temperature [°C], r=relative humidity [%], and T_a=air temperature [°C].

4.4. Capillary pressure

Many methods are developed to obtain the capillary pressure of fresh concrete. Normally one uses a set of sensors sensitive to pressure changes inside the concrete, both to measure vertical and horizontal displacements.

4.5. Setting times

There is developed a standard, ASTM C403 (2008) [16], to determine the initial and final setting time. Here, the fresh concrete is sieved through a 4,75mm sieve to get a matrix free of aggregates. The penetration resistance of the matrix is then tested by using a penetrometer. Another standard-based test is a test where a Vicat needle is used. The test gives similar results to the previous and is based on EN 196-3 (2005).

5. Modelling of plastic shrinking and plastic settlement

Due to the complex behaviour of plastic concrete and its shrinkage mechanisms, it is difficult to accurately model the plastic shrinkage of concrete. Lately, researchers have worked with models of different mechanisms that is associated with plastic cracking, but due to the interactions between water and different types of cement, and the great variations of aggregates, especially the amount of fines, it is difficult do include all the relevant mechanisms in one model. For now, the models that is developed focuses on prediction of drying time [17], plastic shrinkage [18], probability of cracking and its total crack area [19], capillary pressure [20] and effective stress development [21]. Future work within this field will probably be to combine the total understanding in this area and combine this to a model that takes more of the governing mechanisms in fresh concrete into account.

6. Conclusion

The interest of plastic shrinkage in concrete is nothing new. The first research about this topic was done in the 50s, and since the early 2000s a lot of work has been done to improve our understanding of plastic shrinkage cracking in concrete. Our understanding has developed around the perception that shrinkage is introduced by the rise of capillary pressure because of evaporation of water at the surface and the settlement of solid particles. Testing methods to determine the different driver mechanisms for plastic shrinkage has been developed, but there is still work to be done if these instruments should be used out in the field. As for modelling of the development of fresh concrete, several models are proposed. The models take different mechanisms into account, and there is yet no single model that can precisely predict the development of plastic shrinkage cracks based on all the known influencing factors. Although, the new knowledge within this field has deepened our understanding and contributed to a basis for the development of several preventive measures to avoid cracking.

References

[1] *Bentz, D. P. (2014). Report on early-age cracking: causes, measurement, and mitigation.*

[2] *Weiss, W. J., Olek, J. (2003). Characterization of plastic shrinkage cracking in fiber reinforced concrete using image analysis and a modified Weibull function.*

[3] *Lerch, W. (1957). Plastic shrinkage.*

[4] *Holt, E. (2001). Early Autogenous Shrinkage of Concrete.*

[5] *Combrink R., Steyl, L, Boshoff, W. P. (2018). Interaction between settlement and shrinkage cracking in plastic concrete.*

[6] *Uno, P. J. (1998). Plastic Shrinkage Cracking and Evaporation Formulas.*

[7] *Slowik, V., Schmidt, M., Fritzsch, R. (2007). Capillary pressure in fresh cement-based materials and identification of the air entry value.*

[8] *Kayondo, M., Combrinck, R., Boshoff, W.P. (2019). State-of-the-art review on plastic cracking of concrete.*

[9] *Boshoff, W.P., Combrinck, R. (2013). Modelling the severity of plastic shrinkage cracking in concrete.*

[10] *Uno, P.J., (1998). Plastic Shrinkage Cracking and Evaporation Formulas.*

[11] *Solwik, V., Schmidt, M., Fritzsch, R. (2008). Capillary Pressure in fresh cement-based materials and identification of the air entry value.*

[12] *Qi, C., Weiss, J., Olek, J. (2008). Assessing the Settlement of Fresh Concrete Using a Non-Contact Laser Profiling Approach*

[13] *(2004). ASTM C232. Standard Test Method for Bleeding of Concrete.*

[14] *Josserand, L., De Larrard, F. (2004). A method for concrete bleeding measurement*

[15] *Shaeles, C.A, Hover, K.C (1988). Influence of mix proportions and construction operations on plastic shrinkage cracking in thin slabs*

[16] *(2008). ASTM C 403/C 403 M. Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*

[17] *Kwak, H.-G., Ha S.-J. (2006). Plastic shrinkage cracking in concrete slabs. Part II: numerical experiment and prediction of occurrence*

[18] *Radocea, A. (1994). A model of plastic shrinkage.*

[19] *Senthilkumar, S.R.R., Natesan, S.C. (2005). Prediction of restrained plastic shrinkage cracking in plain cement concrete*

[20] *Slowik, V. Schmidt, M., Hubner T., Villmann, B. (2009). Simulation of capillary shrinkage cracking in cement-like materials*

[21] *Ghourchain, S., Wyrzykowski M., Plamondon M., Lura, P. (2019). On the mechanism of plastic shrinkage cracking in fresh cementitious materials*